Science Supporting Dissolved Oxygen Objectives in California Estuaries

Prepared for:
The California Environmental Protection Agency
State Water Resources Control Board
(Agreement Number 07-110-250)

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Executive Summary

California State Water Resources Control Board (SWRCB) is developing nutrient water quality objectives for the State's surface waters, using an approach known as the Nutrient Numeric Endpoint (NNE) framework. The NNE framework establishes a suite of numeric endpoints based on the ecological response of an aquatic waterbody to nutrient over-enrichment (eutrophication; e.g., dissolved oxygen, algal biomass). The SWRCB intends to use dissolved oxygen (DO) as an indicator in the NNE framework for estuaries.

All seven coastal Regional Water Quality Control Boards (RWQCB) have existing basin plan objectives for DO concentrations intended to maintain satisfactory water quality in enclosed bays and estuaries. However, these objectives are not consistent across the individual RWQCBs and reflect outdated science. Thus, recent advances in scientific understanding of DO tolerance in estuarine and marine organisms, as well as new methods for setting protective limits, may provide the technical basis for improved and more consistent objectives to protect beneficial uses.

The primary objective of this document is to evaluate the current scientific basis supporting derivation of DO objectives for estuaries and enclosed bays in California. Ideally, such objectives would be applicable to the approximately 400 estuaries found in California and address regional (i.e., north-south) differences among organisms present.

The scientific approach used in this effort is adapted from the Virginia Province Salt Water Dissolved Oxygen Criteria (USEPA 2000). Briefly, fish and invertebrate species were selected as representative of estuary class, beneficial uses, life history strategies, and regional differences in species distribution across the state. Existing literature was then reviewed for each candidate indicator species or family "surrogates" to document tolerance of the fish or invertebrate species to low DO. Two types of data were sought: 1) Acute data used to derive a maximum concentration (minimum concentration in the case of DO) to protect against short-term mortality, and 2) chronic data used to derive a value protective of lethal and sublethal effects under long-term exposure conditions. These basic data requirements were then compared against data available for species that are representative of California estuaries. The DO tolerance data were then evaluated to establish their suitability for derivation of DO criteria for protecting organisms associated with California estuaries.

Study Findings

Our review found that there were insufficient data to derive criteria for native California species. Specifically, acute data were available for only three native species, and chronic data were not available for any native species. However, there were data available for some introduced species, and USEPA guidelines allow for the use of data from surrogate species (i.e., genus or family level) in cases where data on native species are lacking. Ultimately, by using data from surrogate and introduced species, the minimum data requirements for calculation of acute and chronic criteria were met. In addition, there was sufficient species representation to derive separate *acute* criteria for northern and southern California estuaries that have an "open" surface-water tidal connection to the coastal ocean and those that are intermittently closed (bar-built river mouth estuaries and lagoons). Conversely, there were insufficient data to derive separate *chronic* criteria based on region or estuary type.

Because of insufficient data issues, the SWRCB and its advisory groups had three options:

1. Collect additional DO tolerance data for native California species.
2. Apply the Virginia Province criteria on an interim basis until sufficient data are generated for native species.
3. Calculate DO objectives based on substituting genus or family surrogates for California species.

<u>We chose to proceed with the exercise of calculating DO objectives based on substituting genus or family surrogates for California species</u>. Dissolved oxygen objectives were calculated for the entire state (AllCal), Northern California (NorCal; north of Point Conception), and Southern California (SoCal). Dissolved oxygen objectives related to salmonids or other endangered species (sturgeon) were also calculated, because these species form a subset of the species present in California estuaries. Moreover, salmonids and sturgeon tend to be more sensitive to low DO than most other taxonomic groups, represent RARE and SPAWN beneficial uses, and have historically occupied wider distributions across the State. This substitution approach offers flexibility to establish objectives based on habitat requirements of local species assemblages and protection of applicable beneficial uses. Although the criteria were calculated using USEPA methodology (USEPA 1985), some concern regarding the reliance on introduced and surrogate species data , rather than native California species, may arise. Still, the species sensitivity distributions featured a reasonable number of data points for both acute and chronic conditions; criteria derivations were based on the four most sensitive genera. Reasonable agreement in sensitivity among the most sensitive genera suggests that results would not likely improve with additional estuarine species. Nevertheless, it may be desirable to obtain data for some California native species to increase confidence in the overall conclusions or to develop site-specific criteria.

Criteria that represent broad regions and estuary types are presented in the following table (CMC and CCC refer to acute and chronic values, respectively). The data also support some additional criteria categories that reflected species with limited distributions (e.g., sturgeon); these are described more fully in Section 6 of the report.

Regions and Estuary Types	**CMC**	**CCC**
All California (all systems)	4.0	5.8
Southern California (all systems)	2.9	5.8
All California (intermittently closed systems)	2.3	5.8
All California + salmonids (all systems)	4.0	6.3

In addition to acute and chronic criteria, the Virginia Province Salt Water Dissolved Oxygen Criteria (USEPA 2000) includes a criterion intended to protect cumulative annual larval recruitment. The larval recruitment criterion provides a unique set of protective targets, distinct from the acute criterion that was derived to protect the more hypoxia-tolerant juvenile and adult components of the aquatic community, and allows for varying periods of exposure depending on the concentration of DO. The default data used to derive the larval criterion do not include any California native species, but do include introduced and surrogate species.

To address two basic information gaps, we recommend the following:

1) Collect DO tolerance data for native California fish and invertebrates species. A limitation of our study was finding sufficient data to derive criteria for different types of estuaries. This was compensated to some degree with the acute data, where broad distinctions could be made on a regional basis and between open and intermittently closed systems. However, it was not possible to draw similar distinctions with the chronic data, or to make finer distinctions within the acute data set. Regardless, we would caution against making the distinctions overly precise as setting criteria at lower values based on the apparent absence of key species may limit the ability of these species to utilize or recolonize these areas on an opportunistic basis. In any case, the potential exists to refine the criteria on a site-specific basis.

2) Develop an assessment framework and implementation guidance. A next step in utilizing the calculated DO objectives would be to develop an assessment protocol that specifies the temporal/spatial averaging and data density necessary to make a determination of "impairment". Implementation guidance will be needed to inform agencies and stakeholders about theuse DO objectives in the context of assessment, TMDLs, and NPDES permitting decisions. Guidance will also be needed to address the many estuaries that exhibit naturally occurring seasonal, diurnal, or tidally-influenced periods of low DO. Consequently, consideration should be given to supporting a follow-up study to identify and formalize guidance for monitoring programs and interpretation of DO data. Part of this guidance should include methodologies to interpret temporal/spatial representation data in the context of the acute, chronic, and larval-recruitment criteria limits. Similarly, identification of appropriate averaging periods for acute and chronic criteria should help in establishing defensible objectives. Available guidance and appropriate application/implementation across Regional Boards will provide a level of assessment consistency that is currently lacking.

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1. Introduction

1.1 Background and Context for Review of Dissolved Oxygen Objectives

1.1.1 California Nutrient Numeric Endpoint Framework

Eutrophication of estuaries and coastal waters is a global environmental issue, with demonstrated links between anthropogenic changes in watersheds, increased nutrient loading to coastal waters, harmful algal blooms, hypoxia[1], and impacts on aquatic food webs (Valiela et al. 1992, Kamer and Stein 2003). These ecological impacts of eutrophication of coastal areas can have far-reaching consequences, including fish-kills and lowered fishery production (Glasgow and Burkholder, 2000), loss or degradation of seagrass and kelp beds (Twilley 1985, Burkholder et al. 1992, McGlathery 2001), smothering of bivalves and other benthic organisms (Rabalais and Harper 1992), nuisance odors, and impacts on human and marine mammal health from increased frequency and extent of harmful algal blooms and poor water quality (Bates et al. 1989, Bates et al. 1991, Trainer et al. 2002). These modifications have significant economic and social costs (Turner et al. 1998). According to the USEPA, eutrophication is one of the top three leading causes of impairments of the nation's waters (USEPA 2001). Scientifically-based state water quality objectives and tools that relate these criteria to management controls are needed to diagnose adverse effects from eutrophication.

The USEPA and the California State Water Resources Control Board (SWRCB) have previously developed and vetted a science-based approach to translate narrative water quality objectives for nutrients and biostimulatory substances to numeric targets for lakes and streams (USEPA 2006). This approach, known as the Nutrient Numeric Endpoint (NNE) framework, establishes a suite of numeric endpoints based on the ecological response of the aquatic waterbody to nutrient pollution (e.g., dissolved oxygen (DO), algal biomass). These endpoints would serve as guidance to Regional Boards in implementing narrative nutrient or biostimulatory substance objectives. In addition to numeric endpoints, the NNE framework includes a stressor-biological response tool that links these biological endpoints with nutrient loads and other potential management controls for Total Maximum Daily Load (TMDL) development and implementation.

The NNE conceptual framework has since been adapted for estuaries. In 2007 (USEPA 2007) established a scientific framework to support the development of numeric endpoints for a suite of biological response indicators and highlight data gaps and research recommendations for their development. A subsequent document articulated a broad work plan to address data gaps, develop numeric endpoints and support the efficient and cost-effective development of TMDL tools (McLaughlin and Sutula 2007). In response, the SWRCB has initiated a project to implement this work plan for California estuaries, which includes a review of DO objectives in California.

[1] In this context, hypoxia is defined as the reduction of oxygen concentrations below air saturation (USEPA 2000).

1.1.2 Dissolved Oxygen Objectives in California Estuaries and Regional Inconsistency

Dissolved oxygen is necessary to sustaining the life of all aquatic organisms that depend on aerobic respiration. Eutrophication produces excess organic matter that fuels the development of low surface water DO concentrations (hypoxia) as that organic matter is respired (Diaz 2001). When the supply of oxygen from the surface waters is reduced or the consumption of oxygen exceeds the resupply (via decomposition of excessive amounts of organic matter), oxygen concentrations can decline below the limit for survival and reproduction of benthic (bottom-dwelling) or pelagic (water column dwelling) organisms (Stanley and Nixon 1992, Borsuk et al. 2001, Diaz 2001). Hypoxia has a number of adverse effects on aquatic organisms, including: lowered growth rates, altered behavior, reduced reproductive success, and diminished survival (Diaz and Rosenberg 1995; Breitburg et al. 1997, 2009; Vaquer-Sunyer and Duarte 2008). Changes in the survival and reproduction of benthic and pelagic organisms can result in habitat and biological diversity losses, foul odors and taste, and altered food webs (USEPA 2007). Consequently, management of hypoxia in aquatic habitats has become a global issue (Smith et al. 1987, Karlson et al. 2002, OSPAR 2003, Diaz and Rosenberg 2008).

Dissolved oxygen objectives are essential for managing the effects of eutrophication. Under the Clean Water Act, each State is required to establish DO criteria for its waters, identify which of its waters are “impaired", and monitor TMDLs for known pollutants from municipal and industrial effluents, stormwater, agricultural runoff, and other sources. In California, regulation of surface water quality is directed by the Basin Plans of each Regional Water Quality Control Board (RWQCB). A “Basin Plan” is the master policy document that contains descriptions of the legal, technical, and programmatic bases of water quality regulation in the Region. The plan includes a statement of beneficial water uses that the Regional Board will protect, the water quality objectives needed to protect the designated beneficial water uses; and the strategies and time schedules for achieving the water quality objectives.

All six coastal RWQCBs have numeric DO objectives applicable to estuaries (Table 1.1). However, there is a general lack of consistency among RWQCBs approaches. First, at least one regional board utilizes narrative DO objectives, while the other five are numeric. Second, there is little consistency in the approach for setting thresholds. Objectives are expressed in units of concentration, percent saturation, or deviation from natural conditions. The time scales in which compliance is measured vary from an instantaneous minimum to an average over an annual time scale. Third, no consistency exists in how objectives relate to beneficial uses. Some of this variability is a reflection of the types of beneficial uses associated with species more prevalent in some Regions (e.g., salmonids). This lack of consistency has motivated the SWRCB to undertake a review of estuarine DO objectives, with the goal of developing a consistent approach statewide that protects specific designated uses and aquatic habitats. Notably, the North Coast Regional Water Quality Control Board (Region 1) is currently updating their freshwater DO objectives; their proposed changes are based on the life-cycle requirements of sensitive aquatic species throughout the region based on the designated beneficial use(s) of individual waterbodies.

The purpose of this document is to summarize the science supporting the development of consistent DO objectives for estuarine surface waters statewide. Recommendations for addressing data gaps and implementing criteria are also provided.

1.2 Document Organization

This document is organized into an Executive Summary and 8 sections:

Section 1: Introduction

Section 2: Conceptual Approach for Development of DO Objectives

Section 3: Fish Indicator Species Selection

Section 4: Macroinvertebrate Indicator Species Selection

Section 5: Review of Physiological Effects Data

Section 6: Synthesis of Data Supporting DO Objectives for California Estuaries

Section 7: Summary and Recommendations

Section 8: References

Table 1.1 Summary of Coastal Regional Water Quality Control Board Dissolved Oxygen Objectives. Information in the table was derived from the Basin Plans of each RWQCB, available on the State Water Board Website (www.waterboards.ca.gov). See Table 2.2 for beneficial use definitions.

Region	Summary of Dissolved Oxygen Objectives
North Coast[2] (Region 1)	Dissolved oxygen concentrations shall conform to those limits listed in Table 3-1. For waters not listed in Table 3-1 and where dissolved oxygen objectives are not prescribed the dissolved oxygen concentrations shall not be reduced below the following minimum levels at any time. Waters designated WARM, MAR, or SAL =5.0 mg/L; Waters designated COLD. 6.0 mg/L; Waters designated SPWN 7.0 mg/L; Waters designated SPWN during critical spawning and egg incubation periods 9.0 mg/L.
San Francisco (Region 2)	*Dissolved Oxygen*: For all tidal waters, the following objectives shall apply: In the Bay: Downstream of Carquinez Bridge -5.0 mg/L minimum; Upstream of Carquinez Bridge 7.0 mg/L minimum For nontidal waters, the following objectives shall apply: Waters designated as: Cold water habitat 7.0 mg/L minimum, Warm water habitat 5.0 mg/L minimum. The median dissolved oxygen concentration for any three consecutive months shall not be less than 80 % of the dissolved oxygen content at saturation. Dissolved oxygen is a general index of the state of the health of receiving waters. Although minimum concentrations of 5 mg/L and 7 mg/L are frequently used as objectives to protect fish life, higher concentrations are generally desirable to protect sensitive aquatic forms. In areas unaffected by waste discharges, a level of about 85 % of oxygen saturation exists. A three month median objective of 80 % of oxygen saturation allows for some degradation from this level, but still requires consistently high oxygen content in the receiving water.
Central Coast (Region 3)	Ocean Waters: The mean annual dissolved oxygen concentration shall not be less than 7.0 mg/L, nor shall the minimum dissolved oxygen concentration be reduced below 5.0 mg/L at any time. Inland Surface Waters, Enclosed Bays and Estuaries: For waters not mentioned by a specific beneficial use, dissolved oxygen concentration shall not be reduced below 5.0 mg/L at any time. Median values should not fall below 85 % saturation as a result of controllable water quality conditions.MAR and SPWN: The dissolved oxygen concentration shall not be reduced below 7.0 mg/L at any time.
Los Angeles (Region 4)	At a minimum, the mean annual dissolved oxygen concentrations of all waters shall be greater than 7 mg/L and no single determination shall be less than 5.0 mg/L, except when natural conditions cause lesser concentrations. SPWN: The dissolved oxygen content of all surfaces waters designated as COLD and SPWN shall not be depressed below 7 mg/L as a result of waste discharges. For that known as the Outer Harbor Area of the LA-Long Beach Harbors, the mean annual dissolved oxygen concentrations shall be 6.0 mg/L or greater, provided that no single determination shall be less than 5.0 mg/L.
Santa Ana (Region 8)	Adequate dissolved oxygen is vital for aquatic life. Depression of dissolved oxygen levels can lead to fish kills and odors resulting from anaerobic decomposition. Dissolved oxygen content in water is a function of water temperature and salinity. The dissolved oxygen content of enclosed bays and estuaries shall not be depressed to levels that adversely affect beneficial uses as a result of controllable water quality factors.
San Diego (Region 9)	The dissolved oxygen concentration in ocean waters shall not at any time be depressed more than 10 % from that which occurs naturally, as the result of the discharge of oxygen demanding waste materials. Dissolved oxygen levels shall not be less than 5.0 mg/L in inland surface waters with designated MAR or WARM beneficial uses or less than 6.0 mg/L in waters with designated COLD beneficial uses. The annual mean dissolved oxygen concentration shall not be less than 7 mg/L more than 10% of the time.

[2] Region 1 proposed an amendment to its freshwater dissolved oxygen objectives in September 2008. The new objectives are summarized above.

2. Conceptual Approach for Development of DO Objectives

The Estuarine NNE (E-NNE) technical team is recommending that the SWRCB adopt an approach to setting estuarine DO criteria patterned after the Virginia Province Salt Water Dissolved Oxygen Criteria (USEPA 2000). This approach establishes separate criteria for different life stages (larvae versus juveniles and adults), and introduces the concept of setting DO criteria within a biological framework that integrates time (potentially replacing the concept of an averaging period).

2.1 Hypoxia and Biological Consequences

Hypoxia (i.e., low DO concentrations) as a stressor differs from chemical toxicants in that it can occur naturally. Hypoxia is a consequence of the balance of atmospheric oxygen diffusion to surface waters, the *in situ* production of oxygen by primary producers during daylight hours, and the consumption of oxygen via respiration, decaying organic matter and other biogeochemical processes that consume oxygen within surface waters and sediments. In cases where hypoxia has anthropogenic origins, the assumption is that hypoxia may be reduced by controlling nutrient availability and reducing the supply of oxygen-demanding materials to a waterbody.

Hypoxia exhibits temporal variability on diurnal, tidal, lunar, and seasonal timescales. Seasonal hypoxia often develops in association with stratification. Hypoxic water can occur as stratified water prevents the oxygenated surface water from mixing downward or when upwelled hypoxic water is advected into an estuary from offshore. Hypoxia appears in the lower waters when respiration in the water and sediment depletes oxygen faster than it can be replenished. Breakdown of the stratification allows the surface and bottom waters to mix. Stratification can occur in both deepwater habitat of perennially tidal enclosed bays, such as San Francisco Bay, or in lagoon or river mouth estuaries that are intermittently closed to tidal exchange and are known to "trap salt" [*Largier et al.* 1991]. Diel cycles of hypoxia often appear in stratified or unstratified shallow habitats where nighttime respiration, in combination with water column and sediment oxygen demand, can deplete DO. Tidal and lunar frequencies can become apparent, particularly in poorly flushed areas where greater exchange occurs on flood or ebb tides or during a spring tide.

The response of aquatic organisms to low DO will depend on the intensity of hypoxia, duration of exposure, and the periodicity and frequency of exposure (Rabalais et al. 2002). Organisms have developed several physiological and behavioral adaptations to deal with temporary periods of low oxygen availability. Organisms can: 1) temporarily utilize anaerobic pathways to produce energy (ATP); 2) scavenge oxygen from hypoxic waters and increase the efficiency of oxygen transport to cells; 3) emigrate from hypoxic zones; 3) utilize the abundant oxygen from the surface or breathing aerial sources; or 4) reduce demand for oxygen by reducing activity. In general, these adaptations are well-developed in epibenthic and burrowing animals that commonly experience hypoxia, but poorly developed in animals that inhabit well-oxygenated environments such as the upper water column. However, these are all short-term strategies and will not enable the organism to survive during extended hypoxic periods. Sublethal effects may also occur; for example, reduced motor activity from mild hypoxia may make the animal more vulnerable to predators, or decrease its growth or reproduction.

2.2 Approach to Setting DO Objectives: The Virginia Province Salt Water DO Criteria

The Virginia Province Salt Water Dissolved Oxygen Criteria (USEPA 2000) describes an approach whose fundamental goal is to maintain and support aquatic life communities and their designated uses. Although the criteria are intended to protect aquatic communities, they rely primarily on data generated at the organism, rather than the population level, and are designed to protect the most sensitive life stage of organisms that spend part or all of their life history within an estuary. The approach was developed specifically for the region of the east coast of the US from Cape Cod, MA, to Cape Hatteras, NC, and has been adapted for use in Chesapeake Bay (Batiuk et al. 2009), and other coastal regions of the US.

The approach allows for combining both DO concentration and exposure time into the criteria. Mathematical models are used to integrate effects of hypoxia over time, rather than simply just deriving one number for an averaged period of time. The DO criteria are developed separately for 1) larval life history stages, and 2) juvenile and adult life stages of organisms. The need for separate criteria are based on the theory that different life stages can withstand different degrees of mortality without significant long-term impacts to the population; therefore, the criteria developed for the most sensitive life stage may not need to be applied for the entire population at all times. For example, in nature, larval life stages suffer a high degree of mortality, and the loss of a single larva is not as significant as the loss of an individual juvenile or adult and its predicted reproductive output. Anoxic conditions were not considered because data on the effects of anoxia do not provide information on the threshold requirements of aerobic organisms.

Criteria were developed for both continuous and cyclic hypoxia scenarios, using three specific population measures for which protective criteria were designed: 1) juvenile and adult survival, 2) growth effects, and 3) larval recruitment effects. The methods for developing the criteria used traditional concepts (e.g., final acute value (FAV) and final chronic value (FCV)), and procedures for calculating them were based on the “Guidelines for Deriving Numerical National Water Quality Criteria for the Protection of Aquatic Organisms and Their Uses” (Stephan et al. 1985). Specifically, criteria were derived for:

1. *Juvenile and adult survival*—A lower limit was calculated for continuous exposures using FAV calculation procedures outlined in the *Guidelines* (Stephan et al. 1985), but with data for only juvenile or adult stages. Limits for cyclic exposures were derived from an appropriate time-to-death curve for exposures less than 24 hr.
2. *Growth effects*—A threshold above which long-term, continuous exposures should not cause unacceptable effects was derived from growth data (mostly from bioassays using larvae). This FCV was calculated in the same manner as the FAV for juvenile and adult survival. This threshold limit has no time component (it can be applied to exposures of any duration). Cyclic exposures were evaluated by comparing reductions in laboratory growth from cyclic and continuous exposures.

3. *Larval recruitment effects*—A larval recruitment model was developed to project cumulative losses caused by low DO, wherein the degree of effects depends on the intensity and the duration of adverse exposures. The maximum acceptable reduction in seasonal recruitment was set at 5% (although other percentages also may be appropriate on a site-specific basis), which is equivalent to the protective limit for juvenile and adult survival. Thus, the number of acceptable days of seasonal exposure to low DO decreases as the severity of the hypoxic condition increases. The severity of cyclic exposure was evaluated with a time-to-death model (as in the protective limit for juveniles and adults).

