Science Supporting Dissolved Oxygen Objectives for Suisun Marsh

Photo by USFWS

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Southern California Coastal Water Research Project

Technical Report 830

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List of Acronyms

BOD	Biological Oxygen Demand
CCC	Criterion Continuous Concentration
CMC	Criterion Minimum Concentration
COD	Chemical Oxygen Demand
DO	Dissolved Oxygen
ESA	Endangered Species Act
FAV	Final Acute Value
FM	First Mallard Slough; location within Suisun Bay
FRC	Final Recruitment Concentration
GMAV	Genus Mean Acute Value
LC05	Lethal Concentration to 5% of Organisms
LC50	Median Lethal Concentration
MLLW	Mean low low water
NERR	National Estuarine Research Reserve
NNE	Nutrient Numeric Endpoint
NOAA	National Oceanic and Atmospheric Administration
NPDES	National Pollution Discharge Elimination System
SCCWRP	Southern California Coastal Water Research Project
SWRCB	State Water Resources Control Board
TMDL	Total Maximum Daily Load
TRE	Tijuana River Estuary
USEPA	United States Environmental Protection Agency
USFWS	United States Fish and Wildlife Service

EXECUTIVE SUMMARY

At the request of the San Francisco Bay Regional Water Quality Control Board, the potential for deriving site-specific water quality criteria for dissolved oxygen (DO) in Suisun Bay and Marsh was evaluated. Fish and invertebrate species representative of Suisun Bay and Marsh were identified from the literature and screened against currently available data on sensitivity to low levels of DO (i.e., hypoxia). It was determined that sufficient data were available for either locally-occurring species or their genus or family-level surrogates to calculate values for both the acute criterion minimum concentration (CMC) and chronic criterion continuous concentration (CCC) for DO using USEPA procedures for deriving water quality criteria. The CMC is designed to protect the survival of juvenile and adult organisms under short-term exposure conditions, whereas the CCC is designed to protect organisms from adverse effects on survival, growth and reproduction related to long-term (i.e., indefinite) exposure. The calculated criteria varied, depending upon which species were included, with the most sensitive species being sturgeon and salmon. Based on analysis of the available date, the criteria are shown below:

Species Represented	CMC (Mg/L)	CCC (Mg/L)
General, without Sturgeon	3.0	4.8
General, with Sturgeon	3.3	5.0
General, with Sturgeon and Salmonids	3.3	6.2

These criteria were compared with a subset of DO data collected from Suisun Marsh (summer 2010) to evaluate the extent to which there might be potential for impairment. Based on these data, DO fell below 2 mg/L on several occasions, suggesting that there was potential for acute toxicity during these events. With respect to the potential for chronic effects, DO concentrations fell below 5 mg/L on a relatively frequent basis during June and July, suggesting that growth of sensitive species could be impaired.

In addition to the CMC and CCC, USEPA procedures also allow for calculating the potential adverse effects of hypoxia on the survival of early life stages of fish and invertebrates. This approach is based on a Final Recruitment Concentration (FRC) that is intended to protect the strength of a given year class (i.e., not individuals) over an extended period that encompasses multiple spawning events. While the FRC was developed for the nearshore waters of the East Coast, the underlying model is based on DO response curves and biological data for 9 species that include 7 taxa that are either: 1) present in the Marsh as introduced species; or 2) represent genus or family-level surrogates of species that are present in the Marsh. Consequently, the model is relevant to Suisun Marsh. Notably, when the subset of DO data from Suisun Marsh (i.e., summer 2010) was evaluated against the FRC, the results suggested that there was potential for adverse effects on year-class strength. Overall, given that the example dataset represents very limited spatial and temporal coverage of the Marsh, the potential for adverse effects on survival, growth

and recruitment suggests that the extent of exceedances should be evaluated on a broader scale.

The calculated criteria represent what should be acceptable concentrations with respect to protecting against adverse effects of hypoxia. However, it is acknowledged that there is limited representation of local species in the data set and it may be desirable to develop and include data from additional locally-relevant species in the calculation. That being said, given the breadth of taxa represented in the calculations, it is not likely that additional species would significantly alter the criteria values determined. In terms of implementing the criteria, it would be desirable to develop an assessment protocol that specifies the temporal/spatial averaging and data density necessary to make a determination of "impairment". Policy decisions on DO objectives should also take into account naturally-occurring seasonal, diurnal or tidally-influenced periods of low DO, and guidance will be needed regarding the use of DO objectives in the context of assessment, TMDLs and NPDES-permitting decisions.

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1.0 INTRODUCTION

Eutrophication of estuaries and coastal waters is a global environmental issue, wherein increased nutrient loading to coastal waters has resulted in demonstrated anthropogenic changes in watersheds, including harmful algal blooms, hypoxia[1] and impacts on aquatic food webs (Valiela et al. 1992, Kamer and Stein 2003). The ecological impacts of eutrophication in coastal areas can have significant consequences, including fish-kills and reduced 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 impacts also have significant economic and social costs (Turner et al. 1998).

According to the USEPA (2001), eutrophication is one of the top three leading causes of impairments to the nation's waters, and a scientifically-based approach is needed to establish numeric targets identifying the potential for adverse effects and associated management controls. In California, the USEPA and State Water Resources Control Board (SWRCB) subsequently developed an approach for establishing numeric targets for nutrients and biostimulatory substances in lakes and streams (TetraTech 2006). This approach, known as the Nutrient Numeric Endpoint (NNE) framework, is a suite of numeric endpoints (e.g., dissolved oxygen (DO), algal biomass) related to the ecological response of waterbodies to nutrient pollution. The NNE framework was subsequently adapted to estuaries, with particular focus on identifying biological response indicators and developing the science necessary to support policy decisions on endpoints in the context of developing TMDLs (McLaughlin and Sutula 2007; Sutula 2011).

Because of its importance as a measure of eutrophication and an indicator of the potential for adverse effects, DO is a critical parameter in the context of the NNE framework. Consequently, a study was undertaken to evaluate the scientific basis for determining numeric endpoints for DO in California bays and estuaries (SCCWRP 2011). This study performed an extensive evaluation of the literature to identify DO tolerance data for California species of interest, and showed that sufficient data were available to support calculations of acute and chronic criteria for DO on a state-wide basis using standard USEPA approaches for deriving such criteria. Moreover, the database was extensive enough to permit calculation of *acute* criteria for species assemblages representing both northern and southern California, as well as open and closed estuaries.

Notably, the criteria calculated by SCCWRP (2011) specifically did not apply to the San Francisco Bay and Estuary, largely due to the range of habitats and somewhat unique species assemblages associated with this complex waterbody. Subsequently, SCCWRP was contracted by the San Francisco Bay Regional Water Quality Control Board to determine if DO criteria could be derived for the species assemblage associated with Suisun Bay and Marsh, one of the larger sub-embayments found in the San Francisco Bay and Estuary. This report describes the process of determining key species present in the Bay and Marsh, evaluating available DO tolerance data for these species or related surrogates, and calculating criteria for DO to the extent that appropriate data were available.

