Technical Support for Elkhorn Slough Nutrient Total Maximum Daily Load (TMDL) Development

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1.0 INTRODUCTION

Elkhorn Slough, an estuary draining to Monterey Bay, is located in Monterey County, CA (Figure 1-1). Elkhorn Slough contains the largest tract of tidal salt marsh in California south of the San Francisco Bay and provides much-needed habitat for hundreds of species of plants and animals. The estuary consists of several interconnected channels, including the Old Salinas River channel, Moro Cojo Slough, Bennett, Slough, and Elkhorn Slough proper. The Elkhorn Slough channel is the largest of the channels and is the only one not obstructed by a water control structure at its mouth, and therefore the entire complex is generally referred to as the Elkhorn Slough estuary (Hughes et al. 2011).

Surrounding agricultural practices and tidally driven processes leading to nutrient loading have heavily influenced the estuary over the past 70 years, and long-term data suggest that nutrient levels have increased to the point that the estuary is home to some of the highest dissolved nutrient levels when compared to other estuaries in the United States. Additionally, Elkhorn Slough is known to have high biomass of phytoplankton and macroalgae. The high productivity observed in the estuary causes increased fluctuations in pH, high occurrence of sulfate reducing bacteria, and chronic periods of daytime hyperoxia and nighttime hypoxia and anoxia. Hydrologic alterations in Elkhorn Slough, including dikes, culverts, and tide gates have also caused artificial dampening of the tidal range upstream of water control structures (Hughes et al. 2011).

Elkhorn Slough appears on the State of California's approved 2014 303(d) list[1] for low dissolved oxygen, as well as other constituents (pesticides, sediments, pH, nitrate, and total coliforms). The Central Coast Regional Water Quality Control Board is in the process of developing a total maximum daily load evaluation (TMDL) for biostimulatory substances[2]. This TMDL project will evaluate water quality impairments in the Elkhorn Slough watershed which are caused by exceedances of water quality criteria for dissolved oxygen, pH, un-ionized ammonia, chlorophyll-a, as well as nutrient-related problems caused by high levels of nitrate, orthophosphate, and algal biomass. These exceedances are likely to impact aquatic life uses, but also other beneficial uses such as recreation and fishing.

Extensive monitoring and research related to nutrient biogeochemical cycling has been conducted in the estuary over the past two decades, with several peer-reviewed papers identifying key nutrient-related processes (e.g., Caffrey et al., 2002; Hughes et al., 2011; Hughes et al., 2015; Jeppesen et al., 2018; Wasson et al., 2017). A summary of the data collected across the estuary is presented in a recent report by the Central Coast Water Board, including identification of relationships between different parameters, and description of temporal and spatial trends (Saiz and Keeling, 2016). In addition, a "Water Quality Report Card" has been published by the Elkhorn Slough Reserve, identifying sub-regions within the slough by their water quality (http://elkhornslough.org/water/).

Elkhorn Slough was historically part of an interconnected, extensive estuary that included Bennett Slough, Moro Cojo Slough, Tembladero Slough, and the old Salinas River Channel. Now, all arms of the historic estuary except for the main Elkhorn Slough channel are diked and function mostly as freshwater impoundments. Thus, historic estuarine biodiversity is now only represented in this small area. As such, Elkhorn Slough is the only remnant of the historic estuary with abundant sea otters, eelgrass beds, fish nursery habitat, migratory shorebird foraging, and other numerous ecological habitats, and thus is a major

[1] https://www.waterboards.ca.gov/water_issues/programs/tmdl/integrated2014_2016.shtml

[2] http://www.waterboards.ca.gov/centralcoast/water_issues/programs/tmdl/docs/elkhorn_slough/do/index.shtml

focus of conservation efforts, as well as providing key ecosystem services. If the estuarine network were still interconnected, considering it as a whole would have made sense. But given current hydrology, development of a TMDL only for the Elkhorn Slough is a reasonable approach.

Agriculture is important in the Elkhorn Slough watershed, and erosion of sediments off steep adjacent farm fields was one conspicuous issue recognized decades ago. Reducing nutrients and sediment entering from adjacent farms has been a key priority motivating land acquisition and restoration by the Elkhorn Slough Foundation (Scharffenberger 1999), and local improvements have been documented as a result (Gee et al. 2010).

Dissolved inorganic nutrients enter Elkhorn Slough from a number of sources, including freshwater sources such as Tembladero Slough and the Salinas River to the south, Moro Cojo Slough to the southeast, and Carneros Creek to the north. Adjacent land areas also contribute to nutrient enrichment via runoff. Additionally, in the late spring and early summer, periods of upwelling cause nutrient rich water from Monterey Bay to enter Elkhorn Slough. Only more recently, as a part of a thorough consideration of large-scale management alternatives for the estuary, did it become clear that a very high proportion of the nutrients in the estuary arrive via the old Salinas River channel (Wasson et al., 2015), mostly from the work by K. Johnson at the Monterey Bay Aquarium Research Institute (MBARI). Thus, the existing TMDL for the old Salinas River will provide important benefits to Elkhorn Slough: the historic estuarine network connections still matter, despite vast changes. Carneros Creek, forming the head of the estuary and flowing directly into the main channel, also supplies nutrient inputs, but to a much lesser extent.

While Elkhorn Slough is the only undiked arm of the historic estuary, many of its peripheral wetlands have also been diked (Van Dyke and Wasson 2005). It has become increasingly clear that water quality and biodiversity are very different in the diked vs. undiked portions of the estuary (Ritter et al. 2008, Hughes et al. 2011). Nutrient sources and the consequences of nutrient loading differ, and thus they will be considered separately in the TMDL process.

This report supports the development of the TMDL by proposing nutrient targets for the estuary (Chapter 2) and developing initial estimates of nutrient sources to the Slough using available information and existing simplified modeling tools (Chapter 3). No new model calibration activities are included in the current work; however, these initial estimates provide a basis for further development and a proposed modeling approach to complete the TMDL, and a recommended approach for development of TMDL allocations (Chapter 3).

Figure 1-1. Location of Elkhorn Slough and its contributing watershed

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2.0 DEVELOPMENT OF NUMERIC TARGETS

2.1 INTRODUCTION

Nutrients affect aquatic systems in diverse ways, and the effects on most non-primary producer aquatic life uses are indirect and highly variable depending on additional filters that may be present as shown in conceptual form in Figure 2-1. This conceptual model considers drivers, filters, and primary and secondary indicators of eutrophication and was proposed in a seminal study of coastal eutrophication by Cloern (2001). Nutrients cause enrichment of primary producer and decomposer biomass and productivity, the increase of which leads to changes in the physical and chemical estuarine environment (e.g., reduced oxygen, loss of reproductive habitat, alteration on the availability of palatable algal taxa, etc.). It is these effects which directly result in changes to the biological community (e.g., loss of disturbance sensitive taxa), and ultimately impair the aquatic life uses. Conceptual modeling is an important first step in developing thresholds that translate narrative criteria into numeric values, so that existing knowledge is captured, and proposed modeling efforts are appropriately applied to link nutrient targets to desired assessment endpoints, and that appropriate covariates are considered.

A study was conducted by Hughes et al. (2011) which examined 18 sites within the Elkhorn Slough estuary to assess the elements of Cloern's (2001) conceptual model of coastal eutrophication. A eutrophication expression index (EEI) was developed and implemented to obtain a single value for the expression of eutrophication indicators. The EEI values are categorized as low, moderate, high or hyper eutrophic. The calculated values were then utilized to characterize and map spatial patterns of the index across the 18 sites in the Elkhorn Slough estuary, defining different areas by the highest high water level (Figure 2-2). Correlations of nutrients and filters with the EEI were also determined using principal components analysis (PCA), and tidal range in particular was examined as a key filter in order to clarify its relationship with individual indicators of eutrophication.

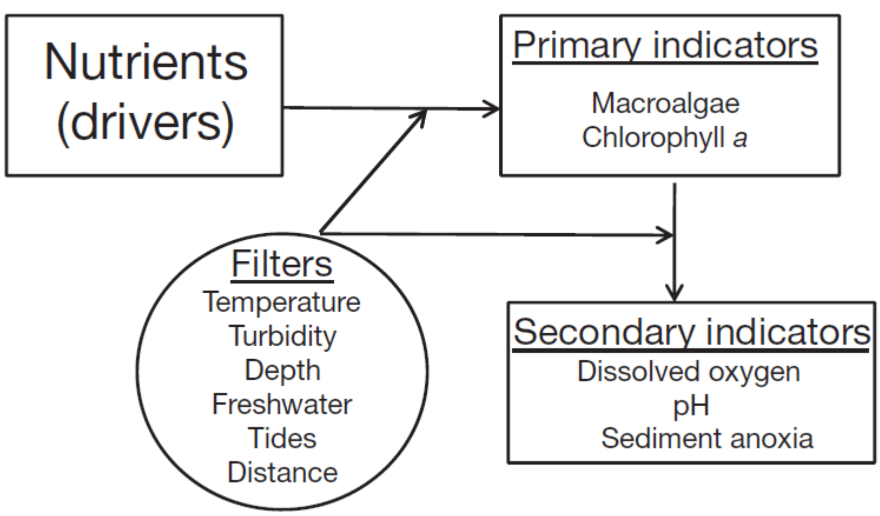

Figure 2-1. Coastal eutrophication model and hypothesis. Source: Hughes et al. 2011, building upon the coastal eutrophication conceptual model of Cloern (2001).

The results of the study showed that nutrient concentrations in Elkhorn Slough were very high in comparison to reported eutrophication thresholds. Although nutrient concentrations were highly variable among sites, 33% of sites had mean nitrogen values exceeding the high nitrogen threshold (>1.0 mg N l^{-1}) and 39% of sites had mean phosphorus values that exceeded the high threshold (>0.1 mg P l^{-1}). The highest nutrient concentrations were observed at sites closest to freshwater inputs, such as the Old Salinas River channel and Carneros Creek. Mean values for all primary indicators of eutrophication, including chlorophyll *a* and floating, subtidal, and intertidal algal mats were moderate at each site, however, at least one primary indicator was high at all sites. Additionally, high algal cover was observed at many sites, although species diversity was lacking, with algal assemblages mostly comprised of a few species of green macroalgae. The study results also showed significant expression of secondary indicators of eutrophication in the Elkhorn Slough estuary, including periods of anoxia, hypoxia, high pH, and anoxic sediments (Hughes et al. 2011).

The EEI indices calculated in the Hughes et al. (2011) study varied spatially across the 18 sites from low to hypereutrophic (Figure 2-2). The main channel was found to be moderately eutrophic in the middle and near the mouth, increasing to highly eutrophic near the head. Overall, the entire estuarine complex received an EEI value of 0.539 and 0.450 for area-based and volume-based assessments, respectively, meaning that the estuary as a whole was moderately eutrophic. PCA analysis revealed that nutrient levels were not strongly correlated with EEI values, while eutrophication filters were strongly correlated with EEI values. The analysis revealed that tidal range, subtidal depth, temperature, freshwater, turbidity, and distance to mouth all appeared to contribute to variation in patterns of eutrophication. Increased tidal range, greater depth, greater salinity, and decreased turbidity all correlated with lower expressions of eutrophication, whereas sites with increased turbidity, increased freshwater inputs, lower depth and lower tidal ranges had increased eutrophication expressions. Further, eutrophication filters were also correlated with primary and secondary eutrophication indicators, with tidal range having the most significant correlation, suggesting that tidal range is the strongest contributor to the separation of sites by eutrophication filters (Hughes et al. 2011).

Another study of the Elkhorn Slough Estuary, Mercado et al. (2014), created a report card to describe the status of the estuary's waters by analyzing water quality data from Elkhorn Slough Reserve measured in 2013. Mercado et al. (2014) considered nutrient chemistry in the evaluation, not just expression of eutrophication. Nine parameters were analyzed, including ammonia, un-ionized ammonia, algal cover, chlorophyll a, nitrate as N, orthophosphate as P, turbidity, dissolved oxygen, and pH. Each parameter was measured monthly at 24 sites and a literature search was conducted for appropriate thresholds (Table 2-1). The frequency, magnitude, and scope with which thresholds were exceeded was examined using a scoring system that produced composite index values and letter grades for each site and parameter. Two scoring systems were used, which were the Water Quality Index (WQI) scoring system, which calculates index values for each site that range from 0 to 100. Table 2-2 presents the condition, grade, and water quality description that corresponds with each range of index values. The second scoring system used in the study was the Magnitude and Exceedance Quotient (WEQ), which looked at scores of individual parameters as opposed to using a single score to account for all parameters. Thematic maps were generated using the scores calculated by these two methods to provide a simple visual representation of the water quality data analysis (Mercado et al. 2014).

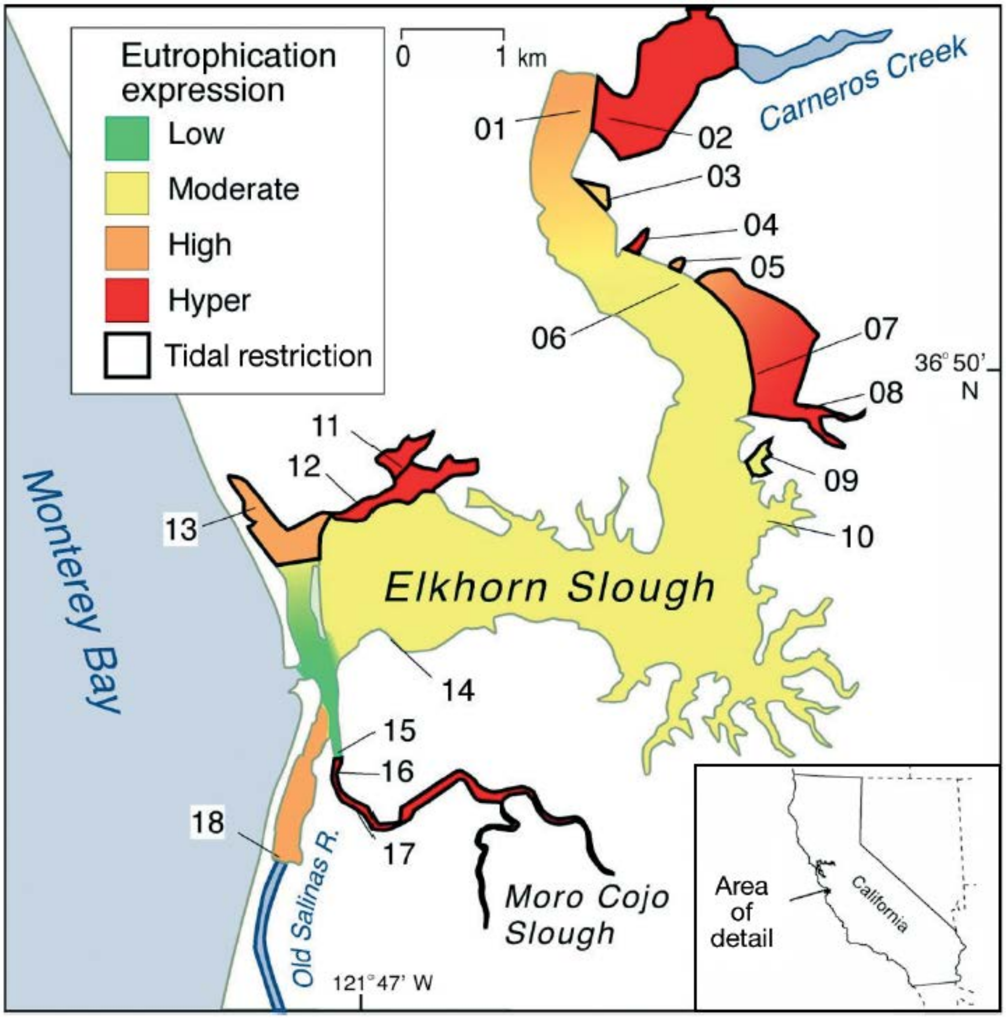

Figure 2-2. Monitoring stations in Elkhorn Slough with spatially interpolated eutrophication indices.
Source: Hughes et. al 2011

Table 2-1. List of parameters and existing thresholds. COLD = cold water aquatic life, EST = estuarine water aquatic life. Source: Mercado et al. 2014

Parameter	Threshold	Beneficial Use	Source
Ammonia	0.1 mg/L	EST	US EPA 1999
Ammonia (Unionized)	0.025 mg/L	COLD and EST	Basin Plan
Algal Cover	20%	COLD	Worcester et.al 2010
Chlorophyll a	15 µg/L	COLD	Worcester et.al 2010
Nitrate as N	1.0 mg/L	COLD and EST	Worcester et.al 2010
Orthophosphate as P	0.13 mg/L	COLD	Williamson R 1994
Turbidity	25 NTU	COLD	Sigler et.al 1984
Dissolved Oxygen	7 to 13 mg/L	COLD	Basin Plan & Worcester et.al 2010
pH	7 to 8.5	COLD and EST	Basin Plan

Table 2-2. Grading scale used in the Water Quality Index. Source: Mercado et al. 2014

Index Value	Condition	Grade	Description
95 – 100	Excellent	A	No virtual threat or impairment. Water quality conditions very close to natural or pristine levels.
80 – 94	Good	B	Only minor degree of threat or impairment. Water quality conditions rarely depart form natural or desirable levels.
65 – 79	Fair	C	Occasionally threatened or impaired. Water quality conditions sometimes depart form natural or desirable levels.
45 – 64	Marginal	D	Frequently threatened or impaired. Water quality conditions often depart from natural or desirable levels.
0 – 44	Poor	F	Almost always threatened or impaired. Water quality conditions usually depart from natural or desirable levels.

The WQI calculations resulted in 13 sites scoring an “F,” three sites scoring a “D,” and six sites scoring a “C.” Two sites scored a “B” and zero sites scored an “A.” The highest scores corresponded with sites located in the Lower Elkhorn Slough area, while every site within the Southern Estuary received a failing grade. Vierra and South Marsh had the highest index values, while Tembladero Slough, and Strawberry Road had the lowest (Figure 2-3).