This Virginia Province approach does not address direct behavioral responses (i.e., avoiding low DO) or the ecological consequences of behavioral responses, such as changes in predation rates or in community structure. Also, the approach does not address the issue of spatial extent of hypoxia; the assumption being that environmental managers would have to judge whether the spatial extent of the low DO area is sufficient to warrant concern.

2.3 Process for Developing DO Objectives

Ideally, data from a variety of fish and invertebrate species should be used to derive objectives for DO that would be generally protective of beneficial uses across the range of nearshore marine and estuarine environments present in the region (USEPA 2001, Batuik et al. 2009). Considerations associated with this process included:

1. Identification of target populations of estuaries;
2. Classification of waterbodies and/or segments of waterbody, and generate list of assigned beneficial uses;
3. Generate list of fish and invertebrate species associated with specific beneficial uses by estuarine class;
4. For each species, identify life stages with respect to seasonality, habitat type and location within estuarine and associated nearshore and/or freshwater habitat areas;
5. Review and summarize data available on physiological effects of hypoxia for each individual species with respect to continuous and cyclic hypoxia scenarios;
6. Run models to look at most sensitive endpoint by species for juvenile and adult survival, growth, and larval recruitment; and
7. Synthesize and package recommended objectives by estuarine class and designated estuarine beneficial use.

To a large extent, the desired information listed above represents site-specific considerations below the leve of detail required to address in a broad regulatory context. Thus, the data evaluation and criteria derivation process for the present study ultimately focuses on species and life stages generally present in the State or region that would be considered representative of the beneficial uses that the criteria were intended to protect. In this context, there would be an option for a regulatory body to apply site-specific criteria if local conditions or species warranted an alternative level of protection.

2.4 Target Population Habitats and California Estuaries Classifications

Existing SWRCB definitions of “enclosed bays” and “estuaries” include:

> ***Enclosed Bays*** *- Indentations along the coast that enclose an area of oceanic water within distinct headlands or harbor works. Enclosed bays will include all bays where the narrowest distance between headlands or outermost harbor works is less than 75 % of the greatest dimension of the enclosed portion of the bay. This definition includes, but is not limited to the following: Humboldt Bay, Bodega Harbor, Tomales Bay, Drakes Estero, San Francisco Bay, Morro Bay, Los Angeles Harbor, Upper and Lower Newport Bay, Mission Bay, and San Diego Bay.*
>
> ***Estuaries and Coastal Lagoons*** *- Waters at the mouths of streams that serve as mixing zones for fresh and ocean water during a major portion of the year. Mouths of streams that are temporarily separated from the ocean by sandbars shall be considered as estuaries. Estuarine waters will generally be considered to extend from a bay or the open ocean to the upstream limit of tidal action, but may be considered to extend seaward if significant mixing of fresh and saltwater occurs in the open coastal waters. The waters described by this definition include, but are not limited to the Sacramento-San Joaquin Delta as defined by Section 12220 of the California Water Code, Suisun Bay, Carquinez Strait downstream to Carquinez Bridge and appropriate areas of Smith River, Klamath River, Mad River, Eel River, Noyo River, Russian River, Pajaro River, Salinas River, Ventura River, Santa Clara River, Santa Margarita River; and appropriate areas of smaller creeks (e.g., Alder Creek, Lagunitas Creek, Pescadero Creek, Scott Creek, Malibu Creek, and San Mateo Creek) would also fit into this category.*

The E-NNE technical team recommended the following interpretation of existing SWRCB definitions of “enclosed bays” and “estuaries” (Sutula et al. 2009a) to more clearly specify target population habitats:

- Any <u>marine</u> or <u>estuarine</u> enclosed bay that has an enclosure ratio of < 75% of longest dimension. This would include enclosed bays, ports, harbors, marinas regardless of the amount of freshwater input to the site
- Any estuary in which seawater is measurably diluted by freshwater; the estuary does not need to have a surface water tidal connection to be considered an estuary (e.g., bar-built estuaries).

This recommendation was accepted the Coastal SAG, the STRTAG, and the SWRCB. The interpretation of existing definitions encompasses approximately 400 coastal drainages within California (Sutula et al. 2009a). Given extent of target population habitats, the following preliminary classification scheme was developed to describe general geomorphic context (Table 2.1, Sutula et al. 2009b).

Table 2.1 Preliminary E-NNE classification scheme.

GEOFORM	SEASONALITY OF INLET OPENING
Enclosed Bay	Perennial
Lagoon	Perennial Intermittent Ephemeral

River mouth estuary	Perennial Intermittent

For the purposes of DO objectives, the E-NNE technical team observed that fish species do not sort in predictable patterns of species occurrence by geoform; rather, distribution of species can be described by a more simple classification scheme of "open" versus "closed" to surface water tidal influence. For those systems that do close, it will be important to specify the time period of closure, as it will influence which species or how often a species can occur there and intersect with particular parts of the life cycle.

2.5 Applicable Beneficial Uses

Table 2.2 gives the definition of the estuarine beneficial uses applicable to DO objectives. This information is used in subsequent sections to derive species lists.

Table 2.2 Definition of beneficial uses associated with target populations habitats.

Marine Habitat (MAR) - Uses of water that support marine ecosystems including, but not limited to, preservation or enhancement of marine habitats, vegetation such as kelp, fish, shellfish, or wildlife (e.g., marine mammals, shorebirds).

Estuarine Habitat (EST) -Uses of water that support estuarine ecosystems including, but not limited to, preservation or enhancement of estuarine habitats, vegetation, fish, shellfish, or wildlife (e.g., estuarine mammals, waterfowl, shorebirds).

Cold Freshwater Habitat (COLD) - Uses of water that support cold water ecosystems including, but not limited to, preservation or enhancement of aquatic habitats, vegetation, fish or wildlife, including invertebrates.

Warm Freshwater Habitat (WARM) – Uses of water that support warm water ecosystems including, but not limited to, preservation or enhancement of aquatic habitats, vegetation, fish or wildlife, including invertebrates.

Wildlife Habitat (WILD) - Uses of water that support terrestrial ecosystems including, but not limited to, preservation and enhancement of terrestrial habitats, vegetation, wildlife (e.g., mammals, birds, reptiles, amphibians, invertebrates), or wildlife water and food sources.

Rare, Threatened, or Endangered Species (RARE) - Uses of water that support habitats necessary, at least in part, for the survival and successful maintenance of plant or animal species established under state or federal law as rare, threatened or endangered.

Spawning, Reproduction, and/or Early Development (SPWN) - Uses of water that support high quality aquatic habitats suitable for reproduction and early development of fish. This use is applicable only for the protection of anadromous fish.

Migration of Aquatic Organisms (MIGR) - Uses of water that support habitats necessary for migration, acclimatization between fresh and salt water, or other temporary activities by aquatic organisms, such as anadromous fish

Commercial and Sport Fishing (COMM) - Uses of water for commercial or recreational collection of fish, shellfish, or other organisms including, but not limited to, uses involving organisms intended for human consumption or bait purposes.

Shellfish Harvesting (SHELL) - Uses of water that support habitats suitable for the collection of filter-feeding shellfish (e.g., clams,oysters and mussels) for human consumption, commercial, or sport purposes.

Aquaculture (AQUA) - Uses of water for aquaculture or mariculture operations including, but not limited to, propagation, cultivation, maintenance, or harvesting of aquatic plants and animals for human consumption or bait purposes.

Contact Water Recreation (REC-1) - Uses of water for recreational activities involving body contact with water, where ingestion of water is reasonably possible. These uses include, but are not limited to, swimming, wading, water-skiing, skin and SCUBA diving, surfing, white water activities, fishing, or use of natural hot springs.

Non-contact Water Recreation (REC-2) – Uses of water for recreational activities involving proximity to water, but not normally involving body contact with water, where ingestion of water is reasonably possible. These uses include, but are not limited to, picnicking, sunbathing, hiking, beachcombing, camping, boating, tidepool and marine life study, hunting, sightseeing, or aesthetic enjoyment in conjunction with the above activities.

3. Fish Indicator Species

3.1 Introduction

The purpose of this section is to present the methods, assumptions and lists of fish species selected for consideration as indicator species for DO. The objectives of the efforts were as follows:

1) Generate a list of fish species associated with specific beneficial uses by estuarine class;

2) For each species, identify life stages with respect to seasonality, habitat type and location within estuarine and associated nearshore and/or freshwater habitat areas

3) Prioritize species for review of physiological impacts.

3.2 Approach and Assumptions

The contents of this section were developed and vetted through a one-day workshop, held March 16, 2010. Participants included fisheries experts who were selected on the basis of their expertise in estuarine fisheries, knowledge of California estuaries, and the natural history of fish species that utilize them. Workshop participants created criteria to determine inclusion on the list, generated the list of species, and generated recommendations for prioritization of the species on the list. This section serves as the workshop report.

3.2.1 General Criteria and Assumption

To develop the species list, a number of criteria and assumptions about the process were made. Ultimately, these criteria should be vetted with the SWRCB and its advisory groups. The criteria and assumptions include:

- The target population of enclosed bays and estuaries identified by E-NNE Technical Team and vetted by SWRCB and advisory groups was used as a starting point to generate a species list; species unique to San Francisco Bay estuary were excluded because the scope of the DO objective review is exclusive of this estuary. Thus, the list represents the diversity of fish species found in the estuarine habitat throughout the state’s estuaries without regard to oxygen sensitivity.

- Species should spend all or a substantial portion of their life histories in estuarine habitats. Thus, only estuarine species found within marine enclosed bays would be included.

- Emphasis was primarily on native fish. However, non-native species were added to the list under either of the following two conditions: 1) species were considered recreationally or commercially important, and 2) species for which data on physiological effects of hypoxia were known to exist. The assumption was that these species would not be prioritized for development of DO objectives, but in cases where alternative species or little data were available, they could be considered.

An extensive list of known estuarine species was produced, then tabulated in two ways: 1) by life-history strategy and habitat type occupied during each life stage, and 2) by geographic range and list of representative beneficial uses. Non-native and freshwater species were designated with footnotes in the respective tables.

3.2.2 Life-History Strategies

Species were first listed, and then grouped by guilds or life-history types, using a modification of Allen (2006) guilds or life-history strategies. The guilds or life-history strategies were as follows:

- **Brackish species** that primarily inhabit the lower salinity end of estuaries, or spend a significant portion of their life-history there.
- **Diadromous species** that migrate at particular stages in their life cycle between freshwater and the marine and estuarine environment. These species use the estuary as a migration corridor; some utilize it as a nursery or reside there as well. For the purpose of this study, diadromous species were subdivided by **Anadromous** and **Catadromous** life-history strategies.
    - **Anadromous** fishes largely grow and mature in the ocean or estuary and move up into freshwater streams to spawn.
    - **Catadromous** species do the opposite, largely rearing and growing in freshwater and moving down into the estuary or ocean to spawn.
- **Resident Estuarine** fishes that spend a substantial portion of their life cycle in the estuary. Marine bays and estuaries are inhabited by a small subset of fishes that spend most of their lives in protected bays and estuaries or closed lagoons with a wide range of salinities.
- **Marine** species that are widespread in the coastal marine environment, but also often occur in the lower or seaward, high salinity regions of open bays and estuaries.
- **Freshwater** species that inhabit larger rivers and can invade coastal lagoons when the lagoons close and retain relatively freshwater at low salinities for extended periods.

Within each guild or life-history strategy, species were listed roughly in order from most common to least prevalent. The general ecological and reproductive characteristics were noted for each species. Notably, since the number of truly estuarine species is relatively small, and estuarine habitats have been particularly impacted by changes, a relatively large number of the species have been assigned special conservation status.

3.2.3 Range and Beneficial Uses

This same set of species was then listed in a separate table by their range among California estuaries, and assigned to applicable beneficial uses (see Table 2.2). Each range was subdivided into three categories: 1) species found throughout California; 2) species found primarily north of Point Conception; and 3) those found primarily south of that point. Categories were determined according to historical occurrence and not by currently reduced ranges. Within each of these three categories, the species were also listed from most to least representative of the estuarine habitat as discussed above.

3.3. Species Lists and Prioritization Rationale

3.3.1 Range and Beneficial Uses

Table 3.1 gives the comprehensive list of species, organized by range and applicable beneficial use, identified during this exercise.

Table 3.1 Comprehensive list of California estuarine species by range and applicable beneficial uses.

RANGE	SUGGESTED INDICATOR SPECIES	Additional Designation		General Aquatic Life Use			Habitat for T&E, Migratory, or Spawning Species			Commercial and Recreational Fisheries			Upstream or Adjacent Beneficial Uses				
		Non-native	Fresh water	BIOL	EST	MAR	RARE	MIGR	SPWN	COMM	SHEL	AQUA	WARM	COLD	FRESH	WET	WLD
All California	Staghorn sculpin (*Leptocottus armatus*)			X	X	X(adult)						X		X	X		X
	Threespine stickleback (*Gasterosteus aculeatus*)			X	X	X(rarely)	X		X					X	X	X	X
	Tidewater goby (*Eucyclogobius newberryi*)			X	X	X(rarely)	X		X					X	X	X	X
	Arrow goby (*Clevelandia ios*)			X	X	X			X				X	X	X(rarely)		X
	Topsmelt (*Atherinops affinis*)			X	X	X			X			X	X		X(rarely)		X
	Steelhead (*Oncorhynchus mykiss*)			X	X	X(adult)	X	X (anad)				X		X	X		X
	Shiner surfperch (*Cymatogaster aggregata)*																
	Bay pipefish (*Syngnathus leptorhynchus*)			X	X	X	X?		X				X?	X	X(rarely)	X	X
	Longjaw mudsucker (*Gillichthys mirabilis*)			X	X	X			X	X			X		X(rarely)		
	Cheekspot goby (*Ilypnus gilberti*)			X	X	X			X				X				
	Pacific herring (*Clupea pallasii*)			X	X	X		X	X	X				X	X(rarely)		X
	Jack smelt (*Atherinopsis californiensis*)				X	X				X				X			
	Bay goby (*Lepidogobius lepidus*)			X	X	X			X					X			X
	Gray smoothhound (*Mustelus californicus*)			X	X	X			X	X				X			
	Brown smoothhound (*Mustelus henlei*)			X	X	X			X	X			X				
	Leopard shark (*Triakis semifasciata*)			X	X	X			X	X			X				
	Pacific lamprey (*Entosphenus tridentata*)			X	X	X	X	X		X				X	X(spawn)		
	Mosquitofish (*Gambusia affinis*)	X															
	Yellowfin goby (*Acanthogobius flavimanus*)	X			X	X			X	X			X		X		
	Mississippi silverside (*Menidia aurdens*)	X			X	X			X				X		X		
North of Point Conception	Starry flounder (*Platichthys stellatus)*			X	X	X(adult)				X				X	X		X
	Prickly sculpin (*Cottus asper*)			X	X	X(larvae)		X(catad)	X					X	X		X
	Coastal cutthroat trout (*Oncorhynchus clarki clarki*)			X	X	X	X	X(anad)						X	X(spawn)	X	X
	Coho salmon (*Oncorhychus kisutch)*			X	X(juv)	X(adult)	X	X(anad)		X				X	X(spawn)	X	X
	King or Chinook salmon (*Oncorhynchus tschawytscha*)			X(juv)	X	X	X	X(anad)		X				X	X(spawn)	X	X
	Longfin smelt (*Spirinchus thaelichthys*)			X	X	X	X	X (est. anad)		X	X			X	X(spawn)	X?	X
	Green sturgeon (*Acipenser medirostris*)				X	X	X	X		X				X	X(spawn)		
	Speckled sand dab (*Citharichthys stigmaeus*)			X	X	X				X				X			
	English sole (*Pleuronectes vetulus*)			X	X	X				X				X			
	Euchalon (*Thaleichthys pacificus*)			X	X?	X	X	X(anad)		X	X			X	X(spawn)	X?	X
	Sharpnose sculpin (*Clinocottus acuticeps*)			X	X	X(adult)	X		X?					X	X(rarely)		X?
	Hitch (*Lavinia exilicauda*)		X														

RANGE	SUGGESTED INDICATOR SPECIES	Additional Designation		General Aquatic Life Use			Habitat for T&E, Migratory, or Spawning Species			Commercial and Recreational Fisheries			Upstream or Adjacent Beneficial Uses				
	Sacramento blackfish (*Orthodon microlepidotus*)		X		X								X		X		
	Tule perch (*Hysterocarpus traski*)		X		X		X								X		
	Sacramento pikeminnow (*Ptychocheilus grandis*)		X		X								X		X		
	Western sucker (*Catostomus occidentalis*)		X		X								X	X	X		
	Western roach (*Hesperoleucas symmetricus*)		X		X		X						X		X		
	Striped bass (*Morone saxatilis*)	X		X	X	X		X		X				X	X		
South of Point Conception	California killifish (*Fundulus parvipinnis*)			X	X	X(rarely)			X				X		X(rarely)	X	X
	Deepbody anchovy (*Anchoa compressa*)			X	X	X			X				X		X(rarely)		X
	Bay anchovy (*Anchoa delicatissima*)			X	X	X			X				X		X(rarely)		X
	Shadow goby (*Quietula y-cauda)*			X	X	X			X				X				X
	Striped mullet (*Mugil cephalus*)			X	X	X(adult)						X	X		X		X
	Diamond turbot (*Pleuronichthys guttulatus*)			X	X	X			X?			X	X		X(rarely)		X
	California halibut (*Paralichthys californicus*)			X	X	X						X	X				X
	Barred pipefish (*Syngnathus auliscus*)			X	X	X(rarely)	X?		X				X		X(rarely)	X	X
	Spotted sand bass (*Paralabrax maculofasciatus*)			X	X	X			X?			X	X				X
	Bay blenny (*Hypsoblennius gentilis*)			X	X	X			X				X				X
	Arroyo chub (*Gila orcutti*)		X		X								X		X		

Brief summaries of life-history strategies, range, and special status are given below for each of the species of interest; additional detail is provided in Appendix 1. Much of the information on the biology and distribution of these species is available in Emmett et al. (1991), Moser et al. (1996), Cailliet et al. (2000), Leet et al. (2001), Moyle (2002), Allen (2006), other more specific documents cited below, and the collective experience of the authors.

BRACKISH SPECIES

Two species, the tidewater goby, *Eucyclogobius newberryi*, and the threespine stickleback, *Gasterosteus aculeatus*, are characteristic of the lower salinity areas of estuaries almost throughout California. The threespine stickleback historically occurred throughout the state, but today is absent in coastal localities south of Ventura County. The tidewater goby occurs from northern Del Norte County to central San Diego County, and is also absent from many localities it originally inhabited. The complete life cycle of each species is spent in the estuary. Threespine stickleback also have both freshwater and anadromous stocks in many systems in central and northern California. The freshwater stocks occur throughout the state, and the anadromous stocks from about San Luis Obispo County northward.

Anadromous Species

Eight anadromous species are included; four salmonids (family Salmonidae), two smelt (family Osmeridae), one sturgeon (family Acipenseridae), and one lamprey (Petromyzonidae). These all spawn in freshwater streams, spend some of their early life in freshwater or estuaries, have special significance to native American peoples and most, if not all, populations have special conservation status. With the exception of the lamprey, all are important commercial or game species. The four salmonids include:

1) Steelhead, *Oncorhynchus mykiss*, which occurs over the whole state of California, and can spend significant time (months) in the estuary if adequate conditions present themselves.

2) Coho salmon, *Oncorhynchus kisutch*, occur in many streams north of Monterey Bay to the Oregon border and beyond, but spend less time in the estuary, often passing through to the ocean fairly rapidly (days to a week or two). Both steelhead and Coho salmon occur in many small-to-large streams within their range.

3) King or Chinook salmon, *Oncorhynchus tschawytscha*, occur north of San Francisco Bay, typically in larger systems like the Russian River, Eel River, Mad River, Mattole River, Redwood Creek, Klamath River, Smith River and a few others. Their juveniles spend some time in the estuaries, usually more than Coho, but less than steelhead.

4) Coastal cutthroat trout, *Oncorhynchus clarki clarki*, occur from the Eel River northward (Humboldt and Del Norte counties) to the Oregon border and beyond. They occur in most of the estuaries and coastal lagoons in this area. The juveniles spend varying amounts of time in freshwater and older juveniles, and adults are largely estuarine. Adults also can spend some time in the ocean (Gerstung 1997, Trotter and Behnke 2008).

5) The euchalon, *Thaleichthys pacificus*, is an osmerid fish occurring north of San Francisco Bay to Oregon and beyond. The marine adults migrate through the estuary to spawn in freshwater in early spring, and the larvae hatch out and return downstream to the ocean in a few days to a few weeks. Their residence time in the estuary is brief, but occurs during the larval and early juvenile stage which is probably one of the most oxygen sensitive stages in their life cycle.

6) The longfin smelt, *Spirinchus thaleichthys*, occurs in San Francisco Bay, and from the Eel River northward, and is largely an estuarine species as a juvenile and adult. It is federally listed. Larvae may occur in the estuary as they descend from nearby freshwater spawning tributaries.

7) The green sturgeon, *Acipenser medirostris*, primarily occurs in the Klamath River estuary as juveniles and to some extent as adults in addition to passing through to spawn up river. It may also occur in other major north coast rivers such as the Eel, Russian, Smith, and Mad rivers. The youngest juveniles occur on the bottom in the estuary, at least in the Klamath River estuary, and possibly the others now or in the future as this species recovers.

8) The Pacific lamprey, *Entosphenus tridentata*, historically occurred from northern Baja California to north of California. The adults reside in marine habitats, but pass through estuaries to spawn in freshwater streams, and usually die after spawning. The larvae, or ammocoetes, burrow into fine sand to muddy substrates and filter feed both in freshwater streams and lower salinity areas of upper estuaries. The larval and juvenile stages are the only life stage to spend significant time in the estuary, possibly up to months. This species has declined precipitously in the last ten years or so (Moyle et al. 2010).

The euchalon, longfin smelt, green sturgeon and lamprey are very rare today, or found in only a few estuaries. Therefore, they should be considered as indicator species primarily based on their conservation status and historical distributions.

Catadromous Species

The prickly sculpin, *Cottus asper*, is the only species considered catadromous, based on studies in central California and observations north of California (Shapovalov and Taft 1954, Kresja 1965, McPhail 2007). Adults typically reside in freshwater streams and lakes and, some populations migrate down into coastal estuaries to spawn. The larvae occur in estuaries and coastal ocean, and the juveniles are often abundant in coastal estuaries. With age and growth, the fish migrate back upstream into freshwater.

Allen (2006) considered striped mullet, *Mugil cephalus*, to be a catadromous species, but we consider it an estuarine species. While some juveniles and adults will invade freshwater streams, only a small proportion of the mullet population does so in California and then only in wet years when fresh water flows are higher and of longer duration.

