Laguna de Santa Rosa Nutrient Analysis
(Revised)

Prepared for

U.S. EPA Region 9 and

North Coast Regional Water Quality Control Board

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1 Introduction

The Laguna de Santa Rosa is the largest tributary of the Russian River and home to threatened and endangered anadromous fish species. The watershed is the metropolitan center of the North Coast Region. Significant land uses include: urban/rural residential, farming, ranching, and forestry. The watershed contains the largest freshwater wetlands complex on the northern California coast, which was designated in 2010 as a "Wetland of International Importance" by the Ramsar Convention (Ramsar, 2015).

Portions of the Laguna de Santa Rosa have been identified as impaired for indicator bacteria, dissolved oxygen, phosphorus, water temperature, sediment, and mercury (among others). These problems are linked to one another in a variety of complex ways as has been laid out in detail in the conceptual models developed for the system (Sloop et al., 2007).

Impairments in the Laguna are in part driven by ongoing external loads of nutrients, sediment, and oxygen-demanding material. However, there is also a significant role played by internal recycling, including regeneration of nutrients from the sediment and creation of biomass (and associated oxygen demand) by plant growth within the Laguna. Infestation of the Laguna by the exotic emergent macrophyte *Ludwigia* spp. plays an important role here. The *Ludwigia* infestation has a feedback effect on water quality as the massive growths slow water and promote deposition of sediment and associated nutrients, while the general shallowing of the system, exacerbated by the macrophytes, is itself a risk factor for additional *Ludwigia* growth (see Section 3). All of these individual factors contribute to exceedances of the Basin Plan (NCRWQCB, 2011) narrative criterion for biostimulatory substances, and all are ultimately related to excess loads of sediment, much of which was delivered under past conditions in the watershed. These sediment loads store and release nutrients and oxygen-consuming organic material and cause shallowing that encourages the growth of *Ludwigia*. Thus, quantifying the sources and status of sediment in the system is a key component for the successful completion of the full suite of pending TMDLs for the Laguna.

Tetra Tech recently completed a report for the North Coast Regional Water Quality Control Board (Regional Board) entitled *Laguna de Santa Rosa Sediment Budget* (Tetra Tech, 2015). That report assembles data and analyses regarding the sources and fate of sediment in the Laguna de Santa Rosa watershed. This companion report summarizes information available on loading of nutrients and organic material to the Laguna. The ultimate goal is to support the development of watershed implementation strategies that can help to simultaneously address the many factors that together contribute to impairment of beneficial uses in the Laguna de Santa Rosa.

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2 Overview of Nutrient-Related Impairments in the Laguna de Santa Rosa

The Laguna de Santa Rosa in Sonoma County, CA is a series of low gradient channels, pools, and wetlands that developed along the western edge of a tectonic depression formed between two tilting crustal blocks (the Santa Rosa block and the Sebastopol block). The system is slow-moving and poorly flushed. As a result it naturally collects runoff, sediment, and nutrients from the surrounding watershed – including urban runoff, agricultural runoff, loads from onsite wastewater systems, and loading from the City of Santa Rosa's Subregional Wastewater Reclamation Facility. It is likely that the Laguna was always a naturally productive system; however, it is also clear that human activities have greatly increased nutrient and sediment loads to the Laguna, as well as altering the hydrology of the system, leading to over-enrichment by nutrients and associated hyper-eutrophication. The waterbody has been officially considered impaired and not fully supporting its beneficial uses since 1990.

2.1 Regulatory Background

Excess nutrients in the Laguna de Santa Rosa result in increased algal and macrophyte growth, which in turn impact dissolved oxygen (DO) levels. Existing regulations regarding water quality are clear on DO objectives, but less clear about nutrient objectives.

The *Water Quality Control Plan for the North Coast Region* ("Basin Plan"; NCRWQCB, 2011) identifies two different sets of numeric water quality objectives for DO. The first consists of three site-specific objectives designed to protect beneficial uses, and the second set is based on life-cycle requirements for aquatic life. The life cycle DO objectives are based on designated aquatic life use ("WARM", "COLD", and "SPWN") (Butkus, 2012d).

Site-specific DO water quality objectives:

- DO levels shall not fall below 7.0 mg/L at any time.
- 90 percent or more of all annual DO levels shall be equal to or exceed 7.5 mg/L.
- 50 percent or more of all annual DO levels shall be equal to or exceed 10.0 mg/L.

Life cycle requirement based DO objectives:

- Waters designated WARM: ≥ 5.0 mg/L minimum DO.
- Waters designated COLD: ≥ 6.0 mg/L minimum DO.
- Waters designated SPWN: ≥ 7.0 mg/L minimum DO.
- Waters designated SPWN: ≥ 9.0 mg/L minimum DO during critical spawning and egg incubation periods.

The Basin Plan does not contain explicit numeric objectives for nutrient concentrations in the Laguna de Santa Rosa; it does, however, contain a narrative water quality objective for biostimulatory substances that states: "Waters shall not contain biostimulatory substances in concentrations that promote aquatic growths to the extent that such growths cause nuisance or adversely affect beneficial uses." This narrative standard implies that some sort of linkage analysis should be undertaken to determine the amount of nutrient and organic matter loading ("biostimulatory substances") that is consistent with holding "aquatic growths" to levels that do not "adversely affect beneficial uses." Determining what levels are appropriate is subject to uncertainty, as is further discussed in Section 6.

The early history of regulatory actions to address nutrient and DO impairments in the Laguna de Santa Rosa is described in the Regional Board's update recommendations for the federal Clean Water Act Section 303(d) List of Impaired Waterbodies (NCRWQCB, 2001):

> *The Laguna de Santa Rosa was added to the 303(d) List in 1990 for high levels of ammonia and low dissolved oxygen (DO) concentrations. A TMDL was completed for the Laguna for ammonia and dissolved oxygen in 1995. The TMDL concluded that high ammonia levels in the Laguna were the result of point and non-point source nitrogen inputs of various forms. Low dissolved oxygen concentrations were a result of inputs of organic matter and nutrients which stimulate algal growth and subsequently cause depressed dissolved oxygen levels when the algae dies and decays.*

The TMDL led to the development of a Waste Reduction Strategy (WRS; Morris, 1995) that focused on nitrogen loading from point and non-point sources and was intended to directly address the ammonia listing as well as reducing excess algal growth, which in turn affects DO levels. Morris noted that there were "artificially high concentrations of nitrogen in the Laguna's water column" and that algal growth potential studies had indicated nitrogen was the most limiting nutrient. The 2011 303(d) List recommendations continue:

> *With the implementation of the WRS and operational improvements at the City of Santa Rosa Waste Water Treatment Plant as well as improvements in waste storage and disposal activities at local dairies, nitrogen inputs to the Laguna were significantly reduced. Following implementation of the WRS and the subsequent attainment of nitrogen ammonia interim concentration goals, as stated in the WRS, the Laguna was removed from the 303(d) List for ammonia and dissolved oxygen in 1998, pursuant to a recommendation by US EPA.*

Despite these improvements, subsequent monitoring revealed that DO levels in the Laguna continued to frequently fall below the Basin Plan minimum DO objective of 7 mg/L and that phosphorus concentrations were elevated. Consequently, California's 2010 303(d) List identified the mainstem of the Laguna de Santa Rosa as not supporting beneficial uses and requiring the development of Total Maximum Daily Loads (TMDLs) for nitrogen, phosphorus, dissolved oxygen, temperature, and sediment. The mainstem of the Laguna de Santa Rosa was also listed as impaired for pathogenic bacteria and mercury, although these impairments are not discussed further in this report. California's 2012 Integrated Report (CWA Section 303(d) List / 305(b) Report; http://www.waterboards.ca.gov/water_issues/programs/tmdl/integrated2012.shtml) removed the listing for nitrogen based on several lines of evidence, including a finding that "phosphorus is the limiting nutrient and reductions in nitrogen loads beyond current levels are not expected to result in added protection of the beneficial use or significant water quality improvements."

2.2 Conceptual Model

Sloop et al. (2007) provide extensive discussions of the impairments of the Laguna de Santa Rosa and the many complex ways that they are related to hydrology, sedimentation, and nutrient loading from the watershed. The overall water quality conceptual model is reproduced in Figure 2-1.

The conceptual model is divided into a series of categories beginning with external loading stressors and other exogenous risk cofactors (A) that progress through a series of response categories (B-F) to beneficial uses (G). The model illustrates potential linkages between categories. The primary response category (B) responds to stressors and exogenous risk cofactors (A) and is linked to changes in the descending categories for physical habitat and water chemistry changes.

Nutrients and organic matter were identified as the primary external stressors for this conceptual model due to unusually high concentrations and external loadings of nitrogen, phosphorus, and organic matter to the Laguna ecosystem. Risk cofactors (such as channel modification) are also stressors that in combination with nutrients can result in degraded conditions.

Reduced DO is linked to external loading of organic matter, and, via algal and macrophyte growth and decay, to external loads of nutrients. Sloop et al. (2007) concluded that the significant factors contributing to low DO "include low flow, low gradient of water, channel morphology, high loadings of nutrients and organic carbon, high sediment oxygen demand, and an abundance of algae and macrophytes."

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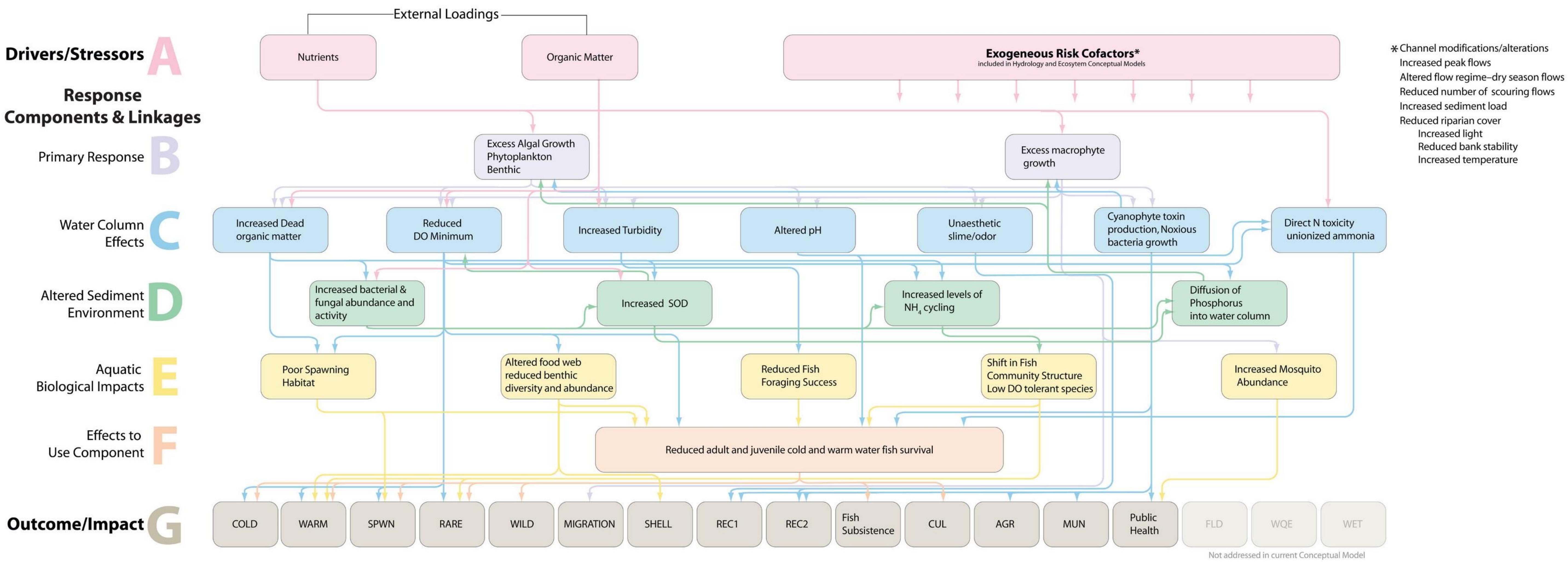