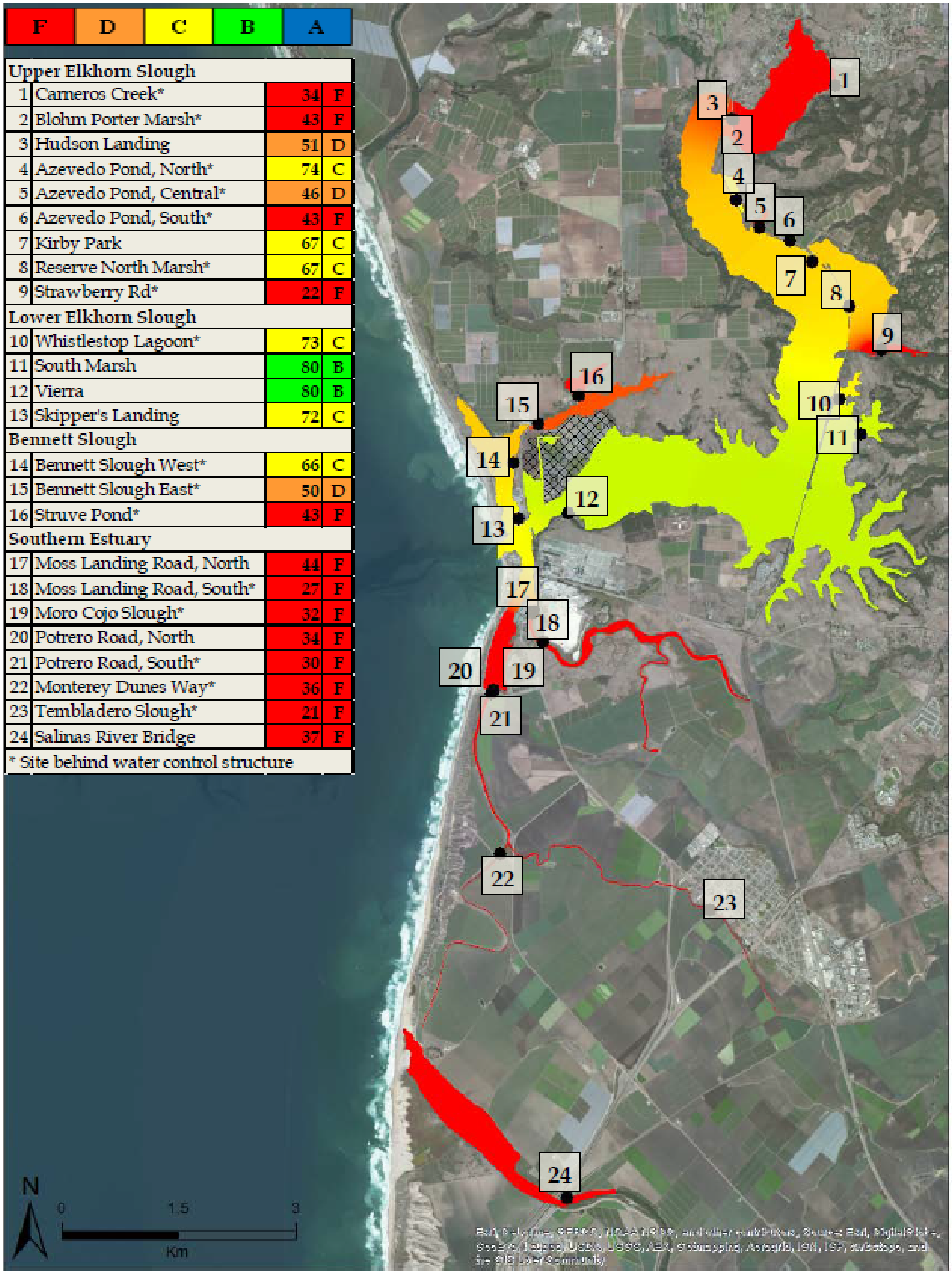

Figure 2-3. Resultant grades and spatial interpolation of index values calculated using the WQI approach. Source: Mercado et al. 2014

Results of the MEQ calculations indicated that algal cover and free ammonia were the parameters of least concern, while the parameters of high concern were phosphate, which scored “F” or “D” for the majority of sites, and dissolved oxygen, which scored less than 79 for every site studied. The lowest grades for nitrate, phosphate, pH, turbidity, and ammonia corresponded with sites located in the Southern Estuary, while the sites located in the Lower Elkhorn Slough received the highest grades for out of all the different regions in the estuary. Results of the MEQ calculations are depicted in Table 2-3 and the spatial interpolation of the calculated index values by parameter is presented in Figure 2-4.

Table 2-3. MEQ Results. Source: Mercado et al. 2014**.**

No data	0-44 = F	45-64 = D	65-79 = C	80-94 = B	95-100 = A

Code	Name	Ammonium	Free Ammonia	Chlorophyll a	Nitrate	Phosphate	Algal Cover	Turbidity	DO	pH
Upper Elkhorn Slough										
1	Carneros Creek*	47	71	27	92	25	100	46	30	43
2	Blohm Porter Marsh*	48	100	66	60	40	89	90	55	80
3	Hudson Landing	43	100	61	93	34	100	73	69	95
4	Azevedo Pond, North*	94	100	92	100	100	100	100	52	82
5	Azevedo Pond, Central*	54	100	48	100	100	49	80	15	64
6	Azevedo Pond, South*	100	100	10	100	4	100	24	28	62
7	Kirby Park	88	100	81	94	100	100	100	63	94
8	Reserve North Marsh*	100	100	87	100	100	100	94	52	88
9	Strawberry Road*	34	79	10	100	77	87	29	1	17
Lower Elkhorn Slough										
10	Whistletop Lagoon*	88	100	71	100	100	100	100	61	94
11	South Marsh	92	100	90	100	100	100	100	54	99
12	Vierra	100	100	92	100	100	100	94	76	100
13	Skipper's Landing	65	100	87	80	100	100	100	54	96
Bennett Slough										
14	Bennett Slough, West*	70	100	100	81	94	100	100	53	77
15	Bennett Slough, East*	100	100	7	100	100	70	18	48	26
16	Struve Pond*	85	92	No data	100	88	73	25	46	41
Southern Estuary										
17	Moss Landing Road, North	48	100	No data	8	37	100	87	78	92
18	Moss Landing Road, South*	13	51	No data	37	54	45	54	41	74
19	Moro Cojo Slough*	49	68	No data	63	46	52	67	61	53
20	Potrero Road, North	47	100	No data	4	27	100	14	56	86
21	Potrero Road, South*	61	100	No data	2	13	100	9	63	61
22	Monterey Dunes Way*	70	100	No data	5	17	100	44	50	41
23	Tembladero Slough*	30	63	No data	1	12	100	17	46	77
24	Salinas River Bridge*	90	100	No data	5	13	100	69	41	37

* Site behind water control structure

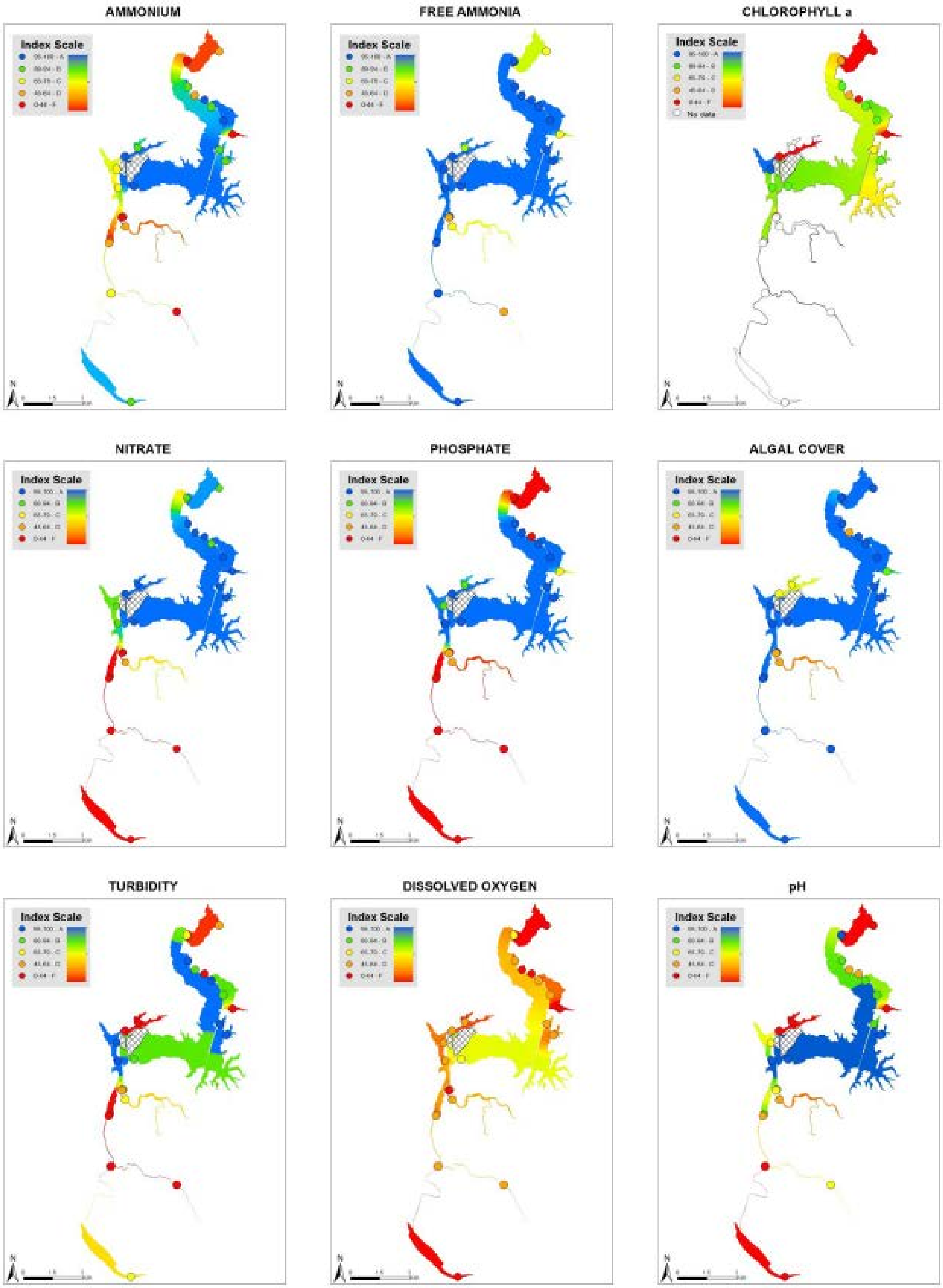

Figure 2-4. Spatial interpolation of parameter by parameter index values calculated using the MEQ approach. Source: Mercado et al. 2014

The results of the Mercado et al. 2014 study suggest variation in water quality conditions in Elkhorn Slough, with the Lower Elkhorn Slough having generally better conditions than the Southern Estuary and Upper Elkhorn Slough regions. Most of the sites that scored low grades or had poor quality were located behind water control structures that restrict tidal flow, with better water quality generally observed in areas near the mouth or along the lower channel, possibly due to unrestricted tidal exchange. The results of the MEQ calculations indicated that the major drivers for degraded water quality in the Southern Estuary were nutrients and turbidity, with nitrate receiving the lowest scores.

2.2 NARRATIVE OBJECTIVES AND BENEFICIAL USE

The Water Quality Control Plan for the Central Coastal Basin (Basin Plan, Central Coast Regional Water Quality Control Board, 2016) Narrative Objective states that “Waters shall not contain biostimulatory substances in concentrations that promote aquatic growths to the extent that such growths cause nuisance or adversely affect beneficial use.” Understanding the beneficial uses provides guidance for developing numeric targets that are indeed protective of these uses. The specific beneficial uses for water bodies include municipal and domestic supply (MUN), agricultural supply (AGR),commercial and sport fishing (COMM), freshwater replenishment (FRESH), industrial process supply (PRO), groundwater recharge (GWR), preservation of rare and endangered species (RARE), water contact recreation (REC1), noncontact water recreation (REC2), wildlife habitat (WILD), cold freshwater habitat (COLD), warm freshwater habitat (WARM), fish migration (MIGR), and fish spawning (SPWN). In addition, coastal water body beneficial uses include industrial service supply (IND); navigation (NAV); marine habitat (MAR); shellfish harvesting (SHELL); commercial and sport fishing (COMM); wildlife habitat (WILD), and fish migration (MIGR).

Waterbody Name	MUN	AGR	PRO	IND	GWR	REC-1	REC-2	WILD	COLD	WARM	MIGR	SPWN	BIOL	RARE	EST	FRESH	NAV	POW	COMM	AQUA	SAL	SHELL
McClusky Slough					X	X	X	X		X		X		X					X			X
Elkhorn Slough						X	X	X	X	X	X	X	X	X	X		X		X	X		X
Los Carneros Creek	X					X	X	X	X		X	X		X		X			X			
Bennett Slough/Estuary						X	X	X	X	X		X	X	X	X				X			X
Parsons Slough						X	X	X	X			X	X	X	X				X			X

2.3 NUTRIENTS AS POLLUTANTS

Nutrients are essential elements for plant growth and include nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), sulfur (S), and silicon (Si). N, P, and K are the primary nutrients, while the major limiting nutrients are N and P most aquatic environments. Nutrients generally have indirect adverse effects on aquatic communities and are not usually directly toxic, although certain forms of N, including ammonia, nitrite, and nitrate can be toxic to aquatic life. Indirect effects of nutrients on aquatic life can result from increased growth and accumulation of plant and algal species, leading to alteration of food sources, habitat structure, and the production of algal toxins. These changes, caused by the increase in primary production, may have also lead to direct effects on macroinvertebrates and fish because of associated alterations in water quality. For example, increases in plant and algal biomass can affect pH and dissolved oxygen levels as shown in the conceptual model in Figure 2-1.

Factors shown to most strongly influence eutrophication in Elkhorn Slough include tidal range, depth, temperature, salinity, distance to the estuary mouth, and turbidity. These factors play a role in the degree of eutrophication and nutrient influence on different portions of Elkhorn Slough. These factors must be considered when recommending numeric targets related to nutrients.

2.4 AVAILABLE GUIDANCE FOR DEVELOPING NUTRIENT TARGETS

Several sources of information are available to inform selection of nutrient targets.

***Criteria Development Guidance: Estuarine and Coastal Waters* (USEPA 2001)**

USEPA published the Nutrient Criteria Technical Guidance Manual for Estuarine and Coastal Marine Waters (USEPA, 2001), which provides methods for developing nutrient water quality criteria. The purpose of the document is to assist states, tribes, and other entities in developing numeric nutrient criteria under the authority of Section 304(a) of the Clean Water Act by providing scientifically defensible technical guidance. The objective is to restore beneficial uses and/or prevent nutrient pollution by reducing anthropogenic input nutrients into estuarine and marine systems. The guidance does not present nutrient criteria for specific water bodies, but consists of USEPA's scientific recommendations regarding defensible approaches for developing nutrient criteria with the intent to use the guidance to develop nutrient criteria for various ecoregions across the country. The criteria developed by USEPA using this guidance will be designed to form the basis for states and tribes to set water quality standards and enable monitoring for achievement of water quality standards. The guidance manual describes several elements of nutrient criterion development.

Nutrient pollution affects the biotic integrity of the nation's waters, contributes to the decline of fish and shellfish populations, and is potentially harmful to public health in the case of toxic algal blooms or waterborne diseases. USEPA's approach outlined in the technical guidance manual outlines a regionalized method for developing nutrient criteria for the estuarine and marine water body types to address these problems. The criteria are based on measurements of reference conditions, which reflect the condition a given body of water would be expected to be in if human impacts were minimized. The variables that are of specific concern include total nitrogen and total phosphorus, which are considered causal variables, and response variables such algal biomass, measured by chlorophyll *a* for phytoplankton and ash-free dry weight for macroalgae, and water clarity, measured by Secchi depth. Additionally, dissolved oxygen can be considered a response variable, especially in waters that have already experienced hypoxia. Another possible variable to consider is algal species composition.

In addition to assessing reference conditions, the guidance manual describes several other elements of nutrient criteria development, which include: putting the reference condition in perspective by understanding the historical status and trends of the water body; understanding historical and present information as well as projecting future consequences by using models of nutrient data; assessing the effects of criteria development on downstream receiving waters; and the compilation and assessment of each element by regional technical experts.

***Technical Approach to Develop Nutrient Numeric Endpoints for California Estuaries* (SCCWRP and Tetra Tech, 2007)**

SCCWRP and Tetra Tech (2007) provides a conceptual framework for development of nutrient numeric endpoints in estuaries and the method is founded on the evaluation of risk relative to designated beneficial uses. The document recommends that biological response indicators provide a more direct risk-based linkage to beneficial uses than nutrient concentrations alone, thus it is useful to evaluate endpoints in addition to only nutrient concentrations. Additionally, the framework recommends using a weight of evidence approach with multiple indicators to determine a numeric endpoint that is more scientifically defensible. The framework suggests that targets should not be set lower than expected values under natural conditions. When natural conditions are not available, other benchmarks include:

- Supporting portions of estuary supporting beneficial uses
- Best available areas
- Data from time periods known to be supporting beneficial uses
- For waters without reference conditions, the 25th percentile of all site values (USEPA 2001)

2.5 TYPES OF NUTRIENT TARGET ENDPOINTS

A variety of primary and secondary indicators are available to provide information about the degree of nutrient influence in an aquatic system. Nutrients in surface water can be measured directly or their effects can be quantified in terms of secondary indicators like algal growth or dissolved oxygen. The following provides a summary of the available indicators that may serve as potential numeric nutrient targets:

Nitrogen and Phosphorus

Nitrogen and phosphorus occur in aquatic systems as dissolved organic, dissolved inorganic, or particulate forms. Transformations between forms of N and P are dependent on environmental conditions, including dissolved oxygen concentrations. Fish and invertebrates are typically not directly adversely affected by excess concentrations of N and P, but are instead affected by stressors that result from excessive N and P enrichment. Examples of negative effects to aquatic fauna associated with N and P enrichment may include decreases in available dissolved oxygen for respiration, microbial infections due to changes in microbial assemblages, release of toxins from blooms of certain toxic algal taxa, increases in pH causing increased concentrations of un-ionized ammonia (a toxic form of N), and alterations in physical habitat and food availability.

Ammonia

Ammonia nitrogen includes both ionized and un-ionized forms, with higher pH favoring the more toxic un-ionized form. Elevated concentrations of ammonia are a common cause of fish kills and can lead to decreases in fish growth, gill condition, hematocrit and organ weight. Ammonia exerts a nitrogenous biological oxygen demand in the aqueous environment which occurs as bacteria consume dissolved oxygen and other microbes oxidize ammonia into nitrite and nitrate. Decreases in fish species diversity and increased occurrences of fish kills can occur as a result of the reduced dissolved oxygen concentrations. In addition, ammonia has nutrient properties that allow for increases in plant growth and thereby can lead to eutrophication.

Dissolved Oxygen

Dissolved oxygen is essential for the growth and reproduction of aerobic aquatic life. Oxygen enters water by direct absorption from the atmosphere or photosynthetic production, and its solubility is affected by temperature and salinity, with lower temperatures allowing water to hold more dissolved oxygen. Low DO can be caused by high concentrations of nutrients that lead to excessive plant growth, and thus increased respiration and decomposition. Fish kills are often attributed to low levels of DO.

Algal cover/Density and Chlorophyll a

Increases in plant, microbial, and algal biomass and changes in species assemblage structure can result from increased nutrient enrichment and increased primary production. Associated negative impacts include increases in the occurrence of microbial infection in invertebrates or fish, decreases in dissolved oxygen concentrations, and increases in pH. Toxic algal blooms can also result from increased primary production and negatively affect fish or invertebrates. Changes in plant assemblages can also alter habitat structure and quantity or quality of food resources for aquatic fauna. Increases in turbidity may also occur as a result of increased suspended organic matter (i.e., phytoplankton or suspended algae) associated with higher primary production. Algal biomass is among the most important indicators of nutrient pollution stress and risk to designated use impairments and is most commonly measured by chlorophyll *a*, one of the photosynthetic pigments found in algae.

Harmful algal blooms

Nutrient enrichment may lead to increases in growth and proliferation of specific types of algae that produce toxins which adversely affect human and ecological health. The presence of a harmful algal bloom is determined by identification of certain cyanobacterial cells or measurement of toxic compounds released during the course of a bloom. A harmful algal bloom may be an indication that nutrient pollution is present and designated uses are impaired.

Submerged aquatic vegetation

An increased quantity or type of submerged aquatic vegetation may be a result of nutrient enrichment. Nutrients cause increased plant growth which can change the quantity and quality of submerged vegetation. Some plants respond more strongly to nutrient influence resulting in a shift in community that can change habitat and food sources.