ESTUARINE SPECIES

We consider sixteen species to be primarily or substantially estuarine in their life-histories, the largest guild or life-history category presented here. These include:

- Three species of clupeomorphs (Clupeidae, Engaulidae)
- Two species of pipefishes (Syngnathidae)
- Four species of gobies (Gobiidae)
- Three species of flatfishes (Bothidae, Paralichthyidae, Pleuronectidae)
- Topsmelt, *Atherinops affinis* (Atherinopsidae)
- California killifish, *Fundulus parvipinnis* (Fundulidae)
- Staghorn sculpin, *Leptocottus armatus* (Cottidae)
- Shiner surfperch, *Cymatogaster aggretaga* (Embiotocidae).

At least ten of these are almost completely estuarine, with populations that include: California killifish, the four species of gobies, the two anchovies, two species of pipefishes, and the topsmelt. For the remaining estuarine species most have marine adult population as marine, but much of the first year, or more, juveniles life remain in bays or estuaries. This latter group includes all three flatfishes: the Pacific herring (*Clupea pallasi)*, the staghorn sculpin (*Leptocottus armatus)*, striped mullet (*Mugil cephalus)*; and the shiner surfperch. This group typically arrives in estuaries as advanced larvae or newly settled juveniles in late winter or early spring, lives and grows in the estuary, and often leaves for the ocean the following winter. Juvenile California halibut and striped mullet may stay in estuaries for two to three years. The species of gobies follow a somewhat reverse pattern in that the adults reside in the estuaries, and the larvae concentrate in the deeper portions of the estuary, often near its mouth, and also disperse along the coast in nearshore waters.

One additional species, the longfin smelt listed above as an anadromous species, spends most of its life in estuaries and might be classified in this estuarine category as well. An argument could be made for including the tidewater goby and some populations of threespine stickleback as "estuarine"; they are currently included in the brackish category above.

The four species of gobies are roughly divide among the estuarine benthic habitat by substrate: the longjaw mudsucker (*Gillichthys mirabilis)* lives in high to low intertidal muddy tidal sloughs or channels. The arrow goby (*Clevelandia ios)*, occurs on both sandy and muddy shallow flats, as do the shadow goby (*Quietula y-cauda*) and cheekspot goby (*Ilypnus gilberti*), but the shadow goby is usually found in muddier habitat than the sandier areas inhabited by cheekspot gobies. As juveniles, all of the latter three species of goby can be found over the same substrates. All of these species live in burrows of other invertebrates or of their own making. The eggs are brooded in the burrows and the larvae occur in the estuary and nearby ocean. The larval stage probably only lasts for a few weeks, but reproduction lasts for several months, so larvae and juveniles are present for much of the year.

The topsmelt and California killifish also reproduce over an extended time period, at least in southern California where small juveniles can be taken in almost all months, but are least abundant in the coldest winter months. The reproductive season is probably progressively shorter to the north. Both species attach their eggs to vegetation, brush, and possibly firmer substrates in the estuary. Most, if not all, their larvae develop in the estuary, although some of the more pelagic topsmelt may be carried out to the nearshore ocean. It is much less likely that any significant numbers of killifish larvae are carried out since they hatch at a more advanced stage with a very short or non-existent larval life. The small hatchlings remain on the bottom and quickly begin foraging as small juveniles.

Two species of pipefishes[3], bay pipefish (*Syngnathus leptorhynchus*) and barred pipefish (*S. auliscus)*, are the two estuarine species of pipefishes in California and have similar life-histories. The males brood the young in a pouch, so there is no free-living egg or larval stage. The duration of the breeding season is not well-known, but possibly not as extensive as the other estuarine species. The adults are relatively sedentary, and usually occur in macrophytes like eel grass, or masses of *Ulva* or *Enteromorpha*-like green algae.

Two species of fishes come into the estuaries to either lay their eggs in the coldest months (Pacific herring), or to give birth to living young in the warm months (shiner surfperch). The larvae and juveniles spend weeks to months in the estuary, as do a proportion of the adults, but substantial populations of adults occur in the ocean as well. It is uncertain whether some populations may be largely estuarine with separate life-history strategies from more marine stocks.

The remaining estuarine species spend some or most of their multi-year adult life in nearshore marine waters and spawn there. However, their larvae orient towards bays and estuaries, and the juveniles settle out or transform there. The juveniles spend several months growing in the estuary. These species include three flatfishes: starry flounder (*Pleuronectes stellatus)*, diamond turbot (*Pleuronichthys guttulatus)* and California halibut (*Paralichthys californicus)*, in addition to striped mullet and staghorn sculpin. The young of all but the California halibut arrive in the winter-early spring time period in southern California, and progressively later to the north. The California halibut tend to arrive later in the spring and summer in southern California, and probably do not utilize estuaries north of San Francisco Bay to a large extent. The starry flounder and diamond turbot are somewhat complementary in distribution, occurring north and south of Pt. Conception, respectively; whereas, the California halibut is primarily south, but does range north to San Francisco Bay.

Two marine species regularly occur in a few estuaries north of San Francisco Bay: the sharpnose sculpin (*Clinocottus acuticeps*) and the saddleback gunnel (*Pholis ornate)*. The saddleback gunnel appears to be a marine fish that occasionally invades estuaries, whereas the sharpnose sculpin is a regular inhabitant of a few estuaries like Ten Mile River, Eel River, and tributaries of Crescent City Harbor.

MARINE BAYS and ESTUARIES

Two species occur primarily in more saline and perennially open marine bays and estuaries, but are rare or absent from the many closed systems with lower salinity and varying degrees of connection with the ocean. These are the spotted sand bass, *Paralabrax maculofasciatus* (Serranidae), and the bay blenny, *Hypsoblennius gentilis* (Blennidae). Both have long-lived larvae in bays and nearshore ocean waters,

[3] Note that the taxonomy is difficult and that up to four or five species exist of pipefishes; the other species apparently are marine and occur rarely in estuaries.

with the bay blenny attaching its eggs to hard substrate and the spotted sand bass spawning in surface and mid-waters of bays and nearshore ocean waters.

MARINE FISH

The nine species of bony fishes, sharks, and rays found in this category (Table 3.2) are primarily marine, but can occur in and near bay and estuary mouths, particularly in larger systems that are perennially open or open much of the time. Despite such occurrence, these species are generally more representative of the marine environment, often dispersing into larger bays and estuaries with high tides, only to retreat to the ocean or the deepest channels near the mouth of the estuary at low tide. In addition, the sharks and rays enter the bays in the warm months to give birth to young; the bays provide nursery areas for the juveniles for months or more. This is particularly true for the leopard shark (*Triakis* semifasciata), the gray smoothhound (*Triakis californicus*), and the round stingray (*Urolophus halleri).*

Although these predominantly marine species somewhat regularly inhabit estuaries, and many other marine species occur intermittently in some enclosed systems like Los Angeles Harbor, Tomales Bay, andHumboldt Bay, for the purpose of this study their sensitivity was considered to be more relevant as marine rather than estuarine indicators. However, as pointed out by Allen (2006), large artificial systems like Los Angeles Harbor can have particular sections, regions, or areas of habitat that take on the characteristics of estuaries.

FRESHWATER SPECIES

In a similar vein, several freshwater species can be found in some estuarine habitats. Thus, five species of freshwater fishes were included because they have been noted in lagoons associated with major drainages north of Point Conception, and include native minnows, suckers, and Tule perch. These species occasionally can be observed in areas of low salinity in the upper end of these estuaries. They can also be observed in large numbers in the spring when larvae and juveniles drift downstream and become concentrated at the stream:lagoon or stream:estuary interface. In addition, when these systems remain closed for long periods and salinities decline below 5-7 ppt, juveniles and adults may become widespread in the lagoons. These species are necessarily limited by the small number of coastal streams with significant native freshwater fish fauna. The native species recorded from California estuaries are Western sucker (*Catostomus occidentalis)*, Sacramento pikeminnow (*Ptychocheilus grandis)*, hitch (*Lavinia exilicauda)*, blackfish (*Orthodon microlepidotus)*, roach (*Hesperoleucas symmetricus)*, and Tule perch (*Hysterocarpus traski)*. Note that the roach from different drainages may prove to be separate species (Moyle 2002).

These species are primarily found in estuaries of the larger streams like the Salinas, Pajaro, San Lorenzo, Russian, and Eel rivers. This group of species could also include one from southern California, the arroyo chub (*Gila orcutti)*, which occurs as native in the Malibu Lagoon, and historically should have occurred in systems in the Los Angeles Basin. It can also be found in the Santa Clara River lagoon at times when it is relatively fresh, but is not considered native to the Santa Clara River (Swift et al. 1993). Several other non-native or invasive freshwater species could be added to this list as well, particularly green sunfish (*Lepomis cyanellus)*, largemouth bass (*Micropterus salmoides)*, black bullhead (*Ameiurus melas)*, mosquitofish (*Gambusia affinis)* and Mississippi silverside (*Menidia audens)*. Drakes Estero on Pt. Reyes

National Seashore also has an established non-native population of Sacramento perch, (*Archoplites interruptus)*. However, they, along with the native freshwater species, may be best utilized as freshwater indicators with the truly estuarine species designated as estuarine indicators.

NON-NATIVE SPECIES

The remaining estuarine species are the non-native species of significance known to occur outside the San Francisco Bay. As noted by Schroeter and Moyle (2006), few non-native species are known from California estuaries. However, the few that have been identified may provide sensitivity data not currently available from native species, and could serve as surrogates for native species. The mosquitofish is the only alien species that occurs in a large number of the estuarine systems throughout the state. The yellowfin goby occurs primarily in large, open systems including harbors, and only rarely strays into smaller and closed systems. The striped bass (*Morone saxatilis)*, is already a well-known estuarine indicator species on the east coast of the United States, and considerable information on its physiology is available. It is also a prominent sport species in California. While its historical California range was larger, it currently occurs primarily in San Francisco Bay and is now a rare and non-breeding species up and down the coast from San Francisco Bay. As predicted by Schroeter and Moyle (2006), the introduced Mississippi silverside has been expanding its range in coastal southern California over the last five years or so (Camm Swift, unpublished observations). In recent literature (Schroeter and Moyle 2006), this species has been called the inland silverside (*Menidia beryllina)*, a coastal, brackish water species in the Gulf of Mexico. However, the freshwater source population for California fish (Oklahoma) has recently been shown to be a separate species (i.e., *Menidia audens)* by Suttkus et al., (2005), as accepted by Nelson et al., (2004). A few additional non-native species, such as sailfin molly (*Peocilia latipinna)* and rainwater killifish (*Lucania* parva) may also become more widespread in California estuaries, particularly in warmer southern California systems.

3.3.2 Species Prioritization

Workshop participants prioritized the list of species in order to reduce the workload associated with the review of physiological effects data. The following rationale was used to prioritize species for inclusion:

- Native species
- State or federal threatened or endangered species
- Prominence in sport or commercial fisheries
- Occurrence in the greatest number of estuaries across the state, or within a region (south or north of Point Conception)
- Representative of life-history strategy
- Species having the greatest number of sensitive life stages within the estuary

Criteria for prioritization of species favored: 1) widespread estuarine residents and fishes typically with both multiple life cycle stages and extended residence in the estuary within their life cycle; 2) threatened and endangered species; and 3) importance in commercial or sport fisheries. In some cases, these criteria were applied in a historical sense, as some species are not as widespread or prevalent today, suggesting the need for surrogate species. In other cases, physiological investigations may conflict with efforts to recover these species. Also, several species may represent multiple habitat categories, have special conservation status, and/or be of long-standing sport fishing importance. Table 3.2 lists the priority species selected and provides summary information on range, life-history strategy, and applicable beneficial uses.

Table 3.2 Priority species selected with summary information on range, life-history strategy, and applicable beneficial uses. Range designations are as follows: All = throughout California, N = North of Point Conception, S = South of Point Conception; O = open and C = closed.

Species	Range	Life-History	Applicable Beneficial Uses					
			EST	MAR	RARE	MIGR	SPWN	COMM
Staghorn sculpin, *Leptocottus armatus* (Cottidae)	All O, C	Nursery	X	X				
Tidewater goby, *Eucyclogobius newberryi* (Gobiidae)	All O, C	Residence	X		X		X	
Topsmelt, *Atherinops affinis* (Atherinopsidae)	All O, C	Residence	X	X			X	X
Starry flounder, *Platichthys stellatus* (Pleuronectidae)	N O, C	Nursery	X	X				X
Arrow goby, *Clevelandia ios* (Gobiidae)	All	Residence	X	X			X	
Threespine stickleback, *Gasterosteus aculeatus* (Gasterosteidae)	All O, C	Residence	X	X	X		X	
Prickly sculpin, *Cottus asper*, (Cottidae)	N	Nursery	X	X		X	X	
Deepbody/Bay anchovy, *Anchoa compressa, delicatissima* (Engraulidae)	S	Residence, Nursery	X	X			X	
Rainbow trout/Steelhead, *Oncorhynchus mykiss* (Salmonidae)	All O, C	Nursery	X	X	X	X		X
Coastal cutthroat trout, *Oncorhynchus clarki clarki* (Salmonidae)	N O, C	Residence	X	X	X	X		X
Coho salmon, *Oncorhynchus kisutch* (Salmonidae	N O, C	Nursery	X	X	X	X		X
King or Chinook salmon, *Oncorhynchus tshawytscha* (Salmonidae)	N O, C	Nursery	X	X	X	X		X
California killifish, *Fundulus parvipinnnis* (Fundulidae)	S O, C	Residence	X	X			X	
California halibut, *Paralichthys californicus* (Paralichthyidae)	All O, C	Nursery	X	X				X
Bay/Barred pipefish, *Syngnathus leptorhynchus, S. auliscus* (Syngnathidae)	All O, C	Residence	X	X			X	

Table 3.2 Continued

Species	Range	Life-History	Applicable Beneficial Uses					
			EST	MAR	RARE	MIGR	SPWN	COMM
Pacific herring, *Clupea pallasi* (often called *C. harengus* in the past) (Clupeidae)	All O	Nursery	X	X			X	X
Shadow goby, *Quietula y-cauda*(Gobiidae)	All O, C	Residence	X	X			X	
Cheekspot goby, *Ilypnus gilberti* (Gobiidae)	All O, C	Residence	X	X			X	
Longjaw mudsucker, *Gillichthys mirabilis* (Gobiidae)	All O, C	Residence	X	X			X	
Diamond turbot, *Pleuronichthys guttulatus* (Pleuronectidae)	All O, C	Nursery	X	X				X

THREATENED AND ENDANGERED SPECIES

Seven of the recommended species are on federal or state threatened and endangered species lists:

- Steelhead (Federally endangered or threatened over much of coastal California)
- Coastal cutthroat trout (listed as Class 2, species of special concern, by the State of California)
- Coho and Chinook Salmon (Federally endangered or threatened in central and northern California)
- Tidewater goby (Federally endangered)
- Green sturgeon (Federally threatened)
- Eulachon (Federally threatened)

All but two of these species have already been identified as being broadly representative of estuaries in a significant portion of California. One of the relatively rare species, green sturgeon, occurs primarily in San Francisco Bay, the Klamath River in California, and possibly a few of the other largest river systems north of San Francisco Bay (e.g., the Eel, Mad, Smith rivers). Thus, the green sturgeon would represent only a few of the more than 400 identified estuaries under consideration. Similarly, the southern population segment (DPS) of the eulachon, *Thaleichthys pacificus* (Osmeridae), from Humboldt and Del Norte counties on the north coast, was recently listed as Federally threatened and has possibly already been extirpated from northwestern California estuaries (Federal Register, 75 FR 13012 [March 18, 2010]). This population is anadromous, traveling through estuaries to spawn in fresh water. The larvae pass back down largely to the marine environment within a few weeks. Thus, it relies on the estuary for passage, but otherwise makes only brief use of estuaries in California. Notably, this species' conservation status may require its priority to be raised under our analysis.

WIDESPREAD SPECIES

The two species with the highest priority are found throughout California: the threespine stickleback and tidewater goby. Both species occur almost throughout the state, are found in the smallest to largest estuarine systems, and use the estuarine habitat for all four stages of its life cycle (i.e., eggs, larvae, juveniles, and adults). Both species are small (typically less than 75 mm long) and live one to three years. The larval life of the tidewater goby is about three weeks (Michael Hellmair, Humboldt State U., unpublished studies); the larval duration of the stickleback is shorter. Stickleback larvae are benthic near the nest for a few days before the juveniles become free-swimming and leave the protection of the guarding male. Tidewater gobies require relatively well-oxygenated sandy substrates to dig burrows for deposition of the eggs 50-150 mm under the surface.

The staghorn sculpin is the only native estuarine species more prevalent than tidewater gobies and threespine stickleback in small to large estuaries. Consequently, this species has been given the third highest priority. Staghorn sculpin larvae and early juveniles come in from the ocean to settle in small to large systems in winter to early spring and spend much of the year feeding and growing in estuaries and bays. At the end of the year, most will leave to the ocean or the mouths of estuaries near the ocean. Thus, they spend most of a year in the estuary. Along the southern coast, this species can remain in closed systems for multiple years when low rainfall and runoff fails to initiate breaching of lagoons to the ocean. Although, the staghorn sculpin has the third highest priority, it is listed first in Table 3.2 because frequency of occurrence was given more weight than the sensitivity of egg and larval stages.

The fourth and fifth priority species , the topsmelt and the arrow goby, are less prevalent than the first three, as they occur primarily in the larger more open systems, particularly north of Point Conception. As noted in the discussion about classification of estuaries (Section 2.2), these two species will occur more frequently in smaller estuaries only in wet years when the estuaries open more frequently. As such, their consistent presence may be restricted to larger systems that open more frequently or are perennially open. For both species, all four life stages occur in the estuary, but with very different strategies and habitats. The topsmelt is a midwater planktivore and benthic grazer that attaches its eggs to vegetation in the estuary; the larvae are pelagic for several weeks. The topsmelt typically reaches 20 cm in length in estuaries and lives up to three or four years, depending on latitude. Like the tidewater goby, the arrow goby lays its eggs in burrows in sand or mud on estuarine flats; its larval stage occurs in the estuary and nearshore coastal zone and probably lasts for a few weeks. Although the larval stage is relatively short, larvae are produced for much of the year, at least in southern California. The arrow goby reaches about 75 mm, lives on the bottom or in burrows. The topsmelt and thearrow goby, after the staghorn sculpin, are probably the most consistently present and abundant species in larger, more open coastal systems throughout the state. The topsmelt becomes less prevalent in some of the cooler systems in the northern part of the state.

The rainbow trout/steelhead, which is anadromous, is the sixth highest priority species in the state is and has been the focus of strong sport-fishing interest. Historically, this species occurred in a large number of systems, but its need for substantial tributary spawning streams has limited its current distribution compared with the tidewater goby or threespine stickleback. The number of systems it occurs in today is substantially reduced, particularly south of Pt. Conception. The steelhead eggs and larvae are found upstream in the gravel of freshwater streams, and the small juveniles (i.e., 40-200 mm) can occur in coastal lagoons and estuaries for several months to a year before leaving for the ocean. juveniles may remain for a second year in the northern part of the state due to slower growth, or in the south with failure of lagoons to open to the ocean in dry years.

The remaining eleven species listed for most or all of California are each individually somewhat less representative of all estuaries, but better represent the subset of open or larger "closed" systems; i.e., closed systems that are frequently open or larger in size. As such, they have lower priority than some species discussed below that are restricted in occurrence to north or south of Point Conception, but better represent all estuaries in each region. Some of these eleven species are more prevalent south of Point Conception, and occur only in the largest systems that get warm in the summer north of Point Conception, including shiner perch, cheekspot goby, and longjaw mudsucker. One species, the bay goby, is more oceanic in the south and occurs only in the largest and deepest estuaries south of Point Conception. It is also found only in the largest tidal systems north of Point Conception. Bay pipefish are also restricted to the largest systems that support eelgrass or other healthy macrophyte communities. Among these eleven species, all but the shiner perch spend all or most of their life-history in these larger systems. Today, Pacific herring occur in the largest open or mostly open systems north of Point Conception, although it historically ranged south to San Diego Bay. This species spends most sensitive life stages (i.e., eggs and larvae) in estuaries and is an important commercial and sport species, which may give it a higher priority in terms of species rankings.

NORTH OF POINT CONCEPTION

Of the species occurring north of Point Conception (Table 3.1), only the starry flounder and prickly sculpin are found in a large number of estuaries throughout the area. The starry flounder come in as larvae, transform into juveniles, and spend months growing in the estuary. The prickly sculpin come down from freshwater tributaries to spawn in the upper estuary, and the larvae and juveniles are usually common to abundant in the upper estuary. In the Big Sur area, this species could be considered an estuarine indicator because only streams with developed estuaries, like the Big and Little Sur Rivers and Carpoforo Creek, have populations of prickly sculpin. In spite of marine dispersal of larvae, The prickly sculpin spends more of its life cycle, including the more sensitive larvae and juvenile life-stages, in the estuary than starry flounder. Thus, these two species are among the best or highest-ranked indicator species north of Point ConceptionThe remaining high priority species north of Point Conception are also limited in distribution: Coho salmon--north of Monterey Bay only; coastal cutthroat trout--Eel River and northward; King salmon--San Francisco Bay northward; and longfin smelt--a few estuaries in Humboldt and Del Norte counties. Of these, only the Coho salmon and coastal cutthroat trout are found in a large number of estuaries within their distribution limits, and only the coastal cutthroat trout spends enough time (several months or more) in the estuary to be considered important as an indicator species. The remaining eight species are much more limited in estuarine occurrence, and were included for various reasons noted above. Thus, in the group of species restricted to north of Point Conception, three species have strong qualifications for indicator species: prickly sculpin, starry flounder and coastal cutthroat trout.

SOUTH OF POINT CONCEPTION

All of the species restricted to south of Point Conception are characteristic of the fewer and larger perennially open and the larger closed systems. Thus, for the larger systems south of Point Conception, species like California killifish, shadow goby, deepbody and bay anchovies, diamond turbot and striped mullet could augment high priority indicator species that represent the whole state (i.e., tidewater goby, longjaw mudsucker, cheekspot goby, arrow goby, threespine stickleback, topsmelt, staghorn sculpin, and steelhead). Ten of these fifteen species (the California killifish, the two species of anchovy, the five species of goby, topsmelt, and threespine stickleback)spend all four life stages (i.e., eggs, larvae, juveniles and adults) primarily in estuaries. These species also found in the benthic, midwater, shallow, deepwater, and both low and high salinity areas of estuarine systems in southern California. As such, the estuaries south of Point Conception have a larger complement of good to excellent potential indicator species whose complete life cycle can occur in estuary habitats. The California halibut would be given a lower priority based on the fact that its sensitive life stages are primarily associated with marine rather than estuarine habitats. However, as a very important commercial and sport species, halibut could be assigned a high priority.

