Development of Sediment Quality Objectives for Enclosed Bays and Estuaries

Dietary Guild and Target Species Development for SQO Indirect Effects Assessment

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I. Introduction

The Sediment Quality Objectives (SQO) indirect effects assessment determines whether sediments meet California's narrative SQO for human health: ***Pollutants shall not be present in sediments at levels that will bioaccumulate in aquatic life to levels that are harmful to human health***. This program determines whether sediment contamination at a site results in an unacceptable health risk to humans because of the consumption of contaminated fish and shellfish (i.e., seafood). Evaluation of the narrative SQO involves two assessment questions:

- Do pollutant concentrations in seafood pose unacceptable health risks to human consumers?
- Is sediment contamination at a site a significant contributor to the seafood contamination?

These questions are evaluated using two indicators: Consumption Risk and Sediment Contribution. For the consumption risk indicator, seafood contamination measurements from the site are used to determine risk posed to local seafood consumers. For the sediment contribution indicator, the same seafood contamination measurements are compared to estimated seafood concentrations that would result from local site exposure. Estimated site exposure is calculated using a bioaccumulation model.

The evaluation of measured and modeled tissue contaminant concentrations is central to the indirect effects SQO. Biology of the local seafood organisms will influence contamination because contaminant exposure will vary with organism diet and movement. This variation in contaminant exposure is a technical issue that must be adequately addressed. Careful consideration must be given to the selection of appropriate local seafood species to sample, and how their dietary uptake is depicted.

There are a range of possible approaches to indicate local seafood dietary exposure. These include use of a generic fish representative of conditions throughout the state, use of a guild approach in which variation in diet is represented by multiple indicator species, or development of site-specific model parameters for local species. Which approach is selected entails a tradeoff between ease and accuracy. A single generic fish may not be adequate to represent local variation. At the same time, detailed dietary and movement characterizations of local seafood species would be impractical in many circumstances. The SQO program should include practical options that are easy to use, while at the same time, incorporating biological realism and local conditions.

A dietary guild approach for indirect effects evaluation

The SQO Scientific Steering Committee (SSC) and Sediment Quality Advisory Committee have recommended the use of a dietary guild approach in the indirect effects program. The operational definition of a dietary guild is:

- **Dietary guild:** *a group of seafood species that consume similar prey types, resulting in similar routes of food web exposure to sediment-associated contaminants.*

The dietary guild approach would provide a more realistic indication of seafood exposure to contaminated sediments than using assumptions for a generic seafood organism. At the same time, the use of diets based on representative species within the guild would address circumstances where local species diet data are not available.

Both benthivory and trophic position are important for defining guilds. Dietary linkage to sediment-associated contaminants will be higher for ***benthivores***: consumers of benthic organisms, such as polychaetes, benthic crustaceans, and benthic mollusks (Burkhard et al. 2003, Melwani et al. 2009b). Trophic position is important because of contaminant biomagnification. Contaminant concentrations, and potential risk of human exposure increases for ***piscivores*** (consumers of fish), which are higher on the food web (Vander Zanden and Rasmussen 1996, Kidd et al. 1998).

In the assessment framework, dietary guilds will be applied to the bioaccumulation model to estimate site sediment contribution to seafood exposure. For each guild, dietary information from a well-characterized indicator species will be used to provide parameter estimates for the bioaccumulation model. Assessment of sediment contribution may use the dietary estimates for the indicator species as parameters for the bioaccumulation model. Alternatively, if local dietary information is available for the local monitored species, these may be input into the model.

The purpose of this document is to describe the development of appropriate species and dietary guilds for use in the SQO indirect effects framework. The results of four tasks are included:

1. Determine list of appropriate seafood species for SQO evaluation
2. Categorize these species into one of several dietary guilds
3. Identify indicator species for each dietary guild
4. Develop representative diet parameters for each indicator species

II. Methods

Criteria for appropriate SQO assessment species

A listing of appropriate species for inclusion in the SQO program was developed based on three criteria:

1. They should be consumed by recreational or subsistence fishers (U. S. EPA 2000).
2. They should be local seafood organisms with limited movement range within the water body (Burkhard 2009).
3. They should exhibit a dietary association with sediments.

Development of the candidate species list

The first step in developing the species list was to determine species caught and consumed by recreational and subsistence fishers in California estuaries and marine embayments. Species consumed by fishers were identified for marine embayments by querying the Pacific states marine recreational fishing (RecFin) database (available at *www.recfin.org*). The query included all data collected in California from 2004 to 2009, obtained by the California Recreational Fisheries Survey (CRFS). The query was limited to inland marine waters (i.e., marine embayments), and was separated among six coastal districts organized from North to South (Pacific States Marine Fisheries Commission (PSMFC) 2008). The relative importance of each species in human diets was estimated based on the total mass (metric tonnes) of that species that were caught and not released, relative to the total mass of fish caught (metric tonnes). All species that composed at least 0.1% of the total mass captured were considered. Additionally, species that composed less than 0.1% of the total mass were considered when sufficient information was available to determine their diet and movement range.