Figure 2-1. Laguna de Santa Rosa Water Quality Overview Conceptual Model (from Sloop et al., 2007)

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3 Nutrients, Sediment, and *Ludwigia* in the Laguna de Santa Rosa

The genus *Ludwigia* comprises a group of invasive aquatic plants from South America, commonly known as water primrose, that have invaded the Laguna de Santa Rosa watershed. The genus contains a number of closely related and difficult to distinguish species. Earlier reports refer to the species present in the Laguna as *Ludwigia hexapetala*. More recent botanical investigations suggest that the invader is either the non-native *Ludwigia peploides* subspecies *montevidensis*, a hybrid, or a species new to California (Sears et al., 2006).

3.1 Impairment of Beneficial Uses Associated with *Ludwigia*

Significant portions of the Laguna de Santa Rosa and its tributary channels experience dense coverage by *Ludwigia*, which trails and floats on the water surface, crowding out most other vegetation (e.g., Figure 3-1).

Figure 3-1. *Ludwigia* Infestation in Bellevue Wilfred Channel Looking Southwest off the Millbrae Road Bridge, June 2007 (from Meisler, 2008)

The *Ludwigia* infestation interferes with management goals in a number of ways, as described by Sears et al. (2006):

> *Invasive Ludwigia is a rapidly growing aquatic shrub currently covering at least 150 acres of shallow-water areas in the Laguna ecosystem. Ludwigia creates a perceived public health threat as densely-growing patches create protective habitat for mosquito species that can carry West*

> *Nile virus (WNV), which reached Sonoma County in 2004. Several Ludwigia-infested areas have seasonal adult mosquito populations more than 100 times greater than normally acceptable. The Marin/Sonoma Mosquito and Vector Control District (MSMVCD) expended more than $80,000 for 2003-04 alone for mosquito control in Ludwigia areas, diverting resources and energy from other parts of the County. Vector Control operators have stated that they have limited ability to control mosquitoes in these areas because dense Ludwigia growth inhibits larvacide applications. If larvacide cannot be properly applied, operators must use pyrethrin-based adulticides, which are less effective overall and tend to have greater negative impacts on fish. In addition, the stagnant eutrophic conditions associated with Ludwigia appear to favor 'foul-water' mosquito species that are superior vectors for West Nile virus (in the genus Culex).*
>
> *Besides threatening public health, WNV has a potential to severely impact resident bird populations. The Laguna de Santa Rosa is a stopover on the Pacific Flyway, and hosts a very diverse bird community. More than a third of the permanent or seasonal avian residents of the Laguna are known to be susceptible to WNV, including the ecologically dominant herons, egrets, raptors, and corvids. Thirty-four of Laguna species are given priority conservation status under the Riparian Habitat Joint Venture, the North American Wetlands Conservation Act (NAWCA) for Coastal California wetlands, and/or California Department of Fish and Game (CDFG) list of Species of Special Concern… Horses on surrounding farms are also vulnerable to the virus … which has unknown effects on other mammalian wildlife.*
>
> *Ludwigia is also a direct threat to the diversity of native plant and animal communities, growing over surrounding vegetation to produce a thick mat of woody perennial stems and decaying plant matter. This mat inhibits the recovery and recruitment of other plants, and eliminates open-water habitats that are important foraging-grounds for birds and other wildlife. As Ludwigia tissue sloughs off and decomposes, microbial growth reduces dissolved oxygen in the water, impacting fish and invertebrate populations. Current efforts to protect and enhance Laguna wetland habitats for migratory birds and waterfowl on the Pacific Flyway are substantially limited by Ludwigia growth, especially in the CDFG's Laguna Wildlife Area where more than 100 acres of floodplain are covered with Ludwigia.*
>
> *Ludwigia may also contribute to flooding in the Laguna system, as plant biomass fills in flood control channels, reducing its capacity for flood-retention and dramatically altering the characteristics of the wetland. Perennial Ludwigia mats slow the movement of water through the system, and likely act as a trap for fine sediments, further reducing capacity and degrading the wetland. Projecting current trends, with no remediation, Ludwigia will potentially lead to a decrease in shallow wetland areas overall, but with increased flooding during storm events.*

The *Ludwigia* infestation is believed to play a key role in the nexus between excess nutrient and sediment loading and impaired DO conditions in the Laguna de Santa Rosa. Dense growths of *Ludwigia*, which are associated with sediment aggradation and excess nutrients as described above in the conceptual model (Figure 2-1), contribute large amounts of biomass, which, upon senescence and decay, deplete DO from the water column. Because *Ludwigia* is an emergent/floating macrophyte, its photosynthetic production contributes little DO to the water column. At the same time, slowing of flow by *Ludwigia* and dense coverage of the water surface reduces the opportunity for reaeration.

3.2 *LUDWIGIA* MANAGEMENT EFFORTS

To address the many threats posed by the *Ludwigia* infestation in the short term, the Laguna de Santa Rosa Foundation undertook a three-year *Ludwigia* control project (Meisler, 2008). In this project, 5.3 miles of channel and 99 acres of floodplain with *Ludwigia* infestation were treated by application of aquatic herbicide followed by mechanical removal of biomass. Herbicide-only applications only temporarily reduced biomass due to *Ludwigia*'s strong regenerative capacities. Further, leaving dead biomass in place creates additional oxygen demand and exacerbates DO problems. Deeper channels treated with herbicide followed by biomass removal retained excellent control for two seasons; however, the dry winter of 2007 resulted in low water levels and some of these areas experienced strong late season regrowth as a result (Meisler, 2008).

The final report of the *Ludwigia* control project reached the following conclusions (Meisler, 2008):

> *Ludwigia is symptomatic of underlying problems in the Laguna. These problems will be solved only through watershed-level efforts including reduction of nutrient, sediment and summer water inputs, as well as physical changes to the problem areas including large-scale restoration. Because these actions take considerable time, efforts should be taken to ensure that ground gained through the project period is not lost.*

Unfortunately, areas treated under the *Ludwigia* control project have since become fully re-infested (personal communication from David Kuszmar, P.E., North Coast Regional Water Quality Control Board, to Jonathan Butcher, Tetra Tech, 12/12/2015), demonstrating the need for "watershed-level efforts" called for by Meisler.

3.3 SENSITIVITY OF *LUDWIGIA* TO ENVIRONMENTAL CONDITIONS

Ludwigia species are recognized as problematic invasives throughout much of the world; however, quantitative analyses of the conditions promoting impairment by *Ludwigia* are scarce. There is general agreement that conditions of slow flow, shallow water, and high nutrient concentrations promote dominance by *Ludwigia* (Fried, 2011; Hussner, 2010); however, quantitative estimates on the degree to which nutrients need to be controlled to reduce impairment by *Ludwigia* are lacking.

One complicating factor is that it is not simply the growth potential of *Ludwigia* that causes impairment of beneficial uses but also the form that the growth takes. The greatest risk to beneficial uses occurs when *Ludwigia* exhibits traits of massive floating mats that choke out other aquatic vegetation, reduce reaeration, and provide breeding grounds for mosquitos and other vectors (Rejmánková, 1992). However, the trailing/spreading trait may respond differently to environmental conditions than the overall growth potential.

Somewhat more work on conditions promoting excessive and deleterious dominance by *Ludwigia* species has been conducted in Europe than in the U.S., as aquarium releases have taken hold and caused problems over many decades in southern and western Europe, starting in France in the 1830s.

The environmental responses of different *Ludwigia* species (*L. peploides, L. hexapetala, L. grandiflora*) are believed to be very similar (Hussner, 2010; Fried, 2011). Their abundance is correlated with increased nutrients and decreased water levels (Hussner, 2010), with optimal growth occurring at water depths of 0.3 – 0.7 m (Dutartre et al., 2007). *Ludwigia* species tolerate a wide range of nutrient conditions, but become dominant under nutrient-rich conditions (Rejmánková, 1992). The European consensus (Fried, 2011) is that nitrogen is generally not limiting on *Ludwigia* growth, while growth can occur over a wide range of phosphorus concentrations. High ambient phosphorus levels are, however, believed to lend *Ludwigia* a competitive advantage (Gerard et al., 2014).

Experimental evaluation of growth potential of *Ludwigia* relative to nutrient concentrations is complicated because the plants can take up nutrients both directly from the water column and through their roots in the sediment. Hussner (2010) examined *Ludwigia* response to eutrophic versus mesotrophic conditions and found that as inorganic N in the sediment decreased from 37 to 5.3 mg-N/kg-solids and inorganic P (as P_20_5) decreased from 112 to 13.6 mg-P/kg-solids, the relative growth rate of *Ludwigia* species declined by about one third. In contrast, Gerard et al. (2014) looked at the sensitivity of *L. grandiflora* and *L. peploides* aboveground biomass to phosphorus concentrations in the water column, contrasting treatments with ambient P concentrations at 30 and 100 μg/L, combined with nutrient poor sediment. A 70 percent reduction in water column P (from 100 to 30 μg/L) resulted in an approximately

33 percent reduction in biomass. The authors, however, note that the “relevance of our study applies to lakes and ponds where the water column has been loaded with phosphorus but the sediment is low in phosphorus…”

It should be noted that the environmental phosphorus concentrations examined by Hussner (2010) and Gerard et al. (2014) are relatively low. The sediment concentrations evaluated by Hussner equate to 0.03 – 0.22 lb-P/ton-sediment, which is much less than is typically observed in suspended sediment in the Laguna watershed (see Section 5.2). Similarly, water column concentrations of phosphorus observed in the Laguna de Santa Rosa are higher than the maximum concentrations evaluated by Gerard et al. (Section 6.2.1).