NON-NATIVE SPECIES

A small number of non-native species are also listed because they may be valuable in the absence of physiological data on native species. For example, considerable information is available on the physiology of the striped bass (*Morone saxatilis)*. Another San Francisco Bay species, the Mississippi silverside, *Menidia audens*, has become common in a few southern California estuaries (e.g., Santa Clara River and Malibu Creek), and may spread to other southern California localities. Much physiological data is available on the genus *Menidia;* this data could presumably apply to this species in California. The yellowfin goby is also primarily a San Francisco Bay species, but is present in several California estuaries like Ballona Marsh/Marina del Rey complex, Los Angeles Harbor, Elkhorn Slough, Tomales Bay, San Diego Bay, and a few others. However, it is perhaps less likely that the yellowfin goby would become important as an indicator given that several other native goby species are available with similar life-history characteristics.

4. Macroinvertebrate Indicator Species

4.1 Introduction

This section presents the assumptions and methods used to identify invertebrate species appropriate for consideration as indicator species for DO in bays and estuaries. The objectives of this effort were similar to those described in the previous Section for fish, including:

1) Generate a list of invertebrate species characteristic of enclosed bays and estuaries;

2) Identify beneficial uses associated with each species; and

3) For each species, identify life stages with respect to seasonality, habitat type and location within estuarine and associated nearshore and/or freshwater habitat areas;

3) Prioritize species for review of literature for physiological impacts associated with hypoxic conditions.

4.2 Approach and Assumptions

As described in Section 3, a list of priority indicator fish species was developed through a workshop of fisheries experts. These participants developed criteria for species selection, and for prioritizing individual species for use as potential indicator species. For consistency, these criteria were also used to select invertebrate species that could serve as indicator species, as well as be the focus of a literature review to identify studies that evaluated effects associated with low DO concentrations (i.e., hypoxia).

4.2.1 General Criteria and Assumptions

The list of enclosed bays and estuaries found along the California coast, as identified by E-NNE Technical Team and vetted by SWRCB and advisory groups, was used as the primary basis for identifying invertebrate species likely to be associated with these habitats; note that the San Francisco Bay estuary was not included because it does not fall under the regulatory scope of California's Enclosed Bays and Estuaries policy. Thus, the potential breadth of species considered included the full complement of invertebrate species found in appropriate habitat throughout the state. More specific criteria were then applied to focus the species selection process; these were:

- Species must spend all or a substantial portion of their life-histories in estuarine habitats; thus, only estuarine species found within marine enclosed bays would be included; and

- Species should be clearly associated with regulatory categories and specific beneficial uses; thus, species that are considered rare or endangered, support recreational or commercial fisheries, or are of known ecological significance would be of primary interest.

Additional considerations include:

- Species should be native to California; non-native species were considered if they met either of the following two conditions: 1) they support recreational or commercial fisheries, and 2) they are species for which data on physiological effects of hypoxia are known to exist; thus, in cases where data were not available for native species, they could provide a basis for assessing effects.

- Species that are identical or closely related to species used to generate the Virginia Province Dissolved Oxygen Criteria (USEPA 2000).

In summary, the species selection process incorporated several elements to ensure that it was comprehensive in terms of the species considered, that it represented the desired species and habitat relationships, and that the species selected could be readily interpreted in the context of beneficial uses. Therefore, fundamental considerations included presence in estuaries and bays, either as residents or during key life-history stages, classification as rare or endangered, focus of recreational or commercial fisheries, and ecological importance. In general, benthic invertebrate infauna were not included because of their innate tolerance to low DO concentrations; however, exceptions to this rule were made if the infaunal species met the above criteria and exhibited planktonic early life stages (e.g., clams).

4.2.2 Life-History Strategies

Life-histories of identified species were reviewed to assess the extent of their potential association with bays and estuaries. Key data sources included general internet inquiries, U.S. Fish and Wildlife and California Department of Fish and Game species accounts, and compendia of coastal marine invertebrates [e.g., Light's Manual (Carlton 2007); Intertidal Invertebrates of California (Morris et al. 1980)].

Identifying (or eliminating) species for further consideration was complicated by study objectives related to the development of DO criteria for enclosed bays *and* estuaries. By definition, estuaries encompass a range of salinities that can vary temporally and spatially from freshwater to marine, thus supporting a wide array of species that vary in their tolerance to salinity. Conversely, enclosed bays typically exhibit a relatively narrow range of salinities, and are populated primarily by marine species. To reduce the extent to which nominally freshwater and marine species were included in the dataset, the following additional criteria were applied:

- Species were included if they are associated with enclosed bays and estuaries, either as permanent residents or during key life-history stages; and

- Species were generally excluded if their distribution patterns and abundance do not depend on the specific habitats (i.e., enclosed bays and estuaries) of interest.

Thus, the selected species were intended to be representative of species that depend upon these specific habitats for overall survival and well-being (e.g., critical spawning and nursery areas). This approach generally eliminated species that utilize these habitats opportunistically.,

4.2.3 Range and Beneficial Uses

Because California estuaries are classified according to “type”, this review also provided an opportunity to evaluate whether there were sufficient data to associate specific species with particular estuary types. Assuming that particular species could be associated with specific estuary types, the presence or absence of certain species from a given estuary might provide insight into the extent of DO-related impacts on a site-specific basis. Conversely, if particular estuary types could not be associated with identifiable species assemblages, or if DO sensitivity data for these species were lacking, these data gaps could be addressed in future studies.

Given that data are already available for species used to generate the East Coast Virginia Province Dissolved Oxygen Criteria, the selected California species were also compared against species in that database to identify California species, or species representing the same genus or family, for which data are available. In the absence of data for a California species, this “nearest neighbor” analysis was used to identify data available for closely related species.

Species that could be readily related to specific beneficial uses were also identified. Rare and endangered species were identified through an internet search of California and Federal listings, first looking for invertebrates, and then invertebrates that fit the remaining selection criteria. The fisheries status of individual species was evaluated by review of California Department of Fish and Game fishery management plans and status reports. Species that support identifiable commercial and/or recreational fisheries were noted and subjected to the remaining selection criteria before being added to the species list. Species not considered rare or endangered, or of significance to commercial or sport fisheries, were included if they could be clearly linked to “ecological significance”; for example, if they were a significant dietary component of fish found in estuaries or enclosed bays (Moyle 2002).

This approach resulted in a preliminary list of species that was then cross-referenced against literature available through the Aquatic Sciences and Fisheries Abstracts (ASFA) database to determine if the list was complete, or if additional species that met the above criteria needed to be added. This search focused on the list of enclosed bays and estuaries identified by SCCWRP, cross-referenced against descriptive terms for invertebrates to identify references that associated specific invertebrate species with specific water bodies. The list provided by SCCWRP included 454 bays and estuaries found along the California Coast (excluding San Francisco Bay); each estuary name was searched individually within the ASFA database. If the results of an estuary name provided more than 100 abstracts, the identifier with wildcard “invert*” was added to the search parameters to reduce the number of studies to less than 100. All returned results were then examined for applicability to the objective. If less than 100 papers for an estuary were identified, all were examined. Papers were selected for further review if they described field studies with native organisms within the estuary; contained results of dietary studies of organisms (e.g., fish, birds) associated with the estuary and likely to be feeding on invertebrates; or were reports of organisms (i.e., invertebrates) collected from the estuary.

Of the 454 bay and estuary locations searched, 409 did not return any results. For the remaining 45 sites, a total of 82 papers provided invertebrate information. All of these papers were reviewed, and the associated invertebrate taxa were recorded. These invertebrates were then compared against the preliminary list to validate species already selected, and to identify additional species for consideration; additional species that met the general selection criteria were subsequently added to the list.

4.3 Species Lists and Prioritization Rationale

4.3.1 Preliminary Species Selection

The preliminary list of candidate species is shown in Table 4.1. This is a comprehensive list representing species of special concern, as well as those associated with specific beneficial uses and/or well-defined ecological roles. Each of the species is briefly described below, along with comments regarding its preliminary selection and criteria for inclusion in the final list.

Abalone—*Haliotis rufescens, H. cracherodii, H. walallensis* and *H. kamstchatkana*. Abalone are typically associated with hard substrates in intertidal and subtidal zones. The genus ranges along the California coast, with more restricted ranges associated with particular species. Some species currently (or historically) support important commercial and/or recreational fisheries, but populations have been markedly reduced by overfishing and withering foot disease, particularly in southern California. *H. cracherodii* is considered endangered by both state and federal agencies. Although abalone are a significant fisheries resource, and also represent one listed species, they are primarily marine with respect to salinity tolerance and are widely distributed along the open coast. Moreover, they do not depend on bays or estuaries either as preferred or essential habitat. Consequently, they do not meet the criteria for inclusion in the final list.

Barnacles—*Balanus sp*. and *Pollicipes sp*. Barnacles are typically associated with hard substrate in intertidal zones, with planktonic larvae. Some species support limited commercial or recreational fisheries. While present in bays and estuaries, these habitats are not preferred or limiting. Consequently, they do not meet the criteria for inclusion in the final list.

Clams—a wide variety of clam species are found along the California coast. Adults are typically sessile, found inter or subtidally, and are generally associated with soft or gravelly bottom substrates where they may be buried at depth or located at or near the substrate surface. Early life stages typically involve a free-swimming planktonic larval period. A number of species support commercial and/or recreational harvest, and include:

- Basket cockle—*Clinocardium nuttali*. Found along the California coast; preferred habitat includes bays and estuaries.
- Bent-nose clams—*Macoma nasuta, M. balthica*. Harvested in commercial and recreational fisheries; preferred habitat includes bays and estuaries.
- Butter clam—*Saxidomas giganteus, S. nuttali*. The focus of commercial and recreational fisheries, distributed from central California north along the coast. Preferred habitat includes protected bays and estuaries.

- Gaper clams—*Tresus nuttali, T. capax*. Found along the California coast, but relatively uncommon. Preferred habitat includes bays and estuaries.
- Geoduck—*Panopea generosa, P. abrupta*. Found in central and northern California; preferred habitat includes bays and estuaries.
- Jacknife clams—*Tagelus californianus, T. affinis, Solen sicarius, S. rostiformis (rosaceus*). *T. californianus* and *S. rosaceus* are found from Santa Barbara south, whereas *S. sicarius* is found throughout California. All three species prefer quiet bays.
- Littleneck clams—*Chiones californiensis, C. fluctifraga, C. undatella, Protatheca laciniata, P. staminea, Tapes phillipinarum* (introduced). Found along the coast of California, although some species have more limited regional representation. Harvested in commercial and recreational fisheries, typically found intertidally and subtidally in bays and estuaries.
- Razor clams—*Siliqua patula, S. lucida*. *S patula* is found from central California north, and *S. lucida* from Monterey south, generally along open coasts. Consequently, these two species were not considered suitable for inclusion in the final species list.
- Soft shell clam—*Mya arenaria*. Introduced; prefers quiet bays and estuaries. Found from San Francisco north.
- Northern quahog—*Mercenaria mercenaria*. Introduced; very limited distribution (e.g., Humboldt Bay, Colorado Lagoon, Alamitos Bay, Long Beach).

Copepods—e.g., *Acartia* sp., *Eurytemora affinis*. Numerous species (*Calanoida*, *Harpacticoida*) of copepods makeup part of the zooplankton present in bays and estuaries. Because of their importance to local food webs, they are recommended for inclusion in the final species list.

Crab—a wide variety of crab species are found along the California coast, and include:

- **Box crab—*Lopholithodes foraminatus***. This species has been reported from bays, and is taken in commercial and recreational fisheries. It is widely distributed along the California coast subtidally to deep water. Because bays and estuaries are not preferred or essential habitat, it does not meet the criteria for inclusion in the final list.
- **Cancer Crabs—*Cancer magister, C. productus, C. antennarius, C. productus, C. anthonyi* and *C. gracilis***. Cancer crabs represent several species that support significant commercial and/or recreational fisheries. While found in a variety of habitats, bays and estuaries are often preferred and are considered essential nursery areas for early life stages. Thus, these species meet the criteria for inclusion in the final list.
- **Fiddler crab—*Uca crenulata***. Found intertidally in estuaries south of Santa Barbara; thus, this species meets the criteria for inclusion in the final list.
- **Hermit crab—*Isochelis sp., Pagurus sp***. While some species may be found in bays, bays and estuaries are not preferred or essential habitat. Consequently, these species do not meet the criteria for inclusion in the final list.
- **Mud crab—*Lophopanopeus bellus*.** Intertidal to subtidal; found in California in bays and open coast, but rare south of San Luis Obispo. Bays and estuaries are preferred habitat; therefore,

this species meets the criteria for inclusion in the final list. The related Harris mud crab (*Rhithropanopeus harrisii*) has been introduced to California, but is largely restricted to the San Francisco Bay and estuary.

- **Sheep crab—*Loxorhynchus grandis***. Found subtidally to depths exceeding 400 feet along the California coast from Marin County south, this crab supports a commercial fishery. There is an onshore migration associated with spawning, but no known dependence on bays or estuaries for rearing of early life stages. Therefore, it does not meet the criteria for inclusion in the final list of species.
- **Shore crabs—*Pachygrapsus crassipes, Hemigrapsus oregonensis***. Found intertidally on rocky coasts, as well as in bays and estuaries throughout California. Larvae are planktonic. Bays and estuaries are not essential habitat, but these crabs are widely distributed in estuaries and associated marshes due to salinity tolerance where they are important in the diet of a number of species, including birds. Consequently, they are recommended for inclusion in the final list.
- **Swimming crabs—*Callinectes bellicosus, C. arcuatus***. Found in shallow bays and lagoons in southern California, from Los Angeles south, thus meeting the criteria for inclusion in final list.
- **Umbrella crab—*Criptolithodes sitchensis***. Found along the California coast south to San Diego primarily in the intertidal zone. Bays and estuaries are not preferred or essential habitat; consequently, it does not meet the criteria for inclusion in the final list of species.

Mussels—*Mytilus californianus, M. galloprovincialis (edulis), M. trossulus, Modiolus rectus*. Mussels are typically attached to hard substrate as juveniles and adults, but early life stages are pelagic. Adult mussels support primarily recreational fisheries. They are widely distributed along the California coast; two of the species (*M. galloprovincialis (edulis) and M. rectus)* are typically associated with bays and estuaries. *M. rectus* has a more limited distribution; i.e., from Bolinas Bay south. Both species merit inclusion in the final list.

Octopus—*Octopus bimaculoides, O. bimaculatus*. These species range from Santa Barbara south. They are found in bays, but bays are not considered essential or primary habitat. Consequently, these species do not meet the criteria for inclusion in the final list.

Opossum shrimp—*Neomysis mercedis*. Opossum shrimp (Mysidae) are important components of nearshore food webs. One species in particular, *N. mercedis*, is associated with estuaries along the central and northern California coast. Consequently, this species merits inclusion in the final list.

Oysters—*Ostrea lurida*. A native oyster, widely distributed along the coast of California; preferred habitat includes bays and estuaries. Therefore, it meets the criteria for inclusion in the final list.

Scallops—*Argopecten aesquilatus, Crassodoma gigantean*. The speckled scallop *A. aesquilatus* formerly supported a small fishery, but is currently rare. It is typically found in shallow bays and lagoons, usually in association with eelgrass, north to Elkhorn Slough. The rock scallop *C. gigantean* is distributed along the entire California coast. It is associated with hard substrate in bays, but also occurs on offshore reefs. Therefore, bays and estuaries are not preferred or essential habitat for this species. Thus, only the speckled scallop meets the criteria for inclusion on the final list.

Sea cucumbers—*Parastichopus californicus, P. parvimensis*. *P. californicus* occurs along the entire California coast, whereas *P. parvimensis* is present from Monterey Bay south. Both species support fisheries, but neither uses bays nor estuaries as preferred or essential habitat. Consequently, sea cucumbers do not meet the criteria for inclusion in the final list.

Spiny lobster—*Panulirus interruptus*. This species is found from Monterey Bay south, and is the focus of significant commercial and recreational fisheries. Their presence in bays is largely opportunistic and associated with rocky or hard substrate (jetties, breakwaters); onshore migrations are associated with spawning, but bays and estuaries are not a requirement for growth and development of early life stages. Nonetheless, eelgrass beds are considered important nursery areas. Consequently, due to its importance as a fishery, and the significance of eelgrass beds as nursery areas, this species is recommended for inclusion in the final list.

Snails—a variety of snails are found in nearshore habitats and support commercial or recreational fisheries.

- **Kellet's whelk—(*Kelleta kelletii*)**. A relatively large gastropod, it is taken in both commercial and recreational fisheries, often in deeper water. It is primarily found in southern California, but has been observed in Monterey Bay. Because it does not use bays or estuaries as preferred or essential habitat, it does not meet the criteria for inclusion in the final list.
- **Moon snail—*Polinices sp.*** Moon snails are often present in bays and estuaries, where they prey on clams and other bivalves. *P. lewisii* is found along the entire California coast, whereas *P. reclusianus* is more common in southern California. These species merit inclusion in the final list.

Sea urchins and sand dollars—*Strongylocentrotus purpuratus, S. franciscanus* and *Dendraster excentricus*. These echinoderms are widely distributed in inter- and subtidal habitats along the California coast. Sea urchins are associated with hard substrate, and sand dollars are typically found in sand. Sea urchins are the focus of commercial and recreational fisheries. However, all three species are primarily marine in terms of salinity tolerance, and do not depend on bays or estuaries as preferred or essential habitat. Thus, they do not meet the criteria for inclusion in the final list.

Shrimp—several species of shrimp are found in nearshore areas of California.

- **Bay or Grass shrimp—*Crangon franciscorum, C. nigricauda, Palaemon macrodactylus***. These medium-sized decapods are most frequently found in bays and estuaries along the California coast. They are typically epibenthic, but also found on pilings, and in eelgrass beds. Where abundant, they support commercial and recreational fisheries. Note that *P. macrodactylus* (Korean prawn) is an introduced species with more limited distribution, but often co-occurs with *Crangon sp*. These species do meet the criteria for inclusion in the final list.
- **Ghost shrimp—*Callianassa* (now *Neotrypaea*) *californiensis*, *C. gigas***. These burrowing shrimp are found in soft bottom substrate in bays and estuaries along the California coast. Adults are tolerant of hypoxia, but larvae are planktonic. Ghost shrimp support recreational fisheries and are included on the final list.

- **Mud shrimp—*Upogebia pugettensis***. This species inhabits similar habitat to ghost shrimp, but is more tolerant of lower salinities. It also supports recreational fisheries and is included on the final list.
- **Coon-striped shrimp—*Pandalus danae***. Found from San Luis Obispo north, this species is found off-shore, as well as in bays. Thus, bays and estuaries are not preferred or essential habitat, and this species does not meet the criteria for inclusion in the final list.
- **Red rock shrimp—*Lysmata californica***. Found in rocky substrate from Santa Barbara south, with an apparently isolated population in Monterey Bay. It supports commercial and recreational fisheries, but its presence in bays appears largely associated with localized presence of suitable habitat in the form of rip rap or rock walls (e.g., breakwaters) and not to any other particular attributes associated with bays. Thus, bays and estuaries are not considered preferred or essential habitat and, therefore, this species is not recommended for inclusion in the final list.

Table 4.1 Comprehensive list of candidate invertebrate species with summary information on range, applicable beneficial uses, and whether estuaries are preferred or essential habitat. Range designations are as follows: All= throughout California, N =North of Point Conception, S= South of Point Conception.

Common Name	Scientific Name	Range	Listed Status	Beneficial Uses	Preferred or Essential Habitat
Abalone	*Haliotis sp.*	All	Endangered (*H. cracherodii*)	MAR, RARE, COMM	No
Barnacle	*Balanus sp., Pollicipes sp.*	All	None	MAR, EST, COMM	No
Basket cockle	*Clinocardium nuttali*	All	None	MAR, EST, COMM, SHELL	Yes
Bent-nose clam	*Macoma nasuta, M. balthic*	All	None	MAR, EST, COMM, SHELL	Yes
Butter clam	*Saxidomas giganteus, S. nuttali*	N	None	MAR, EST, COMM, SHELL	Yes
Gaper Clams	*Tresus nuttali, T. capax*	All	None	MAR, EST, COMM, SHELL	No
Geoduck	*Panopea generosa, P. abrupta*	N	None	MAR, EST, COMM, SHELL	No
Jack-knife Clams	*Tagelus californianus, T. affinis, Solen rostiformis/rosaceus, S. sicarius*	All	None	MAR, EST, COMM, SHELL	No
Littleneck Clams	*Chiones californiensis, C. fluctifraga, C. undatella, Protatheca laciniata, P. staminea, Tapes phillipinarum*	All	None	MAR, EST, COMM, SHELL	Yes
Razor Clams	*Siliqua patula, S. lucida*	All	None	MAR, COMM, SHELL	No
Soft Shell Clam	*Mya arenaria*	N	None	MAR, EST, COMM, SHELL	Yes (Introduced)
Northern quahog	*Mercenaria mercenaria*	Limited	None	MAR, COMM, SHELL	No (Introduced)
Copepods	*Acartia sp., Eurytemora affinis*	All	None	MAR, EST	Yes
Box Crab	*Lopholithodes forminatus*	All	None	MAR, COMM	No

Common Name	Scientific Name	Range	Listed Status	Beneficial Uses	Preferred or Essential Habitat
Cancer Crabs	*Cancer magister, C. productus, C. antennarius, C. anthonyi, C. gracilis*	All	None	MAR, EST, COMM	Yes
Fiddler Crab	*Uca crenulata*	S	None	EST	Yes
Hermit Crabs	*Isochelis sp., Pagurus*	All	None	MAR	No
Mud Crab	*Lophopanopeus bellus*	All	None	EST	Yes
Sheep Crab	*Loxorhynchus grandis*	All	None	MAR, COMM	No
Shore Crabs	*Pachygrapsus crassipes, Hemigrapsus oregonensis*	All	None	MAR, EST	Yes
Umbrella Crab	*Criptolithodes sitchensis*	All	None	MAR	No
Mussels	*Mytilus californianus, M. galloprovincialis (edulis), M. trossulus, Modiolus rectus*	All	None	MAR, EST, COMM, SHELL	Yes
Octopus	*Octopus bimaculoides*	S	None	MAR, COMM	No
Opossum Shrimp	*Neomysis mercedis*	N	None	EST	Yes
Oyster	*Ostrea lurida*	All	None	MAR, EST, COMM, SHELL	Yes
Scallop	*Argopecten aesquilatus*	S	Rare	MAR, COMM, SHELL	No
Rock Scallop	*Crassodoma gigantean*	All	None	MAR, EST, COMM, SHELL	No
Sea Cucumbers	*Parastichopus californicus, P. parvimensis*	All	None	MAR, COMM	No
Spiny Lobster	*Panulirus interruptus*	All	None	MAR, COMM	No
Kellet's Whelk	*Kelleta kelletii*	S	None	MAR, COMM	No

Common Name	Scientific Name	Range	Listed Status	Beneficial Uses	Preferred or Essential Habitat
Moon Snail	*Polinices sp.*	All	None	EST, COMM	Yes
Sea Urchins	*Strongylocentrotus purpuratus, S. franciscanus*	All	None	MAR, COMM	No
Sand Dollars	*Dendraster excentricus*	All	None	MAR	No
Bay or Grass Shrimp	*Crangon franciscorum, C. nigricauda, Palaemon macrodactylus*	All	None	MAR, EST, COMM	Yes
Ghost Shrimp	*Callianassa* (now *Neotrypaea*) *californiensis, C. gigas*	All	None	MAR, EST, COMM	Yes
Mud Shrimp	*Upogebia pugettensis*	All	None	EST, COMM	Yes
Coon-striped shrimp	*Pandalus danae*	N	None	MAR, COMM	No
Red Rock Shrimp	*Lysmata californica*	S	None	MAR, COMM	No

4.3.2 Comparison of Preliminary Species Selection with Species Reported from California Bays and Estuaries

The literature search for California bays and estuaries associated with invertebrates resulted in over 200 entries relating specific invertebrate species to identifiable bodies of water. However, the actual studies varied in level of detail; very few were comprehensive compilations of species present either at the site or in the diet of predators present at the site. More frequently, the papers reported a range extension for a particular species and behavioral interactions between species. Overall, the 82 papers identified and reviewed as part of this process provided limited additional insight as to species that would qualify for the final species list beyond those already selected. Thus, species noted in the papers generally included (1) those that had already been identified by workshop participants; (2) introduced species; and (3) species that are not preferentially associated with bays or estuaries. An additional category included species that may be preferentially associated with bays or estuaries, but do not occur in sufficient abundance to represent a significant fisheries or ecological component. An example would be the California shrimp, *Heptacarpus paludicola* (Hippolytidae).