The RecFin database does not include landings in the Sacramento-San Joaquin River Delta or other estuarine waters of oligohaline or mesohaline salinity. Therefore, the list of potential species was augmented to include commonly consumed species in the Delta. Potential species were identified based on the 2005 to 2008 Delta angler survey of Shilling et al. (2010), and fishery information described by Moyle (2002).

The second step in developing the species list was to determine which of the potential species exhibited appropriate diet and movement attributes for inclusion in the SQO program. Dietary and movement for marine species was summarized based on www.fishbase.com (Froese and Pauly 2010), a California database of nearshore marine fishes (Cailliet 2000), a compilation of dietary habits of marine finfish performed to identify appropriate species for statewide monitoring (SFEI and Moss Landing Marine Laboratories 2009), Moyle (2002), expert guidance (M.J. Allen, pers. comm.), and additional journal literature and technical reports. Additional specific dietary information was obtained for indicator species using detailed dietary compilations performed for previous food web modeling exercises in California (Greenfield et al. 2007, Gobas and Arnot 2010).

Species having extensive offshore, coastal, or inland migration were removed from the list of potential SQO species. Seafood was included in the list of appropriate species if they were piscivorous or at least partially benthivorous. Benthic prey were defined to include polychaete worms, benthic crustaceans (e.g., crabs, amphipods, isopods), mollusks (e.g., bivalves, gastropods, and cephalopods), and echinoderms (e.g., starfish, brittle stars, sea urchins), as well as benthic detritus and benthic algae. Piscivores were retained on the list of potential SQO target species due to their indirect food web exposure to sediment contamination (Vadeboncoeur et al. 2002, Vander Zanden and Vadeboncoeur 2002).

Development of dietary guilds and selection of representative indicator species

Based on the compiled dietary information, species were placed into one of several dietary guilds. Dietary guilds were categorized based on two factors: trophic level and degree of benthic association. For trophic position, categories were separated based on whether the predominant prey was plants, invertebrates, or fishes. Species that consume predominantly benthic invertebrates and do not consume fish were categorized as benthivores. Many species consume invertebrates in combination with another taxa, and these intermediate categories were also included (e.g., invertebrates and plants or invertebrates and fish). Species that consume only fish were categorized as piscivores. Appropriate piscivores included both benthic and pelagic fishes in their diets. For species that consume invertebrates or plants, diets were then categorized as benthic, pelagic, or both benthic and pelagic. Species that only consume pelagic prey (e.g., phytoplankton, zooplankton, or planktivorous fish) were considered inappropriate SQO assessment species and were not included in the final species list.

For each dietary guild, one or two indicator species were selected to provide statewide parameter estimates for the bioaccumulation model. Indicator species were selected based on several criteria. First, these species were important for sport and subsistence fishing, based on proportion of total mass captured in the RecFin database, and reported capture frequency in fish consumption surveys (e.g., SCCWRP and MBC Applied Environmental Sciences 1994, SFEI 2000, Allen et al. 2008, Shilling et al. 2010). Second, the species were captured in most areas of the state, based on the RecFin database, range information in FishBase, and results of recent statewide contaminant surveys (Gassel et al. 2002, Hoenicke et al. 2008). Third, these species had available data to estimate diet and foraging range. An emphasis was placed on quantitative diet data, preferably from gut content studies performed in multiple locations and seasons. Acceptable foraging range information included direct results of telemetry studies, results from tagging or contamination studies from which foraging range could be estimated, or foraging range information for similar California species combined with recommendations provided by local experts (C. Lowe, CSU-Long Beach, Pers. comm.). Finally, preference was given to species that are currently targeted in statewide or regional monitoring programs, such as the Coastal Fish Contamination Program, the Surface Water Ambient Monitoring Program, the Regional Monitoring Program in San Francisco Bay, and the Southern California Bight Regional Monitoring Survey. This criterion was included to promote consistency among programs and should increase data availability for assessment.

Development of dietary matrices for indicator species

Dietary matrices are a key input parameter of food web bioaccumulation models. These are directly entered into the model program and govern food web uptake and trophic transfer of contaminants. In the food web model used in the SQO decision support tool (Arnot and Gobas 2004, Gobas and Arnot 2010), each animal's dietary uptake of contaminants is represented as:

$$k_D * \Sigma(P_i * C_{D,i})$$

where k_D is the dietary uptake rate constant, P_i is the proportion by mass of prey item i in the total diet, and $C_{D,i}$ is the contaminant concentration in prey item i.

As indicated in the structure of this equation, contaminant uptake by each organism is calculated as a function of the biomass and contaminant concentration of each prey type consumed. Since the prey items and proportions in each organism's diet will influence the final calculated contaminant concentration, indicator species diets were developed as input parameters for the bioaccumulation model.