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

2.0 SELECTION OF REPRESENTATIVE SPECIES FOR EVALUATING POTENTIAL DISSOLVED OXYGEN EFFECTS IN SUISUN BAY AND MARSH

Introduction

This section presents the assumptions and methods used to identify species appropriate for consideration as indicator species for DO effects in Suisun Bay and Marsh (hereafter referred to as Marsh). Specific components of this effort included:

1) Identification of candidate fish and invertebrate species found in Suisun Marsh;

2) Selection of a subset of species representative of Suisun Marsh;

3) Characterization of life history stages of each species as they relate to seasonal presence within the Marsh.

This process built upon the previous state-wide effort to identify fish and invertebrate species that would be appropriate to use as indicators of low DO effects across the range of bays and estuaries found in California (SCCWRP 2011). This list was then narrowed to include those species representative of the Marsh. A parallel effort identified additional species that were considered representative of the Marsh, but were not included in the State-wide list due to limited geographical range; these species were retained for additional consideration. Descriptions of life histories and beneficial uses associated with species selected as State-wide indicator species are presented in SCCWRP (2011). Information on species not used as State-wide indicators, but representative of the Marsh, may be found in literature citations provided in the text.

Approach and Assumptions

The general criteria used to select State-wide indicator species for DO are summarized below. These criteria were also applied to species directly associated with Suisun Marsh in order to identify species that occur locally, but are not representative of bays and estuaries on a State-wide basis (e.g., Sacramento splittail). Thus, the suite of relevant indicator species included those whose State-wide distribution encompasses Suisun Marsh, as well as those species that are only found locally.

Specific criteria applied to the species selection process included:

- Species must spend a substantial or critical portion of their life-histories in estuarine habitats;

- 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 are of primary interest.

- Species should be native to California; non-native species were considered if they met any of the following conditions: 1) they support recreational or commercial fisheries; 2) they are of documented ecological importance; or 3) they are species for which data on physiological effects of hypoxia are known to exist; i.e., species used to generate the Virginia Province Dissolved Oxygen Criteria (USEPA 2000) and genus or family level surrogates of these species. Thus, in cases where data were not available for native species, non-native species could provide a basis for assessing effects.

In summary, the species selection process was designed to be comprehensive in terms of the breadth of species considered, with the species selected representing desired species and habitat relationships and beneficial uses. In order to exclude nominally freshwater and marine species found across a range of habitats, the inclusion criteria targeted species that depend on the Marsh for overall survival and well-being (e.g., critical spawning and nursery areas) either as permanent residents or during key life-history stages. In addition, benthic invertebrate infauna were generally 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).

Candidate Indicator Species

Fish

To obtain a subset of species relevant to establishing DO criteria for Suisun Marsh, fish species recorded in Suisun Marsh were obtained from sources that integrate extensive compilations from the general literature and field surveys (e.g., Moyle 2002, O'Rear and Moyle 2010). These species were then compared against the general criteria used to identify candidate indicator species and species that did not meet the criteria for inclusion were subsequently deleted. The excluded species included:

- **Freshwater species**—species that are predominantly found in freshwater, and do not rely on estuaries for completion of critical life history stages; introduced species are noted.
    - Bigscale logperch (*Percina macrolepida*); introduced
    - Black bullhead (*Ameiurus melas*); introduced
    - Black crappie (*Pomoxis nigromaculatus*); introduced
    - Bluegill (*Lepomis macrochirus*); introduced
    - Brown bullhead (*Ameiurus nebulosus*); introduced
    - Channel catfish (*Ictalurus punctatus*); introduced
    - Common carp (*Cyprinus carpio*); introduced
    - Fathead minnow (*Pimephales promelas*); introduced
    - Golden shiner (*Notemigonus crysoleucas*); introduced
    - Goldfish (*Carassius auratus auratus*); introduced
    - Green sunfish (*Lepomis cyanellus*); introduced
    - Hardhead (*Mylopharodon conocephalus*);
    - Hitch (*Lavinia exilicauda*);
    - Largemouth bass (*Micropterus salmoides*); introduced
    - Mosquitofish (*Gambusia affinis*); introduced
    - Redear sunfish (*Lepomis microlophus*); introduced
    - River lamprey (*Lampetra ayresii*);
    - Sacramento blackfish (*Orthodon microlepidotus*);
    - Sacramento pikeminnow (*Ptychocheilus grandis*);
    - Sacramento sucker (*Catostomus occidentalis*);
    - Threadfin shad (*Dorosoma petenense*); introduced
    - Warmouth (*Lepomis gulosus*); introduced
    - White catfish (*Ameiurus catus*); introduced
    - White crappie (*Pomoxis annularis*); introduced

- **Marine species**—species that are predominately found in marine waters, and do not rely on estuaries for completion of critical life history stages
    - Diamond turbot (*Hypsopsetta guttulata*)

- Leopard shark (*Triakis semifasciata*)
- Pacific sanddab (*Citharichthys sordidus*)
- Plainfin midshipman (*Porichthys notatus*)
- Speckled sanddab (*Citharichthys stigmaeus*)
- Surf smelt (*Hypomesus pretiosus*)
- White croaker (*Genyonemus lineatus*)

- **Estuarine species**—species that are predominately found in estuarine waters for at least some critical life history stages; all of the species listed below are introduced.
  - Rainwater killifish (*Lucania parva*)
  - Shimofuri goby (*Tridentiger bifasciatus*)
  - Shokihazi goby (*Tridentiger barbatus*)
  - Wakasagi (*Hypomesus nipponensis*)
  - Yellowfin goby (*Acanthogobius flavimanus*)

Most of the excluded species were non-native, and generally associated with freshwater (e.g., centrarchids). However, several species of native cyprinids (e.g., Sacramento pikeminnow, Sacramento blackfish, hitch, hardhead) were not included because they are typically defined as freshwater species and do not require estuaries to complete their life cycles. A number of predominantly marine species were also excluded (e.g., sanddabs, croakers, leopard shark) because they do not require estuaries to complete their life cycles.

The remaining species were considered representative of Suisun Marsh, and are summarized below.