A number of papers cited amphipods in association with bays and estuaries. Because these organisms are generally considered infaunal, they did not meet the original search criteria, based on their presumed tolerance to low DO concentrations. However, amphipods, particularly the Gammaridea, are represented by an array of species, often distributed by salinity, substrate and tidal elevation, characteristics that contribute significantly to nearshore nutrient cycling. Notably, these species can achieve remarkably high densities in mudflats of bays, estuaries and associated marshes (e.g., 50,000 to 100,000 organisms per m^2) where they serve as food for other invertebrates, fishes, and birds (Grosse and Pauley, 1989). Consequently, because of their contribution to the ecology of bays and estuaries, this group, particularly *Americorphium* sp., *Corophium* sp., *Anisogammarus* sp. and *Eohaustorius* sp., is recommended for inclusion in the final species list.

4.3.3 Nearest Neighbor Comparison of California Species and Species used to Develop the Virginia Province Salt Water DO Criteria

The species identified in the previous sections were then compared against species used to develop the DO criteria for the Virginia Province to evaluate the extent to which California species (and species related at the genus and family levels) are represented in the existing data set and associated calculations. The results are summarized below.

- Amphipods—data are available for a gammaridean amphipod (introduced).
- Clams—several native California species (i.e., chiones, butter clams, littlenecks) were represented at the family level (i.e., Veneridae); the introduced northern quahog (*Mercenaria mercenaria*) is represented at the species level.
- Copepods—data are available for *Eurytemora affinis* at the species level.
- Crab—native *Cancer* crabs are represented at the genus level; the native Mud crab is represented at the family level (Panopeidae), whereas the introduced Harris Mud crab is represented at the species level. Data are available for the introduced green crab (*Carcinus*

maenus), and for native swimming crabs at the genus (*Callinectes*) and family (Portunidae) levels.

- Opossum shrimp—data are available at the family level (Mysidae).
- Oyster—data are available for the native oyster at the family level (Ostreidae), and at the species level for the introduced eastern oyster (*Crassostrea virginica*).
- Shrimp—data are available for native grass shrimp at the genus level (*Crangon*), and for the introduced Korean prawn (*Palaeomon macrodactylus*) at the family level.

This analysis shows that very few native California invertebrate species are represented in the dataset used to develop the DO criteria for the Virginia Province. However, a number of California invertebrate species that are of interest in terms of developing DO criteria for bays and estuaries are represented in the existing database by data for species that are similar at the genus or family level. In addition, the database also includes data for species that have been introduced into California. Thus, in the absence of sufficient data for native California species, there would be the potential to utilize at least some of the data used to develop the DO criteria for the Virginia Province.

4.3.4 Prioritization and Recommended Invertebrate Species List

Based on the preceding analysis, the following California species were recommended for evaluation of empirical data related to adverse effects associated with exposure to low DO:

Table 4.2 List of recommended invertebrate species with summary information on range, applicable beneficial uses, and preferred habitat. Range designations are as follows: All= throughout California, N=North of Point Conception, S= South of Point Conception.

Common Name	Scientific Name	Range	Beneficial Uses	Preferred Habitat
Amphipods	*Americorophium sp., Corophium sp., Anisogammarus sp, Eohaustorius sp.*	All	MAR, EST	Bays, estuaries
Basket cockle	*Clinocardium nuttali*	All	MAR, EST, COMM, SHELL	Bays, estuaries
Bent-nose clam	*Macoma nasuta, M. balthic*	All	MAR, EST, COMM, SHELL	Bays, estuaries
Butter clam	*Saxidomas giganteus, S. nuttali*	N	MAR, EST, COMM, SHELL	Bays, estuaries
Gaper Clams	*Tresus nuttali, T. capax*	All	MAR, EST, COMM, SHELL	Bays
Geoduck	*Panopea generosa, P. abrupta*	N	MAR, EST, COMM, SHELL	Bays
Jack-knife Clams	*Tagelus californianus, T. affinis, Solen rostiformis/rosaceus, S. sicarius*	All	MAR, EST, COMM, SHELL	Bays
Littleneck Clams	*Chiones californiensis, C. fluctifraga, C. undatella, Protatheca laciniata, P. staminea, Tapes phillipinarum*	All	MAR, EST, COMM, SHELL	Bays, estuaries
Soft Shell Clam (introduced)	*Mya arenaria*	N	MAR, EST, COMM, SHELL	Bays, estuaries
Northern quahog (introduced)	*Mercenaria mercenaria*	Limited	MAR, COMM, SHELL	Bays
Copepods	*Acartia sp., Eurytemora affinis*	All	MAR, EST	Bays, estuaries
Cancer Crabs	*Cancer magister, C. productus, C. antennarius, C. anthonyi, C. gracilis*	All	MAR, EST, COMM	Bays, estuaries
Fiddler Crab	*Uca crenulata*	S	MAR, EST	Bays, estuaries

Table 4.2 Continued

Mud Crab	*Lophopanopeus bellus*	All	EST	Bays, estuaries
Harris Mud Crab	*Rhithropanopeus harrisii*	Introduced		Bays, estuaries
Shore Crabs	*Pachygrapsus crassipes, Hemigrapsus oregonensis*	All	MAR, EST	Bays, estuaries
Green Crab	*Carcinus maenus*	Introduced		Bays, estuaries
Swimming Crabs	*Callinectes bellicosus, C. arcuatus*	S	MAR, EST, COMM	Bays, estuaries
Mussels	*Mytilus californianus, M. galloprovincialis (edulis), M. trossulus, Modiolus rectus*	All	MAR, EST, COMM, SHELL	Bays, estuaries
Opossum Shrimp	*Neomysis mercedis*	N	EST	Bays, estuaries
Olympic Oyster	*Ostrea lurida*	All	MAR, EST, COMM, SHELL	Bays, estuaries
Eastern Oyster	*Crassostrea gigas*	Introduced	MAR, COMM, SHELL	Bays, estuaries
Scallop	*Argopecten aesquilatus*	S	MAR, COMM, SHELL	Bays
Spiny Lobster	*Panulirus interruptus*	All	MAR, COMM	Bays
Moon Snail	*Polinices sp.*	All	EST, COMM	Bays, estuaries
Bay or Grass Shrimp	*Crangon franciscorum, C. nigricauda, Palaemon macrodactylus*	All	MAR, EST, COMM	Bays, estuaries
Ghost Shrimp	*Callianassa* (now *Neotrypaea*) *californiensis, C. gigas*	All	MAR, EST, COMM	Bays, estuaries
Mud Shrimp	*Upogebia pugettensis*	All	EST, COMM	Estuaries

5. Review of Physiological Effects Data

5.1 Introduction

This section describes the approach and findings of the effort taken to identify available data relevant to the revision of numeric objectives for DO for California Enclosed Bays and Estuaries. In general, the approach focused on fish and invertebrate species of interest that were initially identified on the basis of meeting the suitability criteria described in Sections 3 and 4.

5.2 Approach

In keeping with the approach described in Section 4.2.1, the literature search was broad, in an effort to encompass all information on the toxicological, physiological and behavioral effects of low DO that might be relevant to setting goals for California waters. Information related to the sensitivity of the selected species to low DO was obtained through database searches, review documents, appendices to the Virginia Province DO criteria document, and contacts with various agency staff. Citations and data of interest were further reviewed to assess whether the data met requirements for use in water quality criteria derivation (Stephan et al. 1985). Specifically, the desired data comprised specific effects or responses (e.g., survival, growth or reproductive endpoints) associated with specific DO concentrations. While of potential interest, studies that evaluated behavioral responses or population and community distributions across DO gradients were not directly applicable to the objective derivation process. Similarly, studies that emphasized physiological responses, such as ventilation and respiration rates, were reviewed to provide insight regarding the potential sensitivity of target species to low DO; however, these works do not provide data that are relevant for establishing numeric objectives. The identification and evaluation of potentially relevant studies and associated data was also extended to genus and family relatives of the identified species. In addition to specific exposure and response requirements, each potential reference was also evaluated to determine if reported data met certain quality assurance requirements, including control survival, well-documented and controlled DO exposure concentrations, and generally sound experimental procedures.

5.2.1 Fish

The indicator species provided in Section 3 were used as a basis for identifying available DO response data in the literature. Major review papers on the effects of hypoxia were thoroughly examined to select primary references of potential relevance to the current effort, based on reference to species or genus names associated with the identified California fish species. These papers included broad-spectrum reviews by Vaquer-Sunyer and Duarte (2008), Breitburg (2002), Gray et al. (2002), Wanamaker and Rice (2000), and USEPA (2000). In addition to these principal review documents, two additional reviews were included: one by Don Miller (USEPA) in 1995 for the USEPA Virginia Province Salt Water Dissolved Oxygen Criteria, and another by Glen Thursby (USEPA) in 2003 as an addendum to the Virginia Province Salt Water Dissolved Oxygen Criteria that considered objectives for warmer and colder habitats relative to the Virginian Province. A keyword search was also conducted to identify the most recent literature that might pertain to the current effort. Key words included: species of interest, DO, hypoxia, tolerance, and effects (survival or growth or reproduction). If the search returned no results, genus was substituted for species. Citations were only included in the results if the literature reported on criteria-applicable endpoints (e.g., survival, growth, reproduction), or endpoints that the author(s) clearly related to criteria-applicable endpoints (e.g., delayed hatch, reduced feeding). Software used to identify and retrieve literature included the Aquatic Sciences and Fisheries Abstracts (ASFA) database, Science Direct©, SpringerLink©, and the National Sea Grant Library Database. In order to fill data gaps where neither the species nor genus was represented in the relevant DO literature for a given California indicator species, an additional step was taken to identify family-level surrogate effects data. In such cases, the Virginian Province Criteria document was reviewed again for species that shared the same family as a California indicator species, and appropriate citations and results were added to the set of acceptable results from the literature.

5.2.2 Invertebrates

The literature was examined for available data on the responses of identified invertebrate species (Section 4) to reduced DO concentrations. Again, the ASFA was used, this time starting with species. Separately, common name, genus and species names were searched. If the returned results for the species were less than 100, all titles and abstracts were examined to determine if any were relevant to this study. If the returned results exceeded 100, "AND oxygen" was added to the search criteria and any returned results were examined for effects data. If no papers were found, "AND hypoxia" was searched with the species name, and any returned results examined for relevance. If neither of these keywords were successful in identifying citations, "AND effects" was used and any returned results examined for relevance. If the species name was unsuccessful in generating over 50 results, only the Genus name was used and the previous search pattern applied. Citations were only accepted if they contained data about organism response in terms of direct effects on mortality, growth, or reproduction. Thus, organism responses to low DO as measured by changes in heart rate, behavior, etc., were not included in subsequent analyses. In total, 83 papers were identified as providing data potentially useful for deriving DO criteria. In addition, the same review papers on DO used for the fish search were examined for reference to species and genus names from the list of California species of interest. Three additional papers were found from this effort. The Virginian Province Criteria document contained data for eight of the genus names from the list, which were also included.

5.3 Findings

5.3.1 General

Collectively, the review papers compiled a broad spectrum of hypoxia-related effects studies and, based on a comparison to our independent literature reviews, identified almost all of the literature that might be considered potentially useful in reviewing the appropriateness of DO objectives for California. Given the robust nature of this database, commonality in certain conclusions across the different reviews lends credibility to generalizations that can be applied across geographic boundaries. For example, Vaquer-Sunyer and Duarte (2008), Gray et al. (2002) and USEPA (2002) all found that crustaceans typically exhibit higher oxygen thresholds (i.e., are more sensitive to low DO) than other marine or estuarine taxa; however, this sensitivity is largely limited to larval life-history stages (USEPA 2000).

The most comprehensive of these documents is a general review entitled "Thresholds of Hypoxia for Marine Biodiversity" (Vaquer-Sunyer and Duarte 2008), which provides a synthesis of 872 published experiments reporting responses to reduced DO concentrations for a total of 206 species. Notably, this paper reported that 10 % of LC50 values[4] in the literature were greater than 4.59 mg oxygen/liter; thus, there is potential for regional differences in sensitivity depending on local species distributions.

5.3.2 Fish

In addition to the review papers cited above, 39 citations were identified in the initial literature search as being of potential interest. Of these, 24 were determined to be useful for deriving objectives. These 24 were divided among the four groups briefly summarized below.

- Native California species: Data were found for 6 native California species, including Pacific herring, three species of salmonids, striped mullet and threespine stickleback.
- Introduced species: Data were found for one species (striped bass).
- Genus and family-level surrogates: Surrogate species were identified at the genus (4), and family (4) levels. Genus-level surrogates included *Acipenser*, *Anchoa*, *Paralichthys* and *Sygnathus* sp.; family-level surrogates represented Atherinopsidae, Pleuronectidae, Gobiidae and Sciaenidae.
- No suitable literature was identified to represent the prickly sculpin *Cottus asper*, staghorn sculpin *Leptocottus armatus* (Cottidae), or the California killifish *Fundulus parvipinnis* (Fundulidae).

[4] LC50 refers to the concentration expected to kill 50% of the exposed organisms.

NATIVE FISH SPECIES

Juvenile threespine stickleback exhibited a LC50 of 0.9 mg/L (Poucher and Coiro 1997). Data were available for three of the California indicator species of salmonids, specifically related to the effect of low DO on the growth of Chinook and Coho salmon (JRB Associates, 1984) and rainbow trout (Pedersen, 1987). These salmonid data were used in the derivation of USEPA's freshwater DO criteria (USEPA 1985); the associated criterion to prevent moderate (~20%) production impairment based on growth responses of salmonids was 6.0 mg/L. This concentration is greater than the limit of 4.8 mg/L derived as the saltwater criterion for the protection of growth in the Virginia Province. Data were also available on the effects of low DO on hatching success and survival of Pacific herring embryos (Coiro, personal communication), as reported by Thursby (2003). The herring embryos failed to hatch by the end of the 14-day exposure, eleven days after the control treatment began hatching. While an LC50 was not established due to test termination, it was reported as > 3.1 mg/L. De Silva and Tytler (1973) exposed herring larvae to reduced oxygen for 12 hrs and derived an LC50 of 2.8 mg/L. Finally, data for striped mullet suggest that they are potentially more sensitive to low DO than other fish species representing the southern California estuaries. Eggs and larval striped mullet from a Hawaiian population were tested by Sylvester (1975), who reported a 48-hr LC50 of 4.5–5.0 mg/L for embryos, and a 96-hr LC50 of 6.4–7.9 mg/L for larvae; adults were able to tolerate 4.4 mg/L. Goodman and Campbell (2007) reported a 24-hr LC50 of 1.4 mg/L for juvenile mullet exposed to low D.O. at 28^{o}C. Of note, the sensitivities of both herring and striped mullet embryos and larvae exceeded the most sensitive response (i.e., LC50 = 3.0 mg/L for the larval mud crab, *Dispanopeus sayii*) used to generate the USEPA's East Coast larval recruitment criterion. Thursby (2004) suggested that it may not be appropriate to include winter-spawning species in deriving criteria primarily intended to address adverse effects associated with summertime hypoxia, since the sensitive life stages would not be present during this period. Conversely, hypoxia may also occur during other seasons, suggesting that the data are relevant.

INTRODUCED FISH SPECIES

Data were available for striped bass, and suggested that larvae from the San Francisco Bay population were more sensitive to low DO than East Coast populations of the same species (Poucher and Coiro, 1997). San Francisco Bay larvae exhibited a 96-hr LC50 of 3.2 mg/L, compared with 2.2 and 2.0 mg/L for larvae from the Hudson River and a Chesapeake Bay tributary, respectively. Conversely, data for juvenile striped bass from these same three geographic regions exhibited no difference in sensitivity to hypoxia, yielding a mean LC50 of 1.4 mg/L (Poucher and Coiro 1998). The extent to which differences between regions/populations reflect actual differences in sensitivity, or small differences in test methodology or ages of actual organisms is unknown; differences (i.e., 17 to 35%) in hypoxia tolerance limits were also reported for mysids (*Americamysis bahia)* and inland silversides (*Menidia beryllina)* obtained from the Gulf of Mexico compared with those from northeast populations (Goodman and Campbell 2007).

SURROGATE FISH SPECIES

Data were found for four species that represent California indicator species as surrogates at the genus level. Three of these were studies with juveniles, and one was with early life stages. The juvenile surrogate/corresponding California species combinations were: Summer flounder (*Paralicthys dentatus)/*California halibut *(Paralichthys californicus),* pipefish (*Syngnathus fuscus*)/bay and barred pipefish (*S. leptorhynchus, S. auliscus*), and shortnose sturgeon (*Acipenser brevirostrum*)/green sturgeon (*A. medirostris*). For the flounder, LC50s for juveniles were 1.1 mg/L at 20°C and 1.6 at 24°C (Miller et al. 2002). A growth-effect threshold for juvenile flounder was reported at 3.5 mg/L, based on three fourteen-day exposure tests at 20°C (Poucher and Coiro 1997). The pipefish LC50 was 1.6 mg/L (Miller et al. 2002). Data for juvenile shortnose sturgeon (*A. brevirostrum*), were used as a genus-level surrogate for the green sturgeon, *A. medirostris*, which is currently on the Federal Threatened Species list. Campbell and Goodman (2004) reported the LC50 for 77-day post-hatch *A. brevirostrum* tested at 25°C at 2.7 mg/L, which is higher than any juvenile fish response reported in the Virginia Province Salt Water Dissolved Oxygen Criteria (USEPA 2000). The study also reported an LC50 of 2.2 mg/L for older juveniles (100-104 days post-hatch) at 25°C; however, this value increased to 3.1 mg/L at a temperature of 30°C. Niklitschek and Secor (2009) reported that optimal feeding for growth of juvenile shortnose sturgeon at 20°C occurred at 70% saturation (approximately 5 mg/L), roughly equivalent to the Virginia Province criterion established to protect from unacceptable growth reduction.

The genus-level surrogate/California species combination with early life-history stages included the bay anchovy (*Anchoa mitchilli*)/deepbody and slough anchovies (*A. compressa, A. delicatissima*). Chesney and Hood (1989) conducted 12-hr exposures with bay anchovy embryos and larvae, and derived LC50s of 2.7 and 1.6 mg/L, respectively.

Nine of the twenty species in the California indicator species list were represented by information at the family level. These included the topsmelt, *Atherinops affinis* (Atherinopsidae); starry flounder *Platichthys stellatus* (Pleuronectidae); the gobies *Eucyclogobius newberryi*, *Clevelandia ios*, *Quietula y-cauda*, *Ilypnus gilberti* and *Gillichthys mirabilis* (Gobiidae); and the yellowfin croaker *Umbrina roncador* (Sciaenidae). Acute toxicity data for juvenile Pacific herring were also available as a family-level surrogate (Clupeidae). Data for family surrogate/California species combinations are summarized below.

Menidia menidia (Atherinopsidae) embryos at 25°C exhibited 33% reduced hatch at 2.8 mg/L; an LC50 was established at 2.3 mg/L. The threshold for growth effects was reported as 4.3 mg/L, measured following a 28-day test beginning with embryos and ending with larvae (Poucher and Coiro 1997). Goodman and Campbell (2007) reported LC50s of 1.2 and 1.4 mg/L for larval *Menidia beryllina* (Atherinopsidae). Juvenile winter flounder (Pleuronectidae) exhibited a mean LC50 of 1.4 mg/L, whereas two species of Sciaenidae, juvenile *Leiostomus xanthurus* and larval *Scianops ocellatus* exhibited LC50s of 0.7 and 1.8 mg/L, respectively (Miller et al. 2002). Larval stages of naked goby (*Gobiosoma bosci*), and skilletfish (*Gobiesox strumosus*) (Gobiidae) were less sensitive, with 10% and 65% mortality at 1.2 and 1.0 mg/L (Saksena and Joseph 1974). Larval stages of the scaled sardine (*Harengula jaguana*) (Clupeidae) exhibited an LC50 of 2.1 mg/L.

Table 5.1 List of priority fish species with available DO effects data.