Food web matrix tables were developed that combine results from the indicator species into generalized food webs. Two food webs were developed: the marine embayment food web and a food web for the Sacramento-San Joaquin Delta and other estuarine embayments. These food web matrices are directly incorporated into the mechanistic bioaccumulation model that is used in the SQO assessment, to simulate the trophic transfer pathways of contaminants into the indicator species.

Diets of the prey items in the marine embayment food web follow the food web structure developed and validated for San Francisco Bay by Gobas and Arnot (2010). Prey species descriptions were generalized for statewide application. Decapod crabs and macrophytes were also included in the food web structure to accurately represent the diets of three indicator species: topsmelt, striped mullet, and spotted sand bass. Parameters for crabs and macrophytes follow those developed by Condon (2007). For the estuarine embayment food web, the dietary matrix was developed to include the prey items for the two selected indicator species: white catfish and common carp (Turner 1966, Moyle 2002, Froese and Pauly 2010). Diets of estuarine crayfish were based on the stable isotope studies by Nystrom et al. (1999) and Roth et al. (2006). Diets of the remaining invertebrate pray items followed Gobas and Arnot (2010).

Diets of the indicator species were developed based on published and unpublished literature specific to each species; this is described in the results for each species. Data used to develop dietary proportions must be measured and reported on a weight or volume-specific basis. Reports of prey frequency or numerical occurrence do not indicate relative weight or volume in the overall diet (Hyslop 1980), and are not appropriate for quantitative description of contaminant bioaccumulation. For this reason, studies that only described prey frequency or numerical occurrence were not used to develop dietary proportions for the indicator species.

III. Results

Appropriate species for evaluation in SQO program

Table 1 lists appropriate species for use in the SQO program, including 43 finfish and 5 shellfish species. Although all species in Table 1 are targeted by recreational anglers, the overall importance as prey species in CA inland marine waters varies widely, as indicated by the RecFin percent of total catch. The most important species by mass were California halibut, spotfin croaker, spotted sand bass, and leopard shark. Appendix A lists species that were evaluated and deemed not appropriate for inclusion. Inappropriate species include white sturgeon (anadromous[1]), striped bass (anadromous), jacksmelt (pelagic diet), chub mackerel (pelagic diet), and 38 additional species.

Table 1 is not intended to represent an exclusive list for assessment purposes. If a local species being considered is not listed in Table 1 or Appendix A, it should be evaluated for suitability on a case by case basis.

Description of dietary guilds

Based on trophic position, and benthic vs. pelagic diet, fishes appropriate for SQO assessment fit into eight dietary guilds. These are organized in Table 2 according to trophic position, with higher trophic position guilds listed first. The "benthic diet with piscivory"guild contains the most species (17 species). The most popular marine species, California halibut, is a piscivore. Two guilds that contained only one species each are included for completeness.

[1] Anadromous species migrate between estuarine waters and the offshore coast, as part of their life history, and therefore are likely to be exposed to site sediments for extremely limited periods.

Table 1. Appropriate species for use in the SQO program. RecFin (%) indicates percent of total catch (by mass) in California inland marine waters, from 2004 to 2009, as indicated in RecFin database.

Common name	Scientific Name	RecFin (%)
Finfish species		
California halibut	*Paralichthys californicus*	11.83%
Spotfin croaker	*Roncador stearnsii*	7.71%
Spotted sand bass	*Paralabrax maculatofasciatus*	5.32%
Leopard shark	*Triakis semifasciata*	3.75%
Barred sand bass	*Paralabrax nebulifer*	2.69%
Bat Ray	*Myliobatis californica*	2.62%
Sargo	*Anisotremus davidsonii*	2.55%
Yellowfin croaker	*Umbrina roncador*	2.43%
White croaker	*Genyonemus lineatus*	1.44%
Black perch	*Embiotoca jacksoni*	1.41%
Striped mullet	*Mugil cephalus*	1.22%
Bonefish	*Albula vulpes*	0.90%
Topsmelt	*Atherinops affinis*	0.85%
Queenfish	*Seriphus politus*	0.74%
Black rockfish	*Sebastes melaops*	0.73%
Kelp bass	*Paralabrax clathratus*	0.61%
White seabass	*Atractoscion nobilis*	0.36%
Pacific angel shark	*Squatina californica*	0.35%
Brown rockfish	*Sebastes auriculatus*	0.34%
Brown smoothhound	*Mustelus henlei*	0.33%
Striped seaperch	*Embiotoca lateralis*	0.29%
Lingcod	*Ophiodon elongatus*	0.27%
Monkeyface prickleback	*Cebidichthys violaceus*	0.25%
Redtail surfperch	*Amphistichus rhodoterus*	0.24%
White seaperch	*Phanerodon furcatus*	0.21%
Pile perch	*Rhacochilus vacca*	0.20%
Shiner perch	*Cymatogaster aggregata*	0.19%
Pacific sanddab	*Citharichthys sordidus*	0.19%
Pacific sanddab	*Citharichthys sordidus*	0.19%
Walleye surfperch	*Hyperprosopon argenteum*	0.18%
Grass rockfish	*Sebastes rastrelliger*	0.17%
Starry flounder	*Platichthys stellatus*	0.16%
Rubberlip seaperch	*Rhacochilus toxotes*	0.14%
Barred surfperch	*Amphistichus argenteus*	0.14%
Cabezon	*Scorpaenichthys marmoratus*	0.12%
Blue rockfish	*Sebastes mystinus*	0.09%
Fantail sole	*Xystreurys liolepis*	0.07%
Senorita	*Oxyjulis californica*	0.07%
Dwarf perch	*Micrometrus minimus*	<0.01%
English sole	*Parophrys vetulus*	<0.01%
Channel catfish	*Ictalurus punctatus*	NA
Common carp	*Cyprinus carpio*	NA
Largemouth bass	*Micropterus salmoides*	NA
White catfish	*Ameiurus catus*	NA