- American Shad (*Alosa sapidissima*); introduced
- Pacific lamprey (*Entosphenus tridentatus*)
- Chinook salmon (*Oncorhynchus tshawytscha*)
- Rainbow trout/steelhead (*Oncorhynchus mykiss*)
- Prickly sculpin (*Cottus asper*)
- Staghorn sculpin (*Leptocottus armatus*)
- Green sturgeon (*Acipenser medirostris*)
- White sturgeon (*Acipenser transmontanus*)
- Delta smelt (*Hypomesus transpacificus*)
- Longfin smelt (*Spirinchus thaleichthys*)
- Longjaw mudsucker (*Gillichthys mirabilis*)
- Bay pipefish (*Syngnathus leptorhyncus*)
- California halibut (*Paralichthys californicus*)
- Starry Flounder (*Platichthys stellatus*)
- Mississippi silverside (*Menidia audens*); introduced
- Striped bass (*Morone saxatilis*); introduced
- Northern anchovy (*Engraulis mordax*)
- Pacific herring (*Clupea pallasi*)
- Sacramento splittail (*Pogonichthys macrolepidotus*)
- Shiner perch (*Cymatogaster aggregata*)
- Tule perch (*Hysterocarpus traskii*)
- Threespine stickleback (*Gasterosteus aculeatus*)

Detailed information on life history strategies associated with most of these species is summarized in SCCWRP (2011), based on information provided in Emmett et al. (1991), Moser et al. (1996), Cailliet et al. (2000), Leet et al. (2001), Moyle (2002), and Allen (2006). For information regarding species not represented in the State-wide list of indicator species, the reader is referred to Moyle's detailed descriptions of the inland fishes of California (Moyle 2002).

Invertebrates

Candidate invertebrates associated with Suisun Marsh are described below, including associated beneficial uses, ecological roles and comments regarding justification for inclusion in the final list. Invertebrates species found in the Marsh were identified from compilations found in the San Francisco Bay Benthic Macroinvertebrate Atlas maintained by the USGS Western Ecological Research Center (www.werc.usgs.gov), as well as Monaco et al. (1991) and NOAA (2007). Given the long history of introduced species of invertebrates in the Marsh, findings from earlier scientific surveys of benthic fauna were also reviewed (Packard 1918 and Painter 1966).

- **Amphipods**—amphipods, particularly the Gammaridea, are represented by an array of species that contribute significantly to nutrient cycling and 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).

- **Bivalves—**bivalves historically have supported significant subsistence, recreational and/or commercial fisheries in the greater San Francisco Bay and Estuary, including Suisun Marsh. More recently, the importance of these fisheries has declined, largely as a function of widespread habitat modifications and introduction of competing non-native species. Nonetheless, they still represent an important faunal component of the Marsh.

    - ***Clams*--**a wide variety of clam species have been reported from Suisun Marsh, but the introduced overbite clam *Potamucorbula amurensis* has largely replaced native species such as the bent-nose clam *Macoma nasuta* and the littleneck clam *Protothaca staminea.* Indeed, *P. amurensis* has been documented at densities exceeding 10,000/m^2. Other species present include the soft shell clam *Mya arenaria* and the Manilla or Japanese littleneck clam *Venerupis (*or *Tapes) phillipinarum*, both of which are introduced. 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.

    - ***Mussels*—**Mussels (Mytilidae) are typically attached to hard substrate or plants as juveniles and adults, but early life stages are pelagic. Some species (e.g., the introduced *Geukensia demissa* and *Musculista senhousia*) may also be found buried in the substrate.

    - ***Oysters***—native oysters (Ostreidae) have been recorded in the Marsh.

- **Copepods—**e.g., *Acartia* sp., *Eurytemora affinis, Pseudodiaptomus* sp. Numerous species of copepods (e.g., *Calanoida*, *Harpacticoida),* both native and introduced, are an important part of the zooplankton component of the food web in bays and estuaries.

- **Crab**—Several species are associated with the Marsh, either as permanent residents or seasonally, depending on life history strategies. Species include the Dungeness crab (*Cancer magister*), primarily in larval and juvenile stages, the introduced Harris mud crab (*Rhithropanopeus harrisii*), and various shore crabs *(e.g., Pachygrapsus crassipes, Hemigrapsus oregonensis*).

- **Opossum shrimp—**Opossum shrimp (Mysidae) are important components of estuarine food webs. One species in particular, *Neomysis mercedis*, is a major component of the local food web, and introduced species are also present.

- **Bay shrimp—**the native grass shrimp *Crangon franciscorum* and the introduced Korean prawn *Palaemon macrodactylus* are present, support fisheries, and are important components of the local food web.

Threatened and Endangered Species

Five of the recommended indicator species are on federal or state threatened and endangered species lists, including:

- Steelhead (Federally endangered or threatened over much of coastal California);
- Chinook (and Coho) salmon (Federally endangered or threatened in central and northern California);
- Green sturgeon (Federally threatened); and
- Delta smelt (Federally threatened).

Both steelhead and salmon have previously been identified as broadly representative of estuaries in a significant portion of California (SCCWRP 2011). Coho salmon have not been recently observed in Suisun Marsh, but it is likely that they used to spawn in streams tributary to the Marsh (Moyle 2002). The green sturgeon occurs primarily in larger estuaries, such as the San Francisco Bay and Klamath River estuaries, and has been collected in the Marsh. Delta smelt are endemic to the San Francisco Bay Estuary, with Suisun Marsh generally considered optimum habitat. An additional species, the Sacramento splittail, was formerly listed by the USFWS as threatened, but that designation has been withdrawn since the population appears to fluctuate naturally, rather than being in a consistent long-term decline. Finally, the USFWS has indicated that the longfin smelt warrants protection under the Endangered Species Act (ESA), but has delayed listing due to more pressing concerns.

3.0 CALCULATION OF NUMERIC DO CRITERIA FOR SUISUN MARSH

Identification of Indicator Species with DO Tolerance Data

The selected species were compared against those in our database of DO tolerance data to develop a "short list" of Suisun Marsh species with corresponding DO sensitivity data. Species not already part of the State-wide list were also identified and additional effort was directed towards locating relevant DO tolerance data. If species-specific data were not available, further effort was made to identify data representing the same genus or family; note that the use of data from surrogate species is consistent with standard USEPA methodology for deriving water quality criteria, and was also used to derive water quality criteria for dissolved oxygen for coastal estuaries and bays along the Atlantic Coast (USEPA 2000). The species (including genus and family surrogates) for which data are available regarding sensitivity to hypoxia are summarized in Tables 3.1 and 3.2 for fish and invertebrates, respectively. Of note, white croaker (*Genyonemus lineatus*) are relatively uncommon in the marsh and were not initially selected as an indicator species. However, they are associated with bays and estuaries (Emmett et al. 1991) and DO tolerance data are available for 3 surrogate species. Consequently, these species have been included in Table 3.1 in an effort to make the dataset as robust as possible.

Table 0.1. Suisun Marsh indicator species (fish) with available DO data.