Species	Data available	Surrogate available	Surrogate used
Staghorn sculpin, *Leptocottus armatus* (Cottidae)	No	None	None
Tidewater goby, *Eucyclogobius newberryi* (Gobiidae)	No	Family level	Naked goby (*Gobiosoma bosci*) and Skilletfish (*Gobiesox strumosus*)
Topsmelt, *Atherinops affinis* (Atherinopsidae)	No	Family level	*Menidia menidia*, *M. beryllina*
Starry flounder, *Platichthys stellatus* (Pleuronectidae)	No	Family level	Winter flounder (*Pseudopleuronectes americanus*)
Arrow goby, *Clevelandia ios* (Gobiidae)	No	Family level	Naked goby (*Gobiosoma bosci*) and Skilletfish (*Gobiesox strumosus*)
Threespine stickleback, *Gasterosteus aculeatus* (Gasterosteidae)	Yes	None	NA
Prickly sculpin, *Cottus asper*, (Cottidae)	No	None	None
Deepbody/Slough anchovy, *Anchoa compressa, delicatissima* (Engraulidae)	No	Genus level	Bay anchovy (*Anchoa mitchilli*)
Rainbow trout/Steelhead, *Oncorhynchus mykiss* (Salmonidae)	Yes	None	NA
Coastal cutthroat trout, *Oncorhynchus clarki clarki* (Salmonidae)	No	Genus level	Rainbow trout/Steelhead, Coho and Chinook salmon
Coho salmon, *Oncorhynchus kisutch* (Salmonidae	Yes	None	NA
King or Chinook salmon, *Oncorhynchus tshawytscha* (Salmonidae)	Yes	None	NA
California killifish, *Fundulus parvipinnnis* (Fundulidae)	No	None	None
California halibut, *Paralichthys californicus* (Paralichthyidae)	No	Genus level	Summer flounder (*Paralichthys dentatus*)

Species	**Data available**	**Surrogate available**	**Surrogate used**
Bay/Barred pipefish, *Syngnathus leptorhynchus, S. auliscus* (Syngnathidae)	No	Genus level	Pipefish (*Syngnthus fuscus*)
Pacific herring, *Clupea pallasi* (Clupeidae)	Yes (early life stage)	Family level (juvenile)	Scaled sardine (*Harengula jaguana*)
Shadow goby, *Quietula y-cauda* (Gobiidae)	No	Family level	Naked goby (*Gobiosoma bosci*) and Skilletfish (*Gobiesox strumosus*)
Cheekspot goby, *Ilypnus gilberti* (Gobiidae)	No	Family level	Naked goby (*Gobiosoma bosci*) and Skilletfish (*Gobiesox strumosus*)
Longjaw mudsucker, *Gillichthys mirabilis* (Gobiidae)	No	Family level	Naked goby (*Gobiosoma bosci*) and Skilletfish (*Gobiesox strumosus*)
Diamond turbot, *Pleuronichthys guttulatus* (Pleuronectidae)	No	Family level	Winter flounder (*Pseudopleuronectes americanus*)
Green sturgeon, *Acipenser medirostrus*	No	Genus level	Shortnose sturgeon (*A. brevirostrum*)
Striped mullet, *Mugil cephalus*	Yes	NA	NA
Striped bass, *Morone saxatilis*	Yes	NA	NA

5.3.3 Invertebrates

In addition to the review papers cited above, 79 citations were identified as being of potential interest for studies addressing low oxygen effects. Following a review of these studies, a subset of 15 references addressing 18 species was considered to be appropriate for criteria derivation. Each reference contained data for a California indicator species, or a member of the genera or family of a species listed as an indicator.

The species for which data that can be applied towards criteria derivation are available were assigned to the four groups briefly summarized below.

- Native California species: Data were found for three native California species: the copepods *Acartia tonsa* and *Eurytemora affinis,* and the blue mussel *(Mytilus edulis)*.
- Introduced species: Data were found for five species: the clams, *Mya arenaria and Mercenaria mercenaria,* the Harris mud crab *(Rhithropanopeus harrisii),* the Eastern oyster (*Crassostrea virginica*), and the green crab (*Carcinus maenus*).
- Genus and family-level surrogates: Surrogates were identified for clams, mussels, amphipods, shrimp and crabs. Surrogate species were identified at the genus (5), and family (7) levels. Genus-level surrogates included *Cancer*, *Calinectes, Crangon, Corophium,* and *Pandalus*; family-level surrogates represented Ampeliscidae, Xanthidae, Majidae, Mysidopsidae, Ostreidae, Palaemonidae and Veneridae.
- No suitable literature was identified to represent: fiddler crab, shore crab, speckled scallop, spiny lobster, moon snail, ghost shrimp and mud shrimp.

NATIVE INVERTEBRATE SPECIES

The sensitivity to low DO has been established for multiple life stages of *Acartia tonsa*, including adult, nauplii and embryos through hatching. Adult *A. tonsa* produced a 24-hr LC50 of 1.2 mg/L, while less sensitive nauplii tolerated a 24-hr exposure at 0.3 to 0.6 mg/L (Stalder and Marcus 1997). These tests were conducted at 20^{o}C and salinity of 30 ppt. Lutz et al., (1998) exposed embryos to near-anoxic conditions and found that short-term exposures were not lethal when embryos were returned to normoxic water. Marcus et al., (2004) conducted two 28-day life-cycle tests at 20^{o}C and found that the number of offspring per female reproductive day was reduced by more than 50% in a 2.0 mg/L treatment relative to offspring production in the control groups. This study also used established population model software to estimate that reproductive effects translated to a mean 17.5% reduction in estimated population growth rate at 2.0 mg/L, and 49% reduction in population growth rate at 0.9 mg/L. Lesser effects for the same endpoints were observed under winter temperatures (i.e., 15^{o}C) (Richmond et al. 2006). *Eurytemora affinis* is apparently less sensitive than *A. tonsa*, as an LT50 of 24 hrs for survival was reported for exposure to 0.6 mg/L at 27^{o}C at 5 ppt salinity (Davis and Bradley 1990).

A study by Wang and Widdows (1991) was conducted with *Mytilus edulis* early life stages. Anoxia tolerance was dependent on stage, with larger larvae being more tolerant. Tests were conducted at

<0.2% saturation and 15^{o}C, resulting in an LT50 of 14.7 hrs for small (106 um) larvae and 38.7 hrs for larger (224 um) larvae. Embryos exposed at 15^{o}C to 0.6 mg/L for 48 hrs failed to develop beyond the gastrula stage.

INTRODUCED INVERTEBRATE SPECIES

Dissolved oxygen exposure response data for five species that have been introduced into California waters were identified in the literature review. Theede et al. (1969) reported an LT50 of 504 hrs for adult softshell clam (*Mya arenaria)* exposed to <0.2 mg/L at a salinity of 15 ppt and temperature of 10^{o}C. The veliger larval stage was also found to be very tolerant, with no effect on survival in a 24-hr exposure to 0.2 mg/L at 20^{o}C. Morrison (1971) reported that *Mercenaria mercenaria* (Veneridae) veligers experienced 80% reduction in growth at 2.4 mg/L in a ten-day test conducted at 25^{o}C. No growth effects were observed at 4.2 mg/L, the next highest test concentration. Baker and Mann (1992) reported on results from a six-day exposure of *Crassostrea virginica* (Ostreidae) juveniles, finding that the LT50 at 1.5 mg/L was 131 hrs. At the same concentration, growth was reduced by 70%. Juveniles of another introduced species, the Harris mud crab, *Rhythropanopeus harrisii* were also found to be relatively tolerant of short-term exposures to low DO, with a reported 24-hr LC50 of 0.5 mg/L (Stickle et al., 1989). Theede et al. (1969) reported an LT50 of 48 hr for adult green crabs (*Carcinus maenus*), based on exposure to <0.2 mg/L at a salinity of 15 ppt and temperature of 10^{o}C. Similarly, Poucher and Coiro (1997) reported a 96-hr LC50 of <0.5 mg/L for juvenile/adult *C. maenus*.

SURROGATE INVERTEBRATE SPECIES

Additional references were found when the search was broadened to include taxonomic nearest-neighbors at the genus and family levels. The five species and the corresponding California indicator species that were represented at the genus level include: *Corophium volutator*/*Corophium* spp.; *Cancer irroratus*/*C. magister*, *C. productus*, C. *antennarius, C. anthonyi, C. gracilis; Calinectes sapidus, C. similis/C. bellicosus, C. arcuatus*; *Pandalus latirostris*/*P. danae*, and *Crangon septemspinosa*/*C. franciscorum, C. nigrocauda.*

Van den Heuvel-Greve et al. (2007) reported on a life-cycle study conducted with the amphipod *C. volutator* exposed to fluctuating oxygen conditions produced by cycling aeration on and off. Tests were conducted at 15 ppt salinity and 17^{o}C. Mortality was only significantly reduced when the average oxygen saturation was 51% (i.e., 4.6 mg/L), with minima of 4% saturation (i.e., approximately 0.36 mg/L). Growth and reproduction effects were apparent at an average concentration of 71% saturation (i.e., 6.5 mg/L) and minima of 43% saturation (i.e., 4.0 mg/L). While average concentration is not considered a precise predictor of effects (USEPA 2002), some constant concentration between the minimum and the mean can be expect to cause an equivalent level of impairment. Consequently, concentrations ≤ 4mg/L would be expected to result in growth and reproductive effects.

Cancer irroratus early life stages were tested by Vargo and Sastry (1977) for tolerance to low DO at various temperatures. In 2 and 4-hr exposures at temperatures from 10 - 30^{o}C, the megalops stage was the most sensitive. At 10, 15 and 20^{o}C the respective 4 hr-LC50s were 1.7, 1.6 and 2.2 mg/L. At 25 and 30C (stress condition), 4-hr LC50s were 3.4 and > 4.7 mg/L respectively. Tests conducted by Miller et al.

(2002) yielded results for exposures of at least four days. For molting larvae at 20°C the LC50 was 2.6 mg/L; for larvae molting to post-larvae the LC50 was 3.0 mg/L. In a seven-day exposure of larvae, statistically significant growth effects were observed at 2.4 mg/L, but not at 3.4 mg/L. It is also of note that Essington and Paulsen (2010), in modeling effects of hypoxia in Hood Canal found that, among the mobile invertebrates, *C. gracilis* and *C. productus* were two of three species for which the modeled relationship between hypoxia and species distribution was predictive.

Tests with juvenile *Calinectes sapidus* and *C. similis* exposed to low DO were the subject of a study by Das and Stickle (1993). In 28-day tests conducted at 24°C; *Callinectes sapidus* was more sensitive than *C. similis*. The 28-d LC50 for *C. sapidus* was 5.0 mg/L. Growth was effected at concentrations of 5.4 mg/L, and less. All crabs exposed to anoxic water died within 3 days, but no other concentration had complete mortality. The 28-d LC50 for *C. similis* was 2.0 mg/L; growth of *C. similis* was also reduced at 5.4 mg/L relative to the saturated water control, but to a lesser degree than *C. sapidus*.

Of note, the coon-striped shrimp, *Pandalus danae*, was originally not selected as an indicator species because it is present off-shore, as well as in bays. However, effects reported by Chiba et al. (2004) for the related *P. latirostris* indicated a relatively high level of sensitivity for adults exposed to low DO. At 2 mg/L, 90% died within 46 hrs, while all shrimp in the control treatment (8 mg/L) survived to the end the test (72 hr). The presence of *P. danae* in bays and estuaries, and the fact that data are available for a surrogate at the genus level, suggests that these data are relevant and should be included. Similarly, the octopus, *Octopus bimaculoides* and *O. bimaculatus* were not included in the original list of indicator species because embayments are not required habitat. Still, it is of note that Poucher and Coiro (1997) reported a 48-hr LC50 of > 3.4 mg/L for *O. burryi* embryos.

Surrogates representing five taxonomic families related to the California indicator species provided data that can be used for criteria derivation. Effects on juveniles exposed to low DO exposures are available for the following families: Ampeliscidae, Palaemonidae, and Mysidopsidae. Data for effects of low DO on embryos and/or larvae are available for Xanthidae, Majidae and Palaemonidae. Note that surrogate data are also available for native clams and oysters at the family level (Veneridae and Ostreidae, respectively), but these data have already been presented in the category of introduced species.

Miller et al. (2002) reported an LC50 of 1.0 mg/L resulting from a four-day exposure of *Crangon septemspinosa* juveniles. The test was conducted at 20°C. In addition, this study reported a 96-hr LC50 for *Ampelisca abdita* (Ampeliscidae) at 26°C as 1.2 mg/L. They also reported LC50s for juvenile *Palaemonetes vulgaris* at 24°C and *P. pugio* at 20°C (Palaemonidae) as 1.0 and 0.7 mg/L, respectively. Poucher and Coiro (1997) reported a 96-hr LC50 for juvenile *Americamysis bahia* (Mysidopsidae) at 26°C as 1.3 mg/L.

Survival results for early life stages of two species of Xanthidae were reported for 96-hr exposures (Miller et al. 2002). For larvae of *Eurypanopeus depressus and Dyspanopeus sayii,* the LC50s were 2.2 and 1.9 mg/L, respectively. In additional tests with *D. sayii* larvae molting to post-larvae, an LC50 of 2.5 mg/L was reported for a 96-hr test at 20°C, while the LC50 for a 10-day test conducted at 25°C was 3.7 mg/L. In the tests with *D. sayii*, growth effects were also determined. Results were reported as chronic values (the geometric mean of the lowest effect concentration and the highest no-effect concentration), and the mean chronic value for ten tests with early life stages was 4.3 mg/L. Miller et al. (2002) also reported an LC50 value of 2.7 mg/L for *Libinia dubia* (Majidae) larvae, and a chronic value of 4.7 mg/L. Growth was reduced by 43% at 4.1 mg/L and no effect was detected at 5.3 mg/L. The same authors reported lethal effects on larvae of *Palaemonetes vulgaris* and *P. pugio*, both exposed for 96 hrs at 25^{o}C, with respective LC50s of 2.1 and 1.6 mg/L.

Table 5.2 List of priority invertebrate species with available DO data.

Species	Data available	Surrogate available	Surrogate used
Basket cockle, *Clinocardium nuttali* (Veneridae)	No	Family level	Soft shell clam (*Mya arenaria*) and Northern quahog (*Mercenaria mercenaria)*
Bent-nose clam, *Macoma nasuta, M. balthic* (Veneridae)	No	Family level	Soft shell clam (*Mya arenaria*) and Northern quahog (*Mercenaria mercenaria)*
Butter clam, *Saxidomas giganteus, S. nuttali* (Veneridae)	No	Family level	Soft shell clam (*Mya arenaria*) and Northern quahog (*Mercenaria mercenaria)*
Gaper clam, *Tresus nuttali, T. capax* (Veneridae)	No	Family level	Soft shell clam (*Mya arenaria*) and Northern quahog (*Mercenaria mercenaria)*
Geoduck- *Panopea generosa, P. abrupta* (Veneridae)	No	Family level	Soft shell clam (*Mya arenaria*) and Northern quahog (*Mercenaria mercenaria)*
Jack-knife clam, *Tagelus californianus, T. affinis, Solen rostiformis/rosaceus, S. sicarius* (Veneridae)	No	Family level	Soft shell clam (*Mya arenaria*) and Northern quahog (*Mercenaria mercenaria)*
Little neck clam, *Chiones californiensis, C. fluctifraga, C. undatella, Protatheca laciniata, P. staminea, Tapes phillipinarum* (Veneridae)	No	Family level	Soft shell clam (*Mya arenaria*) and Northern quahog (*Mercenaria mercenaria)*
Soft shell clam, *Mya arenaria* (Veneridae)	Yes	None	NA
Northern quahog, *Mercenaria mercenaria* (Veneridae)	Yes	None	NA
Copepods, *Acartia sp., Eurytemora affinis* (Acartiidae)	Yes	None	NA
Dungeness crab, *Cancer magister* (Cancridae)	No	Genus level	Atlantic rock crab (*Cancer irroratus*)

Table 5.2 Continued

Species	**Data available**	**Surrogate available**	**Surrogate used**
Brown rock crab, *Cancer antennarius* (Cancridae)	No	Genus level	Atlantic rock crab (*Cancer irroratus*)
Yellow crab, *Cancer anthonyi* (Cancridae)	No	Genus level	Atlantic rock crab (*Cancer irroratus*)
Graceful/Slender crab, *Cancer gracilis* (Cancridae)	No	Genus level	Atlantic rock crab (*Cancer irroratus*)
Fiddler crab- *Uca crenulata* (Ocypodidae)	No	None	None
Mud crab, *Lophopanopeus bellus* (Xanthidae)	No	Family level	Mud crabs (*Eurypanopeus depressus and Dyspanopeus sayii*)
Shore crabs, *Pachygrapsus crassipes, Hemigrapsus oregonensis* (Grapsidae)	No	None	None
Mussels, *Mytilus edulis, M. trossulus* (Mytilidae)	Yes	NA	NA
Opossum Shrimp, *Neomysis mercedis* (Mysidae)	No	Family level	*Americamysis bahia*
Oyster, *Ostrea lurida* (Ostreidae)	No	Family level	Eastern oyster (*Crassostrea virginica*)
Scallop, *Argopecten aesquilatus* (Pectinidae)	No	None	None
Spiny lobster, *Panulirus interruptus* (Palinuridae)	No	None	None
Moon snail, *Polinices* (now *Euspira*) *sp.* (Naticidae)	No	None	None

Table 5.2 Continued

Species	**Data available**	**Surrogate available**	**Surrogate used**
Bay shrimp, *Crangon franciscorum, C. nigricauda* (Crangonidae)	No	Genus level	*Crangon septemspinosa*
Bay or grass Shrimp, *Palaemon macrodactylus* (Palaemonidae)	No	Family level	*Palaemontes vulgaris, P. pugio*
Ghost shrimp, *Callianassa* (now *Neotrypaea*) *californiensis, C. gigas* (Callianassidae)	No	None	None
Mud shrimp, *Upogebia pugettensis* (Callianassidae)	No	None	None
Coon-striped shrimp, *Pandalus danae* (Pandalidae)	No	Genus level	*Pandalus latirostris*
Amphipod, *Anisogammarus sp,* (Gammaridae)	No	None	None
Amphipod, *Americorophium sp.* (Corophiidae)	No	Family level	*Corophium volutator*
Amphipod, *Corophium sp,* (Corophiidae)	No	Genus level	*Corophium volutator*
Amphipod, *Eohaustorius sp.,* (Haustoriidae)	No	None	None

6. Synthesis of Data Supporting DO Objectives for California Estuaries

6.1 Introduction

The purpose of this Section is to provide an example of how DO objectives may be derived using the available data described in Section 5. Determining the scientific basis for establishing criteria for DO in California estuaries is straightforward, and rests on whether there are sufficient relevant data for species of interest to derive numerical values using USEPA guidance (Stephan 1985). As generally applied, USEPA's derivation of water quality criteria results in values (e.g., concentrations) expected to protect against acute (short term) and chronic (longer term) exposures to chemical contaminants or other properties (e.g., temperature) that may be associated with impaired water quality. As a function of how the numbers are derived, they are expected to be protective of most of the species present, rather than all species or individuals. Thus, the general intent is protecting overall ecosystem health, with provisions for extending greater protection to individual species if they are of significant ecological importance or regulatory concern. In general, this approach has been taken with USEPA's DO criteria document for freshwater (USEPA 1985), and also in the more recent DO criteria for marine waters of the Virginia Province (USEPA 2000). The Virginia Province criteria also include DO standards to protect larval recruitment based on the sensitivity and natural history of life stages found in nearshore environments.

The synthesis of available data (Section 5) showed that native California species were poorly represented in the database. Because of the lack of data for native California species, three options exist:

1. Not deriving criteria until sufficient data have been generated for native species.
2. Applying the Virginia Province criteria on an interim basis until sufficient data are generated for native species.
3. Substituting genus or family surrogates for California species.

The first option does not address inconsistencies in regulatory thresholds currently in place in different regions throughout the State. Thus, the level of protection will continue to vary between regions in a manner that does not reflect substantive regional differences in beneficial uses, biological components, or hydrological and chemical dynamics associated with particular waterbodies. In addition, these thresholds will continue to reflect inconsistent interpretation of the science available at the time the regulations were originally promulgated. Moving towards statewide objectives will eliminate these inconsistencies and more appropriately reflect currently available science.

The second option is applying the Virginia Province criteria directly on an interim basis. Given that several California species (albeit introduced) and genus and family representatives were used to derive the Virginia Province criteria, it is not immediately clear whether there is an advantage to simply using the Virginia Province criteria or recalculating the numbers based on California species and their nearest taxonomic equivalents. One justification for applying the Virginia Province criteria would be if it was felt that the calculated values represented a significantly larger database, and, might, therefore, be inherently more robust.

The third option, substituting genus or family equivalents for California species in the criteria derivation process is a generally accepted practice (e.g., USEPA 1985 and 2000). In this case, these "nearest-neighbor" data are available for several invertebrate and fish species, and could be used to supplement data for native California species.

This Section utilizes the third option to illustrate how available data could be used to derive DO criteria. Ultimately, the options for how the State Water Board proceeds with developing numeric objectives and selection of specific thresholds are policy decisions. This Section is meant to inform those decisions.

6.2 Calculation of Numeric Objectives

The calculation of numeric objectives was generally consistent with the approach used by the USEPA to derive DO criteria for the Virginia Province (USEPA 2000). One value was derived from data for short-term effects on the survival of juvenile and adult organisms. A second value was derived from thresholds for sublethal effects. These values are analogous to the traditional CMC and CCC (i.e., acute and chronic limits), respectively. Note that numeric values for salmonids were addressed separately, given their inherent sensitivity to low DO and potential absence from a number of estuaries. For comparison, the numeric objectives were then compared with the criteria developed for other jurisdictions (e.g., Virginia Province and Chesapeake Bay), and also against DO concentrations considered protective of other organisms that may be associated with estuaries on a periodic basis (e.g., salmonids).

The application of the Virginia Province approach and associated calculations reflected the relatively poor representation of native California species in the dataset. Consequently, it was felt that a relatively conservative (i.e., protective) approach to criteria development would be the most robust and defensible until additional data needs are addressed. Therefore, data for all appropriate species, including native and introduced, and genus and family surrogates of the California native indicator species, were combined in the analysis. This approach provided breadth to the analysis, and should more closely approximate the range of species that we are trying to protect in terms of preserving ecosystem function.

6.2.1 Acute Criterion - Protection of Juvenile and Adult Survival (CMC)

A total of 21 data entries quantifying the acute effects of low DO on survival of juvenile and adult organisms were available. Of these, 12 were for invertebrates, and 9 were for fish. However, only 3 were native California species; the remainder were either introduced (5), or genus or family surrogates (13). Genus mean acute values (GMAVs) varied by a factor of 5, and ranged from 0.54 mg/L for the introduced green crab (*Carcinus maenus*), to 2.7 and 2.8 mg/L for the surrogates *Acipenser brevirostrum* (sturgeon) and *Pandalus latirostirus* (shrimp).

The data were ranked by genus on the basis of sensitivity (Table 6.1), and the four most sensitive species (each representing a different genus) were (from lowest to highest) mysid shrimp, herring, sturgeon and pandalid shrimp. Based on the geometric mean of the four most sensitive GMAVs, the Final Acute Value

(FAV) was 3.01, which results in a CMC value of 4.33 mg/L following application of a safety factor to derive LC05s from LC50 data.

Table 6.1 Rankings of the nine most sensitive species, based on acute sensitivity of juveniles to low dissolved oxygen. Also shown are regional distribution and associated estuary types.