NA – data not available for Delta species

Table 2. Dietary guild categories used for SQO species. Example species are included and the selected indicator species for categories are **highlighted in bold**

Dietary guild	Description	Guild species
Piscivore	The majority of the diet is fish. Large predatory invertebrates (e.g., cephalopods, decapod crustaceans, and echinoderms) are also consumed to some degree. 3 species	**California halibut** Pacific angel shark Lingcod
Benthic diet with piscivory	Diet regularly includes a mixture of benthic invertebrates forage fish. The most diverse category. 17 species, including two estuarine species: white catfish and channel catfish.	**Spotted sand bass** **White catfish** Leopard shark Barred sand bass Bat Ray Yellowfin croaker Bonefish White seabass Brown rockfish Brown smoothhound Redtail surfperch Pacific sanddab Grass rockfish Starry flounder Cabezon English sole Channel catfish
Benthic and pelagic diet with piscivory	Diet includes a combination of benthic invertebrates, pelagic invertebrates (e.g., zooplankton, shrimp, and mysidae), and forage fish. 5 species	**Queenfish** Black rockfish Kelp bass Pacific sanddab Blue rockfish
Benthic diet without piscivory	Diet largely composed of small benthic invertebrates, such as amphipods and other crustaceans, bivalve mollusks, and polychaete worms. 10 species	**White croaker** Spotfin croaker Sargo Striped seaperch White seaperch Pile perch Walleye surfperch Rubberlip seaperch Barred surfperch Fantail sole
Benthic and pelagic diet without piscivory	Diet includes a mixture of epibenthic and pelagic invertebrates (e.g., zooplankton, shrimp, and mysids). 3 species	**Shiner perch** Black perch Dwarf perch
Benthic diet with herbivory	Largely consumes benthic invertebrates, benthic algae, and aquatic plants. 3 species, including common carp, an estuarine species.	**Common carp** Monkeyface prickleback Señorita
Benthic and pelagic diet with herbivory	Diet consists of benthic and pelagic invertebrates and plant material, including benthic algae and phytoplankton. 1 species	**Topsmelt**
Pelagic diet with benthic herbivory	Diet includes largely pelagic invertebrates and benthic algae. This includes a substantial component of benthic algae and attached plants, likely as floating detritus. These benthic plants constitute a potential dietary association with sediments. 1 species	**Striped mullet**

Selection and diet description of guild diet indicator species

The sediment chemistry indicator uses a modeling approach to estimate the contribution of contaminants from site sediments. The accuracy of the contribution estimates is enhanced when realistic values for parameters such as trophic status, dietary reliance on benthos, and forage area are used. This section describes the indicator species selected for each guild, the basis for selection, and their diet. The indicator species diets are summarized as percentages for use in the bioaccumulation model.

Piscivore - California halibut

Of the three species in the “piscivore” category (Table 2), California halibut was selected as the indicator species. California halibut has the largest catch (11.8% of total inland catch in the RecFin query) and is caught statewide. Additionally, there are published diet information (Plummer et al. 1983, Wertz and Domeier 1997) and extensive tag-recapture results (Haaker 1975, Tupen 1990, Domeier and Chun 1995, Posner and Lavenberg 1999) to form a basis for feeding and movement parameter development.

Adult California halibut larger than 20 cm are primarily piscivorous, with fish composing the vast majority of their prey by mass. This includes a combination of pelagic prey species such as northern anchovy, as well as benthic species such as gobies and killifish. (Plummer et al. 1983, Wertz and Domeier 1997). Invertebrates that are consumed include large predatory species, such as cephalopods (Wertz and Domeier 1997). Based on this available information, the bioaccumulation model for halibut is parameterized as 98% forage fish, including both benthic and pelagic prey fish (Table 3).