Primary Species	Data Available			Surrogate Species
	Species	Genus	Family	
Three-spine stickleback *(Gasterosteus aculeatus)*			X	Four-spine stickleback *(Apeltes quadracus)*
Rainbow trout/steelhead *(Oncorhynchus mykiss)*	X			--
Coho salmon (*Oncorhynchus kisutch*)	X			--
Chinook salmon *(Oncorhynchus mykiss)*	X			--
Pacific herring *(Clupea pallasii)*	X		X	Scaled sardine (*Harengula jaguana*) Menhaden (*Brevoortia tyrannus*)
American shad (introduced) *(Alosa sapidissima)*			X	Scaled sardine (*Harengula jaguana*) Menhaden (*Brevoortia tyrannus*) Pacific herring (*Clupea pallasi*)
Striped bass (introduced) (*Morone saxatilis*)	X			--
California halibut (*Paralichthys californicus*)		X		Summer flounder (*Paralichthys dentatus*)
Starry flounder (*Platichthys stellatus*)			X	Winter flounder (*Pseudopleuronectes americanus*)
Bay/barred pipefish (*Syngnathus leptorhyncus*)		X		Northern pipefish (*Sygnathus fuscus*)
Mississippi silverside (introduced) (*Menidia audens*)		X		Atlantic, inland silverside *(Menidia menidia, M. beryllina)*
Green/white sturgeon (*Acipenser medirostris, A. transmontanus*)		X		Shortnose sturgeon (*Acipenser brevirostrum*) Atlantic sturgeon *oxyrinchus*)
White croaker (*Genyonemus lineatus*)			X	Spotted Sea-trout (*Cynoscion nebulosus*) Redfish (*Scianops ocellatus*) Spot (*Leiostomus xanthurus*)
Longjaw mudsucker (*Gillichthys mirabilis*)			X	Skilletfish (*Gobiesox strumosus*)

Table 0.2. Suisun Marsh indicator species (invertebrates) with available DO data.

Primary Species	Data Available			Surrogate Species
	Species	Genus	Family	
Amphipods *Ampelisca abdita* (introduced) *Corophium* sp. *Americorophium* sp.	X	X	X	*Corophium volutator*
Copepods (*Acartia sp.; Eurytemora sp.*)	X	X		*Acartia tonsa*
Oyster (introduced, native) (*Crassostrea gigas*; *Ostrea lurida*)	X		X	*Crassostrea virginica*
Mud crab (introduced) *(Rhithropanopeus harrisii)*	X		X	*Eurypanopeus* sp. *Dyspanopeus* sp.
Green crab (introduced) (*Carcinus maenus*)	X			--
Dungeness crab (*Cancer magister*)	X	X		Atlantic rock crab (*Cancer irroratus*)
Bay shrimp (*Crangon franciscorum*)		X		Sand shrimp (*Crangon septemspinosa*)
Littleneck clams (*Protothaca staminea)*	X		X	Northern quahog (*Mercenaria mercenaria*)
Opossum shrimp (*Neomysis mercedis)*			X	Opossum shrimp (*Americamysis bahia*)
Korean prawn (*Palaemon macrodactylus*)			X	Grass shrimp (*Paleomonetes pugio; P. vulgaris*)

Calculation of Numeric Criteria

The calculation of numeric criteria was generally consistent with the approach used by the USEPA to derive DO criteria for the Virginia Province (USEPA 2000), and for enclosed bays and estuaries in California (SCCWRP 2011). One value was derived from data for short-term effects on the survival of juvenile and adult organisms, resulting in an acute limit, or CMC. A second value was derived from thresholds for sublethal effects, resulting in a chronic limit, or CCC. Numeric values for salmonids were addressed separately, given their inherent sensitivity to low DO. Finally, a value was derived specifically for the protection of larval life history stages that focused on protection of overall year-class success, rather than individual survival. The analysis incorporated data for all appropriate species, including native and introduced, and genus and family surrogates of the Suisun Marsh indicator species, to provide breadth and more fully approximate the range of species protected in order to preserve ecosystem function.
The two primary criteria were:

- Criterion Minimum Concentration (CMC). An estimate of the lowest concentration of DO in ambient water to which an aquatic community can be exposed briefly without resulting in an unacceptable adverse effect. This is the acute criterion.

- Criterion Continuous Concentration (CCC). An estimate of the lowest concentration of DO in ambient water to which an aquatic community can be exposed indefinitely without resulting in an unacceptable adverse effect. This is the chronic criterion.

Acute Criterion – Protection of Juvenile and Adult Survival (CMC)

A total of 23 data points (i.e., genus mean acute values or GMAVs) quantifying the acute effects of low DO on survival of juvenile and adult organisms were available. Of these, 11 were for invertebrates, and

12 were for fish. However, only 4 were native California species; the remainder were either introduced (4), or genus or family surrogates (15). The GMAVs varied by over 5-fold, and ranged from 0.38 mg/L for the introduced green crab (*Carcinus maenus*), to 2.33 mg/L for the sturgeon (*Acipenser brevirostrum*) (Table 3.3).

The data were ranked by genus on the basis of sensitivity, with fish representing 9 of the 10 most sensitive genera (Table 3.3). The four most sensitive species (each representing a different genus) were used to calculate the Final Acute Value (FAV), and included (from lowest to highest): bay pipefish (*S. fuscus*), spotted sea-trout (*C. nebulosus*), scaled sardine (*H. jaguana*) and sturgeon (*A. brevirostrum*). Based on the four most sensitive GMAVs, the Final Acute Value (FAV) was 2.33, which resulted in a CMC value of 3.34 mg/L following application of a factor (i.e., 1.43) to derive LC05s from LC50 data. If sturgeon are deleted from the dataset, the four most sensitive species are silversides (*M. beryllina*), pipefish, spotted sea-trout and sardine; the FAV and CMC would then be 2.11 and 3.01 mg/L, respectively. These data and calculations are summarized in Appendix A.

Table 0.3. Rankings of different fish and invertebrate species, based on acute sensitivity (i.e., LC50s) of juveniles or adults to low dissolved oxygen.

Species	Suisun Marsh Equivalent	LC50 (mg/L)
Sturgeon (*Acipenser brevirostrum*)	Sturgeon (*A. medirostris, A. transmontanus*)	2.33
Scaled sardine (*Harengula jaguana*)	Pacific herring (*Clupea pallasi*) American shad (*Alosa sapidissima*)	2.17
Spotted sea-trout (*Cynoscion nebulosus*)	White croaker (*Genyonemus lineatus*)	1.88
Pipefish (*Sygnathus fuscus*)	Pipefish (*S. leptorhynchus*)	1.63
Silversides (*Menidia beryllina*)	Silversides (*M. audens*)	1.59
Striped bass (*Morone saxatillis*)	Striped bass (*M. saxatillis*)	1.58
Redfish (*Scianops ocellatus*)	White croaker (*Genyonemus lineatus*)	1.45
Mysid shrimp (*Americamysis bahia*)	Mysid shrimp (*Neomysis mercedis*)	1.40
Winter flounder *(Pleuronectes americanus)*	Starry flounder *(Platichthys stellatus)*	1.38
Summer flounder *(Paralichthys dentatus)*	California halibut *(Paralichthys californicus)*	1.35
Copepod *(Acartia tonsa)*	Copepod *(Acartia sp.)*	1.26
Oyster (*Crassostrea virginica*)	Oyster (*Ostrea lurida; C. gigas*)	1.19
Menhaden (Brevoortia tyrannus)	Pacific herring (*Clupea pallasi*) American shad (*Alosa sapidissima*)	1.13
Sand shrimp (*Crangon septemspinosa*)	Grass shrimp (*C. franciscorum*)	0.97
Four-spine stickleback *(Apeltes quadracus)*	Three-spine stickleback *(Gasterosteus aculeatus)*	0.91
Amphipod *(Ampelisca abdita)*	Amphipod *(Ampelisca abdita)*	0.9
Grass shrimp *(Paleomonetes pugio, P. vulgaris)*	Grass shrimp *(Palaemon macrodactylus)*	0.87