Changes in fish or benthic communities

Nutrients cause a shift in dynamics of the benthic aquatic community. Habitat may be altered by changing dissolved oxygen dynamics and reducing available habitat in the water column or benthic cover may change in type and quantity, making it less suitable for particular species. The quality and quantity of food sources may be altered. For example, proliferation of species of algae strongly influenced by nutrients might outcompete other types of algae or diatoms used as food by benthic organisms. Additionally, fish that feed on benthic organisms or lower trophic level fish may experience a reduction in their food sources as community composition changes.

2.6 DEVELOPMENT OF TARGETS FOR ELKHORN SLOUGH

Mercado et al (2014) previously recommended targets for the purpose of screening assessments in Elkhorn Slough. The current effort evaluated those targets and expanded upon the previous work to refine those recommendations. Three methods were evaluated to explore options for developing numeric targets for Elkhorn Slough: 1) 25th percentile to represent best available or supporting conditions; 2) Literature search to determine nutrient targets in other estuaries; 3) Literature search to evaluate stressor-response relationships in Elkhorn Slough. These methods and their results are shown in the following sections.

2.6.1 25th percentile (Best available or supporting conditions)

The California freshwater nutrient numeric endpoints (NNE) approach (Tetra Tech 2006) suggests that ambient concentrations of nutrients alone are not likely to sufficiently predict the risk of biostimulation but when used as part of a weight of evidence approach, can help to produce numeric targets with greater scientific validity. The NNE guidance also suggests that targets should not be set lower than values expected under natural conditions. When natural conditions are not available, evaluation of alternative benchmarks are recommended to determine targets associated with the following: 1) Supporting portions of the estuary; 2) Best available areas; 3) Data from time periods known to be supporting uses; 4) the 25th percentile of all site values when reference conditions are not available. Data supporting items 1-3 were not able to be identified for Elkhorn Slough, but monitoring data were available to explore option 4.

Monitoring data (1989-2015) and summary statistics are available for Elkhorn Slough (https://www.waterboards.ca.gov/centralcoast/water_issues/programs/tmdl/docs/elkhorn_slough/do/) and were evaluated to provide potentially representative percentile values for numeric targets in Elkhorn Slough (Table 2-4). Because the sampling locations in Elkhorn Slough represent a variety of hydrologic conditions in terms of mixing and tidal exchange, it may be more appropriate to group sites with similar characteristics to determine expected numeric values. While this methodology is likely to provide an additional line of evidence for selecting numeric targets, it is not expected to be the most robust method for selecting targets. Nutrient dynamics are complex, and the use of a fixed percentile to represent ideal nutrient conditions includes a variety of uncertainties and may be skewed depending on the degree of anthropogenic influence on the water body of interest.

Table 2-4. Summary of data for Elkhorn Slough, all data, all stations 1989-2015.

Analyte Name	N	Mean	Inter-quartile Range	Min	25th Percentile	Median	75th Percentile	Max
Ammonia (NH3) as N, Un-ionized	5828	0.0183	0.0120	0.0002	0.0018	0.0046	0.0137	2.84
Ammonia (NH3+NH4) as N, Total	6349	0.205	0.154	0.025	0.036	0.085	0.190	15.7
Ammonia (NH4) as N, Ionized	2076	0.0621	0.0440	0.0020	0.0370	0.0584	0.0810	0.386
Chlorophyll a	36851	10.59	0.13	0.26	7.91	7.97	8.04	8810.0
Floating Algae	1579	8.11	2.00	0.00	0.00	0.00	2.00	100.0

Analyte Name	N	Mean	Inter-quartile Range	Min	25th Percentile	Median	75th Percentile	Max
Nitrate + Nitrite as N	2253	0.5804	0.1543	0.0043	0.0077	0.0353	0.1619	53.0
Nitrate as N	291024	2.826	1.423	0.010	0.048	0.236	1.471	190.0
Nitrite as N	3041	NA	NA	0.03	NA	NA	NA	15.0
Nitrogen, Total	1300	3.069	0.812	0.025	0.026	0.174	0.839	191.0
Orthophosphate as P	8398	0.233	0.212	0.018	0.047	0.080	0.259	12.0
Oxygen, Dissolved	1181821	6.4	4.0	1.7	4.1	6.4	8.1	43.6
Oxygen, Saturation	1230631	88.3	29.7	22.1	70.9	86.7	100.6	1430
pH	872546	8.1	0.3	6.0	7.9	8.1	8.2	10.8
Phosphorus as P	166	0.586	0.457	0.027	0.283	0.482	0.740	3.5
Salinity	1147695	31.5	2.9	0.0	31.0	33.0	33.9	141.0
Specific Conductivity	806485	49.70	3.64	0.03	48.10	50.30	51.70	66.2
Temperature	1391745	15.6	5.3	5.9	12.8	15.1	18.1	33.7
Turbidity	965073	6.8	4.0	0.1	4.0	5.0	8.0	3800

2.6.2 Literature Search

A literature search was conducted to determine what numeric targets are currently used in other estuaries around the United States and in California.

Other US Estuaries

A literature search was conducted to evaluate the range of numeric targets developed for other estuary systems in the United States (Table 2-5). Those numeric endpoints included parameters including total nitrogen, total phosphorus, chlorophyll a, and dissolved oxygen. In many instances, these values were developed to protect a secondary endpoint, such as dissolved oxygen to support respiration of aquatic organisms or protection of seagrasses.

Table 2-5. Numeric targets developed for other estuaries in the United States

Location	Endpoint	Value
Great Bay, NH	Aquatic Life – DO Aquatic Life - Seagrasses	**0.5 mg/L TN** **10 µg/L Chlorophyll a** **0.32 mg/L TN** **0.75 m^{-1} k_d (light attenuation)**

Location	Endpoint	Value
MA Estuaries Project	Aquatic Life – Seagrass Aquatic Life – Benthic Infauna Severe ecological degradation	**0.30 to 0.50 mg/L TN** **0.40 to 0.60 mg/L TN** **0.80 mg/L TN**
Waquoit Bay, MA	Seagrasses – Loss Seagrass - Disappearance	**30 kg N/ha/y** **60 kg N/ha/y**
Long Island Sound	Seagrasses	**<5.5 µg/L Chlorophyll a** **<0.05 mg/L DIN** **<0.7 m^{-1} k_d (light attenuation)** **<50 kg N/ha/y load**
Chesapeake Bay	Prevent Low DO (deep bay) Prevent Low DO (shallow tributaries) SAV Survival	**7 to 11 µg/L Chlorophyll a** **9 to 14 µg/L Chlorophyll a** **< 15 µg/L Chlorophyll a** **< 1.5 m^{-1} k_d (light attenuation)** **<0.15 mg/L DIN** **<0.65 mg/L TN**
Pensacola Bay, FL	Maintain current conditions (supporting)	**0.49 mg/L TN**
FL Estuaries	Aquatic Life – Seagrasses, Algal Populations, DO	**0.14 to 1.63 mg/L TN** **0.008 to 0.310 mg/L TP** **0.7 to 11.9 µg/L Chlorophyll a**
Yaquina Estuary, OR	Seagrasses – Lower Estuary Seagrasses – Upper Estuary	**0.200 mg/L DIN** **0.040 mg/L Phosphate** **3 µg/l Chlorophyll a** **0.8 m^{-1} k_d** **6.5 mg/L DO** **0.200 mg/L DIN** **0.019 mg/L Phosphate** **5 µg/l Chlorophyll a** **1.5 m^{-1} k_d** **6.5 mg/L DO**

Other California Estuaries

A literature search was conducted to compile preliminary numeric targets potentially applicable to Elkhorn Slough and other numeric targets for estuaries in California (Table 2-6). These endpoints show a variety of indicators including primary measurements of nutrients and quantification of secondary effects like dissolved oxygen, algal cover, and chlorophyll a.

Table 2-6. Numeric targets recommended for California Estuaries

Parameter	Threshold	Beneficial Use or Applicability	Source	Rationale for Endpoint
Algal Cover	20%	COLD	Mercado et al 2014 (Worcester et al 2010)	
Algal Cover	<90g dw/ m^3	Loma Alta Slough (Nontidal Lagoon)		Applicable in dry season
Ammonia	0.1 mg/L	EST	Mercado et al (US EPA 1999)	
Ammonia (un-ionized)	0.025 mg/L	COLD and EST	Mercado et al 2014 (Basin Plan)	
Ammonia (un-ionized)	0.025 mg/L	Inland Surface Waters, Enclosed Bays and Estuaries	Central Coast Waterboard 2016	General objective for all Inland Surface Waters, Enclosed Bays and Estuaries (toxicity objective)
Chlorophyll a	150 mg/m^2	Malibu Creek (Seasonally tidal lagoon)		
Chlorophyll a	< 15 μg/L		Worcester et al 2010	Evidence for eutrophication when NO3-N >1.0 mg/L
Chlorophyll a	8 μg/L	Rivers and Streams	Worcester et al (EPA 200b)	Eutrophy for plankton in rivers and Streams
Chlorophyll a	< 15 μg/L	Lakes and Rivers	Worcester et al 2010 (OAR 2000)	Nuisance phytoplankton growth in lakes and rivers
Chlorophyll a	15 μg/L	COLD	Worcester et al 2010 (NC Administrative Code)	NC value for cold water lakes, reservoirs, and other waters

Parameter	Threshold	Beneficial Use or Applicability	Source	Rationale for Endpoint
Chlorophyll a	40 µg/L	WARM	Worcester et al 2010 (NC Administrative Code)	NC value for warm water lakes, reservoirs, and other waters not applicable to trout
Chlorophyll a	15 µg/L	COLD	Mercado et al 2014 (Worcester et al 2010)	
Chlorophyll a	40 µg/L		Central Coast Waterboard 2016 (NC Administrative Code)	Basin Plan biostimulatory substances objective
Dissolved Oxygen	5 or 7 mg/L to <13 mg/L	Warm or Cold Water and Super Saturation	Worcester et al 2010	
Dissolved Oxygen	7 to 13 mg/L	COLD and EST	Mercado et al 2014 (Basin Plan and Worcester et al 2010)	
Dissolved Oxygen	5 mg/L; Median values not below 85% saturation		Central Coast Water Board 2016 (Basin Plan General Objective)	General objective for all inland surface waters, enclosed bays, estuaries
Dissolved Oxygen	5 mg/L	WARM	Basin Plan Numeric Objective (Basin Plan numeric objective)	Toxicity endpoint
Dissolved Oxygen	7 mg/L	COLD, SPWN	Basin Plan Numeric Objective (Basin Plan numeric objective)	Ecological toxicity endpoint
Dissolved Oxygen	7 mg/L	Ventura River Tributaries and Estuary (River dominated estuary)		
Dissolved Oxygen	2.3 mg/L		Acute Criterion (Virginian Province)	Ecological toxicity endpoint
Dissolved Oxygen	4.8 mg/L		Chronic Criterion (Virginian Province)	Ecological toxicity endpoint

Parameter	Threshold	Beneficial Use or Applicability	Source	Rationale for Endpoint
Dissolved Oxygen	3.8 mg/L	Suisun Marsh	Acute Criterion (Virginian Province Approach)	Ecological toxicity endpoint
Dissolved Oxygen	6.4 mg/L	Suisun Marsh	Chronic Criterion (Virginian Province Approach with Salmonids)	Ecological toxicity endpoint
Floating Algal Mat	40-55%		Worcester et al 2010 (Stevenson et al 1996)	Filamentous algal cover
Floating Algal Mat	50%		Worcester et al 2010 (NDEP 2007)	Filamentous algal cover
Floating Algal Mat	50%		Worcester et al 2010	Evidence for eutrophication when NO3-N >1.0 mg/L
Floating Algal Mat	<30%	Malibu Creek (Seasonally tidal lagoon)		
Macroalgal Cover	<50%	Loma Alta Slough (Nontidal Lagoon)		Applicable in dry season
Macroalgal Cover	<60%	Malibu Creek (Seasonally tidal lagoon)		
Macroalgal Cover (Attached and unattached)	<30%	Ventura River and Tributaries (River dominated estuary)		Seasonal average
Macroalgal Cover (Attached and unattached)	<15%	Ventura River Estuary (intertidal and shallow subtidal area)		Seasonal average
Minimum Taxa Richness	40	Malibu Creek (Seasonally tidal lagoon)		
Nitrate as N	1.0 mg/L		Worcester 2010	Impairment when other evidence of eutrophication

Parameter	Threshold	Beneficial Use or Applicability	Source	Rationale for Endpoint
Nitrate as N	1.0 mg/L	COLD and EST	Mercado et al 2014 (Worcester et al 2010)	
Nitrate as N	1.0 mg/L		Central Coast Waterboard 2016 (California Office of Environmental Health Hazard Assessment)	Basin Plan narrative objective; Public health Goal for human health
Nitrate as N	10 mg/L	MUN, GRW	Central Coast Waterboard 2016 (Basin Plan numeric objective)	Human health toxicity endpoint
Nitrate as N	10 mg/L		EPA	EPA Drinking water standard (human health protective; methemoglobinemia)
Organophosphate as P	0.13 mg/L	COLD	Mercado et al 2014 (Williamson R 1994)	
pH	<9.5		Worcester et al 2010	Evidence for eutrophication when NO3-N >1.0 mg/L
pH	7 to 8.5	COLD and EST	Mercado et al 2014 (Basin Plan)	
pH	>7 to <8.5	Surface Waters, Enclosed Bays and Estuaries	Central Coast Water Board 2016 (Basin Plan General Objective)	General objective for all inland surface waters, enclosed bays, and estuaries
pH	>6.5 to <8.3	MUN, REC-1, REC-2	Central Coast Water Board 2016 (Basin Plan numeric objective)	Basin Plan Numeric Objective
pH	>7.0 to <8.5	COLD, WARM	Central Coast Water Board 2016 (Basin Plan numeric objective)	Basin Plan Numeric Objective
pH	6.5 to 8.5	Ventura River, Tributaries and Estuary		Instantaneous value

Parameter	Threshold	Beneficial Use or Applicability	Source	Rationale for Endpoint
Phytoplankton Biomass	20 µg/L chl a	Ventura River (shallow subtidal area)		Seasonal average
Total algal biomass	150 mg/m^2	Ventura River and Tributaries		Seasonal average
Total algal biomass	150 mg/m^2	Malibu Creek (Seasonally tidal lagoon)		
Total Nitrogen	0.5 mg/L	Central and Southern California Chaparral Ecoregion	Worcester et al 2010 (EPA 2000)	25th Percentile of available data
Total Nitrogen	0.38 mg/L	Xeric West (including Central Coast Region)	Worcester et al 2010 (EPA 2000)	26th Percentile of available data
Total Nitrogen	0.65 mg/L	Malibu Creek (Seasonally tidal lagoon)		Summer
Total Nitrogen	1.0 mg/L	Malibu Creek (Seasonally tidal lagoon)		Winter
Total Phosphorus	0.10 mg/L	Malibu Creek (Seasonally tidal lagoon)		
Total Phosphorus	0.20 mg/L	Loma Alta Slough (Nontidal Lagoon)		
Total Phosphorus	0.05 mg/L	Loma Alta Slough (Nontidal Lagoon)		Dry season only
Total Phosphorus	0.025 mg/L	Loma Alta Slough (Nontidal Lagoon)		Dry season only
Total Phosphorus	0.1 mg/L	Loma Alta Slough (Nontidal Lagoon)		Dry season only
Turbidity	25 NTU	COLD	Mercado et al 2014 (Sigler et al 1984)	

Parameter	Threshold	Beneficial Use or Applicability	Source	Rationale for Endpoint
Dissolved Oxygen	5 mg/L	Suisun Marsh	Chronic Criterion (Virginian Province Approach)	Ecological toxicity endpoint

2.6.3 Stressor Response Relationships in Elkhorn Slough

Stressor response relationships in Elkhorn Slough are not directly evident due to the strong influence of filters such as tidal exchange, temperature and turbidity. These influences are important because of the direct exchange of tidal waters with the greater Monterey Bay into the Elkhorn Slough. As discussed previously, PCA analysis revealed that nutrient levels were not strongly correlated with EEI values, while eutrophication filters were strongly correlated with EEI values. The analysis revealed that the measured filters of tidal range, subtidal depth, temperature, freshwater, turbidity, and distance to mouth all appeared to contribute to variation of eutrophication. One study (Jeppesen et al 2018) that was conducted with two stress tolerant estuarine species, the staghorn sculpin, *Leptocottus armatus* and the Olympia oyster, *Ostrea Lurida* revealed that these indicator species when caged and physically moved to hypereutrophic areas responded negatively to eutrophic sites.

Another study Hughes et al 2015, found a response of the two most common flatfish species English Sole (*Parophrys vetulus*) and speckled sanddab (*Citharichthys stigmaeus*) to hypoxic conditions in the estuary. Decreased offshore fish abundance correlated with prior years of below average DO concentrations throughout the slough. This indicated that the declined estuarine habitats were negatively affecting juvenile fish populations. Interestingly these declines were shown to be mitigated by climatic factors, namely El niño conditions, indicating the significant role eutrophication filters play in complicating stressor response relationships.

The absence of clear stressor-response relationships appears to be a common occurrence among estuaries across the country. For example, a comprehensive study by Bauman and Smith (2017) compiled 15 years of high-frequency data from the National Estuarine Research Reserve System (NERRS) stations. This study included a wide diversity of estuaries from coast to coast and evaluated the nutrient and chlorophyll levels related to pH and DO conditions. The unifying feature found was that metabolism drove fluctuations in pH and DO. Although the study did find higher nutrient levels associated with low pH and DO levels in many systems, nutrients and chlorophyll variations were inversely related in shallow, well mixed systems.

2.7 APPLICATION OF TARGETS

Numeric targets can be applied system-wide or as applicable to only certain portions of the water body. For example, in application of numeric targets to the Chesapeake Bay, Designated Use Zones with different numeric targets were established for the purpose of grouping similar areas and designated uses. In that case, the following zones were developed: Open Water, Deep Channel Seasonal Refuge, Deep Water Seasonal Fish and Shellfish, Shallow Water Bay Grass, Migratory Nursery and Spawning. Elkhorn

Slough could be split into different areas using a classification system such that nutrient dynamics and sensitivity are expected to be similar (USEPA 2001). Several options for developing zones within Elkhorn Slough include elements of the following:

1) Tidal cycles
2) Free moving water, areas behind water control structures
3) Main channels, tidal channels, marshes/wetlands

2.8 RECOMMENDATIONS FOR NUMERIC TARGETS

The available numeric targets are summarized in Table 2-7, as shown by the 25th percentile analysis and literature searches. **The complexity of stressor response relationships precludes the consideration of simple numeric targets in this table**. Use of the 25th percentile is not likely to produce the most scientifically defensible target in this instance, but can be used as a line of evidence and comparison to other targets. Literature-based targets, especially those for chlorophyll *a* and dissolved oxygen are likely to represent the greatest indication of excessive nutrients and conditions that result in eutrophication in areas behind water control structures in Elkhorn Slough. This table serves as a starting point for numeric targets in a future Elkhorn Slough TMDL. Further refinement of these targets is recommended for Elkhorn Slough.

Application of these targets to waters behind control structures is recommended as these areas are often associated with eutrophication due to minimal water movement/ tidal exchange, warm temperatures, and other factors. The combined effects of nutrients and these conditions leads to observed eutrophication including high concentrations of chlorophyll *a* and low dissolved oxygen.

Table 2-7. Summary of recommended available numeric endpoints. Further refinement of these targets is recommended for Elkhorn Slough.