Benthic diet with piscivory - spotted sand bass

Spotted sand bass is the first of two species selected as the indicator species for the “benthic diet with piscivory” category. Spotted sand bass was selected because it is the most important seafood species in the category by mass, and has available diet information (Allen et al. 1995, Mendoza-Carranza and Rosales-Casian 2000).

Two studies were available to develop quantitative dietary composition for spotted sand bass (Allen et al. 1995, Mendoza-Carranza and Rosales-Casian 2000). Both studies reported decapod crabs as the second most important prey type. Allen et al. indicated (1995) mollusks to be the primary prey type, while Mendoza-Carranza (2000) indicated fishes as the most important prey. Based on the average importance in these studies, model input parameters were established to represent benthic and pelagic fishes (35%), crabs (35%) and mollusks (28%) as the major prey items. Phytoplankton and amphipods were both present in the diet but only a very minor contribution to total prey mass, and were each included as 1% of total diet (Table 3).

Benthic diet with piscivory - white catfish

White catfish was selected as an additional indicator species for the estuarine habitats. White catfish is a freshwater species, found in inland estuarine waters, such as the Delta. It was selected as an indicator species because is a commonly captured and consumed prey for sport and subsistence anglers (Moyle 2002), second only to striped bass in frequency and amount caught and consumed (Shilling et al. 2010). Additionally, white catfish is periodically monitored in Delta contaminant surveys, and has published local diet and movement data (Turner and Kelley 1966, Borgeson and McCammon 1967, Davis et al. 2000, Melwani et al. 2009a).

Because white catfish resides in the Delta, its dietary composition is based on an estuarine food web (Table 4). White catfish are carnivorous benthivores, including crayfish and fish in their diets, as well as smaller invertebrates and miscellaneous carrion (Moyle 2002). White catfish prey proportions are based on prey volume composition results of the Delta study performed by Turner (1966). Following this study, model input pararameters indicated forage fish to be a substantial prey item (55% of prey), followed by amphipods (20% of prey), crayfish (11%), mollusks (e.g., *Corbicula fluminea*, 8%), and mysids (6%).

Benthic and pelagic diet with piscivory - queenfish

Queenfish was selected as the indicator species for this category. It has the greatest mass caught by anglers, and has a greater association with soft bottom sediments than some of the other species (e.g., kelp bass, black rockfish and blue rockfish are more associated with rocky and reef habitat).

Two studies developed quantitative mass or volume based estimates of queenfish diets (Hobson and Chess 1976, DeMartini et al. 1985). DeMartini et al. (1985) found that approximately 90% of queenfish prey were northern anchovy. In contrast, Hobson and Chess (1976) found that mysids were the predominant prey item (45%), followed by amphipods (22%), annelid worms (22%), with very small contributions of shrimp, isopods, and fish. Prey proportions for the bioaccumulation model, obtained by averaging the results of these two studies, included benthic and pelagic invertebrates and fish, with the following proportions: pelagic forage fish (48%), mysids (24%), amphipod crustaceans (12%), large and small polychaetes (5% and 6%,respectively), crangonid shrimp (3%), and cumacean crustaceans (2%) (Table 3).

Benthic diet without piscivory - white croaker

White croaker was selected as the indicator species for the “benthic diet without piscivory” category for several reasons. White croaker is captured in all portions of the state, unlike some other heavily caught fish in the category (e.g., sargo and spotfin croaker are only caught in southern California). Among the more commonly targeted species in this guild, the best dietary, life history, and contaminant information are available for white croaker (Sigala et al. 2002, Gobas and Arnot 2005, Melwani et al. 2009b, Gobas and Arnot 2010). Diet parameters developed for white croaker have been validated for PCBs and legacy pesticides in San Francisco Bay, exhibiting low model bias and error (Greenfield et al. 2007, Gobas and Arnot 2010). Finally, white croaker is a target species for multiple contaminant monitoring programs, so a large data set of contaminant and other parameters is available (Gassel et al. 2002, Greenfield et al. 2005, Industrial Economics Incorporated 2007).

White croaker is a bottom-dwelling fish that inhabits large bays and shallow near-shore coastlines. White croaker is a bottom feeder, predominantly consuming benthic invertebrates and fishes. The most common food items are polychaetes, crabs, amphipods, mysids, and small fishes. Several dietary studies in San Francisco Bay found gut contents to include bivalves, polychaetes, crangonid shrimp, and small fishes (Sanchez 2001, Sigala et al. 2002, Jahn 2008). Likely due to this close association with a benthic food web, white croaker tissue chemistry data show statistically significant relationships to sediment chemistry for many trace organic contaminants (CH2M HILL 2003, Melwani et al. 2009b).