American studies seem to have focused on the ability of *Ludwigia* species to remove nutrients from the water column, particularly in treatment wetlands, rather than environmental controls on nuisance growth. These studies do demonstrate that *Ludwigia* is readily able to access water column nutrients. For example:

- Ensign et al. (2006) studied instream nutrient uptake of streams in coastal North Carolina. Ephemeral ditches vegetated with *Ludwigia* sp. were found to remove 65-98% of the dissolved nutrient load delivered from agricultural runoff.
- Deaver et al. (2005) studied the removal of dissolved nutrients by *Ludwigia peploides* in mesocosm experiments based on a 4-hour hydraulic retention rate (HRT). The study showed the following mean nutrient removal efficiencies: 25% removal of dissolved phosphorus, 83% removal of ammonia-N, and 40% removal of nitrate-N.
- Jing et al. (2002) studied the effect of varying HRT on dissolved nutrient removal from constructed wetlands planted with *Ludwigia octovalis*. Nutrient removal efficiencies were measured in constructed wetlands with HRTs varied between 1 to 4 days. The study showed the following range of nutrient removal efficiencies: 16-81% removal of dissolved phosphorus and 32-98% removal of ammonia-N.

In sum, there is wide agreement that *Ludwigia* impairs beneficial uses in the Laguna, and that the overgrowth of *Ludwigia* is promoted by sedimentation (that leads to shallowing) and by excessive nutrient loads – but there is little clear basis in the literature for determining exactly what loads of nutrients and sediments would be consistent with reducing the impact of *Ludwigia* to levels sufficient to support beneficial uses.

4 QUAL2Kw Modeling of Nutrients and DO Impairment

4.1 QUAL2Kw Implementation

The QUAL2Kw model (Pelletier and Chapra, 2008) was selected by Regional Board staff to simulate dissolved oxygen (DO) responses for waters in the Laguna de Santa Rosa watershed. QUAL2Kw simulates steady-state hydraulics and diel water quality conditions in a one-dimensional channel, well-mixed vertically and laterally. Two models were developed: one for Lower Santa Rosa Creek to represent lotic reaches in the lower Laguna watershed, and one for the remnant of historic Lake Jonive along the Laguna de Santa Rosa mainstem at Occidental Road near Sebastopol to represent lentic areas with open water (Figure 4-1). Initial and upstream conditions were defined by nutrient concentration data collected by Regional Board staff in June and September 2008 and by diel DO, water temperature, and pH data collected in 2009. The models were applied to simulations representing summer critical low flow periods (Butkus, 2011a). Following model calibration and corroboration, additional analyses were performed by staff and subsequently by Tetra Tech to help answer key remaining questions regarding the role of various assumptions and sources in contributing to nutrient related impairments in the Laguna.

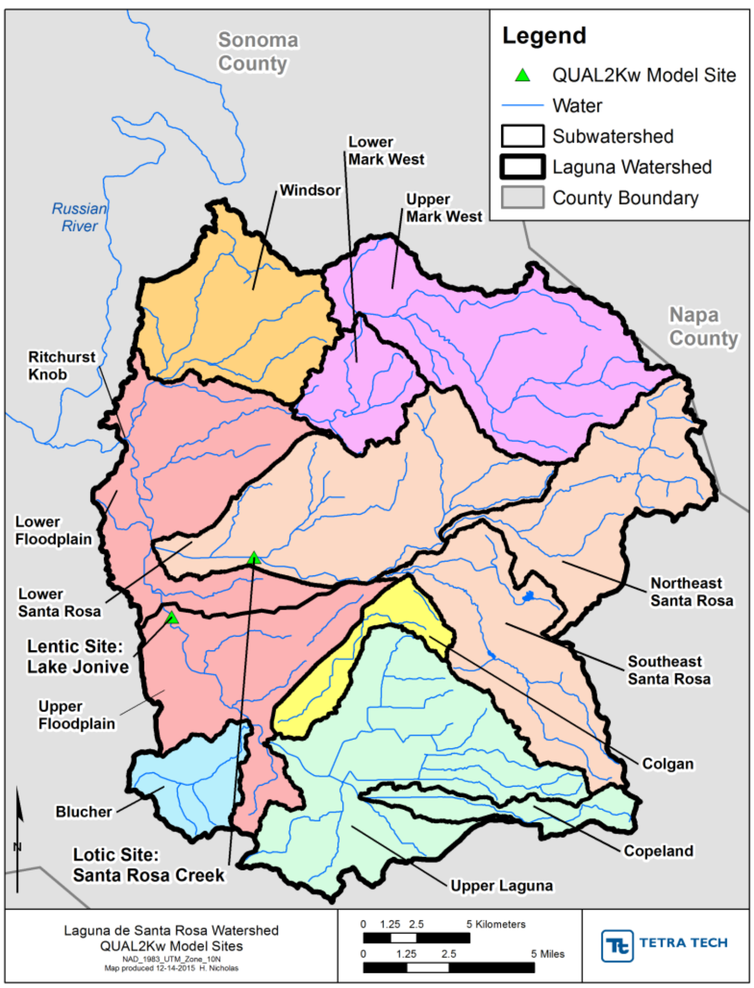

Figure 4-1. Location of QUAL2Kw Model Applications in the Laguna de Santa Rosa Watershed

4.2 MODEL CALIBRATION

The Lower Santa Rosa Creek model was run for 20 days to achieve steady state and calibrated using diel data for August 25-27, 2009. The Lake Jonive model was run for 1,000 days to achieve steady state and calibrated using diel data for September 3-7, 2009. The long run time for Lake Jonive was a result of near-zero flow measurements during this period resulting in very high water residence times.

Calibration of both models required relatively high estimates of sediment oxygen demand (SOD) of 10 g-O_2/m^2/day for Lake Jonive and 2.6 g-O_2/m^2/day for Lower Santa Rosa Creek. Comparison of predicted to observed DO showed no apparent bias for Lake Jonive, but showed a bias of over-prediction of DO for Lower Santa Rosa Creek. Overall, modeled constituents for Lower Santa Rosa Creek were below 5 percent model error with the exception of hourly DO concentrations, which showed a large model error (23.6 percent). Errors in the time course of DO concentrations within the day are likely thrown off by an assumption of zero shading. Critical daily minimum DO for Lower Santa Rosa Creek showed a very low model error (0.05 percent). The Lake Jonive calibration also exhibited a reasonable fit to calibration data, with the largest model discrepancies for phytoplankton, ammonium-N, and nitrate-N (6.1 percent, 5.4 percent, and 5.2 percent, respectively) (Butkus, 2011).

4.3 MODEL CORROBORATION

Regional Board staff conducted a model corroboration exercise for the Lower Santa Rosa Creek model by applying the calibrated model to diel data for July 29 and August 1-2, 2009, while the Lake Jonive model was corroborated using diel data for July 22-26, 2009. For Lower Santa Rosa Creek, the diel pattern of predicted DO generally followed observed values but did not match well with minimum and maximum observed DO. Overall, the model corroboration for Lower Santa Rosa Creek showed a bias of under-predicting DO, in contrast to the pattern of over-prediction observed during model calibration. The Lower Santa Rosa Creek model corroboration showed the highest model errors for organic phosphorus, phytoplankton, and nitrate-N (all greater than 20 percent). For Lake Jonive, the diel pattern of predicted DO generally followed observed values but the model showed high errors for phytoplankton (67.5 percent) and inorganic phosphorus (22.6 percent) (Butkus, 2011a). The discrepancies in predicting observations during the corroboration tests suggest that the calibrated parameter values may not be robust.

4.4 MODEL SENSITIVITY ANALYSES

4.4.1 Input Parameter Sensitivity Analysis

Regional Board staff undertook a variety of sensitivity analyses relative to the assumptions made in the development of the Lake Jonive and Lower Santa Rosa Creek water quality models (Butkus, 2011a). Rate process parameters, initial upstream conditions, and measures of physical features were varied by ±50 percent to develop response sensitivities for predicted DO, phytoplankton, and nutrient concentrations. Results were provided for the six variables exhibiting the highest sensitivity. For Lower Santa Rosa Creek, SOD and bottom algae respiration were the most sensitive parameters for predicting DO (i.e., minimum, maximum, and mean concentrations), while bottom algae respiration and growth were the most sensitive parameters for predicting DO in Lake Jonive. Additionally, upstream and initial hourly temperature and DO concentrations were varied by ±2 degrees Celsius and ±2 mg/L, respectively. The Lower Santa Rosa Creek model was most sensitive to changes in upstream DO for predictions of DO (relative deviations approximately 1 percent), and most sensitive to changes in upstream temperature for predictions of nitrate-N, phytoplankton, and DO (relative deviations for DO were below 5 percent). The Lake Jonive model was sensitive to changes in upstream DO for predictions of minimum and maximum DO concentrations, as well as phytoplankton (relative deviations less than 0.2 percent), and most sensitive to changes in upstream temperature for predictions of nitrate-N and phytoplankton (relative deviations for DO were below 1 percent) (Butkus 2011a).

For Lower Santa Rosa Creek specifically, increasing SOD by +50 percent of the calibrated value (from 2.6 to 3.9 g-O_2/m^2/d) reduced the daily minimum DO from about 6.25 mg/L to about 4.80 mg/L. Decreasing SOD by -50 percent of the calibrated value (from 2.6 to 1.3 g-O_2/m^2/d) increased the daily minimum DO from about 6.25 mg/L to about 7.70 mg/L (Butkus 2011a). This is equivalent to about a 1.1 mg/L increase in daily minimum DO per unit decrease in SOD (g-O_2/m^2/d), and vice versa.

The DO linkage analysis (Butkus 2012c) showed that "oxygen demanding substances in the benthic sediment are the primary mechanism of DO depletion in both lentic and lotic surface water quality models." The response of minimum DO to SOD in the calibrated models (with user-specified reaeration) is shown in the following figures. In both cases, the simulated DO decreases linearly with increasing SOD. (Note that the response shown below for Lake Jonive differs from Figure 11 provided in Butkus, 2012c, which had incorrect assignments of SOD on the x axis).