Dungeness Crab *(Cancer magister)*	Dungeness Crab *(Cancer magister)*	0.78
Littleneck clam (*Protothaca staminea*)	Littleneck clam (*Protothaca staminea*)	0.78
Spot (*Leiostomus xanthurus*)	White croaker (*Genyonemus lineatus*)	0.7
Copepod *(Eurytemora affinis)*	Copepod *(Eurytemora affinis)*	0.6
Harris mud crab *(Rhithropanopeus harrisii)*	Harris mud crab *(Rhithropanopeus harrisii)*	0.51
Green crab *(Carcinus maenus)*	Green crab *(Carcinus maenus)*	0.38

Chronic Criterion – Protection of Sublethal Effects (CCC)

Data from 10 species were available for deriving a chronic criterion for DO, representing 4 fish and 6 invertebrates (Table 3.4). However, the dataset contained no native California species; therefore, the criterion calculation is based on a combination of introduced and surrogate species. In addition, as described in SCCWRP (2011), our criterion derivation process differed slightly from that used by USEPA in deriving a chronic limit for the Virginia Province. Specifically, where multiple data were available for a single species, we used the data that represented the most sensitive life stage and longest exposure duration, rather than averaging across exposure durations and life stages. Based on the available data, this approach 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.

The most sensitive endpoints for chronic effects were associated with amphipod (*C. volulator*; 4.0 mg/L), silversides (*M. menidia;* 4.33 mg/L), summer flounder (*P. dentatus;* 4.52 mg/L), mud crab (*D. sayi;* 4.63 mg/L), grass shrimp (*P. vulgaris;* 4.67 mg/L) and sturgeon (*A. oxyrinchus;* 4.77 mg/L). The calculated chronic values (i.e., CCCs) were essentially the same (i.e., 4.84 mg/L), regardless of whether or not sturgeon were included in the dataset.

Table 0.4. Rankings of different fish and invertebrate species, based on chronic sensitivity (survival and growth) to low dissolved oxygen.

Species	Suisun Marsh Equivalent	Chronic Value (mg/L)[1]
Sturgeon (*Acipenser oxyrinchus*)	Sturgeon (*A. medirostris, A. transmontanus*)	4.77
Grass shrimp *(Paleomonetes vulgaris)*	Grass shrimp *(Palaemon macrodactylus)*	4.67
Say's mud crab (*Dyspanopeus sayi*)	Harris mud crab (*Rhithropanopeus harrisii*)	4.63
Summer flounder *(Paralichthys dentatus)*	California halibut *(Paralichthys californicus)*	4.52
Atlantic silversides (*Menidia menidia*)	Mississippi silversides (*M. audens*)	4.33
Amphipod *(Corophium volutator)*	Amphipod *(Corophium sp.)*	4.0
Mysid shrimp (*Americamysis bahia*)	Mysid shrimp (*Neomysis mercedis*)	3.64
Quahog *(Mercenaria mercenaria)*	Littleneck clam *(Protothaca staminea)*	3.17
Atlantic rock crab *(Cancer irroratus)*	Dungeness crab *(Cancer magister)*	2.87
Striped bass (*Morone saxatillis*)	Striped bass (*M. saxatillis*)	2.80

[1]Chronic value = mean of highest effect concentration and lowest no-effect concentration.

Appropriateness of Criteria

The CMC and the CCC values derived in the previous sections were compared against the actual data to determine whether they were over or under-protective. The CMC (i.e., 3.34 mg/L) was approximately 1.43-fold greater than the GMAV (i.e., LC50 = 2.33 mg/L) for the most sensitive species (sturgeon), suggesting that there might be a small effect (i.e., ≤ 5%) on the survival of this species, but this value is expected to be fully protective of all less sensitive species. Conversely, the CCC values (i.e., 4.84 mg/L) were only marginally higher (i.e., 1.5 - 3.6%) than the chronic values (i.e., 4.77 and 4.67 mg/L) for the two most sensitive species (sturgeon and grass shrimp, respectively), indicating that the associated safety factor is small. This is a function of the calculation procedure and high degree of similarity among the four most sensitive taxa. Consequently, if it is desirable to extend protection to sturgeon, some consideration should be given to using 5.0 mg/L as the CCC; this value would provide a safety margin of 4.8%, and provide greater assurance that this genus is protected from chronic hypoxia. Overall, this analysis suggests that the criteria values are not overly protective, represent general concordance among the top ranks, and are not driven by outliers associated with particularly sensitive species or test results.

DO Criteria for Protection of Salmonids

Notably, the DO criteria derived for the Virginia Province did not incorporate data for salmonids, largely based on a presumed association with freshwater and general lack of representation in estuarine and nearshore marine biological communities (EPA 2000). Conversely, anadramous salmonids play highly important economic, recreational, cultural and ecological roles along the temperate Pacific coast, where estuaries often provide high quality juvenile rearing habitat (e.g., Hayes *et al* 2008). Thus, it is appropriate to address the extent to which the derived CMC and CCC values would be protective of salmonids using the Marsh for migratory passage, as well as extended residence by juveniles. Conversely, protection of embryo and larval (egg-alevin) stages would not be appropriate as these stages would be 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 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. In addition, Alabaster (1988, 1989), reported that upstream migration of Chinook salmon was inhibited at 3.5 mg/L, but not at 5.7 mg/L.

With these numbers as context, the DO criteria derived above can be evaluated to assess the level of protection afforded to salmonids. The CMC values derived in Section 3.3 for Suisun Marsh, with and without sturgeon, are 3.34 and 3.01 mg/L, respectively. Notably, these values are similar to the USEPA acute criterion for salmonids (i.e., 3.0 mg/L for survival), suggesting that they would be reasonably protective of short-term exposures to salmonids. The CCC suggested in Section 3.4 (i.e., 5.0 mg/L), is similar to the USEPA value of 5 mg/L for a 7-day average, but lower than the USEPA 30-day average of 6.5 mg/L, suggesting that growth of salmonids could be impaired under longer-term exposure conditions. In terms of quantitatively deriving a chronic criterion for Suisun Marsh that includes salmonids, the CCC was re-calculated with the salmonid chronic value (i.e., 6 mg/L) included in the top four sensitivity rankings. This calculation returned a value of 6.2 mg/L, which is comparable to the EPA value of 6.5 mg/L for a 30-day average.