Analyte Name	25th Percentile	Literature
Ammonia (NH3) as N, Un-ionized	0.0018	0.025 mg/L
Chlorophyll a	7.9 ug/L	8-15 ug/L
Floating Algae	0	30-50%
Macroalgal Cover	--	<30-<50%
Nitrogen, Total	0.026	0.65-1.0 mg/L
Oxygen, Dissolved		4.8-7 mg/L
Phosphorus as P	0.28	0.10-0.20 mg/L

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3.0 NUTRIENT LOAD ESTIMATION

Past work has established many of the key pathways and characteristics of nutrients and eutrophication in Elkhorn Slough. Dissolved inorganic nutrients enter Elkhorn Slough from several different sources from the watershed and from Monterey Bay through tidal exchange. The main freshwater sources include the Salinas River and Tembladero Slough to the south (these are connected to Elkhorn Slough by the Old Salinas River Channel), Moro Cojo Slough, Carneros Creek, as well as runoff from surrounding land areas that are not connected to the estuary by flow channels. Periods of upwelling in Monterey Bay in late spring and early summer (Chapin et al. 2004) may potentially be an important source of nutrients. Water from the Old Salinas River (OSR) channel is believed to be a major source of nutrients and is tidally transported upstream into the main channel of Elkhorn Slough (Jannasch et al. 2008). Carneros Creek is the head of the estuary and water from the creek flows directly into the estuary, although the nutrient supply is smaller than from the OSR channel. In part this is because the flows entering Elkhorn Slough through the OSR channel drain much larger watersheds in the south of the slough. Surface water flow estimates to Elkhorn Slough (on an annual basis) have been provided in the nutrient TMDL for Salinas River, with more than three quarters of the freshwater flow derived from the OSR and Tembladero Slough (Osmolovsky et al., 2013). As will be discussed below, the flow estimates are highly uncertain.

A detailed analysis in support of a TMDL for nutrients in the adjacent and connected Salinas River and Moro Cojo watersheds is available (Osmolovsky et al., 2013). This TMDL was approved by USEPA in 2015. Specifically, the TMDL addresses nitrogen and orthophosphate compounds in the Lower Salinas River watershed, Reclamation Canal Basin, and Moro Cojo Slough subwatershed. These areas exhibit elevated nutrient concentrations associated with intensive irrigated agriculture, primarily producing strawberries, lettuce, and other vegetables. Similar agricultural land uses are present in the Elkhorn Slough watershed, albeit the Elkhorn Slough watershed has a lower percentage of the total watershed devoted to crops than the Salinas (approximately 8% compared to approximately 34%) (Saiz and Keeling, 2016; Osmolovsky et al., 2013).

The direct drainage to Elkhorn Slough consists of 11 subbasins, as defined in Saiz and Keeling (2016) and shown in Figure 3-1. Satellite derived land use within the watershed at a 30-m resolution was tabulated from the 2011 National Land Cover Database (NLCD) for 2011 (Figure 3-2). The USDA SSURGO soils coverage shows hydrologic soil groups, a measure of soil infiltration capacity, ranging from A (highest infiltration) to D (lowest infiltration) (Figure 3-3). For the Elkhorn Slough watershed, a majority of the soils belong to HSG B. These are grouped with the limited area in HSG A. HSG C/D soils indicate soils that behave like D soils (low infiltration) unless artificial drainage is used, in which case they behave like C soils.

Table 3-1 summarizes the distribution of land use and soils in the watershed.

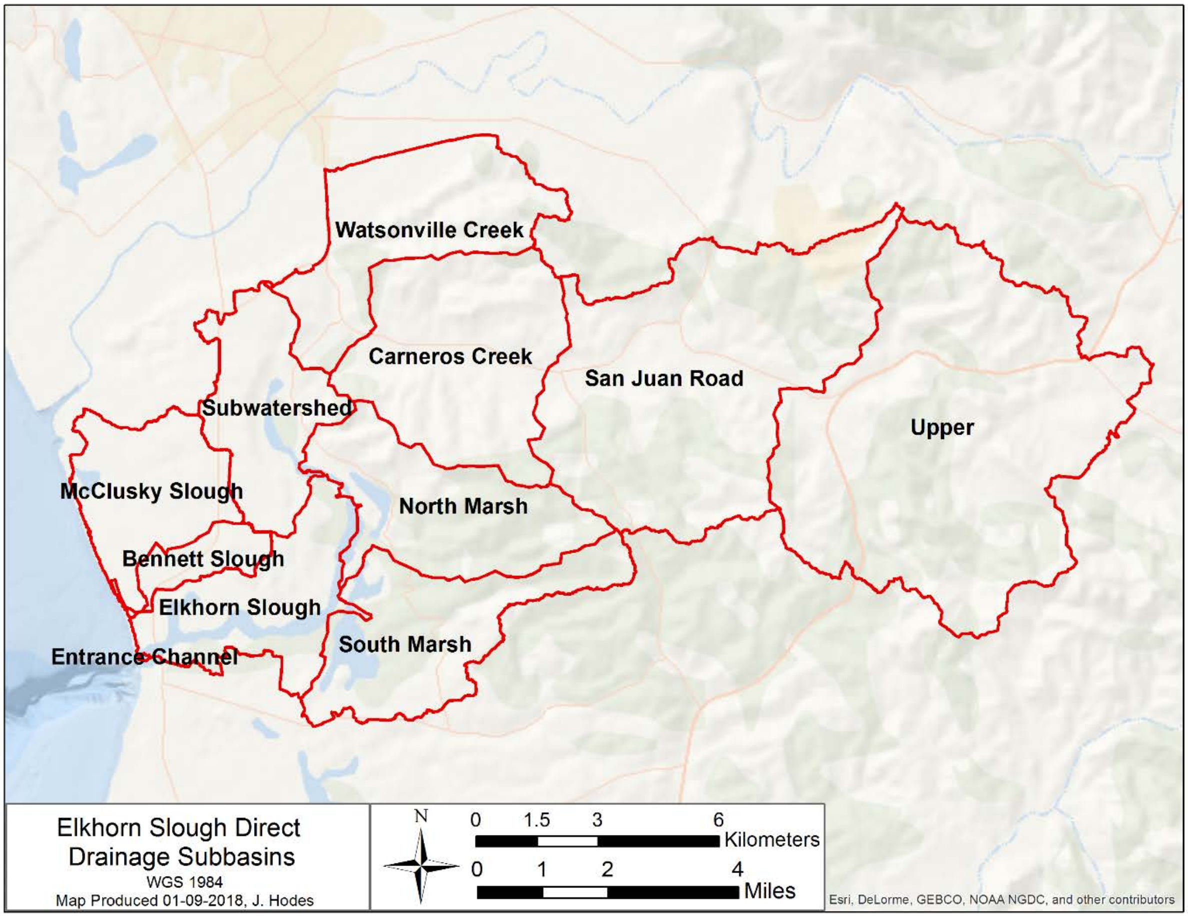

Figure 3-1. Elkhorn Slough Watershed Subbasins

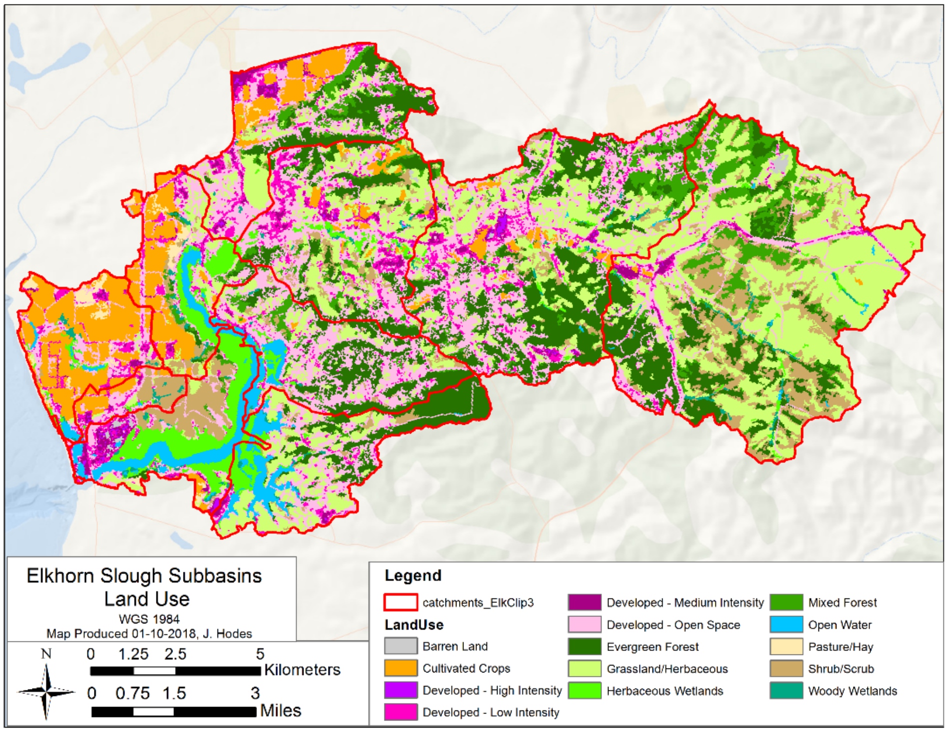

Figure 3-2. 2011 NLCD Land Cover in the Elkhorn Slough Direct Drainage

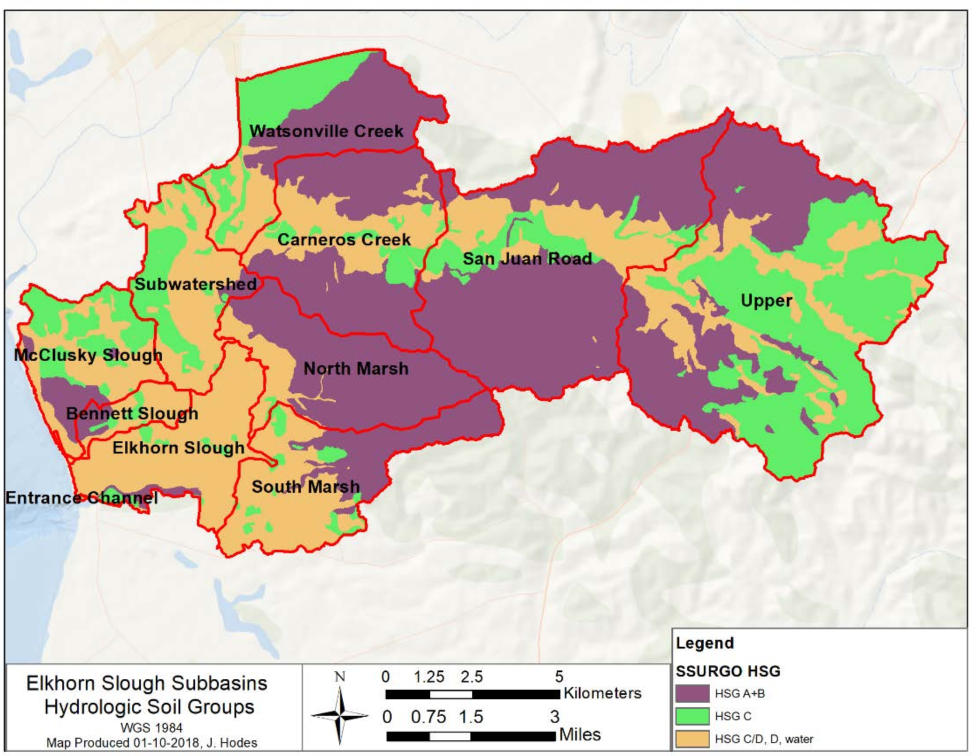

Figure 3-3. SSURGO Hydrologic Soil Groups, Elkhorn Slough Watershed

Table 3-1. Land Use and Soils, Elkhorn Slough Watershed (including McClusky Slough)

Land Cover	A+B	C	C/D, D	*Total Acres*
Water	0	0	1,065	*1,065*
Developed-Open Space	4,149	1,143	2,259	*7,551*
Developed - Low Intensity	638	498	770	*1,907*
Developed - Medium Intensity	68	238	273	*580*
Developed - High Intensity	6	39	47	*93*
Barren Land	36	9	28	*73*
Evergreen Forest	5,071	315	334	*5,721*
Mixed Forest	1,709	269	292	*2,270*
Shrub/Scrub	806	1,008	1,092	*2,906*
Grassland/Herbaceous	2,636	2,699	2,468	*7,803*
Pasture/Hay	18	82	126	*226*
Cultivated Crops	489	1,515	699	*2,703*
Woody Wetlands	38	79	172	*289*
Herbaceous Wetlands	63	88	1,301	*1,452*
Total	*15,728*	*7,982*	*10,927*	*34,637*

As noted above and in Chapter 2, an important distinction can be made between the portions of the Slough that are subject to natural tidal mixing and those with restricted mixing due to the presence of tide gates and levees designed to “reclaim” wetlands for agricultural activities (Figure 3-4).

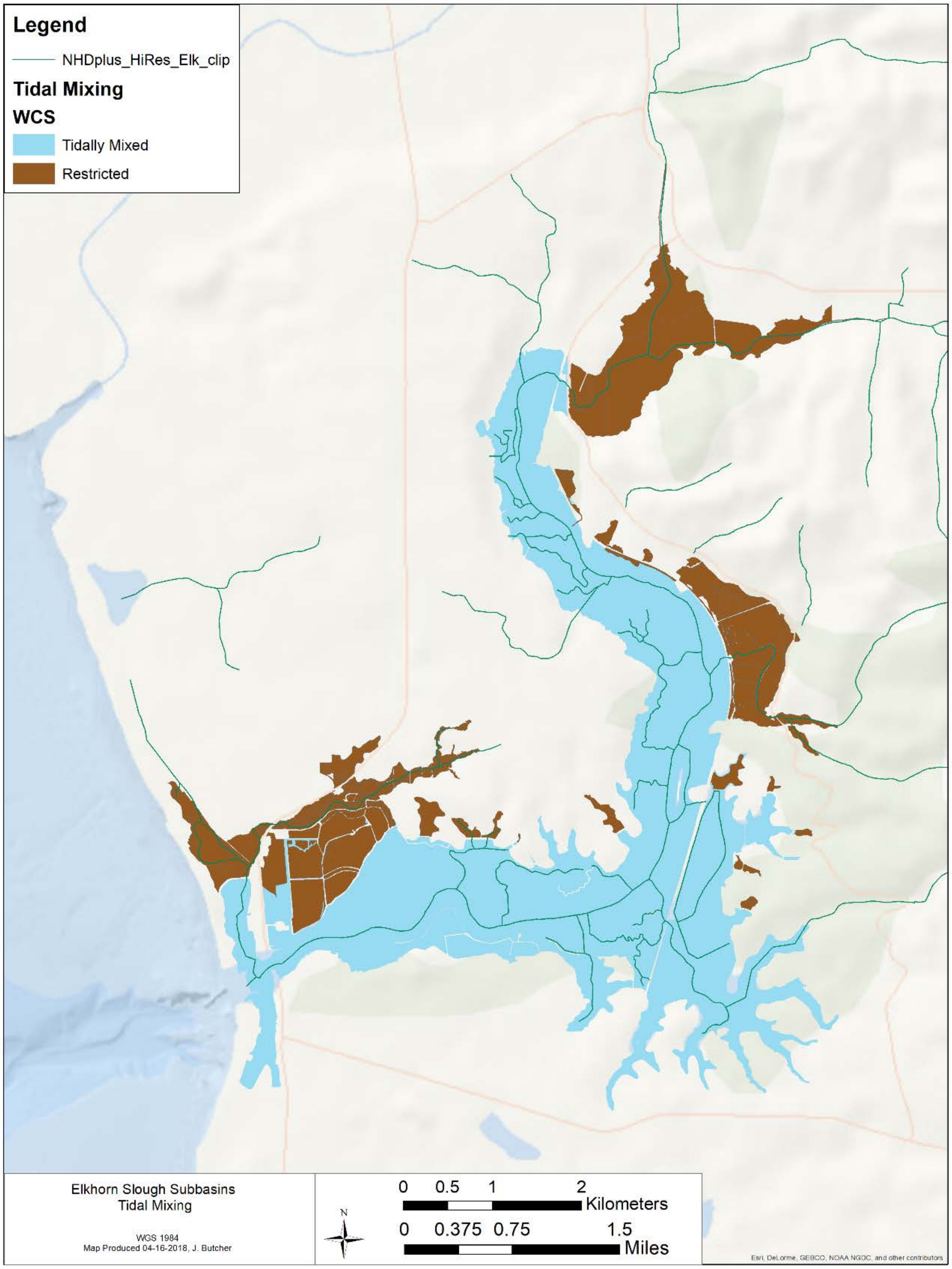

Figure 3-4. Tidal Mixing Characteristics of Elkhorn Slough

3.1 EXTERNAL NUTRIENT LOADS

3.1.1 Watershed Loads from Direct Drainage

3.1.1.1 STEPL Analysis

Agricultural land use within the Elkhorn Slough direct drainage is similar to that found in the adjacent Moro Cojo and Salinas River watersheds. As part of the TMDL for those watersheds, a STEPL loading model was developed (Osmolovsky et al., 2013). STEPL – the Spreadsheet Tool for the Estimation of Pollutant Load (Tetra Tech, 2017) is a simplified spreadsheet model of pollutant loading. STEPL calculates annual nutrient loading based on estimated runoff volume and pollutant concentrations in the runoff water as influenced by factors including the land use distribution and management practices. The STEPL model used in the Salinas River TMDL appears to provide a good match to loads inferred from monitoring in the river. Table 3-2 shows average annual loading rates from STEPL.

Table 3-2. STEPL Loading Rates from Salinas River TMDL (Osmolovsky et al., 2013)

Land Use	Total N (lb/ac/yr)	Total P (lb/ac/yr)
Developed	5.32	0.71
Agriculture	26.16	5.48
Grazing Land	3.34	1.15
Forest/Undeveloped	0.33	0.12

The STEPL land use categories are more broadly defined than those in NLCD, so the NLCD classes were aggregated, with miscellaneous categories assumed to fall within the undeveloped land use

Applying the loading rates in Table 3-2 to the Elkhorn Slough land areas in Table 3-1 provides a rough estimate of the average annual nutrient load from the direct watershed of Elkhorn Slough. The resulting load estimates are shown, by subbasin, in Table 3-3. The subbasins are organized by the three zones (Upper Elkhorn, Lower Elkhorn, and Bennett Slough) as presented in the Elkhorn Slough "Report Card" (Mercado et al., 2014). The STEPL-estimated loads are especially high for McCluskey Slough as the land use in this watershed is predominantly row crop agriculture (see Figure 3-2), which has the highest estimated loading rates.

Table 3-3. STEPL-based Watershed Load Estimates for Elkhorn Slough

Subbasins	N Load (lb/yr)	P Load (lb/yr)	Zone
Carneros Creek	15,775	3,111	Upper Elkhorn
North Marsh	8,203	1,405	
San Juan Road	23,714	4,738	
Subwatershed	20,732	4,267	
Upper	19,882	5,581	
Watsonville Creek	18,857	3,694	
Elkhorn Slough	4,575	855	Lower Elkhorn
Entrance Channel	20	3	
South Marsh	6,750	1,475	
Bennett Slough	4,685	914	Bennett Slough
McClusky Slough	32,441	6,641	
Total	**155,634**	**32,684**	

3.1.1.2 Uncalibrated HAWQS/SWAT Model

As a check on the reasonableness of the STEPL results we used an automated, uncalibrated watershed model contained in the EPA Hydrologic and Water Quality System (HAWQS; https://epahawqs.tamu.edu). HAWQS (Texas A&M, 2017) is a web-based interactive water quantity and quality modeling system that employs as its core modeling engine the Soil and Water Assessment Tool (SWAT), an internationally-recognized public domain model. HAWQS provides users with interactive web interfaces and maps; pre-loaded input data; outputs that include tables, charts, and raw output data; a user guide, and online development, execution, and storage of a user's modeling projects. Pre-set model delineations and corresponding meteorological data go down to the HUC12 scale, which corresponds to the Elkhorn Slough watershed.