The food web model parameters for white croaker (Table 3) are the same as the parameters in previously validated case studies (Greenfield et al. 2007, Gobas and Arnot 2010). The modeled diet largely includes benthic invertebrates: polychaete worms (40%), amphipod crustaceans (20%), and cumacean crustaceans (20% *Nippoleucon hinumensis*). Additional invertebrate prey include benthopelagic mysids (10%) and crangon shrimp (5%). Sediment consumption is also included as 5% of white croaker diets, because croaker are roving benthic grazers that siphon sediments to consume prey (C. Lowe, pers. comm.).

Benthic and pelagic diet without piscivory - shiner perch

Shiner perch was selected as the indicator species for this category because the biology and diet of this species is better understood the other two species in this guild. As with white croaker, bioaccumulation model application has previously been validated for shiner perch (Greenfield et al. 2007, Gobas and Arnot 2010). Additionally, shiner perch has been the subject of several diet studies (Odenweller 1975, Hobson and Chess 1986, Sigala et al. 2002, Jahn 2008), and has been used for contaminant monitoring in multiple estuaries and marine embayments (Gassel et al. 2002, Allen et al. 2004, Greenfield et al. 2005). Despite its small size, shiner perch is frequently caught by recreational fisherman due to high abundance and ease of capture. Although it comprises a minor component of angler catch by mass, it is distributed statewide and caught in all regions.

Shiner perch exhibit similar life history to other surfperch species, such as silver surfperch (*Hyperprosopon ellipticum*) and walleye surfperch (*Hyperprosopon argenteum*). They are generally epibenthic feeders, primarily feeding off the sediment surface or on epifauna of hard structures. Odenweller (1975) reported that for Anaheim Bay shiner perch, the primary food source was zooplankton and benthic organisms, including bivalves, gastropods, polychaetes, tunicates, and fish eggs. Several dietary studies in San Francisco Bay indicate particular reliance on benthic and epibenthic crustaceans, augmented by polychaetes and clams (Roberts et al. 2002, Jahn 2008).

The bioaccumulation model parameters used for shiner perch (Table 3) follow those established by Gobas and Arnot (2010): sediments (5%); benthic polychaete worms (20%), amphipod crustaceans (20%), and cumacean crustaceans (20); benthopelagic mysids (15%); and pelagic phytoplankton (10%) and zooplankton (10%).

Benthic diet with herbivory - common carp

Common carp was selected as the indicator species for the benthic with herbivory guild. Carp were chosen because there are extensive data available to characterize the diet and movement of this species (Crook 2004, Stuart and Jones 2006, Jones and Stuart 2009, Osborne et al. 2009, Froese and Pauly 2010). Common carp is a freshwater and brackish water species, and is found in inland estuarine waters such as the Delta and the San Gabriel River (Moyle 2002). Though historically regarded as a “rough fish” in the U.S., carp are opportunistically caught and consumed by California sport and subsistence anglers (Chiang 1998, Allen et al. 2008, Shilling et al. 2010). Monitoring in the Delta and other statewide and national monitoring programs has indicated organic contaminant exposure in carp (Davis et al. 2000, de Vlaming 2008, Stahl et al. 2009).

Carp are predominantly benthic omnivores, rooting in the benthos for vegetation and benthic invertebrates (Moyle 2002). Although dietary studies have not been performed in the Delta or other California estuaries, Froese and Pauly (2010) summarize studies on common carp diet in eleven separate water bodies, globally (Bisht and Das 1981, Maitland and Campbell 1992, Specziár et al. 1997, Specziár et al. 1998, Blanco et al. 2003, Talde et al. 2004). These results were used to establish the dietary prey types and proportions used for the bioaccumulation model (Table 4). The predominant item consumed is sediment (29%), based on the detritivorous behavior of carp, tendency to take silty sediments into their mouths (Moyle 2002), and frequent reporting of abundant detritus in the gut (Bisht and Das 1981, Maitland and Campbell 1992, Talde et al. 2004). Macrophytes (submerged vascular plants) are the second most important item (20%), as carp frequently consume plant material. Benthic invertebrates consumed include amphipods (10%), mollusks (14%), annelids (worms, 1%), and decapod crustaceans (i.e., crayfish, 4%). Carp also consume zooplankton (11%), mysids (6%), and benthic fish (1%).

Benthic and pelagic diet with herbivory - topsmelt

Topsmelt is the only species that fits the SQO selection criteria for the benthic and pelagic diet with herbivory guild. Topsmelt comprised 0.85% of the statewide recreational catch, by mass, suggesting some degree of consumption by anglers. Topsmelt diets include benthic and pelagic invertebrates, benthic algae, and phytoplankton (Marine Biological Consultants Inc. and SCCWRP 1980, Logothetis et al. 2001, Horn et al. 2006, Visintainer et al. 2006, Greenfield and Jahn 2010). Studies in Newport Bay (Allen 1980, Marine Biological Consultants Inc. and SCCWRP 1980) and San Francisco Bay (Visintainer et al. 2006, Greenfield and Jahn 2010) provide somewhat contrasting results. The Newport Bay studies indicate substantial contribution of benthic herbivory, and the San Francisco Bay studies indicate a combination of benthic and pelagic invertebrates in the diet. Morphometric analyses by O'Reilly and Horn (2004), and by Horn et al. (2006) indicate dietary adaptations for herbivory, suggesting that plant material constitute a primary component of topsmelt diets. Combining the results from these studies, the bioaccumulation model input parameters are set with herbivory constituting a moderate dietary proportion (20% of topsmelt prey as phytoplankton and 20% as submerged plants). Benthic amphipods constitute the other major prey item (40%), with minor contributions from zooplankton (8%), sediments (5%), mysids (5%), polychaetes (1%), and cumaceans (1%) (Table 3).