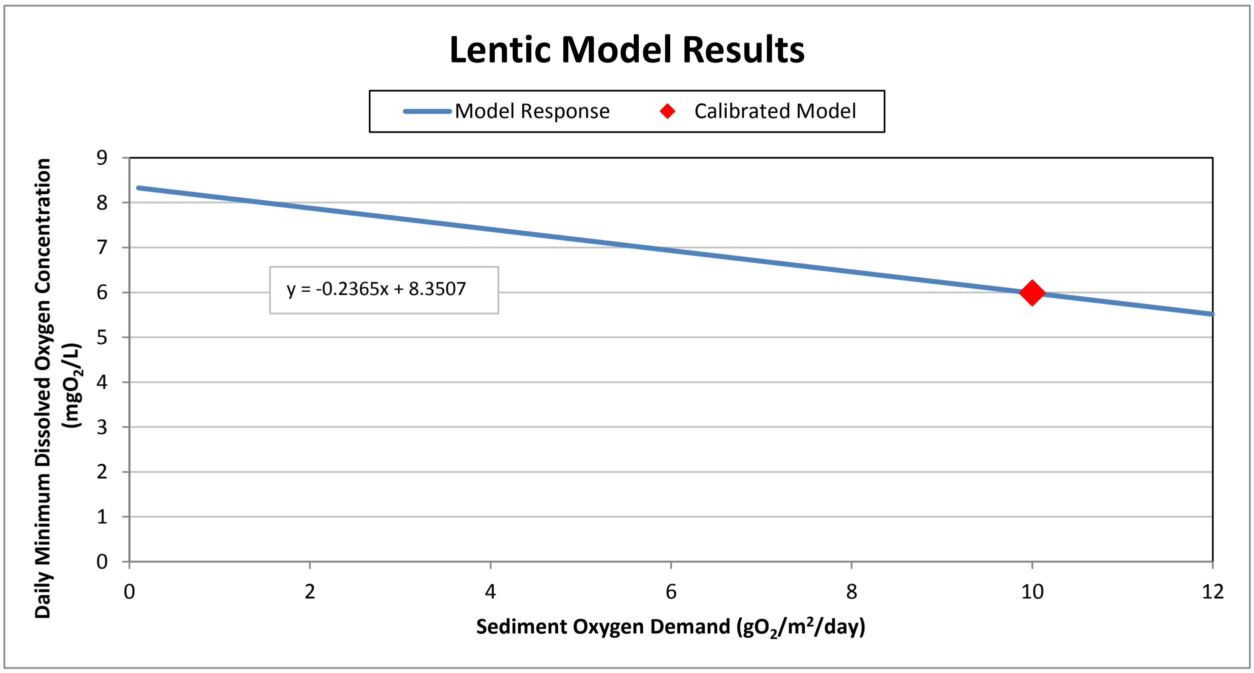

Figure 4-2. Sensitivity of Minimum DO to Sediment Oxygen Demand in the Lake Jonive QUAL2Kw Model

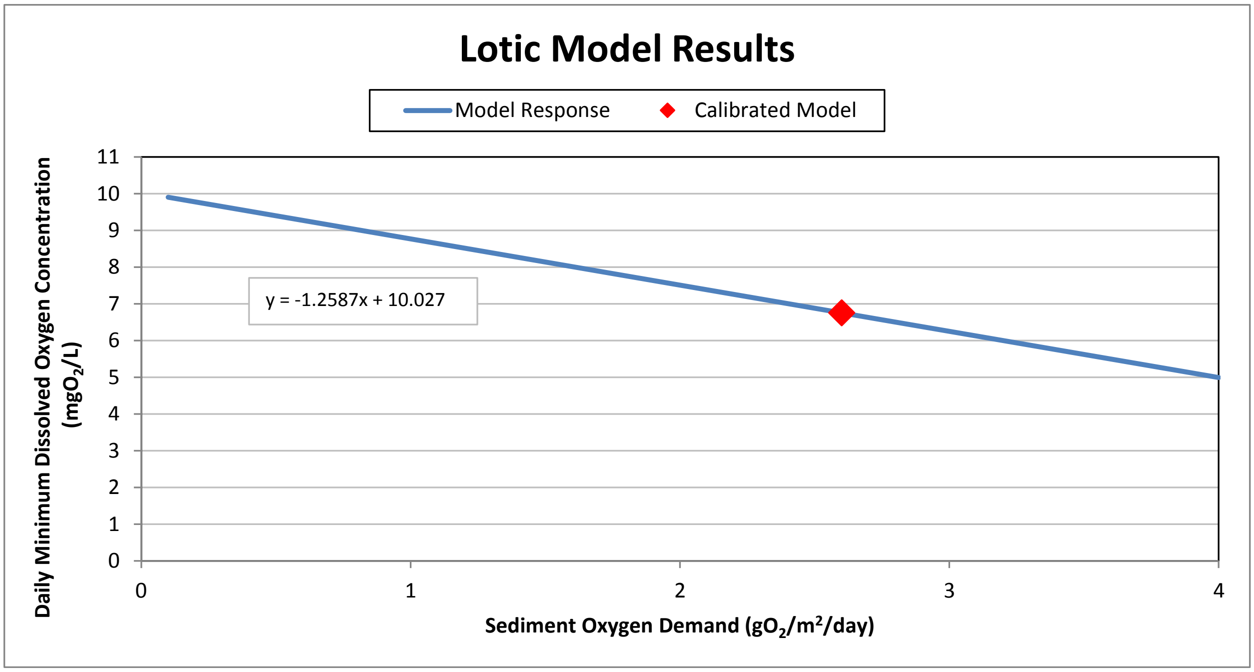

Figure 4-3. Sensitivity of Minimum DO to Sediment Oxygen Demand in the Lower Santa Rosa Creek QUAL2Kw Model

The previous work by Regional Board staff had not examined the sensitivity of the models to the reaeration rate, which is another major component of the DO balance. The default for QUAL2Kw is to use the composite method of Covar (1967) to estimate reaeration rates based on depth and flow; however, this choice is over-ridden if reaeration rates are explicitly entered on the Reach Rates tabs, as was done in the Lower Santa Rosa Creek and Lake Jonive model applications. Regional Board staff apparently calibrated these rates to 2.86 day^{-1} for Lower Santa Rosa Creek and 4.41 day^{-1} for Lake Jonive. These rates differ significantly than those that would be calculated by the Covar method (10.49 day^{-1} for Lower Santa Rosa Creek and 0.05 – 0.63 day^{-1}, depending on whether wind effects are represented, for Lake Jonive). The current specifications with a higher reaeration rate in slowly moving Lake Jonive than in Lower Santa Rosa Creek seems suspect and the estimates are likely a tradeoff with the specified SOD values. For example, a similar fit in Lower Santa Rosa Creek could likely be obtained with higher reaeration and higher SOD. Model sensitivity to reaeration rate is summarized in Figure 4-4 and Figure 4-5.

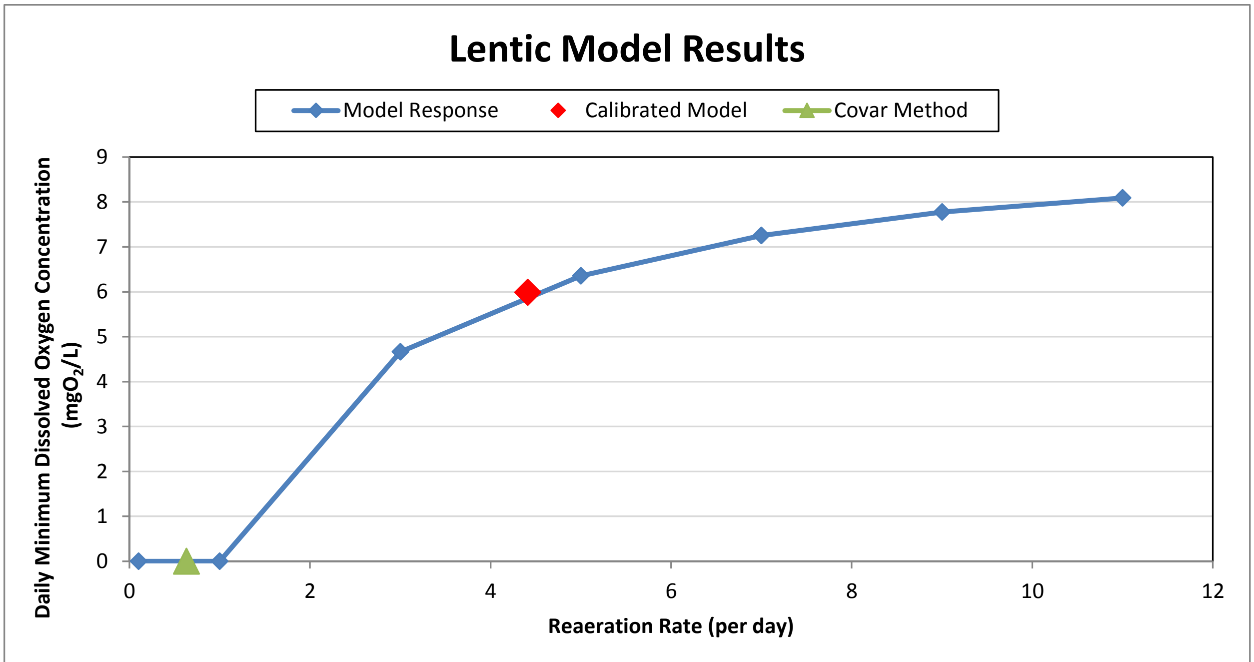

Figure 4-4. Sensitivity of Minimum DO to Reaeration Rate in the Lake Jonive QUAL2Kw Model

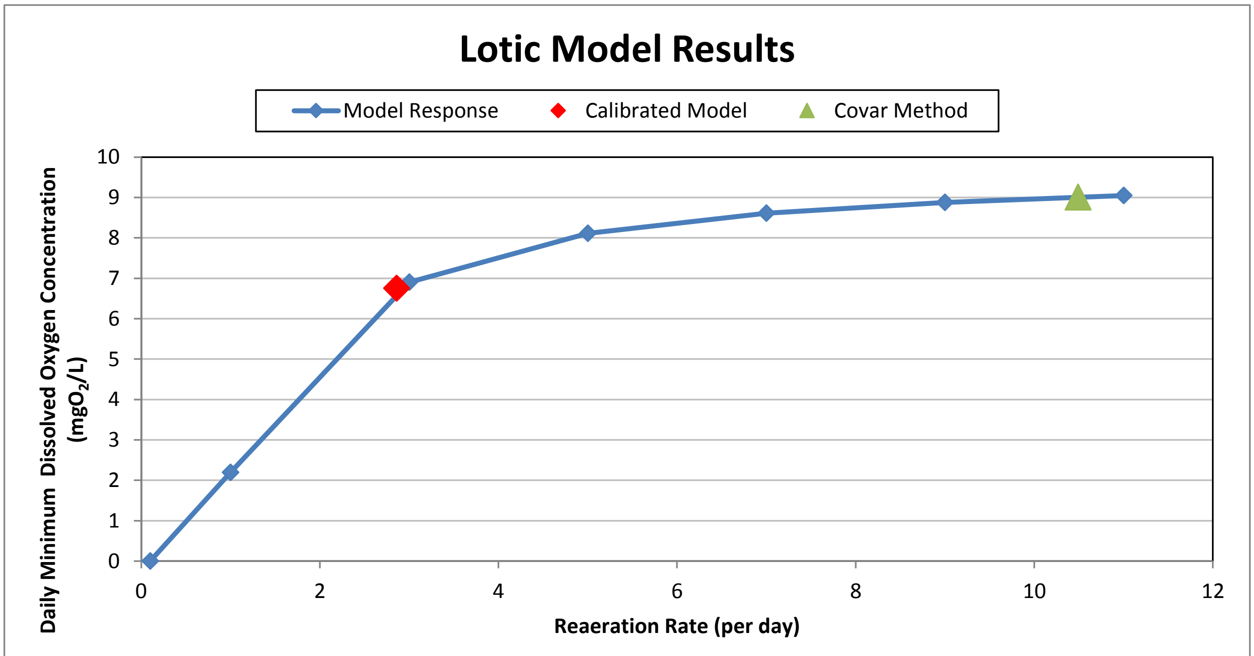

Figure 4-5. Sensitivity of Minimum DO to Reaeration Rate in the Lower Santa Rosa Creek QUAL2Kw Model

Sensitivity of model DO predictions to reaeration rate may be of particular interest in light of the fact that the floating/creeping habit of *Ludwigia* reduces reaeration opportunity at the water surface.