Species	California Equivalent	Distribution	Estuary Inlet Status	LC50 (mg/L)
Shrimp (*Pandalus latirostris*)	Shrimp (*Pandalus danae*)	NorCal	Open	2.76
Sturgeon (*Acipenser brevirostrum*)	Sturgeon (*Acipenser medirostris*)	NorCal	Open	2.7
Sardine (*Harengula jaguana*)	Herring (*Clupea pallasi*)	AllCal	Open	2.1
Mysid shrimp (*Mysidopsis bahia)*	Mysid Shrimp (e.g.*, Neomysis mercedis*)	AllCal	Open, Closed	1.56
Striped bass (*Morone saxatilis*)	Same	NorCal	Open, Closed	1.55
Oyster (*Crassostrea virginica*)	Oyster (*Ostrea lurida*)	AllCal	Open, closed	1.5
Striped mullet (*Mugil cephalus*)	Same	SoCal	Open	1.4
Winter flounder (*Pleuronectes americanus*)	Diamond turbot (*Pleuronichthys guttulatus*)	AllCal	Open, closed	1.4
Sand shrimp (*Crangon septemspinosa*)	Grass shrimp (*Crangon franciscorum*)	AllCal	Open, closed	1.34

Given that green sturgeon are restricted to a very few estuaries, it would be possible to calculate a criterion for all species except sturgeon. In this case, the four most sensitive species would be striped bass, mysid shrimp, herring and pandalid shrimp. The FAV would be 2.69 mg/L, resulting in a CMC value of 3.84 mg/L.

Interestingly, the distribution of the two most sensitive species (i.e., sturgeon and pandalid shrimp) does not include southern California. Thus, it would be possible to derive a criterion directly applicable to species found in southern California. In this case, the most sensitive species found only in northern and central California would be deleted from the dataset and the criterion recalculated using sensitive species with distribution patterns that include southern California. Thus, data for sturgeon, pandalid shrimp and striped bass would be deleted, and the four most sensitive species would be striped mullet, oyster, mysid shrimp, and herring. Based on these data, the FAV is 2.05 mg/L, and the calculated CMC is 2.92 mg/L.

Finally, given that herring and striped mullet are typically associated with larger open systems, these species could be deleted, and a criterion calculated for southern California that might be applicable to estuaries that are periodically closed. In this instance, the most sensitive species would be sand shrimp, flounder, oyster and mysid shrimp; the FAV would be 1.59 mg/L, and the CMC would be 2.28 mg/L. A similar calculation for northern California estuaries that are periodically closed could also be performed. The most sensitive species would include flounder, oyster, striped bass and mysid shrimp; the FAV would be 1.60 mg/L, and the CMC would be 2.29 mg/L.

6.2.2 *Chronic Criterion - Protection of Sublethal Effects (CCC)*

A total of 11 data points were available for deriving a chronic criterion for DO, representing 4 fish and 7 invertebrate species. However, the dataset contained no native California species; thus, the criterion calculation is based on data for three introduced species and eight genus or family-level surrogates. In addition, our data selection process differed slightly from that used by USEPA in deriving a chronic limit for the Virginia Province. In our case, where multiple data were available for a single species, we selected data that represented the most sensitive life stage and longest exposure duration, whereas USEPA averaged data across exposure durations and life stages. We believe that the approach used is appropriate given that DO effects tended to be more pronounced with increasing exposure duration, and effects that occur at more sensitive life stages will tend to carry through subsequent life stages. Examples of differences in sensitivity associated with different life-history stages and exposure durations are shown in Table 6.2 In these examples, the sensitivity of mysids increases with exposure duration, which could be a function of cumulative effects. With the grass shrimp, the data suggest that sensitivity of the earlier life stages is clearly greater than later life stages. In both cases, the calculated geometric mean would not be protective of "chronic effects" or the most sensitive life stages.

Table 6.2 Effect of different life stages and exposure durations on sensitivity to low DO.

Species	Life Stage	Duration (days)	MATC (mg/L)	Geomean (mg/L)
Mysid	< 48-hr juv	10	1.96	2.67
	< 48-hr juv	28	3.64	
Grass shrimp	Newly hatch	8	4.79	3.15
	<16 hr	7	4.51	
	<16 hr	8	4.71	
	Stage 1-3	7	1.89	
	Post-larval	14	3.04	
	Post-larval	14	2.72	
	Post-larval	14	1.94	

Note that the USEPA averaging procedure used the geometric mean, which tends to result in a lower value than the arithmetic mean. This averaging method works well for most toxicants where the effect is reduced at lower concentrations, but the effects associated with low DO tend to increase at low concentrations. Thus, not only is this conservative approach justified, it should help address some of the uncertainties associated with deriving a chronic criterion for California waters; e.g., the fact that no native species are represented in the dataset and no provision is made for increased oxygen requirements associated with higher temperatures (the USEPA approach explicitly assumes that their DO tolerance thresholds do not represent any additional stress associated with elevated temperature, which not only increases the metabolic requirements of poikilothermic[5] organisms, but also reduces concentrations associated with DO saturation).

The most sensitive endpoints for growth effects were associated with crab larvae (4.67 and 5.60 mg/L), shrimp larvae (4.79 mg/L), silversides (4.33 mg/L), and sturgeon (5.0 mg/L). Calculated chronic values were similar (i.e., 5.8 and 5.9 mg/L, respectively), regardless of whether or not sturgeon were included in the dataset. Given the relatively few number of species on which these criteria are based, and the lack of native species, there is no justification for splitting the data further into regional or closed and open system classifications. That being said, the crab and shrimp larvae and silversides could be considered representative of all regions and systems.

6.2.3 Appropriateness of Criteria

The CMC and CCC values derived above were compared against the actual data to determine whether they were over or under-protective. In general, the CMC values were close to being within a factor of 1.4 of the SMAV for the most sensitive species for each category, suggesting that there might be a small (e.g., 5%) effect level associated with that species, and fully protective of lower-ranked species. Similarly, the CCC values were generally marginally higher than the MATC for the most sensitive endpoint and species. Given that the MATC can be considered an approximation of the IC25, these data suggest that there might be a small level of chronic effect on the most sensitive species, but should be fully protective of lower ranked species. Overall, this analysis generally suggests that the calculated values should be protective of ecosystem function, but not excessively so. In addition, selection of the most sensitive endpoints for a given species (rather than the average) limits the potential for adverse effects, and similarity of values among species generally suggested concordance or consistency among the top ranks. Thus, the derived values were based on data associated with more than one organism, and not driven by outliers associated with particularly sensitive organisms or test results.

6.2.4 DO Objectives for Protection of Salmonids

Although not directly incorporated into the DO criteria derivation process up to this point, it is appropriate to address the extent to which the CMC and CCC values derived above are protective of salmonids in estuaries. While there is a greater diversity of salmonid species in northern California, this is not simply a regional issue as steelhead population segments extend into southern California. Thus, while steelhead may not be associated with every estuary, they are or have been associated with estuaries in every region along the coast. Consequently, consistent with ongoing efforts to recover these populations, it is appropriate to consider DO limits that are protective of steelhead and other salmonids in estuaries. These uses would include migratory passage, as well as extended residence by juveniles and adults. Conversely, protection of embryo and larval (egg-alevin) stages would not be appropriate as these stages are associated with freshwater spawning sites located further upstream.

Given the expected uses, both acute and chronic criteria would apply, in order to address temporary fish passage and extended residence, respectively. In this context, USEPA (1986) freshwater criteria include a

[5] Organisms, including fish and invertebrates, that have a body temperature that varies with the temperature of their surroundings.

minimum value of 4 mg/L, a 7-day average value of 5 mg/L and a 30-day average of 6.5 mg/L. However, the criteria document notes that these values are not “no-effect levels”, but are expected to be generally protective at the population level. For context, the USEPA concluded that 1) DO concentrations below 3 mg/L would result in acute mortality; 2) 4 mg/L would have a severe impact on production (i.e., growth), hence its use as a 1-day minimum; 3) 5 mg/L would have a moderate impact on production, hence its use as a 7-day average; and 4) 6 mg/L would have a smaller (i.e., approximately 20 %) impact on production, hence the use of 6.5 mg/L for the 30-day average; finally, 8 mg/L was associated with no adverse effects. Notably, for sites where natural conditions precluded achieving the applicable criteria, the USEPA indicated that the minimum acceptable DO concentration would be 90% of the natural concentration.

Other relevant data include Alabaster (1988, 1989), who reported that upstream migration of Chinook salmon was inhibited at 3.5 mg/L, but not at 5.7 mg/L. The Province of British Columbia proposed criteria protective of juvenile and adult salmonids in estuaries and freshwater of 5 and 8 mg/L, for the instantaneous minimum and 30-day average, respectively (BC Ministry of Environment). They acknowledged that some sites might naturally exhibit lower DO concentrations, particularly on a seasonal basis, and indicated that under those conditions DO should not be allowed to drop below natural levels. These regulators also noted that their criteria were more protective than those promulgated by USEPA (1986).

With these numbers as context, the DO objectives derived for enclosed bays and estuaries can be compared to assess the level of protection afforded to salmonids. The CMC values derived above for the state-wide suite of bays and estuaries, with or without sturgeon, are 4.3 and 3.8 mg/L, respectively. Both values are similar to the USEPA acute criterion for salmonids, and suggest that a CMC of 4 mg/L would be reasonably protective of beneficial uses, including salmonids. However, calculated acute values for southern California “open” estuaries (2.9 mg/L and “closed” estuaries (approximately 2.3 mg/L) are substantially lower and would not be protective. In these cases, there would be justification for increasing the CMC to 4 mg/L if protection of salmonids was appropriate. Substituting the salmonid acute value (i.e., 3 mg/L) into the equations for southern California (all systems), and northern and southern California closed systems, results in calculated values of 4.2, 4.0 and 4.1 mg/L, respectively, further supporting the basis for 4 mg/L as a threshold for protecting salmonids in these systems from acute effects associated with low DO.

The calculated chronic values for California (5.8 – 5.9 mg/L) are lower than the 30-day average (6.5 mg/L) recommended for salmonids, suggesting that growth would be inhibited to at least some extent, but that migration would not be impaired. Thus, in cases where protection of salmonids is important, consideration should be given to applying the chronic criterion for salmonids (i.e., 6.5 mg/L). In terms of deriving a chronic criterion for California that includes salmonids, a calculation was performed with the salmonid MATC (i.e., 6 mg/L) included in the top four sensitivity rankings. This adjustment returned calculated values of 6.3 to 6.5 mg/L, depending upon whether sturgeon were included in the species mix. Thus, these calculations provide explicit support for using 6.5 mg/L as a criterion for chronic exposure in areas where salmonids are considered of primary importance with respect to protecting beneficial uses.

6.2.5 Comparison to Other DO Criteria

For perspective, the objectives calculated here are summarized and compared with those derived for other jurisdictions in Table 6.3. Some clear differences in the criteria between jurisdictions emerge; for the acute criteria, the presence of sturgeon and pandalid shrimp (i.e., AllCal or NorCal species) increases the CMC substantially. Removal of these species brings the values more closely into line with East Coast criteria; similarly, reducing the scope to focus only on closed systems further reduces the CMC. The major differences associated with chronic criteria are associated with the more conservative process of selecting data for the most sensitive life stages and longer exposure durations. Finally, inclusion of data that reflect the higher sensitivity of salmonids to low DO further increases the values.

Table 6.3 Comparison of different criteria for dissolved oxygen; data are in mg/L.

Jurisdiction	CMC	CCC
USEPA Virginia Province	2.2	4.8
Draft Southeast	3.0	4.8
Chesapeake Bay (open water)	3.5	5
USEPA Salmonid	4.0	6.5
All California and Northern California	4.3	5.8
All California and Northern California w/o sturgeon	3.8	5.8
Southern California	2.9	5.8
Northern and Southern California (closed systems)	2.3	5.8
All California + salmonids	4.3	6.3
Closed systems + salmonids	4.1	6.3

For simplicity, the following criteria simplified on the basis of categories and species might be considered; inspection of actual data suggests that these numbers would be protective of associated beneficial uses.

Table 6.4 Potential simplification of criteria categories from Table 6.3. Data are in mg/L.

Category	CMC	CCC
All California (all systems)	4.0	5.8
Southern Californial (all systems)	2.9	5.8
All California (closed systems)	2.3	5.8
All California + salmonids	4.0	6.3

6.2.6 Use of the CMC to Assess Potential Impacts Associated with Shorter Exposure Periods

Fluctuations in DO concentrations can occur on a diurnal basis, leading to periods in which DO might fall below the CMC for short periods of time. Based on results of tests that evaluated acute toxicity as a function of time, the Virginia Province Salt Water Dissolved Oxygen Criteria (USEPA 2000) provides guidance for evaluating the potential for adverse effects in cases where exceedences are of relatively short duration (i.e., <24 hr), in order to establish whether beneficial uses may be compromised. To apply this approach, DO data would need to be available for sufficiently short intervals (e.g., ≤2-hr intervals) to allow for characterization of exposure in terms of concentration and associated time period. The expected impacts for each interval are totaled, and the cumulative effect is then compared with the benchmark to determine if effects were present. It should be noted that, due to their rapid response to low concentrations of DO, this approach is not intended to be applied to water bodies where protection of salmonids is of primary concern.

6.2.7 Larval-Recruitment Criterion for Assessing Impacts of Episodic Low DO

In the context of water quality criteria, to protect against short-term and longer exposures, the CMC and CCC are typically applied as functions of time; for example, as one-hour maximums and four-day averages, respectively. While this approach is generally protective when applied to conventional toxicants, particularly under conditions associated with continuous discharges, low DO conditions may occur as episodic events or at regular intervals to varying degrees over an extended period of time; for example, nighttime periods of hypoxia may occur repeatedly on a seasonal basis. Indeed, laboratory tests have demonstrated that effects from exposures to short-term periods of low DO cannot be predicted based on daily average concentrations (USEPA 2000).

To provide a means of addressing this issue, USEPA developed a short-term response model based on empirical observations of mortality in invertebrate larvae exposed to low DO conditions consistent with tidal and diel timeframes. The results of the empirical mortality model are then incorporated into a larval recruitment model that integrates the effects of exposures to low DO as they accumulate on an annual (or seasonal) basis. Thus, the final output is based on cumulative larval survival, accumulating the losses that occur as sensitive life stages are exposed to fluctuating conditions of hypoxia on a daily basis. The model was designed to allow for some impacts to individual cohorts or broods, but without affecting (i.e., <5% effect) the overall strength of a given year class. Thus, the recruitment model incorporates life-history characteristics, in addition to responses to low DO (USEPA 2002).

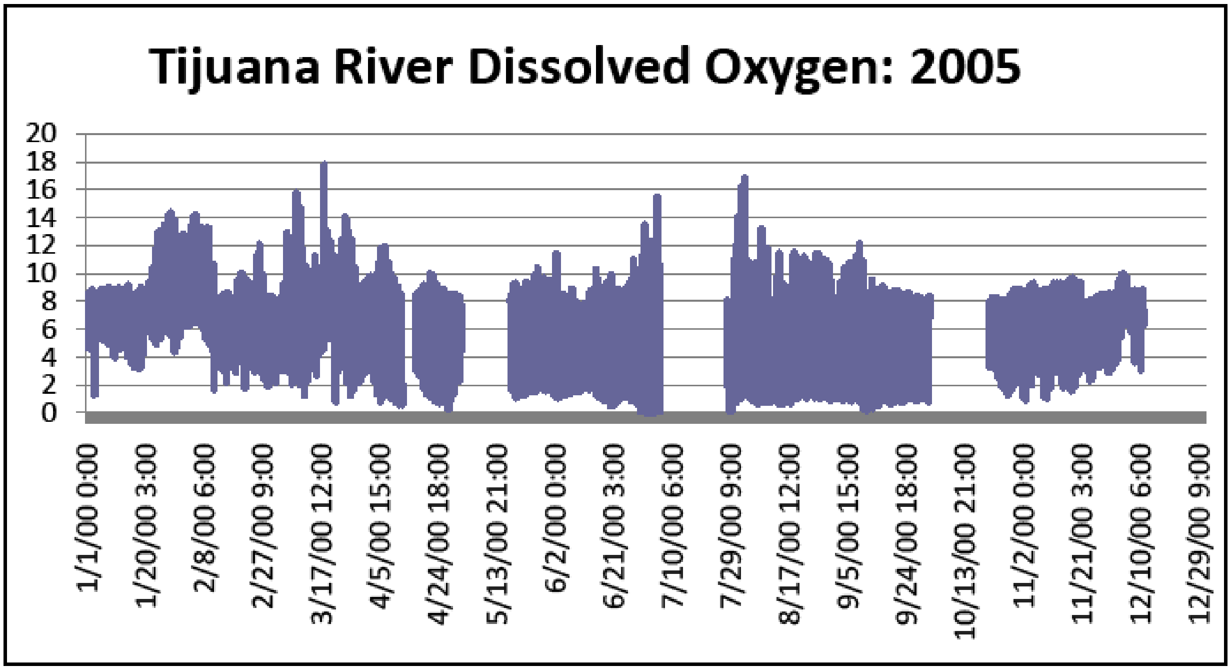
Notably, the underlying response data that form the basis of the model were derived from laboratory exposures of species generally related to California species. In keeping with the approach for CMC and CCC derivation, the four most sensitive species were used to determine the limits for acceptable exposure; these included two crab species (*Eurypanopeus* and *Dyspanopeus*), lobster (*Homarus*) and striped bass (*Morone*). All except the lobster represent California species at the species level, or as family-level surrogates, and deleting the lobster does not substantially change the criteria limits. Thus, the model should be applicable, at least on a provisional basis, to California estuaries.

As an example of applying the larval recruitment model to short-term and intermittent periods of low DO, DO data from semi-continuous monitoring sondes were downloaded from the NOAA National Estuarine Research Reserve (NERR) Centralized Data Management website (http://cdmo.baruch.sc.edu). This site provides quality-assured water quality data from 28 reserves located throughout the U.S; California data are available from San Francisco Bay, Elkhorn Slough and the Tijuana River, dating from 1995 to the present. For this example, a data set from the Boca Rio station for 2005 was randomly selected from among the Tijuana River estuary stations (Figure 6.1). The Boca Rio station is a shallow site (<1 M NGVD) located in a large channel approximately 300 m north of the Tijuana River mouth. The full-year data set was largely complete, with three gaps (in May, July and Sept-Oct) of approximately two weeks each; these gaps were filled by copying the preceding and following data sets, and splitting the appropriate number of days from each.

Hourly DO data from the Boca Rio station were then input into the D.O. Criteria Software (DOCS), a Visual Basic Program developed by SAIC under contract to USEPA Office of Water, to determine the extent of exceedences of the cumulative larval recruitment criterion (USEPA 2000). For this particular dataset, the magnitude of exceedences was 164 times the allowable limit for low DO exposures. Simply put, if 5% of the entire seasonal recruitment of larvae were lost in one day, these conditions would be equivalent to 164 days that would incur that same 5% loss due to mortality induced by low DO.

It is important to note that the average DO concentration for this site from the season with the worst hypoxia (i.e., June through September) was 6 mg/L. Thus, use of mean exposure concentrations or single measurements of DO would not have been adequate to characterize the impacts of hypoxia that were likely present on a daily basis. Finally, the use of continuous or semi-continuous data monitoring in conjunction with the larval recruitment model provides agencies with an opportunity to rank or prioritize different water bodies with respect to extent and magnitude of impacts, assuming that the needs for nutrient management relate to the degree of impairment. Thus, rankings could be based on a numeric characterization of the extent of exceedences. This process could also be used to evaluate the effectiveness of remediation measures by observing trends in the extent of exceedences over time.

Figure 6.1 2005 daily DO concentrations (mg/L) at the Boca Rio Site in the Tijuana River.



6.3 Significance of Data Gaps

A number of data gaps were identified as part of this study. In spite of the fact that sufficient data are available to derive DO criteria for California enclosed bays and estuaries, this was accomplished primarily through the use of data for introduced species and genus and family surrogates because DO tolerance data are lacking for most of the primary species of interest. Thus, identifying estuary types and associated species of greatest interest, and developing actual data for at least a subset of these species may be appropriate to ensure that the approach taken to develop DO criteria for California estuaries is indeed representative and protective.

The simplest application of DO criteria is to apply the derived values directly without regard to duration, season or spatial context; in other words, presuming a worst-case persistent exposure. However, this approach provides very little resolution with respect to the need for management actions (i.e., prioritizing needs for nutrient reduction). Notably, the Virginia Province DO criteria document does contain an experimentally-derived short-term response model so that the extent of impairment associated with short-term (e.g., tidal, diurnal) fluctuations in DO concentrations of <24-hr duration can be evaluated. However, this approach requires the use of semi-continuous data records of DO concentrations.

The Virginia Province Salt Water Dissolved Oxygen Criteria (USEPA 2000) also uses semi-continuous DO data to identify impacts on larval recruitment. The extent to which this approach could be applied in a California context beyond use of USEPA default parameters depends on the availability of natural history data for key California species (e.g., number of broods in a season, duration of critical larval period), as these data are required for the associated calculations. Thus, in addition to semi-continuous DO data, in order to fully implement this approach, a literature review should be undertaken to characterize the relevant life-history parameters for appropriate species.

Another data gap is related to impacts of low DO on salmonids in *estuarine* habitats. Studies suggest that estuaries are important rearing areas for juvenile salmonids (e.g., Chinook salmon, steelhead), with benefits of increased growth which further increases their overall chances of survival and recruitment (see, for example, Hayes et al., 2008). Coastal cutthroat trout typically spend extensive periods in estuaries, as may adults of other species that enter the estuary when the berm breaches, but flows are insufficient to allow additional upstream movement (Moyle 2002). Thus, estuaries provide critical habitat for these species. This situation is compounded by the fact that most coastal anadromous salmonid populations are currently given some level of special status (i.e., threatened or endangered), which suggests a conservative approach should be taken with respect to maintaining suitable water quality conditions. However, data are generally lacking in terms of DO thresholds for adverse effects on juvenile salmonids (i.e., survival and growth) under estuarine conditions. While it is possible to extrapolate from studies conducted in freshwater by converting DO concentrations using adjustments for temperature and salinity, empirical verification may be desirable. This may be of particular concern, given interactions between DO, salinity and temperature. Thus, elevated temperatures often associated with estuaries in California could place additional stress on populations of concern (note that the Virginia Province DO Criteria explicitly did not address DO and temperature interactions, but noted that they were of potential concern because DO requirements typically increase as temperature approaches the upper thermal limits for a given organism).