Because the HAWQS application is uncalibrated it is not directly applicable for regulatory purposes. It does, however, provide a useful line of evidence as to whether the STEPL estimates are reasonable, and gives some indication as to whether a SWAT application for the watershed is likely to be useful. Any formal application of a watershed model as part of the TMDL should be performed under an appropriate modeling Quality Assurance Project Plan (QAPP).

The HAWQS system identifies the Moro Cojo watershed as upstream of Elkhorn Slough, but allows tabulation of results for the Elkhorn Slough direct drainage separately (Figure 3-5). The SWAT model auto-generated by HAWQS runs from water year 1980-2015 and drops the first two years to allow for model spin up. We modified the default model only to add irrigation to agriculture as this is known to be a dominant aspect of the hydrology of the watershed. The resulting loading rate estimates for total N are within about 19 percent for total N and about 50 percent for total P. This suggests that the STEPL estimates are within the correct order of magnitude, and that a SWAT model, with appropriate calibration, can likely be successful for the watershed.

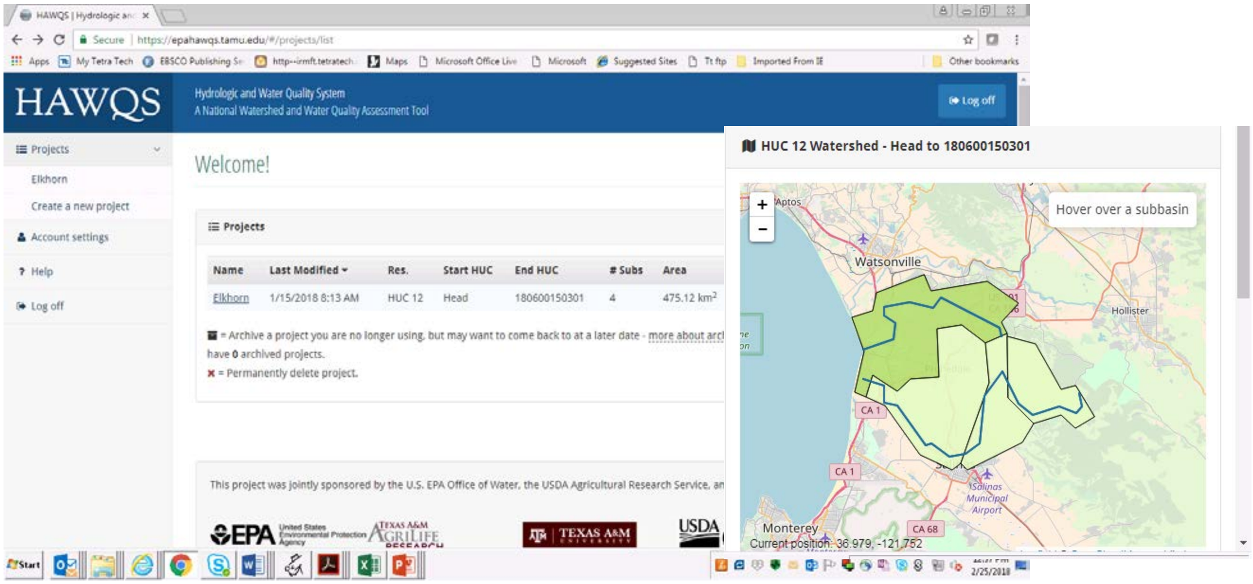

Figure 3-5. HAWQS Interface for Elkhorn Slough Drainage

Table 3-4. Comparison of STEPL and HAWQS/SWAT Estimates of Nutrient Loading Rates for Elkhorn Slough Direct Drainage

Model	Total N (lb/ac/yr)	Total P (lb/ac/yr)
STEPL	4.64	0.97
SWAT/HAWQS	3.74	0.45

3.1.2 Loads via Old Salinas River

The OSR connects the Salinas River Lagoon to Elkhorn Slough. The OSR enters Elkhorn Slough just upstream of the mouth, but flood tide excursions can mix any load entering from the OSR upstream into the Slough. Because of the very high nutrient concentrations present in the Salinas River, OSR is believed to be a significant contributor of nutrients to Elkhorn Slough.

In addition to the Salinas River, the OSR connects Moro Cojo Slough and the Gabilan/Tembladero watershed to Elkhorn Slough. We can estimate nutrient loads from these systems if we have estimates of flow and concentration. The lower part of the OSR (within the Moss Landing Harbor area) is tidally influenced, with bi-directional flow, complicating the estimates. We therefore selected monitoring stations at tide gates that define the usual limit of tidal mixing in the OSR above Tembladero Slough, in Moro Cojo Slough, and in Tembladero Slough itself.

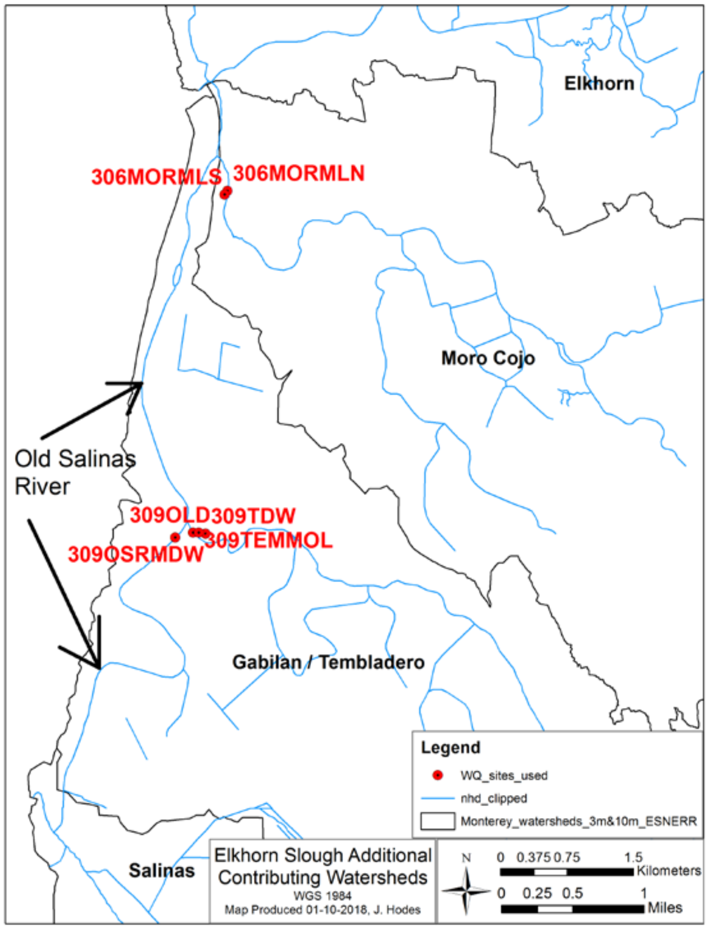

Figure 3-6. Tributary Monitoring Stations on Old Salinas River, Moro Cojo Slough, and Tembladero Slough

Monitoring at the stations above the tide gates has focused on inorganic nutrients (NO_3-N, NO_2-N, NH_4-N, and PO_4-P). Limited measurements of total N are available, while total P is not monitored at these stations. Osmolovsky et al. (2013, Figure 4-1) shows that almost all N in agricultural streams was in the form of nitrate in the Salinas River area (consistent with results for Tembladero Slough), but only about half of the N was present as nitrate in estuary streams after biological uptake (consistent with observations for Moro Cojo and OSR in the reach above Tembladero). While data on total P are very limited, Osmolovsky et al. (2013, Figure 4-2) also suggested that orthophosphate P was around 80 percent of total P. Resulting estimates of inorganic and total nutrient concentrations are shown in Table 3-5.

Table 3-5. Estimated Tributary Nutrient Concentrations (mg/L) for Old Salinas River Inputs to Elkhorn Slough

Tributary	Station	Inorganic N	Total N	Inorganic P	Total P
Moro Cojo	306MORMLS	1.58	2.12	0.48	0.59
Tembladero	309TEMMOL, 309TDW	27.69	27.80	0.47	0.58
OSR above Tembladero	309OSRMDW	19.55	35.04	0.42	0.53

Note: Most monitoring has focused on inorganic N and total P. Total N concentrations are based on limited data (n =13 to 15). Total P estimates are based on an assumption that inorganic P is about 80% of total P.

Continuous flow gaging is not available for the OSR, Moro Cojo, or Tembladero Slough. The Salinas River TMDL (Osmolovsky et al., 2013) does provide estimates of flows from each of these watersheds. These estimates are the mean annual flow volumes reported with NHDPlus, version 1 and were developed using a simple unit area runoff model. Those estimates are now believed to be obsolete and were replaced in NHDPlus version 2 (McKay et al., 2012) by new estimates of average flow using the revised runoff model of McCabe and Wolock (2011). The McCabe and Wolock model is essentially a grid-based accounting of precipitation minus evapotranspiration, with flow accumulation. It can accommodate transfers, withdrawals, and losses to groundwater – but only when there is external information. That creates considerable challenges for the OSR as flow into the OSR from Salinas Lagoon is controlled by a lift gate that is used to manage water levels in the lagoon when the lagoon opening is not closed by a sand bar. The estimates from the two versions of NHDPlus vary drastically, with NHDPlus Version 2 accounting only for the direct drainage to the OSR, and not for any flow releases from Salinas Lagoon. The NHDPlus estimates also do not include the contributions from irrigated agriculture. An independent estimate of average flows in this system was calculated to support the Salinas salt TMDL investigations and includes irrigation and groundwater exchange with the underlying aquifer system (Tetra Tech, 2015), which suggest much of the OSR flow is lost to the aquifer. The three results are compared in Table 3-6.

Table 3-6. Comparison of Flow Estimates for Old Salinas River and Tributaries (AF/yr)

	NHDPlus v1 as cited in Osmolovsky et al., 2013	NHDPlus v2, EROM_Ext file	Tetra Tech (2015) – average year
Moro Cojo	4,017	1,724	2,301
Tembladero	26,080	28,051	14,936
Old Salinas River above Tembladero	26,222	28	329
Total	56,319	29,803	17,566

None of these estimates appears particularly reliable, and they are not developed on a consistent time basis. The NHD v1 estimate, which would be based on estimated drainage area, is likely to be altogether wrong. In the data report, Saiz and Keeling (2016) cite the estimate from Osmolovsky et al. (2013) and compare it to several other estimates. Specifically, the EIR for Pure Water Monterey (DD&A, 2016) suggested that the OSR contributes a freshwater inflow to Elkhorn Slough of 21,733 AF during the summer months (i.e., average inflow of 30 cfs), while a Master's Thesis of Novak (2011) estimates the summer freshwater inflow at between 12,783 and 38,350 AF. In contrast, Johnson (2008) fit a mixing model to observed continuous salinity patterns at the LO1 mooring in Elkhorn Slough with an estimated freshwater inflow from OSR of 19,188 AF for the whole year (based on 0.5 cms 12/1 – 4/11 and 0.3 cms for the remainder of the year).

Osmolovsky et al. (2013) also report estimated May-September flow estimates based on instantaneous flow measurements of 7.08 cfs for Old Salinas River at Monterey Dunes Way, 14.2 cfs for Tembladero Slough at Haro Rd. and 4.15 cfs for Moro Cojo Slough at Highway 1. Flows in Tembladero and Moro Cojo Slough are expected to be greater in the winter rainy season, although irrigation supports perennial flow during dry weather; however, it is unclear how much flow enters OSR from Salinas Lagoon during the winter as high flows that open the lagoon mouth would preclude use of the lift gate to direct flows into OSR.

OSR at Portrero Road South is below the confluence of OSR and Tembladero Slough but above a tide gate. This station has an average PO_4-P concentration of 0.437, which is between the concentrations for OSR above Tembladero and Tembladero Slough; however, in the case of salinity, which should be conservative, both average and median concentrations in OSR at Portrero Road South are greater than the averages and medians in both OSR at Monterey Dunes Way and Tembladero Slough at Haro Road, so the mixing fraction of OSR versus Tembladero cannot be inferred from the data.

The various flow estimates cannot be reconciled at this time. To provide a rough estimate of loads derived from the OSR system we assume that annual flow in the OSR above Tembladero is reasonably represented by the dry weather flow rate of 7.08 cfs (equal to 5,129 AF/yr), and that total freshwater flow from the OSR system (including Moro Cojo and Tembladero Slough) is around 25,000 AF/yr, while the ratio between Moro Cojo and Tembladero flows is equal to the ratio obtained from the instantaneous flow measurements (4.15/14.2). This requires scaling up the Moro Cojo and Tembladero flows by a factor 1.494 to account for higher winter flows. Table 3-7 shows the resulting flow and load estimates.

Table 3-7. Estimated Nutrient Loads from Old Salinas River, Tembladero Slough, and Moro Cojo Slough

	Flow (AF/yr)	Total N (mg/L)	Total P (mg/L)	Total N Load (lb/yr)	Total P Load (lb/yr)
Old Salinas River	5,129	35.04	0.53	488,479	7,403
Tembladero Slough	15,376	27.80	0.58	1,161,733	24,396
Moro Cojo Slough	4,495	2.13	0.59	25,962	7,258
Total	25,000			1,676,175	39,057

3.1.3 Atmospheric Deposition

Atmospheric deposition can be an important source of nitrogen load. Deposition occurs in both wet and dry forms. Wet deposition of N is easily measured in rainfall and is monitored by the National Acid Deposition Program (NADP). In contrast, dry deposition is very difficult to measure directly and is usually estimated by combining air concentration with deposition modeling. To address this problem, the NADP has produced estimates of total N deposition by combining NADP monitoring with output from the Community Multi-Scale Air Quality Model (CMAQ0, as described in Schwede and Lear (2014).

Gridded annual data from NADP for total deposition mass of NOx and NH_4 is available for the years 2000-2015 (http://nadp.sws.uiuc.edu/committees/tdep/tdepmaps/). These data were assembled for grid cells corresponding to Elkhorn, McClusky, and Bennett Slough water and wetland areas – but excluding the water areas draining into the OSR, as total loads are already accounted for in these areas based on monitoring data as described in Section 3.1.2. The raw deposition rates as kg-N/ha/yr were converted to lb-N/ac/yr and applied to the water and wetland areas.

Atmospheric deposition of P also occurs, mostly as dust, but little monitoring data is available. We therefore apply the rate adopted for the Salinas River TMDL (Osmolovsky et al., 2013) of 0.6 kg-P/ha/yr, which was ultimately cited back to a Chesapeake Bay document (USEPA, 1994) and may not be fully appropriate to Elkhorn Slough. Table 3-8 shows the resulting estimates. The estimates are separated into deposition to waters behind control structures and waters that are tidally mixed.

Table 3-8. Estimated Atmospheric Deposition of Nutrients to Elkhorn Slough

Area	Total Acres	lb-N/yr	lb-P/yr
Behind Water Control Structures	854	4,800	417
Tidally Mixed	2,130	11,970	1,140
Sum	2,984	16,770	1,597

3.1.4 Tidal Loading from Monterey Bay

The deep channel for Moss Landing Harbor allows strong tidal mixing of the main body of Elkhorn Slough. Each tidal cycle replaces a large proportion of the tidal prism within the Slough with water from Monterey Bay; thus, Monterey Bay is itself a source of nutrient loading to the Slough.

The data report (Saiz and Keeling, 2016) reports an average inflow rate to Elkhorn Slough from Monterey Harbor and Ocean of 4,107,620 AF/yr, derived from DD&A (2016). We rechecked this estimate based on Malzone (1999) who states that the tidal prism volume is 1.31×10^7 m^3 and that 50 – 75 percent of the tidal prism volume is exchanged with each tidal cycle. Based on 706 tides per year and a central estimate of 62 percent exchange, this is equivalent to an inflow of 4,648,736 AF/yr, which is within 15 percent of the DD&A estimate. Therefore, we use the tidal exchange rate from DD&A.

Nutrient concentrations (especially nitrate concentrations) in Monterey Bay are strongly influenced by processes of coastal upwelling that occurs along eastern ocean margins when equatorward winds act in combination with the Coriolis force to move surface waters offshore, drawing deeper water to the surface

(Chavez et al., 2000). This upwelled water is relatively rich in nutrients and supports high levels of phytoplankton growth. Chavez et al. show that the seasonal patterns of nitrate N concentrations in Monterey Bay are largely coherent with the upwelling index, with both peaking in the summer. (Note that nitrate N is relatively depleted in ocean waters and high concentrations observed during upwelling events are in the range of 0.25 mg-N/L; much less than the concentrations in agricultural drainage, which often approach 30 mg-N/L).

To estimate the nutrient load associated with the incoming tidal flux we use data from the Monterey Bay Aquarium Research Institute C1 mooring, located 5 km off Moss Landing (Elrod et al., 2008; raw data supplied by personal communication from Ken Johnson, 2/22/2018). For 1998 – 2005, the average for PO_4 was 0.78 µM (0.0242 mg-P/L) and the average for NO_3 was 4.43 µM (0.06205 mg-N/L). While the concentrations are low compared to terrestrial sources, the exchange volumes are large. The resulting estimated loads are 693,101 lb-N/yr and 270,317 lb-P/yr.

Note that the nutrients present offshore in Monterey Bay are to some extent derived from outflow from Elkhorn Slough. They can also be affected by the discharge plume from the Salinas River under the right current conditions.

The coherence between upwelling and Monterey Bay N concentrations suggests that the loading rate from Monterey Bay is likely higher during summer and on stronger tides. Because nutrient concentrations within the Slough are greater than those in the Bay, this input will be balanced by an even larger output of nutrients on the ebb tide. Resulting concentrations in the Slough are discussed in Section 3.2.

3.1.5 Load Summary

The preceding sections describe the current best estimates of average annual external nutrient loads to the estuary. These load estimates have a high level of uncertainty, especially about the terrestrially derived loads. They also are distributed unevenly across Elkhorn Slough. Finally, they do not constitute a full mass balance because the losses of nutrients (export to Monterey Bay, denitrification) are not tabulated. Current estimates of external nutrient loads are summarized in Figure 3-7 and Figure 3-8. These are presented as percentages, rather than loads, to emphasize the uncertainty in current load estimates.

In terms of loads to the whole of Elkhorn Slough (including Bennett Slough and McClusky Slough, and areas of Elkhorn Slough behind water control structures), exchange with Monterey Bay is estimated to be the major source of total P load, and one of the larger sources of total N load. (As we will see below, while Monterey Bay is estimated to contribute about 27% of the total N load to the Slough the percent contribution is much higher for the mainstem of the Slough near the mouth.) Tembladero Slough is estimated to be a major source of total N, mostly due to the very high nitrate concentrations reported from this waterbody. The OSR contribution estimate (from upstream of Tembladero Slough) is entirely dependent on the highly uncertain flow estimates. The Upper Elkhorn fraction, which includes the contribution from Carneros Creek at the head of the Slough, is relatively small relative to the Slough as a whole, but is the major contributor to the upstream areas that are cut off from tidal mixing.