4.4.2 Macrophyte Nutrient Uptake

One concern identified with the QUAL2Kw modeling framework was its ability to adequately simulate the large beds of *Ludwigia* spp. found throughout the Laguna. *Ludwigia* is an emergent macrophyte.

QUAL2Kw does not explicitly simulate macrophytes, but does contain routines that address planktonic and attached benthic algae. The benthic algal routines are often used to approximate the growth of submersed macrophytes, but are not fully applicable to floating or emergent macrophytes, which do not experience the same light limitations.

The original efforts by Regional Board staff at QUAL2Kw model development for Lower Santa Rosa Creek and Lake Jonive (Butkus, 2011a) assumed that *Ludwigia* obtained nutrients for growth from sediments and did not draw nutrients from the water column. A subsequent literature review (Butkus, 2012b) indicated a wide range of dissolved nutrient uptake by *Ludwigia*, so a sensitivity analysis was performed in which the fraction of phosphorus and nitrogen supplied from the water column was varied between zero and 100 percent, both separately and together, in order to simulate nutrient availability to macrophytes. Model results for Lake Jonive showed very little sensitivity in all modeled constituent concentrations as a result of varying dissolved nutrient availability. However, Lower Santa Rosa Creek showed sensitivity for many constituents. With increasing dissolved nitrogen, a large (72 percent) decrease occurred in the diel range of DO concentration accompanied by a large (49 percent) decrease in phytoplankton concentration, suggesting a shift of productivity to macrophytes and away from phytoplankton. Water column concentrations of inorganic phosphorus, ammonia-N, and nitrate-N in Lower Santa Rosa Creek also decreased by 51 percent, 83 percent, and 92 percent, respectively (Butkus, 2012b). Although model results showed that a change in nitrogen availability affected DO concentrations in Lower Santa Rosa Creek due to a shift in productivity, the report did not recommend selection of a different parameter value for macrophyte nutrient availability.

4.4.3 Sediment Flux Rates

QUAL2Kw includes a sediment diagenesis module that computes a steady-state balance of accumulation, decay, and re-release of chemical constituents from the sediment bed. Simulations were run by Regional Board staff to compare sediment flux rates calculated by QUAL2Kw's sediment diagenesis module to the rates determined from model calibration with the diagenesis module off (Butkus, 2012a). The goal of this analysis was to help evaluate the relative importance of current versus historic sediment pollutant sources. In theory, differences in sediment fluxes between calibrated rates and predictions from the diagenesis module should indicate that loading at higher rates prior to the time period simulated is affecting the model. However, because QUAL2Kw is a steady-state model (with diel variability) it is not easy to ascertain whether this excess SOD is due to historical processes or simply loading that has occurred during the previous wet season.

The nutrient flux rates set through model calibration included supplementary SOD and nutrient fluxes to achieve a reasonable representation of the observed DO and nutrient concentrations. For Lake Jonive, calibrated fluxes for sediment ammonium-N, and inorganic P were 29 to 64 percent higher than the rates calculated by the sediment diagenesis module. For Lower Santa Rosa Creek, the ammonium-N fluxes determined in calibration were twice as large as those estimated with the sediment diagenesis model. Both the calibrated model input and the sediment diagenesis model have no sediment flux of inorganic P as the sediment-water interface remains oxygenated. For Lower Santa Rosa Creek, daily minimum, daily maximum, and daily mean DO concentrations were 21 percent, 17 percent, and 20 percent higher, respectively, when using calculated sediment flux rates compared to the calibrated rates. Little change in simulated DO was seen in the Lake Jonive model.

The results of these experiments suggest that legacy sediments in Lake Jonive are responsible for about 50 percent of sediment oxygen demand exerted in the lake, and about 32 percent of the sediment oxygen demand in Lower Santa Rosa Creek. As noted above, however, the nature of the model does not allow determination of whether this loading was recent (e.g., previous wet season) or the net result of decades of loading.

4.5 DO Linkage Analysis and Loading Capacity Assessment

Regional Board staff undertook a linkage analysis with the QUAL2Kw models to establish a relationship between nutrient loads, SOD, and instream water quality response; in particular, DO concentration. Model results of daily minimum DO concentration were used to assess support of aquatic life uses (e.g., SPWN, WRM, and COLD). External and internal nutrient loads were reduced by factors ranging from 10 percent to 90 percent, and increased by 120 percent from current loads to evaluate the effect of nutrient loading on resulting daily minimum DO concentrations. For both Lake Jonive and Lower Santa Rosa Creek, among external loads only reductions in total carbon loading showed a positive improvement in minimum daily DO concentrations. These results were assumed to be due to the high calibrated SOD values in both models (Butkus 2012c).

SOD is caused by the biological oxidation of organic matter on and in the sediment. This organic matter can originate from the watershed (e.g., leaf litter, organic solids) or from internal production of algal and macrophyte biomass that is deposited in the sediment. To isolate the role of SOD in the QUAL2Kw model applications, Regional Board staff set headwaters DO concentrations to just meet DO criteria using observed diel DO cycles. The SOD rate in each model simulation was then reduced until the model results showed that the daily minimum DO criteria were met (Butkus 2012d).

For Lower Santa Rosa Creek, achieving the critical period SPWN criterion required a 70 percent reduction in SOD, and the non-critical SPWN criterion was met with a 12 percent SOD reduction. No SOD reduction was needed to meet the COLD criterion. For Lake Jonive, the WARM minimum DO criterion was met with no SOD reduction, and the COLD (rearing) criterion was met with a 1 percent SOD reduction.

Because both SOD and the range of diel DO fluctuations are linked to algal productivity and respiration, the model output was also used to assess phosphorus reductions to achieve the target SOD reductions. Only reductions in total phosphorus loads were considered for the decrease in algal biomass because it was assumed that nitrogen deficits would be made up by stimulation of nitrogen fixation by native aquatic plants, such as the water fern *Azolla filliculoides*, which is widespread throughout the Laguna de Santa Rosa watershed.

The modeled relationship between total phosphorus and SOD showed that a 7 percent reduction in total phosphorus in Lake Jonive could achieve the 1 percent reduction in SOD needed to meet the COLD (rearing) criterion. The Lower Santa Rosa Creek model results indicated that the needed reduction in SOD could not be met by reductions in total phosphorus loading to control autochthonous biomass alone, and that allochthonous organic material load from the watershed would also need to be reduced to meet the desired SOD reduction. In addition to phosphorus load reductions, the report suggested that benthic sediment removal may also be an effective mechanism for controlling internal loads of total phosphorus by reducing the rate of nutrient recycling (Butkus 2012d).

4.6 Discussion of Model Limitations

Throughout the QUAL2Kw model calibration and corroboration process, several key limitations were identified that will impact the model's effectiveness as a tool for developing quantitative loading capacity estimates in the TMDL process. However, it is agreed that the model can be useful as part of a weight-of-evidence approach that adequately addresses the limitations and uncertainties.

The limited data available to define initial and upstream conditions in the model are recognized as one of the main factors affecting its usefulness. The model was found to be very sensitive to these values which were based on just four measurements of nutrient concentrations at each site, collected during June 2008 (one sample) and September 2008 (three samples). The 2008 grab sample data were combined with diel water quality measurements collected in 2009 (including DO, temperature, pH, and conductivity) to define initial and upstream conditions. While the data are limited in themselves and reflect uneven seasonal sampling, the model linkages are also only valid if the assumption that water quality conditions in 2008 and 2009 were the same is true. Further analysis also showed that stream flows in 2008 and 2009 (mean seasonal low flows) reflected decadal lows and were not necessarily representative of typical summer conditions for the Laguna.

The steady state QUAL2Kw model is set up for summer critical low flow conditions, which does not allow for evaluation of storm event impacts, conditions over time, or the cumulative impacts of wastewater discharges. Diel data were not collected during winter discharge conditions. However, a sensitivity analysis performed using mock wastewater discharges to Lower Santa Rosa Creek and Lake Jonive indicated minimal impacts from wastewater relative to other sources (Butkus, 2012a). Another consideration is that it is not clear how the model would perform over a range of flows since model calibration and corroboration were both performed at low flow. Model sensitivity to flow rate has not been evaluated.

Another of the major concerns with selection of the QUAL2Kw framework, which currently only incorporates bottom algae routines, was its ability to sufficiently simulate *Ludwigia*, an emergent macrophyte. In the initial model calibration and corroboration scenarios, it was assumed that macrophytes only used sediment nutrients for growth and did not draw nutrients from the water column. Sensitivity analyses were performed to begin to evaluate the model response upon increasing the fraction of water column dissolved phosphorus and nitrogen. While the Lake Jonive model showed little sensitivity to changes in these parameters, Lower Santa Rosa Creek showed sensitivity for many constituents in response to increased water column dissolved nitrogen, suggesting a shift of productivity from phytoplankton to macrophytes. Literature rates on water column nitrogen and phosphorus uptake by *Ludwigia* were found to vary widely (15-100 percent) (Butkus, 2012b). Consequently, no modifications were made to the original calibration and corroboration in response to these findings. The resulting degree of uncertainty combined with limitations on representative modeling of the effect of *Ludwigia* on water quality in the Laguna emphasize the limits of the model's application as a quantitative tool.

5 Modeling of Nonpoint Nutrient Loading Sources

A process-based watershed model that is calibrated and validated for nutrients is not available for the Laguna de Santa Rosa watershed – in large part due to limitations in data available for model development and calibration. Potter and Hiatt (2009) did develop a Soil and Water Assessment Tool (SWAT) model of watershed runoff and sediment loading; however, the comparison of model predicted sediment loads and concentrations to observed data was poor (monthly Nash-Sutcliffe coefficients of model fit efficiency less than zero and a large percent low bias relative to observed values). That model has not been further developed for nutrients, and such development is not recommended unless a better sediment calibration can be achieved due to the importance of sediment transport in the delivery of phosphorus loads.

Lacking a process-based watershed model that can simulate nutrient loading, Regional Board staff developed an empirical, data-based model of nutrient loading. This tool, the Land Cover Loading Model (LCLM) is described in Section 5.1. An alternative analysis for phosphorus loading based on association with sediment is presented in Section 5.2.

5.1 Land Cover Loading Model

5.1.1 Development of the Land Cover Loading Model

The Land Cover Loading Model (LCLM) was developed by Regional Board staff beginning in 2010. The original memorandum documenting the LCLM (Butkus, 2010) has been revised in draft several times, but a final revised version has not yet been formally released. A revised draft markup (Butkus, 2013) is the most recent version available as of this writing and is relied on in this discussion.