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. However, hypoxic 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. Moreover, laboratory tests have demonstrated that effects from exposures to short-term periods of low DO cannot be predicted on the basis of daily average concentrations (USEPA 2000).

Thus, based on empirical observations of short-term mortality in various fish and invertebrates, the USEPA (2000) developed a model for evaluating responses in cases where DO conditions vary within short (i.e., <24 hr) exposure periods, consistent with tidal and diel timeframes. To apply this approach requires semi-continuous data, as would be collected from a deployed instrument array, in order to characterize exposure in terms of concentration and associated time period. The model effectively translates the CMC to a time-dependent graduated concentration curve, where the lower DO concentration limit applies to a one hour or less exposure, graduating to a higher DO concentration limit for exposures of up to 24 hours.

The short-term response model may be applied for protection of juveniles and adults, as related to the CMC, and also to evaluate the effects of hypoxic conditions that effect the survival of fish and invertebrate larvae. The resulting estimates of larval mortality were also incorporated into a recruitment model that integrates the effects of exposures to low DO as they accumulate on an annual (or seasonal) basis. Thus, the final output of the recruitment model is based on cumulative larval survival; i.e., accumulating the losses that occur as sensitive larval 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, without affecting (i.e., <5% effect) the overall strength of a given year class. Thus, the recruitment model incorporates species-specific life-history characteristics (i.e., the duration of the period larvae are produced, as well as the development time associated with individual cohorts), in addition to responses to low DO (USEPA 2000).

The underlying response data that form the basis of the larval recruitment model were derived from laboratory exposures of species representing 9 genera, of which 7 are present in the Marsh at the individual, genus or family level. Thus, the model should be applicable, at least on a provisional basis, to Suisun Marsh.

As an example of applying the larval recruitment model to short-term and intermittent periods of low 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), which provides quality-assured water quality data from 28 reserves located throughout the U.S, including San Francisco Bay, dating from 1995 to the present. This example used a dataset from 2010 from First Mallard Slough (38° 11' 41.70 N, 122° 1' 58.02 W), which is located in Suisun Marsh within the Rush Ranch Open Space Preserve. The site is located at the intersection of First Mallard (FM) with Cutoff Slough, which is a major offshoot of Suisun Slough connecting to Montezuma Slough and ultimately Suisun Bay. First Mallard empties the northwestern portion of Rush Ranch, and water quality is influenced by the larger watershed, including the Sacramento River, water-control practices in Suisun Marsh, and localized runoff from immediately adjacent uplands. Local sources of pollutants include runoff from roads, ranchlands and the Potrero Hills Landfill, in addition to regular boating activities. The sonde is moored to treated wood pilings placed approximately 10 meters into the entrance of FM, at approximately a third of the width across the slough. During deployment, the sonde rests approximately 0.5 meters above the soft silt sediment surface and typically experiences a salinity range of 0.7 to 8.1 psu. Tidal fluctuations range from approximately -0.3 to 1.8 meters relative to MLLW (based on 2012 NOAA tide predictions for Montezuma Slough Bridge), and local depths vary from approximately 0.66 to 2.94 meters.

DO data from the FM station measured at 15-min intervals over the period 28 May – 12 September 2010 are shown in Figure 3.1. These data were input into the DO Criteria Software (DOCS), a Visual Basic Program developed by SAIC, Inc., 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 exceedances was 3.5 "Criteria Units"; given that 1 Criteria Unit is equivalent to 5% of annual larval recruitment, this result suggests that the cumulative effect of the DO concentrations evaluated would have been between 15 and 20% of the entire seasonal recruitment of sensitive larvae associated with this waterbody. Note that there is a level of uncertainty associated with this assessment in that the life history parameters of the model (e.g., number of broods, duration of larval period, etc.) have not been tailored to best represent the species as they occur in Suisun Marsh. For comparison, a similar calculation performed on data from the Tijuana River estuary (TRE), resulted in an estimated 164 "Criteria Units", suggesting that the TRE experiences significantly greater frequency and magnitude of hypoxic events relative to Suisun Marsh (SCCWRP 2011).

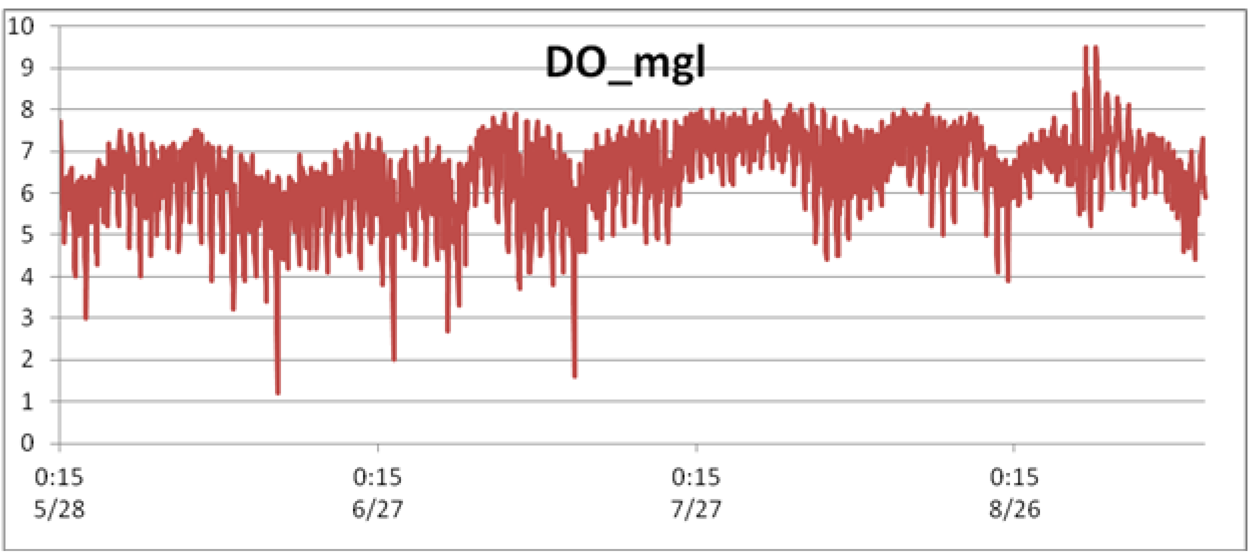
Inspection of Figure 3.1 shows that DO dropped to ≤ 3 mg/L on 5 occasions, with 2 of these occasions approaching 1 mg/L. Given that the duration of these events were 1-2 hours, it would be expected that these exposures could have resulted in acute mortality of juvenile and adult organisms (i.e., "fish kill"). Interestingly, the timing of these events was inconsistent with typical diel patterns associated with DO concentrations in marshes wherein 24-hr minima would generally be associated with night-time or early morning hours, reflecting long antecedent periods of oxygen consumption, compared with daytime hours when photosynthetic activity occurs and oxygen is produced. Specifically, the DO minima recorded in FM generally occurred between 1115 and 1415 hours. Collectively, the timing of these events, their relatively short duration and discrete pattern of occurrences potentially suggests that they may be associated with operational events (i.e., discharge of hypoxic water or materials with high oxygen demand), rather than representing overall fluxes in marsh productivity.