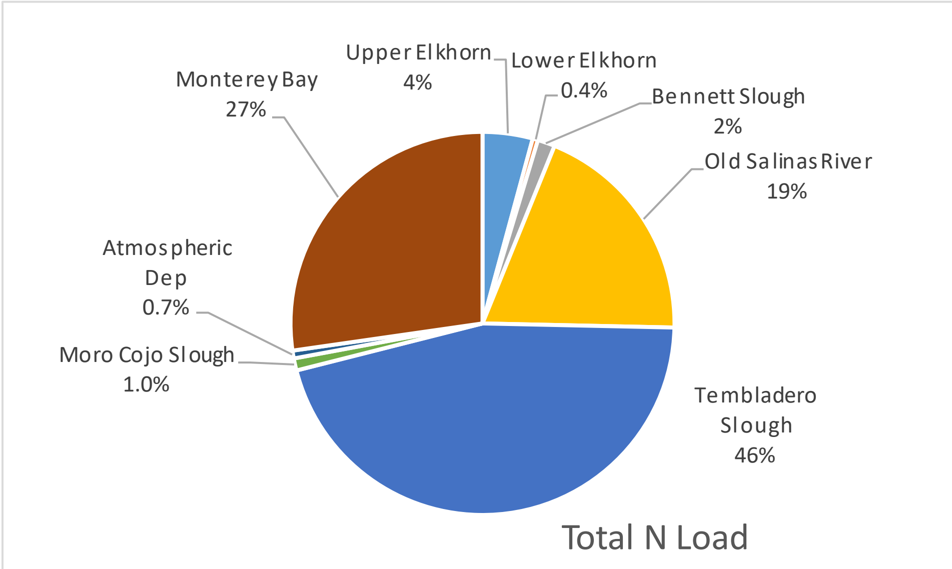

Figure 3-7. Average Annual External Loads of Total N to Elkhorn Slough

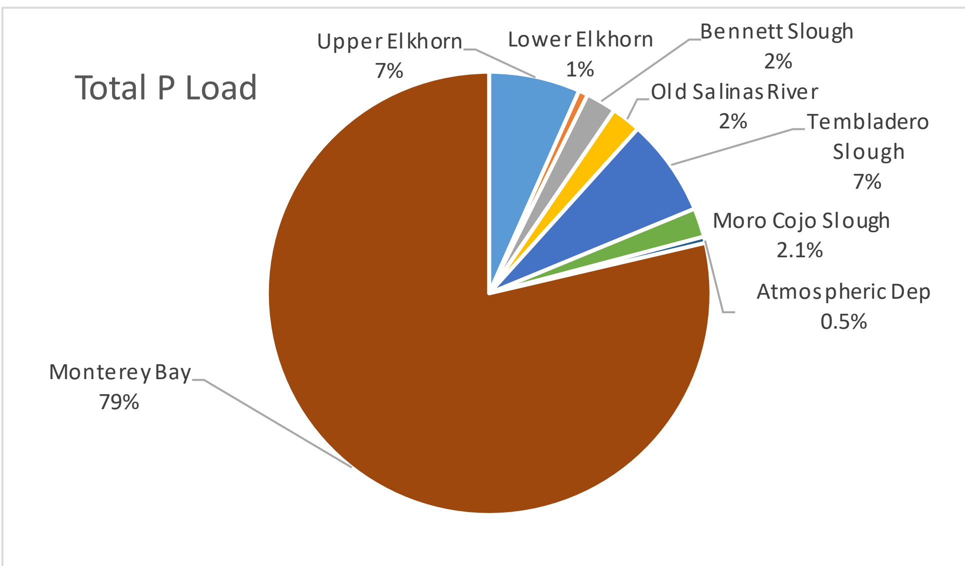

Figure 3-8. Average Annual External Loads of Total P to Elkhorn Slough

Dr. Ken Johnson of MBARI developed a rather different mass balance analysis of the lower portion of Elkhorn Slough in an unpublished presentation (Johnson, 2015) and accompanying spreadsheets. MBARI operates several Land/Ocean Biogeochemical Observatory (LOBO) mooring stations that have collected continuous observations of water surface elevation, velocity, temperature, salinity, nitrate, and other parameters at stations in Elkhorn Slough and offshore. The LOBO L01 mooring is located upstream of Moss Landing Harbor near the downstream end of Elkhorn Slough and above the confluence with OSR. Johnson (2015) conducted a multi-year (2005-2015) mass balance of nitrate N at the L01 mooring by combining the net volumetric flux of water with observed concentrations to estimate inflows and outflows of nitrate N relative to this location. Total inflow of nitrate N was partitioned into nitrate N derived from Monterey Bay with the remainder assumed to be due to land-based inputs advected upstream from OSR (given the assumption that the contribution of Carneros Creek and other tributaries is small). The difference between total input and total output calculated at L01 was taken to represent losses in the system, estimated at 25% of influent nitrate N. Over 2005 – 2015, the estimated total nitrate N input relative to L01 was about 350 tons/yr from “land-based” sources (i.e., from the OSR inflow) and 450 tons/yr from Monterey Bay – thus attributing 56 percent of the nitrate N at L01 to tidal influx from Monterey Bay.

Johnson’s estimate that 56 percent of the nitrate N load at L01 is due to tide from Monterey Bay contrasts with our estimate that 27 percent of the total nitrate N load to the entire estuary is due to tide from Monterey Bay. The difference could well be in the uncertainty in the flow estimates from OSR; however, it is also the case that these are measures of different things. Johnson’s estimates apply specifically to the mass balance around the L01 mooring, which is in the main channel near the entrance to the Slough and at a location where the influence of tidal influx from the Bay would be at a maximum. Upper reaches of Elkhorn Slough would likely have a greater influence from OSR sources (which are pushed upstream ahead of the flood tide as described in Section 3.2), as well as local tributary inputs. The attribution of inflow flux at L01 to the Bay versus land sources also depends on the uncertain estimates of nitrate N concentrations in the Bay.

3.2 MIXING AND LOAD DISTRIBUTION WITHIN THE SLOUGH

Nutrient loads enter Elkhorn Slough from a variety of sources with uneven relative importance throughout the Slough. In an analysis of external nutrient loads (Section 3.1), the dominant sources are tidal mixing from Monterey Bay and loads carried into Elkhorn Slough by the OSR channel, located just upstream of the mouth of the Slough. These downstream sources have little or no effect on the portions of the Slough that are largely cut off from tidal mixing by water control structures (Figure 3-4), where nutrient concentrations presumably depend on the local watershed. The inputs from OSR behave differently depending on the tidal phase: during ebb tides, they are entrained and flow directly out into Monterey Bay; however, during flood tides they can be advected up to the head of tidal influence within the Slough.

Examination of seasonal patterns of total N concentration at selected well-monitored points (see Figure 3-9) along the Slough thalweg illustrates some of the complexities of mixing that occur. Figure 3-10 shows monthly N concentrations at Skipper’s Landing (station MSLSKL), just upstream of the Slough entrance. Medians are plotted to damp the influence of outliers, and only data after 2002 are used to remove the influence of the 1995/6 Porter Marsh tide gate repair and extensive restoration efforts around Azevedo Pond in 2002 (Gee et al., 2010) – although this likely had little effect on conditions at MSLSKL. Remember that the nitrate-N concentration in Monterey Bay is on the order of 0.06 mg/L, while that in the OSR is on the order of 22 mg/L. The pattern at this station suggests substantial influence of high nitrate water from OSR during March through May, with reversion toward the Monterey Bay background concentration during the remainder of the year.

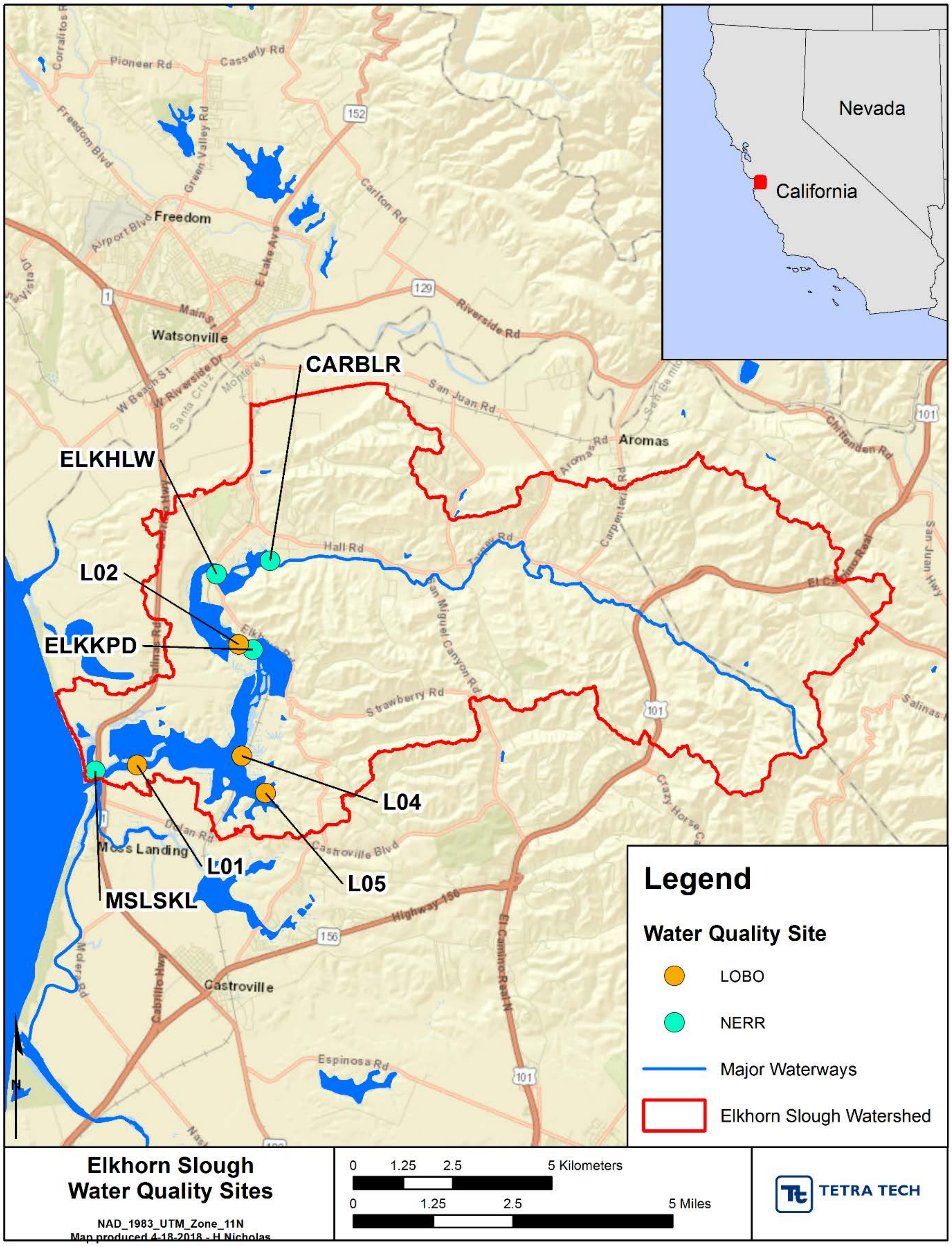

Figure 3-9. LOBO Moorings and Selected NERR Volunteer Monitoring Sites in Elkhorn Slough

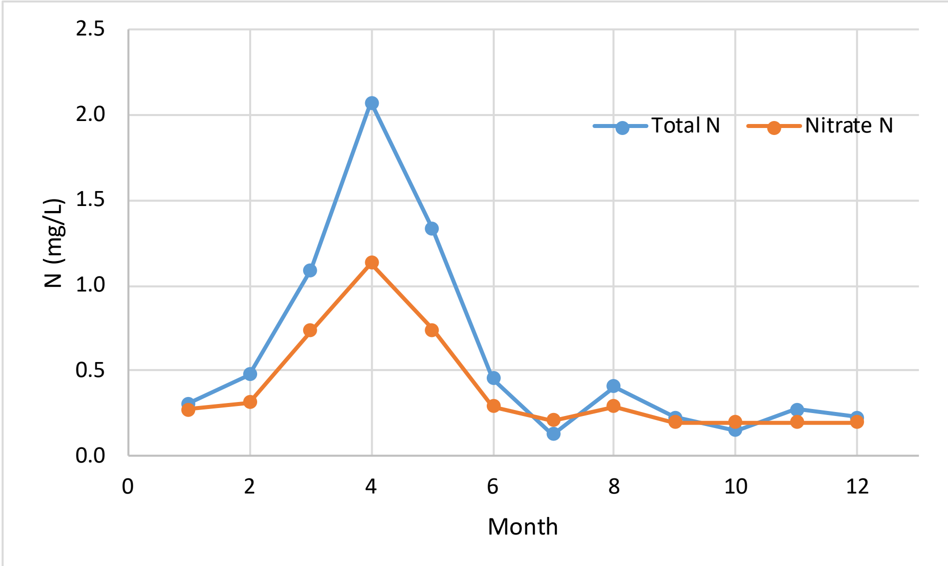

Figure 3-10. Monthly Median N Concentrations at Skipper's Landing (MSLSKL), 2002-2015

Moving upstream to Kirby Park (station ELKKPD), the same general pattern is seen, but with much lower concentrations. Note that many nitrate-N observations are reported as non-detect at a detection limit of 0.2 mg/L and no corrections for censored data are made in the plot.

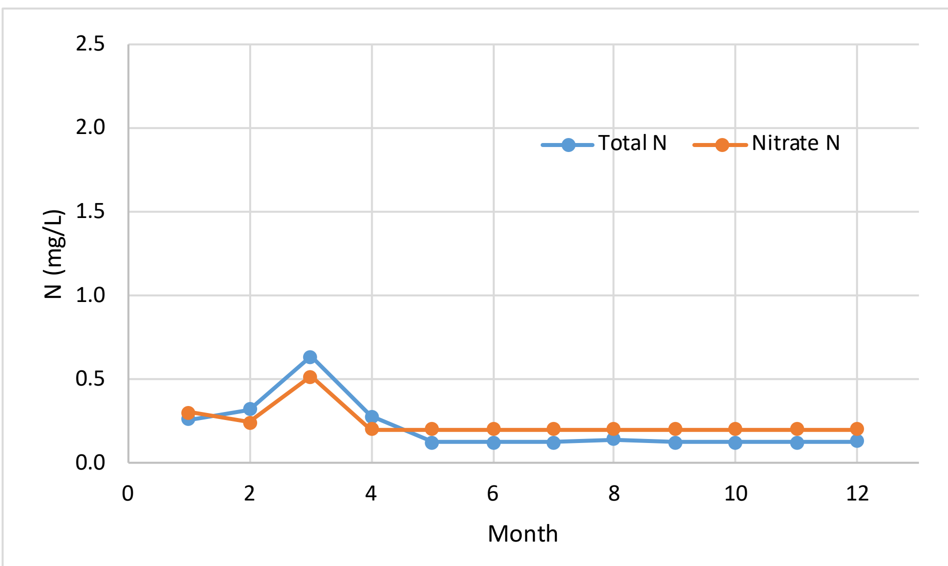

Figure 3-11. Monthly Median N Concentrations at Kirby Park (ELKKPD), 2002 – 2015

Moving further upstream to Hudson's Landing (station ELKHLW), the spring peak appears to be preserved, but background concentrations through the rest of the year are higher and there appears to be a second nitrate N peak in July (Figure 3-12). Note that the nitrate-N median is often higher than the total-N median due to larger sample size. The secondary peak in July may represent the effects of local agricultural drainage.

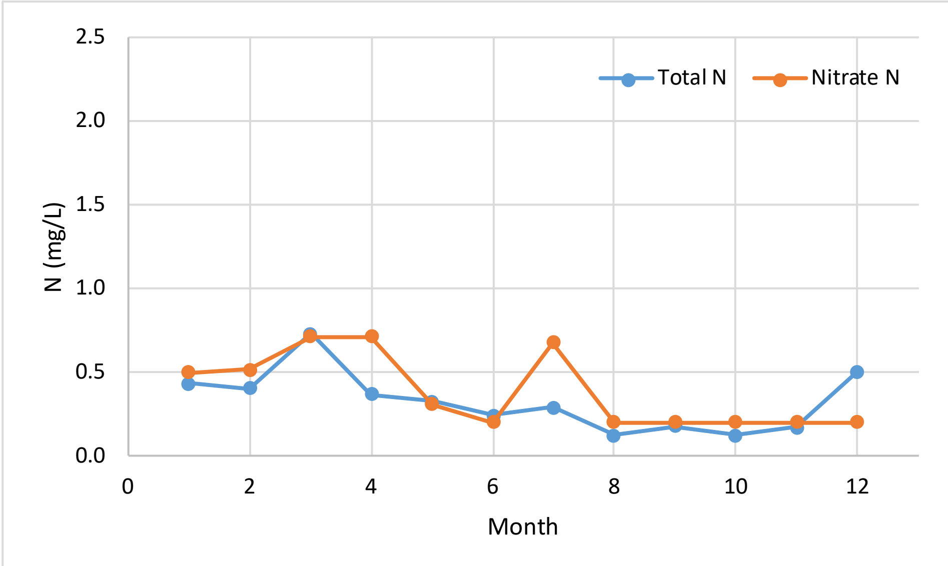

Figure 3-12. Monthly Median N Concentrations at Hudson's Landing (ELKHLW), 2002 – 2015

Finally, Figure 3-13 shows concentrations in Carneros Creek, above the tide gates at the head of the estuary. Here, the spring peak associated with tidal mixing from OSR has disappeared, but nitrate N is elevated in the summer, with much higher total N in the summer and fall (indicating algal uptake and processing). The higher summer N concentrations here affect the Hudson's Landing station, but only by a small amount as flow in Carneros Creek during the summer is usually very low.

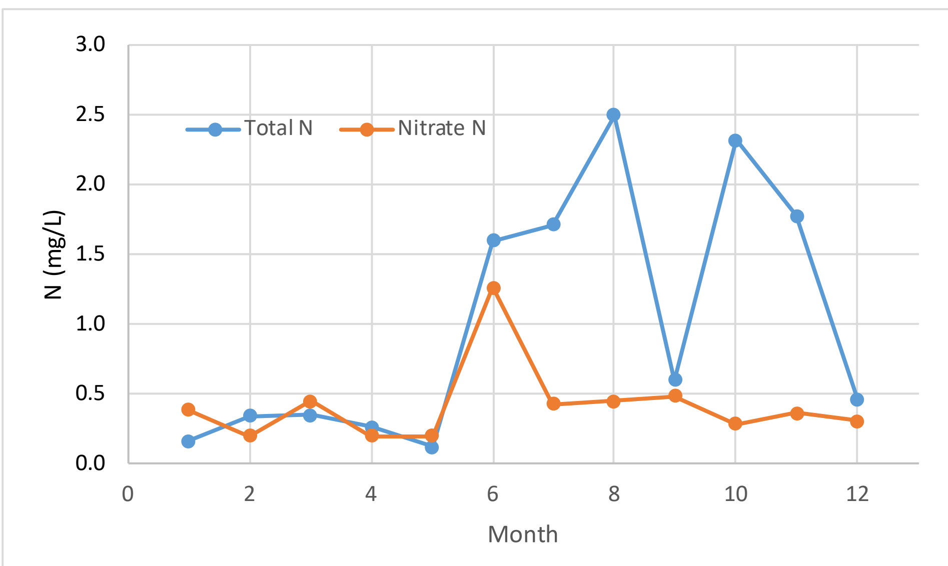

Figure 3-13. Monthly Median N Concentrations, Carneros Creek above Tide Gates (CARBLR), 2002 - 2015

Two detailed, three-dimensional hydrodynamic models of Elkhorn Slough have been created to examine flow and sediment transport in the system, particularly in regards to the changes caused by the creation of Moss Landing Harbor and potential mitigation options. These used the TRIM3D (Monismith et al., 2005; subsequently maintained by the University of California Santa Clara Environmental Fluid

Mechanics Lab) and Delft3D (PWA, 2008) modeling frameworks. Both models feature long run times, even for relatively short calibration periods, and are not readily available. (The Delft3D model included 58,000 grid cells and simulation of one tidal cycle at a 30-second time step required 1.5 days of computer time; the TRIM3D model was reported to require hours of computer time to run a single day.) The level of detail in such three-dimensional models is well in excess of what is needed to understand seasonal nutrient mixing in the Slough, for which a simpler approach would be preferable. The Delft3D modeling (PWA, 2008) does provide several useful conclusions based on model sensitivity analysis. Most importantly, "sensitivity analyses evaluated inflows typical of the calibration and validation periods and did not address peak values associated with large storm events and/or extreme runoff events associated with localized flooding. The freshwater inflows were small when compared with the tidal flow and they did not alter the flow characteristics that drive geomorphic change (e.g., current velocity in the slough channel and/or tidal inundation of the marsh plain)". In addition, the operation of the Moss Landing Power Plant (which withdraws cooling water from the harbor and discharges to Monterey Bay, has "negligible impact" on hydrodynamics in the Slough landward of the U.S. 1 crossing.