6.4 Application of DO Criteria

While USEPA guidance is intended to establish numerical values that are protective, it does not provide details as to *how* to evaluate a body of water with respect to the potential for DO limitations, or what constitutes "impaired" with respect to overall conditions associated with a given waterbody. **We recommend that this guidance be developed to ensure consistent implementation of DO objectives across Regional Boards.** Such guidance might include details associated with sampling design, such as methodology, frequency and spatial extent. Ideally, data from a properly executed sampling plan should readily lend themselves to interpretation of the frequency and extent of observed exceedances, an indication of the impaired status of a given waterbody from temporal and spatial perspectives, and constructive follow-up activities designed to reduce impacts. Some points to consider include:

1) **Assessment.** A protocol should be developed that specifies where, when and how samples should be collected. In particular, it is important with DO to specify whether sampling a single depth is sufficient, or whether samples should be collected at the surface, mid-depth and bottom, or integrated over depth. The assessment protocol should provide clear guidance regarding the temporal and spatial extent of sampling, the density of data (grab or continuous samples), and the targeted assessment window (seasonal or year round) that are required in order to make an assessment. For example, is one sample/site sufficient to support a designation of impairment, or is there consideration of the relative spatial extent (both vertically and horizontally) of exceedances when considering the water body as a whole?

2) **Allowances for natural hypoxia and muted tidal flushing.** Hypoxic conditions can exist on a localized basis even under natural conditions. Thus, natural variations in tidal flow, condition of the berm at the mouth of a lagoon and/or vertical stratification of the water column due to thermal or salinity conditions can all reduce water circulation and associated gas exchange. Similarly, areas with muted tidal exchange (natural or anthropogenic) such as backwater tidal channels or areas impounded by levees, dikes, or flood gates can also result in reduced DO concentrations. Thus, the SWRCB should consider if, and how, to provide allowances for circumstances resulting in "natural hypoxia", as well as hypoxic conditions resulting from muted tidal exchange in estuaries.

3) **Considerations of allowances for short-term fluctuations in DO.** Conditions may occur in which DO might fall below the CMC for short periods of time. The SWRCB should consider a recommendation for implementing USEPA guidance (2000) for evaluating the potential for effects in cases where short-term exceedances of the CMC occur, in order to establish whether beneficial uses may have been compromised. This would require that DO be monitored at sufficiently short intervals (e.g., ≤2-hr intervals) to characterize the actual exposure.

4) **Considerations of multiple, competing beneficial uses.** Estuaries may serve multiple functions, such as shipping channels, marinas and industrial facilities, in addition to providing a range of habitats that provide nursery and rearing areas. Thus, it is possible that different objectives could be applied in a spatial context, depending on habitat and associated beneficial uses, with more stringent objectives being applied to ecologically sensitive areas. With this approach, the acute limit might be applied to shipping channels and harbor areas, and both acute and chronic limits applied to more ecologically sensitive areas. This approach recognizes that certain areas will not support consistent use by established biological communities because of continued disturbance and habitat modification, but does protect transient uses (e.g., fish passage, migration).

Ultimately, guidance for implementing the objectives might suggest a tiered approach, with initial triggers followed by more detailed investigation to determine if spatial extent and severity warrant designation as impaired. Biological attributes of the system (i.e., species composition) might also be considered in the designation of impairment, with the presence of sensitive species providing an indication that observed exceedances are within the range of "natural" fluctuations.

7. Summary and Recommendations

7.1. Introduction

As noted in the previous section, some potential issues are associated with deriving and applying DO objectives in California bays and estuaries. To at least some extent, DO tolerance data are lacking for California species of particular concern, making it necessary to use data from surrogate species. In addition, central and northern California are represented by different faunal assemblages than typically found in southern California; thus, one criterion may not be applicable for all regions if, for example, the most sensitive species are associated with only one region. Alternatively, there may not be adequate species representation to derive regionally-based criteria. Conversely, sensitive key species (e.g., green sturgeon) may only be associated with relatively few estuaries, suggesting site-specific applications may be appropriate even within a regional context. In the USEPA DO criteria for the Virginia Province, an important provision is made for establishing a DO criterion intended to protect larval recruitment. However, this approach relies on life-history data that may not be available for key California species; thus, regulators would need to rely on USEPA default values for implementation. In addition, interpreting and applying DO criteria in a spatial and temporal context is not straightforward, particularly in estuarine systems that may naturally exhibit appreciable fluctuations in DO concentrations in both spatial and temporal scales. Finally, the breadth and diversity of water bodies that the objectives are intended to protect is substantial; over 400 water bodies ranging from large, well-flushed systems to small lagoons that can be closed for most of the year or even for several years in a row. Thus, the extent to which criteria can be derived for different types of systems depends on identifying organisms that are representative of each category, and then determining whether any associated DO tolerance data are available.

7.2 Data Gaps and Recommendations for Science Supporting DO Objectives for California Estuaries

The objective of this study was to determine the scientific basis for deriving DO objectives for California enclosed bays and estuaries. Significant data gaps exist on effects of low DO for native California species. In order to derive DO objectives that adequately capture variability of ecology and estuarine beneficial uses in the State, three types of recommendations are given to address these data gaps:

Data gaps were evident for native California species tolerance to low DO.

1) Generate data for California native species tolerance to low DO.

2) Develop data for salmonid tolerance to low DO under estuarine conditions to confirm appropriate thresholds.

3) Identify representative and appropriate species, determine sensitivity to low DO at different life stages, and characterize associated natural history characteristics (e.g., duration of larval period).

7.2.1 Generate Data for Native California Species Tolerant to Low DO

Following general USEPA guidance, we were able to canvass the literature and derive reasonably credible criteria. However, the criteria are based to a large extent on data for introduced species and genus and family-level surrogates. Similarly, given the breadth of water bodies (i.e., bays and estuaries) covered by the regulation, application of criteria to specific classes of water bodies (e.g., intermittently tidal southern California estuaries) depends on knowledge of species likely to be present, as well as data for those species. To some degree it was possible to make reasonable inferences as to appropriate acute criteria to apply to different classes of water bodies because the database available was comparatively extensive and contained surrogates that could be deemed representative of different conditions. However, the database for chronic data was more limited, and might benefit from data obtained directly from native species of interest. Thus, while there is no reason to assume that the numbers are not protective based on physiological and ecological similarities, additional confidence could be gained by obtaining data for native California species of interest. Therefore, we recommend that additional data on DO effects for native California species be developed.

Conversely, given that the surrogates used to derive the chronic criteria would likely be associated with most types of systems, and are largely present throughout the state, the numbers would be unlikely to change significantly. This, of course, does not rule out the potential for developing site-specific guidelines based on unique assemblages of species.

7.2.2 Develop Data for Salmonid Tolerance to Low DO under Estuarine Conditions

For estuaries and bays where protection of salmonids is of importance, these species would tend to drive the criteria applied. However, the current DO limits for salmonids are largely based on data derived from exposures in freshwater. Thus we recommend developing data for salmonid tolerance to low DO under estuarine conditions to confirm appropriate thresholds.

7.2.3 Determine Sensitivity to Low DO at Various Life Stages and Characterize Corresponding Natural History

Implementation of the USEPA's modification to the chronic criterion to adjust for potential impacts on larval recruitment is potentially a desirable option. However, to do so at a level beyond the current default model inputs would require detailed natural history information on native species of interest, specifically duration of spawning season, number of broods, length of larval period, and so on. Conversely, this option may not be applicable in waters where protection of salmonids is of regulatory importance, since these species will drive the objective applied. Thus we recommend identifying representative and appropriate species, determine sensitivity to low DO at different life stages, and characterize associated natural history characteristics (e.g., duration of larval period).

7.3 Monitoring and Implementation

As part of the larger context of nutrient limits, clear and consistent guidance needs to be provided for interpreting and applying DO data in the context of determining if beneficial uses are at risk. In addition, critical review of the averaging periods associated with the limits would be desirable to determine optimum durations for CMC and CCC to ensure that these are implemented in a manner that maximizes protection for beneficial uses. Recommendations include:

1) Develop standardized protocols and/or guidance for measurement of DO in estuaries, including the spatial (across estuary) and temporal density (surface vs. bottom) of data collection triggers, and scope of follow-up studies identified; and

2) Develop an assessment framework that clearly articulates how data would be applied to make a determination of whether the estuary is has impaired beneficial uses. For example, optimization of averaging periods may be the most efficient regulatory approach for implementing DO objectives. Thus, from an operational perspective, the dataset from the Tijuana River could be evaluated statistically to determine to the optimum balance of averaging periods for the CMC and CCC to minimize adverse effects (this information would also be helpful in terms of identifying the most appropriate sampling designs in terms of frequency and duration for monitoring DO).

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Appendix 1

Table A1.1. Estuarine indicator species by habitat features occupied by different life stages organized by life-history types or guilds (modified from Allen 2006).

Species	BURROWS IN SUBSTRATE	ON BOTTOM, BENTHIC	IN WATER COLUMN	ROCK, GRAVEL, HARD SUBS	IN MACRO-PHYTES	SAND	MUD	MICRO-CARNI-VORE	GRAZER HERBI-VORE	CARNI-VORE	FILTER FEEDER	MARINE	EST-UARINE	FRESH-WATER	TIME IN ESTUARY, years
BRACKISH															
Tidewater goby															
Eggs	X					X							X	X	6-10 days
Larvae			X		X			X					X	X	15-30 days
juveniles		X	X	X	X	X	X	X					X	X	to 0.5 years
Adults	X, just during breeding	X		X	X	X	X	X					X	X	1-2 years
Threespine stickleback															
Eggs		X				X	X	X						X	0
Larvae		X	X		X	X	X	X					X	X	5 to 15 days
Juveniles		X	X		X	X	X	X				X	X	X	0.5 to 1.0 years
Adults		X	X		X	X	X	X				X	X	X	1-3 years
ANADROMOUS															
Rainbow or Steelhead trout															
Eggs	X			X										X	0
Larvae	X			X										X	0
Juveniles			X					X		X			X	X	1-3 years
Adults			X					X		X		X	X (anadromous)	X (spawn)	pass through (anadrom)
King or Chinook salmon															
Eggs														X	0
Larvae														X	0
Juveniles		X	X	X	X	X				X			X	X	1 to two years
Adults		X								X		X (mostly)	X(anadromous)	X(spawn)	pass through (anadrom)
Coho salmon															
Eggs	X			X										X	0
Larvae	X			X										X	0
Juveniles			X					X		X			X	X	1 year
Adults			X					X		X		X(mostly)	X (anadrom	X (spawn)	pass through

Species	BURROWS IN SUBSTRATE	ON BOTTOM, BENTHIC	IN WATER COLUMN	ROCK, GRAVEL, HARD SUBS	IN MACRO-PHYTES	SAND	MUD	MICRO-CARNI-VORE	GRAZER HERBI-VORE	CARNI-VORE	FILTER FEEDER	MARINE	EST-UARINE	FRESH-WATER	TIME IN ESTUARY, years
													ous)		only (anadrom)
Coastal cutthroat trout															
Eggs	X			X										X	0
larvae, alevins	X			X										X	0
Juveniles			X					X		X			X	X	1-3 years
Adults			X					X		X		X	X(anadro mous, resident)	X (spawn)	3-8 years
Euchalon															
Eggs		X		X										X	0
Larvae			X					X				X	X	X(drift to estuary and ocean)	few days or weeks drifting down
juveniles			X					X				X(mostly)	X		mostly in ocean
Adults			X					X				X	X(anadro mous)	X(anadro mous)	mostly in ocean
Green sturgeon															
Eggs														X	
Larvae		X											X	X	
juveniles		X											X	X	1-100
Adults		X								X		X	X (anadrom ous)	X (spawn)	
Pacific lamprey															
Eggs	X, burried in gravel			X										X	0
Larvae	X, burried in gravel										X			X	0
juveniles	X	X				X	X							X	1-2 years
Adults		X								X				X, spawning only	passage only (anadromo us)
CATADROMOUS															
Prickly sculpin															
Eggs		X		X									X	X	10-30 days
Larvae			X					X				X	X	X	10-30 days
juveniles		X		X		X	X			X			X	X	0.5 to 1.0 years
Adults		X		X		X	X			X			X	X	1-3 years

Species	BURROWS IN SUBSTRATE	ON BOTTOM, BENTHIC	IN WATER COLUM N	ROCK, GRAVEL, HARD SUBS	IN MACRO-PHYTES	SAND	MUD	MICRO-CARNI-VORE	GRAZER HERBI-VORE	CARNI-VORE	FILTER FEEDER	MARINE	EST-UARINE	FRESH-WATER	TIME IN ESTUARY, years
ESTUARINE SUBSTANTIALLY															
Staghorn sculpin															
Eggs		X		X								X			20-40 days
Larvae			X					X				X	X		20-40 days
juveniles	X	X				X	X			X			X	X	1-Jan
Adults	X	X				X	X			X		X	X		1 to 3
Topsmelt															
Eggs					X								X		5-10 days
Larvae			X					X				X	X	X	10-30 days
juveniles			X					X	X			X	X	X	1-2 years
Adults			X		X			X	X			X	X		1-3 years
Starry flounder															
Eggs			X									X	X		0
Larvae			X					X				X	X		30-Oct
juveniles		X				X	X	X					X	X	1-2 years
Adults		X				X	X	X				X (mostly)	X		1-2 years
Arrow goby															
Eggs	X											X	X		5-10 days
Larvae			X					X				X	X	X	10-30 days
juveniles	X	X				X	X	X				X	X	X	1 year
Adults	X	X				X	X	X				X	X	X	1-3 years
California killifish															
Eggs		X		X	X							X	X		1-5 days
Larvae			X, days only					X				X	X		1-5 days
Juveniles		X													0.25-0.50 years
Adults	X, occasion-ally burrow into	X		X	X	X	X	X				X	X	X	1-3 years
California halibut															
Eggs			X									X, mostly	X		0
Larvae			X					X				X	X		3-6 weeks, mostly ocean
Juveniles		X				X	X			X		X	X,mostly		1-3 years
Adults		X				X	X			X		X	X		25-30 yrs, mostly ocean

Species	BURROWS IN SUBSTRATE	ON BOTTOM, BENTHIC	IN WATER COLUMN	ROCK, GRAVEL, HARD SUBS	IN MACRO-PHYTES	SAND	MUD	MICRO-CARNI-VORE	GRAZER HERBI-VORE	CARNI-VORE	FILTER FEEDER	MARINE	EST-UARINE	FRESH-WATER	TIME IN ESTUARY, years
Deepbody/Bay anchovy															
Eggs			X									X	X		4-6 days
Larvae			X								X	X		X	30-40 days
Juveniles			X								X	X	X		0.5-1 year
Adults			X								X	X	X		1-3 years
Pacific herring															
Eggs		X			X								X	X	10-15 days
Larvae			X					X				X	X, mostly	X	2-3 months
juveniles			X					X			X	X	X	X	1-2 years
Adults			X					X			X	X	X	X (spawn)	3-15 years
Diamond turbot															
Eggs			X									X	X		5-10 days?
Larvae			X					X				X	X		5-6 weeks
juveniles		X				X	X	X				X	X	X	half to one year
Adults		X				X	X	X				X	X		8-9 years old
Longjaw mudsucker															
Eggs	X											X	X		5-10 days
Larvae			X					X				X	X		25-40 days
juveniles	X	X				X	X			X		X	X	X	half to one year
Adults	X	X				X	X			X		X	X		3-5 years
Shadow goby															
Eggs	X														5-10 days
Larvae			X					X				X	X		10-30 days
juveniles		X				X	X	X				X	X		0.5-1 year
Adults	X	X				X	X	X				X	X		1-3 years
Bay/Barred pipefish															
Eggs	Brooded by male, see adult														
Larvae	Brooded by male, see adult														
juveniles					X			X				X	X	X(rarely)	0.5-1 year
Adults					X			X				X	X	X(rarely)	1-3 years
Longfin smelt															
Eggs		X											X	X	0
Larvae			X					X					X	X	30-60 days

Species	BURROWS IN SUBSTRATE	ON BOTTOM, BENTHIC	IN WATER COLUMN	ROCK, GRAVEL, HARD SUBS	IN MACRO-PHYTES	SAND	MUD	MICRO-CARNI-VORE	GRAZER HERBI-VORE	CARNI-VORE	FILTER FEEDER	MARINE	EST-UARINE	FRESH-WATER	TIME IN ESTUARY, years
juveniles			X					X				X	X		0.5-1 year
Adults			X					X				X	X	X(spawn)	2-4 years?
Striped mullet															
Eggs			X									X	X		0
Larvae			X					X				X	X		1-4 weeks
juveniles			X						X		X	X	X	X	1-3 years
Adults		X	X			X	X		X		X	X, mostly to spawn	X	X	2-7years
Cheekspot goby															
Eggs	X					X						X	X		5-10 days
Larvae			X					X				X	X		20-40 days
juveniles	X	X				X		X				X	X		0.5-1 year
Adults	X	X				X		X				X	X		1-3 years
Shiner surfperch															
Eggs	live-bearing														
Larvae	live-bearing														
juveniles												X	X		0.5-1 year
Adults		X	X	X	X			X				X	X		1-3 years
MARINE BAYS, ESTUARIES															
Bay blenny															
Eggs		X		X								X	X		5-10 days?
Larvae			X					X				X	X		30-50 days?
juveniles		X		X				X	X			X	X		0.5-1.0 years
Adults		X		X				X	X			X	X		1-3 years
Spotted sandbass															
Eggs			X									X	X		1-2 DAYS
Larvae			X					X				X	X		20-30 DAYS
juveniles		X		X	X	X				X		X	X		1-2 years
Adult		X													6-20 YEARS
OTHER MARINE															
Jacksmelt															
Eggs					X							X	X		7 days
Larvae			X									X	X		24-40 days
juveniles			X					X	X			X	X		1-6 mos
Adults			X					X	X			X	X		to 11 yrs

Species	BURROWS IN SUBSTRATE	ON BOTTOM, BENTHIC	IN WATER COLUMN	ROCK, GRAVEL, HARD SUBS	IN MACRO-PHYTES	SAND	MUD	MICRO-CARNI-VORE	GRAZER HERBI-VORE	CARNI-VORE	FILTER FEEDER	MARINE	EST-UARINE	FRESH-WATER	TIME IN ESTUARY, years
English sole															
Eggs			X									X			3-4 days
Larvae			X					X				X			8-10 wks
juveniles		X								X		X	X		0.5-1..0 yrs
Adults		X								X		X			
Yellowfin croaker															
Eggs			X									X	X		?
Larvae			X					X				X	X		?
Juveniles		X						X				X	X		0.5-1.0 yrs
Adults		X								X		X	X		5+ yrs?
Speckled sand dab															
Eggs			X									X			
Larvae			X									X	X (?)		
Juveniles		X				X	X			X		X			0.5-1 yr
Adults		X				X	X			X		X	X (?)		1-3 yrs
Gray smoothhound															
Eggs	live bearing														
Larvae	live bearing														
juveniles		X				X	X			X		X	X		~one year
Adults		X				X	X			X		X	X		Mulitpl4e years
Leopard shark															
Eggs	live bearing														
Larvae	live bearing														
juveniles		X				X	X			X		X	X		~ one year
Adults		X				X	X			X		X	X		Multiple years
Spotted turbot															
Eggs			X									X	X		4-6 days?
Larvae			X									X	X		5-7 wks?
juveniles		X				X	X					X	X		0.5-1.0 yrs
Adults		X				X	X					X	X		3+ yrs
Round stingray															
Eggs	live bearing														
Larvae	live bearing														
juveniles	X	X				X	X	X				X	X		Multiple years
Adults	X	X				X	X	X				X	X		
Barred sand bass															

Species	BURROWS IN SUBSTRATE	ON BOTTOM, BENTHIC	IN WATER COLUMN	ROCK, GRAVEL, HARD SUBS	IN MACRO-PHYTES	SAND	MUD	MICRO-CARNI-VORE	GRAZER HERBI-VORE	CARNI-VORE	FILTER FEEDER	MARINE	EST-UARINE	FRESH-WATER	TIME IN ESTUARY, years
Eggs			X									X	X		Few weels
Larvae			X									X	X		
Juveniles		X	X(rarely)	X		X	X			X		X	X		1+ years
Adults		X	X(rarely)	X		X	X			X		X	X		3-8 years
Bat Ray															
Eggs	Live bearing														
Larvae															
Juveniles		X	X			X	X	X				X	X		1+ years
Adults		X	X			X	X	X				X	X		2+ years
FRESHWATER															
Pikeminnow															
Eggs		X		X										X	
Larvae			X					X						X	
Juveniles		X	X	X		X	X						X	X	2-3 mos.
Adults		X	X	X		X	X			X			X	X	1-3 mos
Western sucker															
Eggs		X		X										X	
Larvae			X			X	X	X					X	X	1-2 wks
juveniles		X		X		X	X	X	X				X	X	2-8 wks
Adults		X		X		X	X		X				X	X	1-2 yrs
Hitch															
Eggs		X		X										X	
Larvae			X											X	1-2 wks
juveniles			X					X					X	X	1-6 mos
Adults			X					X					X	X	1-2 yrs
Blackfish															
Eggs					X									X	5-10 days
Larvae			X		X			X					X	X	15-30 days
juveniles			X					X					X	X	1-6 mos
Adults			X								X		X	X	0.5-3 yrs
Tule perch															
Eggs	live bearing														
Larvae	live bearing														
juveniles		X	X	X	X	X	X	X				X	X	X (rarely)	1-6 mos
Adults		X	X	X	X	X	X	X				X	X	X (rarely)	0.5-3 yrs
NON-NATIVE SUBSTANTIALLY ESTUARINE															
Striped bass															

Species	BURROWS IN SUBSTRATE	ON BOTTOM, BENTHIC	IN WATER COLUM N	ROCK, GRAVEL, HARD SUBS	IN MACRO-PHYTES	SAND	MUD	MICRO-CARNI-VORE	GRAZER HERBI-VORE	CARNI-VORE	FILTER FEEDER	MARINE	EST-UARINE	FRESH-WATER	TIME IN ESTUARY, years
Eggs			X										X	X	2-4 days
Larvae			X					X					X	X	15-30 days
juveniles			X	X	X	X	X			X			X	X	0.5-3 yrs
Adults			X	X	X	X	X			X		X	X	X	3-20 yrs
Mississippi silverside															
Eggs					X								X	X	4-30 days
Larvae			X					X					X	X	3-5 wks
juveniles			X		X			X					X	X	0.3-3 yrs
Adults															
Yellowfin goby															
Eggs	X					X	X						X		20-30 days
Larvae			X										X		few wks?
juveniles						X	X	X					X	X	1-6 mos
Adults		X				X	X	X				X	X	X	1-3 yrs
Mosquitofish															
Eggs	livebearing														
Larvae	livebearing														
juveniles			X		X			X					X	X	1-30 days
Adults			X		X			X					X	X	0.1-2 yrs
Rainwater killifish															
Eggs					X							X	X	X	9-12 days
Larvae		X										X	X	X	7-10days
juveniles		X	X	X	X	X	X	X				X	X	X	1-6 mos
Adults		X	X	X	X	X	X	X				X	X	X	1-2 yrs
Sailfin molly															
Eggs	live bearing														
Larvae	live bearing														
juveniles					X			X	X				X	X	0.1 to 0.2
Adults					X			X	X				X	X	1 to 2