Pelagic diet with benthic herbivory - striped mullet

The only species that met the SQO selection criteria for the pelagic diet with herbivory guild was striped mullet. Striped mullet are adapted to consume plant material, with most dietary studies indicating sizable contributions of plants and algae, as well as detritus (i.e., sediments). They are unusual among marine fish in California in that sediments and plant material often constitute the majority of their diet (Allen 1980, Marine Biological Consultants Inc. and SCCWRP 1980, Wells 1984, Blanco et al. 2003), resulting in their classification in a separate dietary guild. This is reflected in the selected prey proportions for the bioaccumulation model (Table 3). Following the average results of global published diet studies of adults (Marine Biological Consultants Inc. and SCCWRP 1980, Wells 1984, Blanco et al. 2003), 75% of the diet is composed of sediments and plant material (30% sediments, 35% benthic macrophytes, and 10% phytoplankton). The remaining diet includes zooplankton (10%) and benthic invertebrates (5% mollusks, 5% amphipods, and 5% polychaetes).

Food web matrix tables

Table 3 represents a generalized food web structure of California marine embayments that includes the diets of the seven indicator fish species found in this habitat. These diets include fifteen benthic and pelagic animal prey items, in addition to phytoplankton, macrophytes (submerged aquatic plants), and direct consumption of sediment. Dietary proportions for the indicator species vary, representing the range of feeding guilds encountered in California marine embayments. The diets of benthic and pelagic prey items (invertebrates and small forage fishes) are also represented. This includes six different forage fish, to indicate the range of dietary habits among small marine forage fish.

Table 4 represents a generalized food web structure of California estuarine waters. This food web structure is based on the Sacramento-San Joaquin Delta and includes the diets of the two indicator fish species found in that habitat (channel catfish and common carp). Crayfish are present in the Delta and constitute a prey item for both catfish and carp.

Table 3. Food web structure for marine embayments used in bioaccumulation model. Diet items are presented in columns and all values indicate percentage importance. SQO indicator species are highlighted in boldface.

Biota	Sediment	Phytoplankton	Submerged macrophytes	Zooplankton	Small polychaetes	Large polychaetes	Amphipods	Cumaceans	Mysids	Mollusks	Decapod crabs	Crangon shrimp	Forage fish – herbivore	Forage fish – planktivore	Forage fish - primarily benthivore	Forage fish – benthivore	Forage fish - mixed diet i	Forage fish - mixed diet ii
Zooplankton	.	100	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
Small polychaetes	90	5	.	5	.	.	.	.	.	.	.	.	.	.	.	.	.	.
Large polychaetes	90	5	.	5	.	.	.	.	.	.	.	.	.	.	.	.	.	.
Amphipods	30	35	.	35	.	.	.	.	.	.	.	.	.	.	.	.	.	.
Cumaceans	15	65	.	20	.	.	.	.	.	.	.	.	.	.	.	.	.	.
Mysids	10	45	.	45	.	.	.	.	.	.	.	.	.	.	.	.	.	.
Mollusks	30	65	.	5	.	.	.	.	.	.	.	.	.	.	.	.	.	.
Decapod crabs	44	1	10	10	.	.	20	15	.	.	.	.	.	.	.	.	.	.
Crangon shrimp	.	30	.	30	.	.	.	.	40	.	.	.	.	.	.	.	.	.
Forage fish – herbivore	.	80	.	20	.	.	.	.	.	.	.	.	.	.	.	.	.	.
Forage fish – planktivore	.	20	.	35	.	.	20	15	10	.	.	.	.	.	.	.	.	.
Forage fish - primarily benthivore	5	5	.	20	15	15	10	10	10	.	.	10	.	.	.	.	.	.
Forage fish – benthivore	.	.	.	.	20	20	15	15	.	.	.	25	.	.	.	.	5	.
Forage fish - mixed diet i	5	10	.	20	5	5	25	25	5	.	.	.	.	.	.	.	.	.
Forage fish - mixed diet ii	5	.	.	.	5	10	15	15	20	.	.	20	.	5	.	.	5	.
Shiner perch	5	10	.	10	10	10	20	20	15	.	.	.	.	.	.	.	.	.
Topsmelt	5	20	20	8	.	1	40	1	5	.	.	.	.	.	.	.	.	.
White croaker	5	.	.	.	20	20	20	20	10	.	.	5	.	.	.	.	.	.
California halibut	.	.	.	.	.	.	.	.	1	.	.	1	8	45	25	10	.	10
Spotted sand bass	.	1	.	.	.	.	1	.	.	28	35	.	.	10	.	15	.	10
Queenfish	.	.	.	.	6	5	12	2	24	.	.	3	.	48	.	.	.	.
Striped mullet	30	10	35	10	.	.	3	.	2	10	.	.	.	.	.	.	.	.