Dr. Ken Johnson of MBARI created a simplified box model of mixing in Elkhorn Slough (Figure 3-14). The model uses tidal prism theory of mixing over the tide cycle (e.g., Kuo and Neilson, 1988) and is driven by tides at Moss Landing, freshwater inflows, and a description of tidal prism volume as a function of tide height. After optimization of rate processes, the box model provides a reasonable fit to salinity and nitrate at the LOBO L01 and L02 moorings (see Figure 3-9), even without time-varying freshwater inflows. The box model is capable of quickly approximating the hydrodynamic results from the detailed TRIM 3-D model of Elkhorn Slough (Monismith et al., 2005), but runs quickly allowing a full year to be simulated in minutes. The box model is thus a highly useful tool for investigating mixing in the Slough and can potentially be used as a predictor for nutrient concentrations along the Slough mainstem.

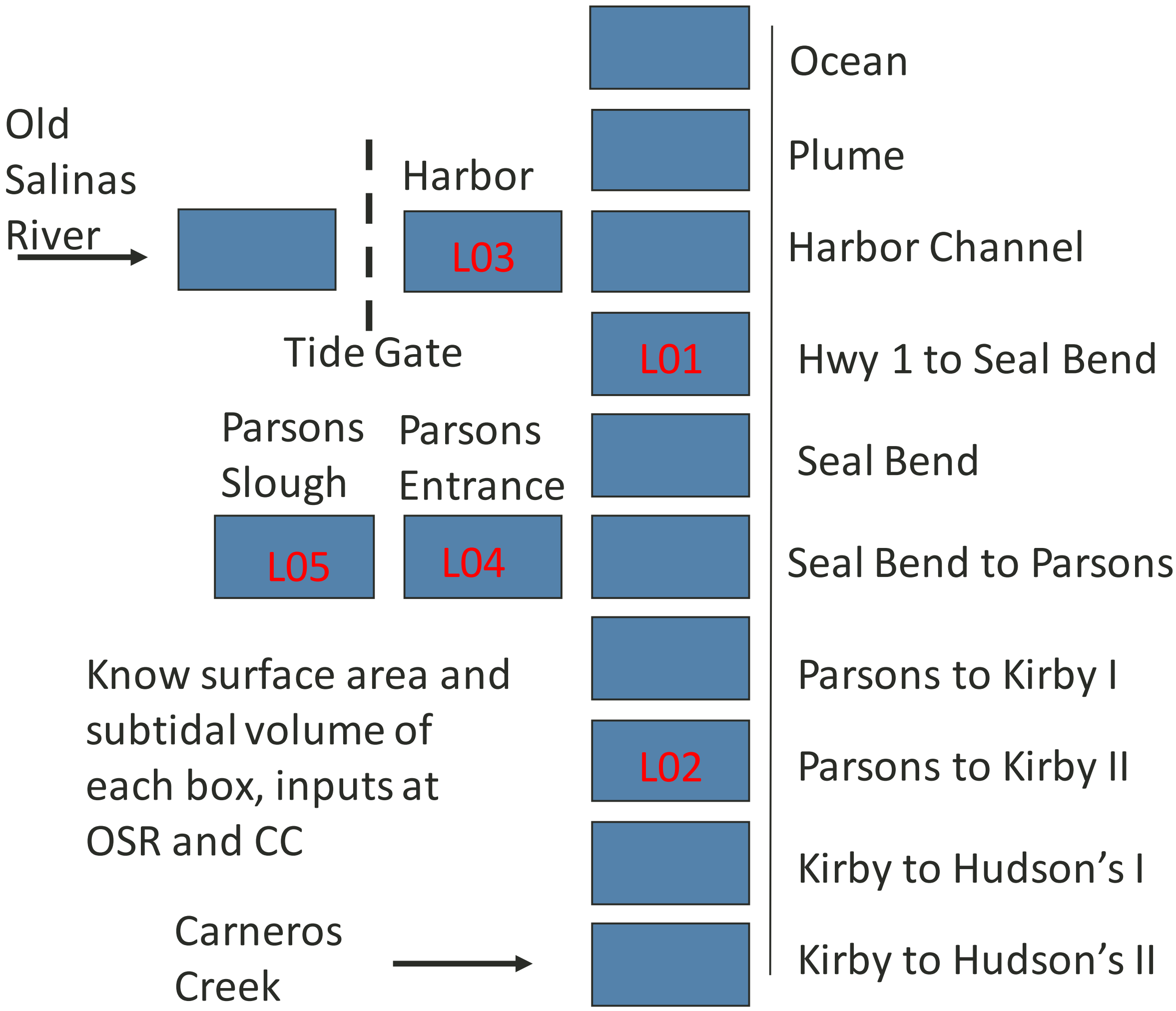

Figure 3-14. Schematic of Box Model of Elkhorn Slough with LOBO Mooring Locations (Figure courtesy of Ken Johnson)

Dr. Johnson provided copies of the optimized box models for wet season and dry season conditions, where wet season is specified as January 1 through April 11. The wet and dry models differ in their specification of freshwater inflows: The wet season model has inflows of 0.5 m^3/s from OSR and 0.1 m^3/s from Carneros Creek, while the dry season model has an inflow of 0.1 m^3/s from OSR and zero from Carneros Creek. Concentrations are specified for the freshwater inflows and the ocean boundary.

We ran the models with a nominal concentration of 100 at a single inflow point and all other inflows set to zero. This yields output that shows the fractional percentage of an input source concentration that is present in each box of the model as average of ebb slack and flood slack conditions (Table 3-9). From this table, it is first obvious that the Bay concentration is mixed throughout the mainstem, with more than 99 percent preserved except in the OSR entrance channel. The OSR source is diluted by the tidal inputs, but is present up to the head of tidal mixing. While the boundary concentrations are greatly reduced within the Slough boxes, the OSR source concentrations are on average several hundred times greater than the Bay concentrations for nitrate N, thus the small fraction still represents a large contribution to the total concentration observed at a point.

Table 3-9. Box Model Predictions of Fraction of Boundary Concentration Present in Selected Boxes

Source	Harbor		Old Salinas River		Parsons to Kirby II		Kirby to Hudson's II	
	winter	summer	winter	summer	winter	summer	winter	summer
Bay	99.07%	99.33%	76.54%	67.32%	99.34%	99.54%	99.34%	99.54%
OSR	0.93%	0.67%	23.42%	32.65%	0.66%	0.46%	0.66%	0.46%
Carneros	0.30%	0.00%	0.04%	0.09%	2.23%	0.00%	8.18%	0.00%

Note: Concentration contributions from different sources are additive in the box model. The contribution from a given source to the concentration at a specific location is the fraction shown in the table times the boundary concentration.

Considerable variability is present in the concentrations at the boundaries. Some basic statistics for NO_3-N are shown in Table 3-10.

Table 3-10. Box Model Boundary Concentrations for NO_3-N (mg/L)

Boundary	Average	75th Percentile	Maximum
Monterey Bay (MBARI C1)	0.062	0.092	0.254
OSR (309OSRMDW)	19.5	26.5	190
Carneros (306CARBLR)	1.34	1.24	16.3

Note: Results for 309OSRMDW and 306 CARBLR are from Appendices in Saiz and Keeling (2016)

Figure 3-15 compares box model results with the boundary concentrations from Table 3-10 to the observed median and 75th percentile concentrations at several stations, showing general consistency in results.

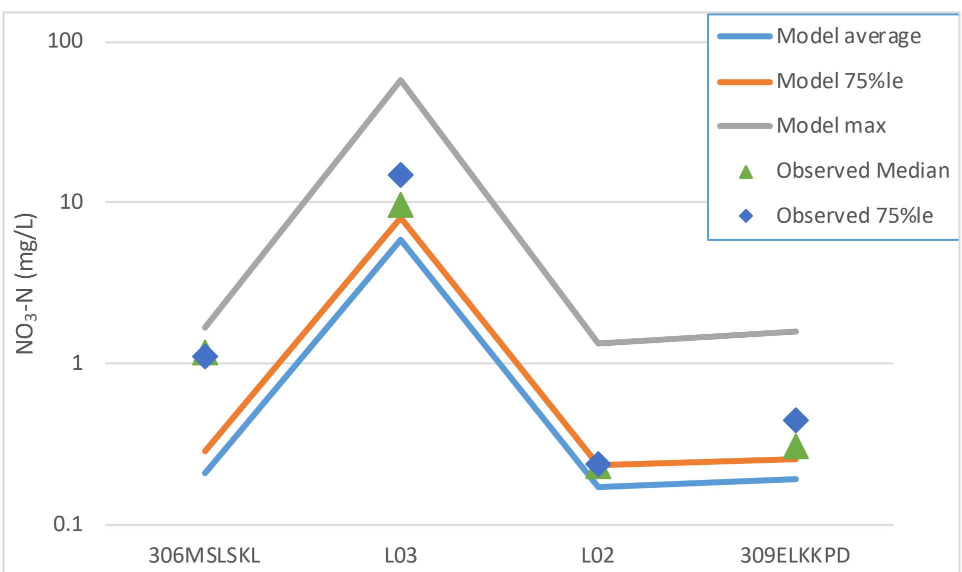

Figure 3-15. Box Model Results Compared to Observed NO_3-N Concentrations

Initial tests of the box model approach thus show promise, despite numerous simplifying assumptions, such as use of two constant freshwater inflows for the wet and dry seasons, respectively. Further development of a box or tidal prism model using full time series of freshwater inflows and concentrations would thus appear likely to yield a better estimate of mixing of different load sources and resulting concentrations in the Elkhorn Slough mainstem. The results are most applicable to the main channel (plus Parsons Slough channel) and would not provide resolution to predict concentrations in side channels.

3.3 SUMMARY OF AVAILABLE MODELING TOOLS AND SUPPORTING DATA

There is a wealth of water quality monitoring data available for Elkhorn Slough and its tributaries, from many locations and collected over many years, as summarized in Saiz and Keeling (2016). These data could provide a firm basis for calibration and validation of nutrient fate and transport models. On the other hand, there is a notable lack of reliable, long-term freshwater inflow monitoring data.

Nutrient numeric endpoints for Elkhorn Slough are anticipated to be defined separately for the tidally mixed sections and those that are isolated behind water control structures. Simplified mixing models, such as Dr. Johnson's box model, appear to be highly relevant and useful tools for evaluating the relationship between source loads and ambient nutrient concentrations in the tidal portion of the estuary. On the other hand, the box model is not relevant to predicting nutrient concentrations for the areas isolated behind water control structures. Nutrient concentrations in those waters are driven by local watershed runoff, as indicated by a study showing significant improvement of water quality in tidally restricted wetlands following restoration activities in the subwatershed (Gee et al. 2010). A calibrated watershed model does not exist at this time, but initial experiments with the uncalibrated HAWQS/SWAT system suggest such a SWAT-based approach is feasible and appropriate for the agricultural land uses in the area. An older version of SWAT was successfully applied for the sediment TMDL in the adjacent Pajaro River watershed (Tetra Tech, 2004) and a new SWAT model is reportedly being developed for the Gabilan/Tembladero watershed by Kim Null.

SWAT models would improve ability to predict nutrient loads derived from the watershed, especially those affecting areas with restricted tidal exchange. This is a critical unmet need currently, since most research and models have focused on the tidally flushed main channel of Elkhorn Slough, and yet it is the tidally restricted sites that have the worst water quality, consistently scoring Fs on the water quality report card (http://elkhornslough.org/water/). Watershed models would also help to clarify the freshwater flows from the direct drainage to Elkhorn Slough as well as flows in Moro Cojo and Tembladero Slough to OSR. They may not, however, be of much use for determining the flows from the upper part of the OSR.

Uncertainty is especially high for the flow released from Salinas Lagoon into the OSR. This is a potentially significant source of nutrients to Elkhorn Slough, but the releases are managed to control water levels in the Salinas Lagoon when the Lagoon mouth is closed by sand, and so are difficult to predict. Further investigations should be pursued with those responsible for managing the tide gates to see to what extent the flow into the OSR is estimable or predictable. Such analyses will inform the old Salinas River TMDL process as well as the Elkhorn Slough TMDL process.

An end goal for this analysis is to develop a recommended approach for development of TMDL allocations, preferably using tools that can be applied in-house by the Regional Board staff. What needs to be done to develop allocations suitable for an approvable TMDL will depend in part on the nature and form of the TMDL targets that are currently being developed in a separate report. Depending on how the targets are specified it may or may not be necessary to develop more detailed and sophisticated modeling tools than the simplified analyses presented in this report.

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4.0 RECOMMENDED APPROACH FOR DEVELOPMENT OF TMDL ALLOCATIONS

Chapter 2 establishes that there is ample evidence to develop reasonable and appropriate numeric nutrient targets to address eutrophication in Elkhorn Slough. Sufficient evidence exists to recommend specific targets; it is now the purview of the Regional Board to select appropriate targets based on the assembled evidence. The technical evidence suggests that targets should best be expressed in terms of seasonal total N and total P concentration targets, with separate targets for the tidally mixed and tidally restricted portions of Elkhorn Slough. Even if the concentration targets are the same for these two zones they should be addressed separately because nutrient concentrations in these two zones are subject to different influences. The tidally mixed zone has large nutrient mass inputs from Monterey Bay and from the tidally induced mixing of Old Salinas River water into the upstream parts of Elkhorn Slough. The tidally restricted marshes, behind levees or tide gates, have nutrient concentrations that are primarily driven by local watershed inputs.

Chapter 3 demonstrated that there is a substantial body of evidence on the sources, fate, and transport of nutrients entering the Slough. There are also significant uncertainties, particularly as regards freshwater inflows from the Old Salinas River, and the direct tributaries to upper Elkhorn Slough and groundwater contributions. To the extent feasible, those uncertainties should be refined and reduced to provide a more complete and accurate linkage analysis that will describe the relationship between nutrient load sources and nutrient load concentrations with the tidal and non-tidal portions of Elkhorn Slough. This chapter is focused on identifying tools that may be appropriate to develop this linkage. We believe that the uncertainties related to flows and loads can be refined to the extent needed to develop specific load allocations through the development of some relatively simple modeling tools. In the sections below we describe an overall allocation strategy and identify modeling approaches for refining the load allocations.

4.1 ALLOCATION STRATEGY

The tools described in the following section will provide the technical basis for developing TMDL allocations. Exactly how these allocations will be developed in part represents a policy decision as to what loads are controllable and how needed reductions should be apportioned to different source sectors.

A TMDL is a means for recommending controls needed to restore and maintain the quality of water resources (USEPA, 1991). TMDLs represent the total pollutant loading that a waterbody can receive without violating water quality standards. The TMDL process establishes allowable loadings for a waterbody based on the relationship between pollution sources and in-stream water quality conditions. 40 CFR §130.2(i) states that a TMDL calculation is the sum of the individual Waste Load allocations for point sources and the load allocations for nonpoint sources and natural background in a given watershed, and that TMDLs can be expressed in terms of either mass per time, concentration, toxicity, or other appropriate measure. The TMDL must also consider seasonal variations and include a margin of safety (MOS) that takes into account any lack of knowledge about the causes of the water quality problem or its loading capacity.

A TMDL targets a level of pollutant loading by adding the pollutant sources, both point and nonpoint, and a margin of safety. A TMDL is typically expressed as:

$$\text{TMDL} = \text{WLAs} + \text{LAs} + \text{MOS}$$

where:

WLA = Waste Load Allocation – the portion of the loading to the water body assigned to each existing and future permitted point source of the pollutant;

LA = Load Allocation – the portion of the pollutant loading assigned to existing and future nonpoint sources of the pollutant;

MOS = Margin of Safety – an accounting of the uncertainty of the pollutant load and the quality of the water body.

The sum of the Waste Load Allocations and Load Allocations must be less than or equal to the Loading Capacity of the waterbody, which is the total amount of pollutant load that can be added while not impairing uses. The Loading Capacity will be determined through application of the linkage analysis tools to relate the instream water quality targets to sources of nutrient loads.

The linkage analysis tools will also provide a basis for evaluating the extent to which full implementation of the Salinas River nutrient TMDL will help mitigate conditions in Elkhorn Slough,

For Elkhorn Slough, nutrient loads are derived primarily from nonpoint sources, including irrigated agriculture. There are not traditional point source discharges. However, there are permits in place for Municipal Separate Storm Sewer (MS4) discharges. Specifically, the City of Salinas holds a Phase I MS4 permit and discharges to Elkhorn Slough via Gabilan Creek and Tembladero Slough. There is likely also some developed land in the watershed that is covered by Phase II Small General MS4 permits. Nutrient loading sources subject to these permits will need to be addressed via WLAs; however, this is expected to be a minor part of the total nutrient loads to Elkhorn Slough.

Load Allocations may be expressed on either a lumped or source-specific basis in a TMDL; however, to support effective implementation planning it is usually necessary to define Load Allocations by source type. Two of the first steps that the Regional Board will need to take in planning the development of Load Allocations are (1) to decide on the level of specificity in the allocations (e.g., an LA might be assigned to all agricultural runoff entering the upper portion of Elkhorn Slough, and (2) to identify loads for which reductions are feasible versus those where reductions are not feasible. For instance, N loads associated with upwelling conditions in Monterey Bay might well be concluded to not be reducible by any feasible actions and therefore not subject to reductions as part of the TMDL – which could increase the amount of reductions that would need to be obtained elsewhere. After these determinations, the Regional Board would need to develop a strategy for distributing the remaining portion of the Loading Capacity to potentially controllable sources. Many different strategies could be applied here such as equal percentage reductions from all controllable sources, most cost-effective reductions, or market based approaches such as nutrient trading.

Because nutrient targets are expected to be established separately for the tidally mixed mainstem of Elkhorn Slough and for tidally restricted areas, allocations will need to take both types of targets into account. For the tidally restricted areas, only the local land-based sources derived from the directly draining watershed are applicable. These same load sources will also be one part of the total suite of loads that affect the Elkhorn Slough tidally mixed mainstem. In general, it is anticipated that meeting targets within tidally restricted areas will pose the greatest loading constraints on the direct drainage watershed.