Butkus (2013) describes the development of the pollutant loading functions in the LCLM as follows:

> *Regional Water Board staff selected nutrient loading rates for each land cover category based on sampling pollutant concentrations in runoff from forest, rangeland, crop and pasture, orchards and vineyards, non-sewered residential, sewered residential, and commercial land covers from 2009-2010 (NCRWQCB, 2010).*
>
> *Samples were collected during both wet and dry periods as identified by federal guidance (USEPA, 1992) and federal regulations (40 CFR 122.21(g)(7)(ii)). The LCLM addresses the distribution of loads between wet and dry periods. Dry period loads were derived from the measured pollutant concentration data and estimates of the base flow at the sampling location. Wet period loads were derived from measured pollutant concentration data and sampling location flows estimated as the combined base flow plus the storm event runoff flow. Statistical hypothesis test results showed significant differences between wet period and dry period concentrations and between the land covers assessed (NCRWQCB, 2010)…*
>
> *Loading rates were estimated from a limited numbers of water samples collected from catchments representing various land covers in the Laguna watershed (NCRWQCB, 2010). Butkus (2010) showed that the samples collecting was biased to larger flows that the historical distribution of flows. To account the bias from the limited samples, Monte Carlo simulations were conducted to provide estimates of the range of loads across the full range of climatic conditions (extreme dry to extreme wet periods). Monte-Carlo simulation was used to address the potential bias from using only flows observed during sampling events. Monte Carlo simulation is a stochastic method that accounts for the inherent variability of data sets. Monte Carlo simulations rely on*

> *repeated random sampling to obtain numerical results as distributions. The probability distributions from the flow, precipitation, and concentration records were applied to the loading models repeatedly until descriptive statistics converged in the resulting loading distribution…*
>
> *Table 3* [in Butkus, 2013 – see Table 5-1 below] *compares the median and mean loading rate values. The central tendency for years with wet days represents the 2-year return period. A 2-year return period storm has a 50% chance of occurring each year and is represented at the center of the x-axis on the load duration curves. The 2-year return period was estimated to be 13.4% wet days per year. The 2-year return period was used to estimate annual loads.*

Sample sites used for land use monitoring were selected randomly from a set of candidate sites with the requirement that at least 50 percent of the drainage area was occupied by the target land use (NCRWQCB, 2010). Sampling was done at road crossings. Drainage areas associated with the individual sample sites are not given; however, the median size appears to have been on the order of 800 acres.

5.1.2 LCLM Results

The summary table of loading rates provided in the LCLM report (Table 5-1) presents dry weather and wet weather loading rates as if the weather type occupied the full year. The annual result is then the mixture of the two types based on the two-year return period (i.e., 13.4% wet days, as noted above).

Table 5-1. Median and Mean Unit Area Loading Rates by Land Cover in the LCLM

Land Cover	Period	Total Phosphorus (lb/ac/yr)		Total Nitrogen (lb/ac/yr)	
		Median	Mean	Median	Mean
Forest	Dry	0.04	0.43	0.25	2.74
	Wet	0.64	1.87	3.86	12.37
	Annual	0.12	0.62	0.73	4.03
Cropland and Pasture	Dry	0.39	5.27	0.23	8.37
	Wet	11.97	57.01	30.60	258.27
	Annual	1.94	12.19	4.29	41.78
Rangeland	Dry	0.10	1.07	0.62	6.37
	Wet	4.73	17.88	15.73	37.93
	Annual	0.72	3.32	2.64	10.59
Residential with Sewer	Dry	0.17	1.65	0.89	8.74
	Wet	9.00	15.28	37.71	70.43
	Annual	1.35	3.47	5.81	16.99
Orchards and Vineyards	Dry	0.29	4.40	0.59	5.27
	Wet	6.24	15.53	19.85	48.77
	Annual	1.09	5.89	3.16	11.08
Residential without Sewer	Dry	0.19	2.27	0.48	6.32
	Wet	10.13	30.19	40.65	73.69
	Annual	1.51	6.00	5.85	15.33
Commercial	Dry	0.09	0.98	0.57	7.25
	Wet	7.14	12.74	43.35	66.08
	Annual	1.03	2.55	6.29	15.12
Other Land Uses	Dry	0.18	2.30	0.52	6.44
	Wet	7.12	21.50	27.39	81.08
	Annual	1.11	4.86	4.11	16.42

Note: Table from Butkus (2013). Analyses omitted one “Residential without Sewer” sample from 10/15/2009 due to QA/QC concerns (personal communication from Steve Butkus, North Coast Regional Water Quality Control Board, to Jonathan Butcher, Tetra Tech, 12/28/2015). Annual loading rates are based on a 2-year return period (50% probability to exceed).

Table 5-1 gives both mean (average) and median (50th percentile) results. The data distributions shown in Butkus (2013) exhibit a strong skew, with mean concentrations often higher than the 75th percentile load. To protect against undue influence by outliers, Butkus (2013) recommended use of the median load rates as the best indicator of the central tendency of the distribution. Estimated total phosphorus loads by this method are summarized in Table 5-2, and, not surprisingly, are dominated by wet period loads. Estimated total nitrogen loads are shown in Table 5-3 and are about three times greater than the phosphorus loads.

On the whole (i.e., per unit acre), LCLM results found that “Cropland and Pasture” had the highest total phosphorus loading rates during wet and dry periods. The highest total nitrogen loading rate during the dry period was for “Residential with Sewer,” and the highest total nitrogen loading rate during the wet period was “Commercial”. Wet period loading rates are always significantly higher than dry period loading rates for all land use classes. When total annual loads by land use area are tabulated, the highest total phosphorus loads (Table 5-2) and total nitrogen loads (Table 5-3) are attributed to Cropland and Pasture. An analysis of the Cropland Data Layer for 2013 reveals that vineyards cover approximately 7% of the entire watershed area, while other crop types cover less than 1%. As the LCLM created a separate land cover class for “Orchards and Vineyards,” the “Cropland and Pasture” land cover class is about 99% Pasture and 1% Cropland.

Table 5-2. LCLM Estimates of Typical Total Phosphorus Loads by Land Cover

Land Cover	Laguna Watershed Land Cover Area (acres)	Median Wet Period Load (lb/yr)	Median Dry Period Load (lb/yr)	Median Annual Load (lb/yr)
Forest	48,315	4,150	1,734	5,884
Cropland & Pasture	44,458	71,130	14,903	86,032
Rangeland	21,767	13,777	1,949	15,726
Residential with Sewer	15,348	18,474	2,255	20,729
Orchards and Vineyards	12,825	10,699	3,239	13,938
Residential without Sewer	9,857	13,346	1,580	14,926
Commercial	8,577	8,191	682	8,873
Other Land Uses	1,461	1,391	230	1,622
Total Watershed	162,608	141,159	26,571	167,730

Note: Table from Butkus (2013). Analyses omitted one “Residential without Sewer” sample from 10/15/2009 due to QA/QC concerns (personal communication from Steve Butkus, North Coast Regional Water Quality Control Board, to Jonathan Butcher, Tetra Tech, 12/28/2015). Annual loading rates are based on a 2-year return period (50% probability to exceed). Note that land use categories and acreages reported here differ somewhat from Tetra Tech’s analyses.

Table 5-3. LCLM Estimates of Typical Total Nitrogen Loads by Land Cover

Land Cover	Laguna Watershed Land Cover Area (acres)	Median Wet Period Load (lb/yr)	Median Dry Period Load (lb/yr)	Median Annual Load (lb/yr)
Forest	48,315	24,927	10,271	35,198
Cropland & Pasture	44,458	181,867	8,745	190,611
Rangeland	21,767	45,779	11,742	57,520
Residential with Sewer	15,348	77,378	11,821	89,199
Orchards and Vineyards	12,825	34,032	6,542	40,575
Residential without Sewer	9,857	53,579	4,128	57,706
Commercial	8,577	49,708	4,241	53,948
Other Land Uses	1,461	5,351	656	6,006
Total Watershed	162,608	472,620	58,145	530,764

Note: Table from Butkus (2013). Analyses omitted one "Residential without Sewer" sample from 10/15/2009 due to QA/QC concerns (personal communication from Steve Butkus, North Coast Regional Water Quality Control Board, to Jonathan Butcher, Tetra Tech, 12/28/2015). Annual loading rates are based on a 2-year return period (50% probability to exceed). Note that land use categories and acreages reported here differ somewhat from Tetra Tech's analyses.

Examination of the Regional Board staff's calculation sheets demonstrates that selection of the mix of wet and dry periods at the 50th percentile year provides a reasonable approximation of average hydrologic conditions across all years analyzed for the wet-dry distribution (1931 – 2009); however, the interquartile range on the Monte Carlo analysis for nutrient loading conditions is large (for example, the median annual loading rate for total phosphorus from cropland has an interquartile range of 0.7 to 6.2 lb/ac/yr). An important source of uncertainty is the use of the median load results from the Monte Carlo analysis for nutrient loading conditions rather than the mean (average). The median is appropriate for the stated goal of estimating "typical" loads during a "typical" year; however, the bulk of sediment and phosphorus loading may occur during large events. In addition, it is possible that the monitoring on which the LCLM is based could be biased low for more intensive land uses because the selection requirement was that the drainage area contain at least 50 percent of the target land use. Thus, sampling for a vineyard site could represent a mix of relatively high loads from vineyards with lower loads derived from vacant rangeland. Given these concerns, we recalculated LCLM loading estimates based on mean, rather than median loading rates (Table 5-4). The resulting estimates are about 5 times greater for total phosphorus and six times greater for total nitrogen than the typical-year loads based on the median analysis; however, they are subject to high uncertainty and influenced by data outliers.

Table 5-4. LCLM Estimates of Mean Annual Phosphorus and Nitrogen Loads by Land Cover

Land Cover	Laguna Watershed Land Cover Area (acres)	Mean Annual Total Phosphorus Load (lb/yr)	Mean Annual Total Nitrogen Load (lb/yr)
Forest	48,315	30,048	194,642
Cropland & Pasture	44,458	541,935	1,857,418
Rangeland	21,767	72,246	230,545
Residential with Sewer	15,348	53,230	260,687
Orchards and Vineyards	12,825	75,524	142,157
Residential without Sewer	9,857	59,153	151,102
Commercial	8,577	21,865	129,672
Other Land Uses	1,461	7,100	23,990
Total Watershed	*162,608*	*861,102*	*2,990,213*

Note: Tabulation is based on the land use categories and acreages in Butkus (2013), which differ somewhat from Tetra Tech's analyses. Analyses omitted one "Residential without Sewer" sample from 10/15/2009 due to QA/QC concerns (personal communication from Steve Butkus, North Coast Regional Water Quality Control Board, to Jonathan Butcher, Tetra Tech, 12/28/2015).