Table 4. Food web structure for the estuarine Sacramento-San Joaquin Delta used in bioaccumulation model. Diet items are presented in columns. SQO indicator species are highlighted in boldface.

Biota	Sediment	Phytoplankton	Macrophytes	Zooplankton	Annelid worms	Amphipods	Decapods (crayfish)	Mysids	Mollusks	Benthic forage fish	Pelagic forage fish
Zooplankton	.	100	.	.	.	.	.	.	.	.	.
Annelid worms	90	5	.	5	.	.	.	.	.	.	.
Amphipods	30	35	.	35	.	.	.	.	.	.	.
Decapods (crayfish)	.	5	5	.	10	40	.	.	40	.	.
Mysids	10	45	.	45	.	.	.	.	.	.	.
Mollusks	30	35	.	35	.	.	.	.	.	.	.
Benthic forage fish (e.g., yellowfin goby)	5	.	.	.	32	32	.	.	31	.	.
Pelagic forage fish (e.g., Mississippi silverside)	.	.	.	100	.	.	.	.	.	.	.
White catfish	.	.	.	.	.	20	11	6	8	25	30
Common carp	29	4	20	11	1	10	4	6	14	1	.

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Appendix A. California finfish species found in inland marine embayments deemed not appropriate for indirect effects SQO evaluation. See Methods section for description of criteria for appropriate species. RecFin (%) indicates percent of total catch (by mass) in California inland marine waters, from 2004 to 2009, as indicated in RecFin database.

Common name	Reason species is inappropriate	RecFin (%)
Albacore	Migratory; does not typically inhabit estuaries or marine embayments	0.14%
American shad	Pelagic planktivore	0.61%
Blacksmith	Pelagic planktivore	0.05%
Bluefin tuna	Does not typically inhabit estuaries or marine embayments; pelagic	0.01%
Bocaccio	Exhibits extensive movement and tends to live far offshore in deep waters	0.26%
California corbina	Primarily surfzone feeder - inappropriate movement characteristics	1.18%
California lizardfish	Insufficient information on diet; reef associated	0.20%
California scorpionfish	Transient - range up to 200 miles	0.38%
California sheephead	Kelp bed/ rock reef resident - inappropriate habitat	0.14%
Chinook salmon	Anadromous	0.33%
Chub (pacific) mackerel	Pelagic diet	3.27%
Coho salmon	Anadromous; not legal to fish in CA	0.01%
Dolphinfish	Highly migratory	0.40%
Giant seabass	Classified as critically endangered; not legal to fish in CA	0.12%
Gopher rockfish	Resides in rocky crevasses of rocky reefs and other hard relief areas (i.e. not sediment associated)	0.04%
Gray smoothhound	Migratory (from Southern to central CA in summer)	0.14%
Green sturgeon	Anadromous species; Classified as endangered; not legal to fish in CA	0.01%
Halfmoon	Pelagic diet	0.21%
Jack mackerel	Pelagic diet	0.08%
Jacksmelt	Large pelagic component in diet	5.10%
Kelp rockfish	Pelagic diet	0.01%
Northern anchovy	Pelagic diet	0.42%
Largemouth bass	A popular sport fish in the Delta but generally avoided by fish consumers	-
Olive rockfish	Midwater species; very low proportion of catch in marine embayments	0.02%
Opaleye	Diet predominantly kelp bed and other attached and suspended plants (not sediment associated)	1.87%
Pacific barracuda	Migratory	0.36%
Pacific bonito	Migratory	3.43%
Pacific chub mackerel	Pelagic diet	
Pacific hake	Generally occurs offshore	0.00%
Pacific herring	Pelagic diet	0.34%
Pacific sardine	Pelagic diet	0.57%
Plainfin midshipman	Pelagic diet	0.01%
Salema	Pelagic diet	0.04%

Seven gill shark	Extensive migration of great distances	1.06%
Shortfin corvina	Researched extensively on line - can find nothing on movement patterns	0.60%
Shovelnose guitarfish	Primarily surfzone feeder - inappropriate movement characteristics	0.69%
Spiny dogfish (shark)	Extensive migration of great distances	0.06%
Striped bass	Anadromous	9.39%
Thresher shark	Generally occurs offshore	0.07%
White sturgeon	Anadromous	11.44%
Yellowtail	Migratory and pelagic	0.36%
Zebra perch	Transient	0.30%