We do not envision changing the morphology and mixing regime of the Slough and its tributary areas as a TMDL strategy. However, if such changes are evaluated for other purposes (e.g., habitat), it will be necessary to take that into account.

All TMDLs are required to include a Margin of Safety (MOS) to account for uncertainty in understanding the relationship between pollutant discharges and water quality impacts. The Margin of Safety may be provided explicitly through an unallocated reserve or implicitly through use of adequately conservative assumptions in the analysis.

As a result of the decision *Friends of the Earth, Inc. v. EPA, et al.*, No. 05-5015 (D.C. Cir. 2006), USEPA issued a memorandum entitled *Establishing TMDL "Daily" Loads in Light of the Decision by the U.S. Court of Appeals for the D.C. Circuit in Friends of the Earth, Inc. v. EPA et. al., No. 05-5015 (April 25, 2006) and Implications for NPDES Permits* in November 2006 that recommended that all TMDLs and associated load allocations (LAs) and Waste Load allocations (WLAs) include a daily time increment in conjunction with other temporal expressions (e.g., annual, seasonal) that may be necessary to implement the relevant water quality standards.

USEPA (2007) issued a draft guidance document entitled *Options for Expressing Daily Loads in TMDLs*. Following Option 2 in that guidance, we recommend that a variable daily load expression may be most appropriate for Elkhorn Slough. This option allows for variable expression that may be used when the applicable daily load value is determined as a function of a particular characteristic that affects loading or waterbody response, such as flow or season. For the Elkhorn Slough TMDL, the daily *average* load for nutrients could first be expressed in terms of the daily average inflow multiplied by the seasonal concentration target. The daily expression of the *maximum* load could then be defined, again consistent with USEPA (2007), as the 95th percentile inflow estimate (for the appropriate season) multiplied by the seasonal concentration target.

4.2 LINKAGE ANALYSIS TOOL DEVELOPMENT

4.2.1 Develop SWAT model of direct drainages to Elkhorn Slough.

In Chapter 3, preliminary load estimates were developed using an automated, uncalibrated watershed model contained in the EPA Hydrologic and Water Quality System (HAWQS; https://epahawqs.tamu.edu). HAWQS (Texas A&M, 2017) is a web-based interactive water quantity and quality modeling system that employs as its core modeling engine the Soil and Water Assessment Tool (SWAT), an internationally-recognized public domain model developed by the U.S. Department of Agriculture (USDA) Agricultural Research Service (ARS). Experiments with the HAWQS/SWAT framework suggest that a calibrated SWAT model of the direct drainage areas is likely to be both successful and useful. SWAT has also been successfully applied to the adjacent Pajaro and a SWAT model is currently being developed for the Gabilan/Tembladero watershed. SWAT simulates long-term, continuous hydrology and water quality at the watershed-scale (Arnold et al., 1998; Neitsch et al., 2011). SWAT was specifically designed to study dynamic effects of water and land management practices on diverse soil types, terrain, and under spatially varied weather. Of the different watershed models available (Borah and Bera, 2003), we recommend SWAT for this study because (1) it is relatively cost-effective to apply, (2) represents specific crop rotations, (3) explicitly represents plant growth and agricultural management practices (e.g., fertilization, tillage, drainage) that are of key importance to nutrient loads from the Elkhorn Slough directly contributing watershed, and (4) typically has broad acceptance among agricultural producers due to its ARS support. SWAT has been widely applied to test the effectiveness of agricultural conservation practices (e.g., Arabi et al., 2007; Cho et al., 2010; Ullrich and Volk, 2009).

Continuous gaging data are lacking for direct calibration of flow simulations in Carneros Creek and other freshwater tributaries to Elkhorn Slough; however, the calibration would be supported by extensive monitoring of nutrient concentrations. Confirmation of the freshwater contribution can be supported by ensuring that the SWAT predictions, in conjunction with the estuarine Box Model (item 2) provide a match to observed seasonal salinity patterns in the upstream end of Elkhorn Slough.

Development of a reliable SWAT model should be pursued in cooperation with the agricultural community. It will be important to assure that realistic crop rotations and management practices characteristic of the area are included. Both irrigation of crops and drainage of cropland appear to be key factors in determining the runoff and pollutant loading response in the watershed.

4.2.2 Update and refine tidal mixing Box Model.

The estuarine Box Model developed by Ken Johnson and described in Section 3.2 appears to be a successful and appropriate tool for evaluating mixing of different sources within the mainstem of Elkhorn Slough – and will thus be a useful tool for linking different source loads to numeric nutrient endpoints within the Slough. In particular, a model of this level of complexity can be used to calculate contributions at any point along the Slough mainstem as a function of source dilution ratios. Specifically, the average seasonal concentration at a given point will be the sum of the boundary concentrations from each source times the dilution ratio that links that boundary to the point of interest. The Box Model provides an efficient means for longer-term simulations of mixing in the Slough that is appropriate to estimate the seasonal average concentrations that are most relevant to nutrient targets.

The existing Box Model can be adapted and refined to better support load allocations. The model should be modified to accept time series of concentrations at the major boundaries along with time series of flows for the freshwater boundaries. These modifications should be relatively simple to implement and will provide a more precise linkage to the loads derived from the freshwater inflows.

4.2.3 Assemble additional information on freshwater inflows from Old Salinas River.

A key source of uncertainty for application of the Box Model is estimating the inflow from the Old Salinas River channel (including the Old Salinas River itself as well as flows from Gabilan/Tembladero and Moro Cojo Slough). Work reported to be currently underway on development of a SWAT model for Gabilan/Tembladero should help to constrain these freshwater inflows. Gaged flows for Reclamation Ditch near Salinas (USGS gage 11156250) are available from 2002 on, and provide direct measurement of flows from 53 square miles of drainage area.

The largest uncertainty regarding freshwater inflows via Old Salinas River appears to be estimates of the managed diversions from the Salinas River estuary into the Old Salinas River channel. Additional information should be sought on the management of this diversion. In addition, extensive research on groundwater modeling of the Salinas River aquifers is available and should be consulted to estimate groundwater exchanges between the aquifers and Old Salinas River channel (Montgomery Watson, 1997; MCWRA, 2006; Brown and Caldwell, 2015).

In the end, there is likely to be residual uncertainty in the estimates of freshwater inflows via the Old Salinas River, but this is expected to have only a small impact on the estimates of seasonal average loading that will form the basis of allocations. That the flows assigned to the Old Salinas River are reasonable can be confirmed through the Box Model representing observed salinity cycles at the LOBO monitoring stations.

4.2.4 Assemble additional information on groundwater contributions and loading from the Slough sediments

Another key source of uncertainty is the lack of information on nutrient loading from groundwater and from the Slough sediments (nutrient flux from the sediment). Gathering information on these two sources will help quantify nutrient loading to the Slough and help Central Coast Water Board staff assign allocations. Additionally, this information will help prioritize management practices in the watershed.

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5.0 REFERENCES

Arabi, M., J.R. Frankenberger, B.A. Engel, and J.G. Arnold. 2007. Representation of agricultural conservation practices with SWAT. *Hydrol. Process*., doi: 10.1002/hyp.6890.

Arnold, J.G., R. Srinivasan, R.S. Muttiah, and P.M. Allen. 1998. Large area hydrologic modeling and assessment, Part I: Model development. *J. Am. Water Resour. Assoc*., 34:73-89.

Baumann, H. and Smith, E.M., 2017. Quantifying metabolically driven pH and oxygen fluctuations in US nearshore habitats at diel to interannual time scales. Estuaries and Coasts, pp.1-16.

Borah, D.K. and Bera, M., 2003. Watershed-scale hydrologic and nonpoint-source pollution models: Review of mathematical bases. *Transactions of the ASAE*, 46(6), p.1553.

Brown and Caldwell. 2015. State of the Salinas River Groundwater Basin. Prepared for the Monterey County Water Resources Agency by Brown and Caldwell Consulting Engineers, Walnut Creek, CA.

Caffrey J.M., Harrington N., Ward B. 2002. Biogeochemical processes in a small California estuary. 1. Benthic fluxes and pore water constituents reflect high nutrient freshwater inputs. *Marine Ecology Progress Series*, 233: 39−53.

Central Coast Regional Water Quality Control Board. 2016. Water Quality Control Plan for the Central Coastal Basin, March 2016 Edition. California Environmental Protection Agency. http://www.waterboards.ca.gov/centralcoast/publications_forms/publications/basin_plan/index.shtml

Chapin, T.P., J.M. Caffrey, H.W. Jannasch, L.J. Coletti, J.C. Haskins, and K.S. Johnson. 2004. Nitrate sources and sinks in Eklhorn Slough, California. Results from long-term continuous in situ nitrate analyzers. *Estuaries* 25(y): 882-894.

Chavez, F.P., R.P. Michisaki, G.E. Friederich, J.T. Pennington, B. Schlining, C. Fayos, P. Walz, C. Sakamoto, R. Hopcroft, R. Kudela, C. Castro, E. Mauri, and K.R. Buck. [2000]. A Ten-Year Time Series from Monterey Bay, California: Season, Interannual and Long-term Patterns. Monterey Bay Aquarium Research Institute, Montery, CA. https://ww3.mabari,org/bog/projects/contralcal/intro.htm, accessed 4/9/18.

Cho, J., R.R. Lowrance, D.D. Bosch, T.C. Strickland, Y. Her, and G. Vellidis. 2010. Effect of watershed subdivision and filter width on SWAT simulation of a coastal plain watershed. *J. Am. Water Resourc. Assoc*., 46:586-600.

DD&A Inc. (Denise Duffy & Associates, Inc.). 2016. Consolidated Final Environmental Impact Report for the Pure Water Monterey Groundwater Replenishment Project. January 2016. http://purewatermonterey.org/reports-docs/cfeir/

Elrod, V.A., K.S. Johnson, S.E. Fitzwater, and J.N. Plant. 2008. A long-term, high-resolution record of surface water iron concentration in the upwelling-driven central California region. *Journal of Geophysical Research*, 113, C11021, doi:10.1029/2007JC004610.

Gee. A.K., K. Wasson, S.L. Shaw, and J. Haskins. 2010. Signatures of restoration and management changes in the water quality of a Central California estuary. *Estuaries and Coasts*, doi:10.1007/s12237-010-9276-3.

Hughes, B.B., J. Haskins, K. Wasson and E. Watson. 2011. Identifying factors that influence expression of eutrophication in a central California estuary. *Marine Ecology Progress Series,* 439: 31-43.

Hughes, B.B., Levey, M.D., Fountain, M.C., Carlisle, A.B., Chavez, F.P. and Gleason, M.G., 2015. Climate mediates hypoxic stress on fish diversity and nursery function at the land–sea interface. *Proceedings of the National Academy of Sciences*, 112(26), pp.8025-8030.

Jannasch, H.W., L.J. Coletti, K.S. Johnson, S.E. Fitzwater, J.A. Needoboa., and J.N. Plant. 2008. The Land/Ocean Biogeochemical Observatory: A robust networked mooring system for continuously monitoring complex biogeochemical cycles in estuaries. *Limnology and Oceanography Methods,* 6: 263−276.

Jeppesen, R., M. Rodriquez, J. Rinde, J. Haskins, B. B. Hughes, L. Mehner, and K. Wasson. 2018. Effects of hypoxia on fish survival and oyster growth in a highly eutrophic estuary. *Estuaries and Coasts,* 41(1): 89-98..

Johnson, K. 2008. Oxygen and Nutrient Dynamics in Elkhorn Slough: Impacts of Management Alternatives. PowerPoint presentation, unpublished.

Johnson, K. 2015. Elkhorn Slough Water Quality Monitoring and Trends – LOBO Data. PowerPoint presentation, unpublished.

Johnson, K., J. Needoba, N. Nidzieko, and Team LOBO. 2007. Modeling Biogeochemical Processes in Elkhorn Slough: or What Do You Do with > 1,000,000 Data Points. Presentation fo Elkhorn Slough Foundation.

Kuo, A.Y., and B.J. Neilson. 1988. A modified tidal prism model for water quality in small coastal embayments. *Water Science and Technology*, 20: 133-142,

Malzone, C.M. 1999. Tidal Scour and its Relationship to Erosion and Sediment Transport in Elkhorn Slough. M.S. Thesis, Department of Geology, San Jose State University, San Jose, CA.

McCabe, G.J., and D.M. Wolock. 2011. Independent effects of temperature and precipitation on modeled runoff in the conterminous United States. *Water Resources Research*, 47, W11522, doi:10.1029/2011WR010630.

McKay, L., T. Bondelid, T. Dewald, J. Johnston, R. Moore, and A. Rea. 2012. NHDPlus Version 2: User Guide. Prpared for Office of Water, U.S. Environmental Protection Agency by Horizon Systems.

MCWRA. 2006. Monterey County Groundwater Management Plan. Monterey County Water Resources Agency, RMC Water and Environment, and Luhdorff & Scalmanini Consulting Engineers.

Mercado, L., J. Haskins, and R.K. Preisler. 2014. A Report Card of Water Quality for the Elkhorn Slough Estuary. Elkhorn Slough Technical Report Series 2014: 1. Elkhorn Slough Foundation.

Monismith, S., N. Jones, M. Bela, N. Nidzieko, A. Paytan, G. Misra, and J. Street. 2005. Hydrodynamics and Sediment Dynamics in Elkhorn Slough. Report to Monterey Bay Sanctuary Foundation. Dept. of Civil and Environmental Engineering, Stanford University.

Montgomery Watson. 1997. Salinas Valley Integrated Groundwater and Surface Model Update, Final Report. Prepared for Monterey County Water Resources Agency.

Neitsch, S.L., J.G. Arnold, J.R. Kiniry, and J.R. Williams. 2011. Soil and Water Assessment Tool, theoretical documentation, version 2009. TR-406. Texas Water Resources Institute, College Station, TX.

Novak, T. 2011. Nitrate Transport to Coastal Monterey Bay: Investigating Source Inputs from Elkhorn Slough. A thesis presented to the faculty of the Moss Landing Marine Laboratories, California State University Monterey Bayhttp://www.elkhornsloughctp.org/uploads/files/1332869994NOVAK_FINALthesis2011.pdf.

Osmolovsky, P., Harlan, L., Hamilton, M., Worcester, K., Keeling, M., Paradies, D.M., Hammer, P., Barricarte, M., and S. Saiz, 2013. Total Maximum Daily Loads for Nitrogen Compounds and Orthophosphate for the Lower Salinas River and Reclamation Canal Basin, and the Moro Cojo Slough Subwatershed, Monterey County, California. Final Report. Prepared for the California Regional Water Quality Control Board Central Coast Region, San Luis Obispo, CA.

PWA. 2008. Elkhorn Slough Tidal Wetlands Project, Hydrodynamic Modeling and Morphologic Projections of Large-Scale Restoration Actions, 100% Draft Report. Prepared for The Elkhorn Slough Tidal Wetlands Project by Philip Williams & Associates, Ltd., San Francisco, with H.T. Harvey & Associates, 2nd Nature, Edward Thornton, and Stephen Monismith.

Ritter, A. F., K. Wasson, S. I. Lonhart, R. K. Preisler, A. M. Woolfolk, K. A. Griffith, S. Connors, and K. W. Heiman. 2008. Ecological signatures of anthropogenically altered tidal exchange in estuarine ecosystems. *Estuaries and Coasts*, 31:554-571.

Saiz, S.G., and S. Keeling. 2016. Total Maximum Daily Loads for Biostimulatory Substances in the Elkhorn Slough Watershed, Data Analysis Report. California Regional Water Quality Control Board, Central Coast Region, San Luis Obispo, CA.

Scharffenberger, T. 1999. Elkhorn Slough Watershed Conservation Plan. Elkhorn Slough Foundation and the Nature Conservancy.

Schede, D.B., and G.G. Lear. 2014. A novel hybrid approach for estimating total deposition in the United States. *Atmospheric Environment*, 92:207-220.

SCCWRP (Southern California Coastal Water Research Project) and Tetra Tech. 2007. Technical Approach To Develop Nutrient Numeric Endpoints For California Estuaries. On the internet at https://www.waterboards.ca.gov/water_issues/programs/nutrient_objectives/development/docs/techapproach_estuaries2007.pdf

Tetra Tech. 2004. Technical Support Document for Establishment of a Suspended Sediment Total Maximum Daily Load for the Pajaro River Watershed. Prepared for California Regional Water Quality Control Board, Central Coast Region by Tetra Tech, Inc., Fairfax, VA,

Tetra Tech. 2006. Technical Approach to Develop Nutrient Numeric Endpoints for California. Prepared for U.S. EPA Region 9 and California State Water Resource Control Board by Tetra Tech, Inc., Lafayette, CA. On the internet at https://www.waterboards.ca.gov/water_issues/programs/nutrient_objectives/development/docs/techapproach_freshwater2006.pdf.

Tetra Tech. 2015. Salinas River Watershed Area Salt Modeling. Prepared for California Central Coast Regional Water Quality Control Board and U.S. EPA Region IX. Tetra Tech, Inc., Research Triangle Park, NC.

Tetra Tech. 2017. User's Guide, Spreadsheet Tool for the Estimation of Pollutant Load (STEPL), Version 4.4. Developed for U.S. Environmental Protection Agency by Tetra Tech, Inc., Fairfax, VA.

Texas A&M. 2017. HAWQS v1.0 User Guide. Prepared for USEPA Office of Water. Spatial Sciences Laboratory, Texas A&M AgriLife Research, College Station, TX.

Ullrich, A., and M. Volk. 2009. Application of the Soil and Water Assessment Tool (SWAT) to predict the impact of alternative management practices on water quality and quantity. Agri. Water Manage., doi: 10.1016/j.agwat.2009.03.010.

USEPA (United States Environmental Protection Agency). 1991. Guidance for Water Quality-Based Decisions: The TMDL Process. EPA 440/4-91-001. U.S. Environmental Protection Agency, Office of Water, Washington, DC.

USEPA. (United States Environmental Protection Agency). 1994. Chesapeake Bay Program: Watershed Model Application to Calculate Bay Nutrient Loadings: Final Findings and Recommendations. EPA 903-R-94-042. Modeling Subcommittee of the Chesapeake Bay Program, U.S. Environmental Protection Agency, Annapolis, MD.

USEPA (United States Environmental Protection Agency). 2007. Options for Expressing Daily Loads in TMDLs. U.S. Environmental Protection Agency Office of Wetlands, Oceans & Watersheds, June 22, 2007 Draft.

USEPA (United States Environmental Protection Agency). 2001. Nutrient Criteria Technical Guidance Manual: Estuarine and Coastal Marine Waters. On the Internet at: https://www.epa.gov/nutrient-policy-data/criteria-development-guidance-estuarine-and-coastal-waters.

Van Dyke, E., and K. Wasson. 2005. Historical ecology of a central California estuary: 150 years of habitat change. *Estuaries,* 28:173-189.

Wasson, K. R. Jeppesen. C. Endris, D. C. Perry, A. Woolfolk, K. Beheshti, M. Rodriguez, R. Eby, E. B. Watson, F. Rahman, J. Haskins, and B.B. Hughes. 2017. Eutrophication decreases salt marsh resilience through proliferation of algal mats. *Biological Conservation*,. 212: 1-11.

Wasson, K., B. Suarez, A. Akhavan, E. McCarthy, J. Kildow, K. S. Johnson, M. C. Fountain, A. Woolfolk, M. Silberstein, and L. Pendleton. 2015. Lessons learned from an ecosystem-based management approach to restoration of a California estuary. *Marine Policy,* 58:60-70.