Alternatively, it is possible that these results were due to natural conditions in which groundwater from the surrounding marshland drains into the slough as water levels drop with outgoing tidal cycles. Depending on the duration and magnitude of the low tide, it is possible that these inputs could travel far enough downstream to reach the monitoring site before being pushed back and diluted with the incoming tide.

The data in Figure 3.1 were also evaluated to obtain a preliminary assessment of the potential for chronic impacts. The presence of periods where DO falls below 5 and 6 mg/L suggests that there is potential for adverse effects on growth, with the severity of effect depending on species and duration.

To the extent that data from this station are representative of local marsh water quality, this analysis indicates a condition that periodically approaches or falls below identified protective thresholds (i.e., acute and chronic criteria). Consequently, a more complete analysis of the spatial extent and frequency of these events would be required to characterize the extent of impairment relative to beneficial uses of interest. In addition, interpretation of cause would be facilitated by additional information regarding local land uses and practices, relationships with tidal cycles, and interactions with groundwater hydrology.

Figure 0.1. Dissolved oxygen concentrations in Suisun Marsh (First Mallard Slough) between May and September 2010.



SUMMARY AND RECOMMENDATIONS

This effort evaluated the extent to which appropriate data were available for deriving site-specific water quality criteria for dissolved oxygen for organisms inhabiting Suisun Bay and Marsh. Using data for species found in the Marsh, as well as for genus and family-level surrogates, it was possible to derive acute and chronic criteria (i.e., CMC and CCC) for DO using USEPA procedures. The suggested acute and chronic criteria are presented below, reflecting the presence of increasingly more sensitive species (i.e., sturgeon and salmonids) in the calculations.

Species Represented	**CMC (Mg/L)**	**CCC (Mg/L)**
General, without Sturgeon	3.0	4.8
General, with Sturgeon	3.3	5.0
General, with Sturgeon and Salmonids	3.3	6.2

USEPA procedures also allow for calculation of the potential for adverse effects of hypoxia on larval recruitment over an extended period that encompasses multiple spawning events. Using a limited dataset from Suisun Marsh (i.e., Figure 3.1), the potential for adverse effects on larval recruitment was evaluated and it was concluded that some adverse effects on year-class strength would be expected.

This limited dataset was also evaluated with respect to the derived CMC and CCC values. DO fell below 2 mg/L on several occasions, suggesting that there was potential for acute toxicity to multiple species. In terms of chronic effects, DO concentrations during June and July fell below 5 mg/L on a relatively frequent basis, suggesting that growth of a number of species could be adversely affected.

Most of the recommendations contained in the development of State-wide DO criteria for enclosed bays and estuaries (SCCWRP 2011) would also apply to the development and application of site-specific criteria for Suisun Marsh. One consideration is the limited representation of local species in the data set and the potential desirability of including data from additional locally-relevant species in the calculations. That being said, it is not a trivial effort to generate these data and, given the breadth of taxa represented in the calculations, it is not likely that additional data would significantly alter the criteria values determined. Thus, the criteria derived above should be reasonably protective.

Recommendations for implementation of DO criteria on a State-wide basis would also apply in a site-specific context, such as Suisun Marsh (SCCWRP 2011). Briefly, while the calculated acute, chronic and larval protection criteria provide scientifically defensible guidance with respect to levels of hypoxia that are expected to be acceptable, it would be desirable to develop assessment protocols that provide guidance regarding the temporal and spatial extent of the data required to characterize ecological conditions. In addition, the protocols should provide a description of what constitutes a determination of "impairment" (e.g., number of observations, magnitude and frequency). Policy decisions on DO objectives should also take into account naturally-occurring seasonal, diurnal and tidally-influenced periods of low DO, and implementation guidance will be needed regarding the use of DO objectives in the context of ecological assessment, TMDLs and NPDES-permitting decisions.

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APPENDIX A – Acute Criterion Calculations

List of Fish and Invertebrate Species with Acute DO Data Relevant to Suisun Marsh

Rank	GMAV (LC50)	Species	Common name	Present or Surrogate
23	0.38	*Carcinus maenus*	Green crab	present
22	0.51	*Rhithropanopeus harrisii*	Harris' mud crab	present
21	0.6	*Eurytemora affinis*	Copepod	present
20	0.7	*Leiostomus xanthurus*	Spot	*Genyonemus lineatus* (Sciaenidae)
19	0.78	*Protothaca staminea*	Littleneck clam	Veneridae
19	0.78	*Cancer magister*	Dungeness crab	present
18	0.87	*Palaemonetes pugio* *Palaemonetes vulgaris*	Marsh grass shrimp Grass shrimp	*Palaemon macrodactylus* (Palaemonidae)
17	0.9	*Ampelisca abdita*	Amphipod	present
16	0.91	*Apeltes quadracus*	Four spine stickleback	*Gasterosteus aculeatus* (Gasterosteidae)
15	0.97	*Crangon septemspinosa*	Sand shrimp	*Crangon franciscorum*
14	1.13	*Brevoortia tyrannus*	Atlantic menhaden	*Clupea pallasii* (Clupeidae) *Alosa sapidissima* (Clupeidae)
13	1.19	*Crassostrea virginica*	Eastern oyster	*Ostrea lurida* (Ostreidae)
12	1.26	*Acartia tonsa*	Copepod	present
11	1.35	*Paralichthys dentatus*	Summer flounder	*Paralichthys californicus* (Paralichthyidae)
10	1.38	*Pleuronectes americanus*	Winter flounder	*Platichthys stellatus* (Pleuronectidae)
9	1.4	*Americamysis bahia*	Mysid shrimp	*Neomysis mercedis* (Mysidae)
8	1.45	*Scianops ocellatus*	Redfish	*Genyonemus lineatus* (Sciaenidae)
7	1.58	*Morone saxatilis*	Striped bass	present
6	1.59	*Menidia berylina*	Silversides	*Menidia audens*
5	1.63	*Sygnathus fuscus*	Northern pipefish	*Sygnathus leptorhynchus*
4	1.88	*Cynoscion nebulosus*	Sea trout	*Genyonemus lineatus* (Sciaenidae)
3	2.17	*Harengula jaguana*	Scaled sardine	*Clupea pallasii* (Clupeidae) *Alosa sapidissima* (Clupeidae)
2	2.33	*Acipenser brevirostrum*	Shortnose sturgeon	*Acipenser medirostris, A. transmontanus*
1	2.55	Salmonidae	Trout, salmon	present