5.1.3 LCLM Corroboration

The strongest corroboration for the performance of the LCLM is comparison to two other methods of estimating phosphorus loads that demonstrate that LCLM load predictions are reasonable. Those comparisons are provided below in Section 5.4. Additionally, Butkus (2013) presented a number of lines of evidence to corroborate LCLM results. These are summarized immediately below along with some supplementary comparisons developed by Tetra Tech.

5.1.3.1 Staff Literature Review

Regional Board staff conducted a literature review to compare published land use-based loading rates with the results of the LCLM. Unit area nutrient loading rates for total nitrogen and total phosphorus were obtained from some fifteen different published sources as they specifically applied to the land use categories of forest, rangeland, cropland and pasture, orchard and vineyard, sewered residential, non-sewered residential, and commercial lands. Literature values used for comparison were assumed to represent a median hydrologic year, and can vary widely depending on precipitation, source activity, and soils. The LCLM memorandum (Butkus, 2013) does not compute statistics on the literature values, but rather compares results visually by plotting mean values alongside LCLM results. Visual inspection of the literature values plotted against the LCLM results shows general agreement on loading rates by land use. In general, a wider distribution of mean loading values were seen from literature for nitrogen than for phosphorus, with the greatest range seen for commercial lands, orchards and vineyards, and rangeland. The ranges of reported mean loading rates for total phosphorus and total nitrogen are compared to LCLM results in Table 5-5.

Table 5-5. Range of Mean Annual Loading Rates Reported in Published Literature Compared to LCLM Median Annual Loading Rates

Land Use Category	Literature Mean Total Phosphorus (lb/ac/yr)	LCLM Median Total Phosphorus (lb/ac/yr)	Literature Mean Total Nitrogen (lb/ac/yr)	LCLM Median Total Nitrogen (lb/ac/yr)
Forest	0.05 – 0.21	0.12	0.64 – 2.55	0.73
Rangeland	0.09 – 1.01	0.72	0.89 – 14.75	2.64
Cropland and Pasture	0.45 – 1.39	1.94	1.78 – 8.92	4.29
Orchard and Vineyard	0.45 – 1.78	1.09	1.78 – 14.75	3.16
Non-Sewered Residential	0.18 – 1.33	1.51	0.89 – 8.90	5.85
Sewered Residential	0.36 – 1.86	1.35	1.78 – 9.42	5.81
Commercial	0.36 – 3.04	1.03	1.78 – 17.55	6.29

Note: LCLM analyses omitted one “Residential without Sewer” sample from 10/15/2009 due to QA/QC concerns (personal communication from Steve Butkus, North Coast Regional Water Quality Control Board, to Jonathan Butcher, Tetra Tech, 12/28/2015).

The LCLM median annual loading rates recommended for application by Butkus (2013) generally fall within the range of mean loading rates by land use reported in published literature; however, the LCLM total phosphorus loading rates for the cropland and pasture and non-sewered residential land use categories are greater than the upper ends of the literature ranges.

5.1.3.2 Uncalibrated GWLF Model

Regional Board staff used an uncalibrated application of the Generalized Watershed Loading Functions (GWLF) model (Haith et al., 1992) as another line of evidence to corroborate LCLM results (Butkus, 2013). GWLF is designed to provide scoping level estimates of pollutant loading from mixed land cover watersheds using NRCS curve number and Universal Soil Loss Equation calculations. Staff combined measured concentrations of baseflow nutrients from dry weather samples collected in 2008 in the Laguna de Santa Rosa watershed with an uncalibrated representation of storm runoff and erosion (Butkus, 2010). Staff concluded the LCLM and GWLF models overall produce qualitatively “similar” estimates of annual pollutant loads, with a wide variation between tributary load estimates. Overall, the GWLF model over-estimated both total phosphorus and total nitrogen loads as compared to the LCLM estimates.

5.1.3.3 Comparison to TMDL Analyses

As noted above in Section 2.1, a previous TMDL for nitrogen was developed for the Laguna de Santa Rosa by Morris (1995) based on an assessment conducted by CH2M Hill (1994). Pollutant loading rates were estimated for land use categories based on storm and dry weather sampling completed in 1994 for multiple storm events and dry periods. Unit area loading rates for nitrogen differ from those estimated by the LCLM. Nitrogen loads from non-irrigated agriculture, estimated at 13.1 lb/ac/yr, are similar to the LCLM mean estimate for orchards and vineyards of 11.1 lb/ac/yr; however, the estimates for urban/developed land uses (2.4 lb/ac/yr plus 0.7 lb/ac/yr for areas on septic systems) and undeveloped land (0.1 lb/ac/yr) are much lower than the estimates produced by the LCLM. The differences are likely mostly due to the limited sampling data available for the 1994 effort.

Few other nutrient TMDLs that provide nonpoint source nutrient loading rate estimates are available for the immediate region. However, the Central Coast Regional Board has several completed nutrient TMDLs which may provide relevant comparisons to the Laguna de Santa Rosa: Pajaro River, Lower

Salinas River, and Santa Maria River. These regional nutrient TMDLs generally address: nitrate, low dissolved oxygen, chlorophyll *a*, and orthophosphate (CCRWQCB, 2015; 2013a; 2013b).

The Central Coast nutrient TMDLs used the EPA's Spreadsheet Tool for Estimating Pollutant Loads, version 4.0 (STEPL; Tetra Tech, 2011), which predicts annual loading based on event mean concentrations for storm runoff events. The assumed nutrient event mean concentrations for each land use category for the Central Coast TMDLs are derived from a variety of literature sources (Table 5-6).

Table 5-6. Nutrient Event Mean Concentrations by Land Use Specified for STEPL Modeling in Central Coast TMDLs (CCRWQCB, 2015; 2013a; 2013b)

Land Use	Santa Maria TMDL		Salinas TMDL		Pajaro TMDL	
	N (mg/L)	P (mg/L)	N (mg/L)	P (mg/L)	N (mg/L)	P (mg/L)
Agriculture	11.4[1,2]	0.64[1]	11.4[1,2]	0.64[1]	11.4[1,2]	0.64[1]
Forest	0.2[3]	0.1[3]	0.2[3]	0.1[3]	0.2[3]	0.1[3]
Rangeland	0.25[4]	0.27[2]	0.25[4]	0.27[2]	0.25[4]	0.21[2]
Urban	1.5-2.5[3]	0.15-0.4[3]	4.0[5]	0.53[1]	1.9-3.62[6]	0.15-0.5[6]

Data sources cited in TMDL documents:

1-Southern California Coastal Water Research Project, Technical Report 335 (Nov. 2000) Appendix C
2-US Dept. of Agriculture MANAGE database
3-STEPL default values for a specific land use type
4-California Rangeland Watershed Laboratory
5-Average for western cities from Shaver et al., 2007
6-Natonal Stormwater Quality Database (version 3, 2 Feb 2008)

The resulting annual unit-area nutrient loads reported in each of the Central Coast TMDLs are summarized in Table 5-7 and compared to the LCLM annual median and mean loading rates from Table 5-1. For nitrogen, the Central Coast values tend to fall between the LCLM median and mean loading rates for agricultural and urban land uses, but are lower than the LCLM rates for rangeland and forest land uses. LCLM phosphorus loads also appear to be higher than the Central Coast estimates for undeveloped lands. Higher loads in the LCLM are likely directly related to differences in annual precipitation – Santa Rosa receives about 31 inches per year, whereas Salinas and Santa Maria receive only 15.5 and 14 inches per year, respectively.

Comparison on a concentration basis between the Central Coast STEPL modeling event mean concentration assumptions and wet weather samples from the 2009-2010 Laguna de Santa Rosa watershed intensive monitoring used by Regional Board staff as the basis for the LCLM is shown in Table 5-8. For total phosphorus, the concentrations are in general agreement, except that the Laguna de Santa Rosa monitoring revealed higher average concentrations for runoff from rangeland than the STEPL estimates, which were taken from a general USDA database. Nitrogen results are more discrepant, with the Laguna de Santa Rosa watershed monitoring yielding lower results for agriculture, and higher results for forest and rangeland. The difference for agriculture seems reasonable, as the Central Coast TMDLs are for areas that grow irrigated salad and fruit crops on land that often has drain tiles, which promote nitrogen export. Higher concentrations for forest and rangeland may reflect the greater rainfall in the Laguna de Santa Rosa area, which both results in more atmospheric deposition of N and greater leaching.

Table 5-7. Comparison of Estimated Unit-Area Nutrient Loads for Central Coast TMDLs to LCLM Estimates

Land Use	Santa Maria TMDL		Salinas TMDL		Pajaro TMDL		LCLM		
	N (lb/ac/yr)	P (lb/ac/yr)	N (lb/ac/yr)	P (lb/ac/yr)	N (lb/ac/yr)	P (lb/ac/yr)	Comparable Land Use	Median/ Mean N (lb/ac/yr)	Median/ Mean P (lb/ac/yr)
Agriculture	40.03	2.60	18.25	3.02	19.25	2.10	Cropland and Pasture	4.29/41.78	1.94/12.19
							Orchard & Vineyard	3.16/11.08	1.09/5.89
Urban	10.32	1.59	5.34	0.71	6.10	0.72	Commercial	6.29/15.12	1.03/2.55
							Residential with Sewer	5.81/16.99	1.35/3.47
							Residential no Sewer	5.85/15.33	1.51/6.00
Rangeland	0.83	0.75	1.75	0.66	0.73	0.48	Rangeland	2.64/10.59	0.72/3.32
Forest	0.38	0.19	0.21	0.08	0.24	0.12	Forest	0.73/4.03	0.12/0.62

Source: CCRWQCB, 2015; 2013a; 2013b. LCLM analyses omitted one “Residential without Sewer” sample from 10/15/2009 due to QA/QC concerns (personal communication from Steve Butkus, North Coast Regional Water Quality Control Board, to Jonathan Butcher, Tetra Tech, 12/28/2015).

Table 5-8. Comparison of STEPL Event Mean Nutrient Concentrations from Central Coast Nutrient TMDLs to Average Wet Weather Concentrations from Laguna de Santa Rosa Watershed Monitoring

Land Use	Total Phosphorus (mg/L)		Total Nitrogen (mg/L)	
	Central Coast TMDLs	Laguna de Santa Rosa Monitoring	Central Coast TMDLs	Laguna de Santa Rosa Monitoring
Agriculture	0.64	0.55 – 1.84	11.4	1.73 – 9.14
Forest	0.1 – 0.2	0.08	0.2	0.52
Rangeland	0.21 – 0.27	0.67	0.25	1.41
Urban	0.15 – 0.53	0.19 – 0.93	1.5 – 4.0	1.04 – 2.37

Note: Ranges cover separate land use subcategories (e.g., orchard, vineyard, and cropland within agricultural class.) LCLM analyses omitted one “Residential without Sewer” sample from 10/15/2009 due to QA/QC concerns (personal communication from Steve Butkus, North Coast Regional Water Quality Control Board, to Jonathan Butcher, Tetra Tech, 12/28/2015).