Suisun Acute Species (GMAVs) Data Summary	
23 species + sturgeon and salmonids	
12 inverts, 13 fish	22 GMAVs + sturgeon and salmonids
21 introduced or surrogate species; 4 native species	

Calculation of Final Acute Value for WQC--with sturgeon

Suison with sturgeon

Compound: DO

Total number of GMAVs: **23**

Rank	1/GMAV	lnGMAV	(lnGMAV)**2	P=R/(N+1)	SQRT(P)
4	0.6135	-0.48858	0.23871	0.16667	0.40825
3	0.53191	-0.63127	0.3985	0.12500	0.35355
2	0.46083	-0.77473	0.6002	0.08333	0.28868
1	0.42918	-0.84587	0.71549	0.04167	0.20412
Sum:		-2.74045	1.95291	0.41667	1.2546

S2= 3.25538
S= 1.80427
L= -1.25102
A= -0.84757
FAV= 0.42845

FAV	2.334
"ratio"	1.430
CMC	**3.34**

1/GMAV	GMAV	
0.61	1.63	pipefish
0.53	1.88	seatrout
0.46	2.17	herring
0.43	2.33	sturgeon

Calculation of Final Acute Value for WQC--without sturgeon

Suison without sturgeon

Compound: DO ALL

Total number of GMAVs: **22**

Rank	1/GMAV	lnGMAV	(lnGMAV)**2	P=R/(N+1)	SQRT(P)
4	0.62893	-0.46373	0.21505	0.17391	0.41703
3	0.6135	-0.48858	0.23871	0.13043	0.36116
2	0.53191	-0.63127	0.3985	0.08696	0.29488
1	0.46083	-0.77473	0.6002	0.04348	0.20851
Sum:		-2.35831	1.45247	0.43478	1.28158

S2= 2.56771
S= 1.60241
L= -1.10298
A= -0.74467
FAV= 0.47489

FAV	2.106
"ratio"	1.430
CMC	**3.01**

1/GMAV	GMAV	
0.63	1.59	silversides
0.61	1.63	pipefish
0.53	1.88	seatrout
0.46	2.17	herring

APPENDIX B – Chronic Criterion Calculations

List of Fish and Invertebrate Species with Chronic DO Data Relevant to Suisun Marsh

Rank	Species	Common name	Life Stage	Duration	Endpoint	SMCV	Present or Surrogate
11	*Morone saxatilis*	Striped bass	juvenile	21	-	2.80	yes
10	*Cancer irroratus*	Atlantic rock crab	larval stage 5 to megalopa	7	G,S	2.87	*Cancer magister*
9	*Mercenaria mercenaria*	Northern quahog	embryo-larvae	14	G	3.17	Veneridae
8	*Americamysis bahia*	Mysid	<48 hr old juvenile	28	G	3.64	*Neomysis mercedis*
7	*Corophium volutator*	Amphipod	life cycle		G, R	4.00	*Corophium, Americorophium* (Gammaridae)
6	*Menidia menidia*	Atlantic silverside	embryo to larva	28	S,G	4.33	*Menidia audens*
5	*Paralichthys dentatus*	Summer flounder	newly metamorphosed juvenile	10	G	4.52	*Paralichthys californicus*
4	*Dyspanopeus sayi*	Say's mud crab	larvae	8-11	G	4.63	*Rhithropanopeus harrisii*
3	*Palaemonetes vulgaris*	Daggerblade grass shrimp	newly hatched	8	G	4.67	*Palaemon macrodactylus*
2	*Acipenser oxyrinchus*	Atlantic sturgeon	juvenile	10	G	4.77	*A. transmontanus, A. medirostris*
1	*Oncorhynchus sp.*	Salmonids	juvenile	-	G	6	yes

Suisun Marsh Chronic Data Summary
10 species + salmonids
4 fish + salmonids
6 inverts
All introduced or surrogates, except salmonids

Derivation of Final Chronic Values for DO in Suisun Marsh Based on the Presence of Different Species

Calculation of Final Chronic Value for WQC--most sensitive species w/o sturgeon or salmonids

Compound: DO ALL

Total number of SCVs: **9**

Rank	1/SCV	lnSCV	(lnSCV)**2	P=R/(N+1)	SQRT(P)
4	0.23095	-1.46557	2.14789	0.4	0.63246
3	0.22124	-1.50851	2.27561	0.3	0.54772
2	0.21598	-1.53256	2.34873	0.2	0.44721
1	0.21413	-1.54116	2.37517	0.1	0.31623
Sum:		-6.0478	9.1474	1	1.94362
	0				
	S2=	0.0619			
	S=	0.2488			
	L=	-1.63284			
	A=	-1.57721			
	FCV=	0.20655		**CCC**	4.84

1/SCV	SCV	
0.23	4.33	silversides
0.22	4.52	summer flounder
0.22	4.63	mud crab
0.21	4.67	grass shrimp

Calculation of Final Chronic Value for WQC--most sensitive species with sturgeon

Compound: DO ALL

Total number of SCVs: **10**

Rank	1/SCV	lnSCV	(lnSCV)**2	P=R/(N+1)	SQRT(P)
4	0.22124	-1.50851	2.27561	0.36364	0.60302
3	0.21598	-1.53256	2.34873	0.27273	0.52223
2	0.21413	-1.54116	2.37517	0.18182	0.4264
1	0.20964	-1.56235	2.44093	0.09091	0.30151
Sum:		-6.14457	9.44044	0.90909	1.85317
	0				
	S2=	0.02945			
	S=	0.17161			
	L=	-1.61565			
	A=	-1.57727			
	FCV=	0.20654		**CCC**	4.84

1/SCV	SCV	
0.22	4.52	summer flounder
0.22	4.63	mud crab
0.21	4.67	grass shrimp
0.21	4.77	sturgeon

Calculation of Final Chronic Value for WQC--most sensitive species with sturgeon and salmonids

Compound: DO ALL

Total number of SCVs: **11**

Rank	1/SCV	lnSCV	(lnSCV)**2	P=R/(N+1)	SQRT(P)
4	0.21598	-1.53256	2.34873	0.33333	0.57735
3	0.21413	-1.54116	2.37517	0.25	0.5
2	0.20964	-1.56235	2.44093	0.16667	0.40825
1	0.16667	-1.79176	3.2104	0.08333	0.28868
Sum:		-6.42782	10.3752	0.83333	1.77427
	0				
	S2=	0.99321			
	S=	0.9966			
	L=	-2.04901			
	A=	-1.82617			
	FCV=	0.16103		**CCC**	6.21

1/SCV	SCV	
0.22	4.63	mud crab
0.21	4.67	grass shrimp
0.21	4.77	sturgeon
0.17	6.00	salmonids