5.1.3.4 Dry Weather Loading from Independent Samples

An additional corroboration test performed by Butkus (2013) was based on samples collected during the summer of 2008 near the mouth of each of the major tributaries draining to the Laguna. These samples were not used in LCLM development. Summer 2008 was a drought period, so the samples were assumed to represent dry weather loading conditions. Weighted average loads based on land use in each tributary and LCLM unit area dry weather loading rates were compared to loads estimated for each tributary using 2008 measured concentrations and flows scaled from the USGS gaging location at Trenton-Healdsburg Road. Statistical tests did not identify any significant differences in median or mean loads from the two methods in a majority of tests, suggesting that the LCLM estimates are consistent with measured dry-weather loads.

5.2 Phosphorus Loading as a Function of Sediment Loading

Inorganic phosphorus loads from the land surface are particle-reactive, and primarily move with sediment. Organic phosphorus loads, which are mostly associated with detrital plant material, also move with sediment. Typically, watershed nonpoint source loads of dissolved phosphorus are small relative to particulate loads on an annual basis[1]. Therefore, a separate line of analysis was developed to relate phosphorus loads to sediment loading in the watershed, as described in the sediment budget report (Tetra Tech, 2015).

5.2.1 Upland Loads

Estimates of sediment loads can be converted to estimates of phosphorus loads through application of sediment potency factors (pounds of phosphorus per ton of sediment). The 2009-2010 land-use monitoring conducted by Regional Board staff included total phosphorus, dissolved phosphorus, and total suspended sediment. For the purposes of the approximate analysis of load based on sediment transport, we assumed that only sorbed phosphorus is associated with sediment load and that the sorbed load transported during larger flow events is the major component of annual phosphorus loading to the Laguna; and further that wet period loads will dominate the total loading process. In many instances within this sampling effort TSS was not fully quantified and was often reported at the detection limit of 15 mg/L[2]. Therefore, in relation to load prediction, we analyzed the phosphorus potency only on wet period samples where the reported TSS concentration was greater than 15 mg/L.

Phosphorus potency was computed for each valid sample, and averages and medians were calculated for land use classes employed in both the LCLM applications (as reported in Table 1 of Butkus, 2013) and the RUSLE sediment load modeling (as reported in Table 5-3 of Tetra Tech, 2015). Given the influence of outliers on the averages and the fact that most sediment moves during storm events, the median wet weather potencies were selected for further analysis.

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[1] Although relatively small on an annual basis, it is worth noting that dissolved phosphorus loads from sources such as agricultural irrigation and recycled water runoff, dry weather MS4 discharges, and leaky septic systems can account for a significant fraction of dry weather nutrient loads. These loads are often discharged during periods of low flow and under critical water quality conditions, when they are most likely to be bioavailable to growing macrophytes and algae.

[2] NCRWQCB (2010) incorrectly reports the TSS detection limit as 0.015 mg/L (personal communication from David Kuszmar, P.E., North Coast Regional Water Quality Control Board, Watershed Protection Division to Jonathan Butcher, Tetra Tech, 12/12/2015).

Table 5-9. Phosphorus Sediment Potency in Laguna de Santa Rosa Land Use Monitoring Data, 2009 - 2010 Wet Weather Samples with TSS > 15 mg/L

RUSLE Land Use	LCLM Land Use	Average Wet Potency (lb-P/ton-sediment)	Median Wet Potency (lb-P/ton-sediment)
Cropland	Cropland and Pasture	61.00	14.92
Pasture	Cropland and Pasture	61.00	14.92
Grass	Cropland and Pasture	61.00	14.92
Vineyard	Orchard and Vineyard	26.70	8.17
Water/Wetland	N/A	0	0
Forest	Forest	8.86	3.00
Developed	Commercial, Residential with Sewer, Non-Sewered Residential	29.02	7.04
Barren	Rangeland	15.43	3.98
Shrubland	Rangeland	15.43	3.98

Analyses omitted one “Residential without Sewer” sample from 10/15/2009 due to QA/QC concerns (personal communication from Steve Butkus, North Coast Regional Water Quality Control Board, to Jonathan Butcher, Tetra Tech, 12/28/2015).

The phosphorus potencies reported in Table 5-9 appear elevated for land uses affected by human activity. National surveys (Parker et al., 1946; Mills et al., 1985) report that the typical P_2O_5 concentration of surface soils in this part of California should be approximately in the range of 0.10 – 0.19%. As P_2O_5 is 44 percent P, the likely background phosphorus content of soils should be on the order of 0.88 to 1.67 lb/ton. Because phosphorus is preferentially sorbed to fine clay particles, eroded sediment should be enriched relative to the total soil content. The enrichment ratio varies with the intensity of events and is a function of the clay content of the soil; however, for annual analysis enrichment ratios in the range of 2 – 5 are common (Mills et al., 1985; Novotny and Olem, 1994). This suggests that phosphorus potency ought to be in the range of 2 to 8 lb/ton. Both average and median potencies are well above this range for cropland and pasture land use categories, while only the average estimates appear clearly elevated for the vineyard and developed land use categories.

Applying the median wet weather potency factors to the RUSLE delivered sediment estimates in Table 5-3 of Tetra Tech (2015) results in the loading estimates shown below in Table 5-10. The distribution by land use is shown graphically in Figure 5-1.

Table 5-10. Estimated Upland Phosphorus Load based on RUSLE Sediment Yield and Sediment Potency

Land Cover	Laguna Watershed Land Cover Area (acres)*	RUSLE Sediment Delivery Rate (t/ac/yr)	RUSLE Sediment Yield (tons/yr)	Median Wet Potency (lb-P/ton Sediment)	Phosphorus Load from Sediment Delivery (lb-P/yr)
Cropland	405	0.138	56	14.92	837
Pasture	142	0.075	11	14.92	159
Grass	47,199	0.075	3,548	14.92	52,945
Vineyard	10,264	0.138	1,419	8.17	11,598
Water/Wetland	1,123	0.025	28	0.00	0
Forest	33,152	0.112	3,709	3.00	11,113
Developed	49,334	0.119	5,872	7.04	41,325
Barren	28	0.107	3	3.98	12
Shrubland	19,427	0.135	2,625	3.98	10,446
Total	*161,075*	*0.107*	*17,271*	*7.44*	*128,435*

* Excluding drainage area below Ritchurst Knob. Note that the land use tabulations used here (Tetra Tech, 2015) differ from those developed for the LCLM (Butkus, 2013).

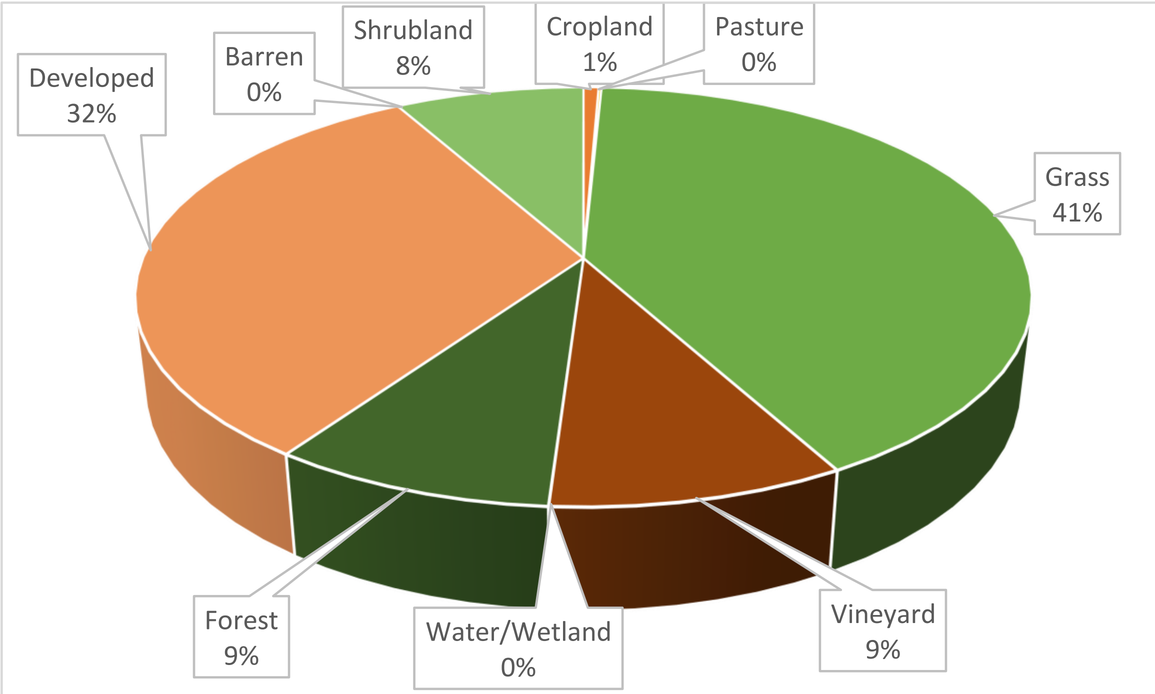

Figure 5-1. Source Attribution of Annual Upland Phosphorus Load for the Laguna de Santa Rosa Watershed Estimated from RUSLE Analysis

The phosphorus load from the entire watershed estimated using the sediment potency approach (128,435 lb/yr, as reported above in Table 5-10) is somewhat lower than the LCLM load based on medians (167,730 lb/yr, as reported in Table 5-2), and much smaller than the LCLM load based on averages (861,102 lb/yr, as reported in Table 5-4). Individual land uses are delineated differently in the LCLM and the RUSLE sediment potency applications. In particular, the sum of the RUSLE-based Cropland, Pasture, and Grass land-cover areas together best match up with the "Cropland & Pasture" land cover category in LCLM, with a total estimated phosphorus load that is substantially lower than the LCLM model. Estimates of loading from vineyards, the sum of developed land, and shrub or rangeland areas are similar between the two approaches, although somewhat lower for the RUSLE-based sediment potency approach. The RUSLE-based analysis attributes a greater load to forest, even though the tabulation of forest area is less. Some differences between the two methods are expected due to the uncertainty in estimating event mean concentrations and sediment potency factors from limited data; however, there may also be a systematic under-estimation using the sediment potency approach as it does not account for dissolved-phase loads. In addition, the RUSLE-based analysis does not account for phosphorus associated with sediment that derives from sources other than upland erosion, as discussed in the next section. Analysis of total nitrogen loads using the sediment potency approach was not attempted because a large fraction of the nitrogen load is expected to move in soluble form.

5.2.2 Phosphorus and Other Sources of Sediment Loads

The sediment budget for the Laguna de Santa Rosa watershed (Tetra Tech, 2015) suggests that only about 19% of the total sediment load in the watershed is derived from upland erosion processes described by the RUSLE model. Of the remainder, the largest source is channel degradation. Other sources include colluvial soil creep, gully formation, and road-related erosion.

The monitoring data described in NCRWQCB (2010) occurred at roads and with contributing drainage areas that appear to be on the order of 800 acres. The monitoring data are thus likely, to a large extent, to include the effects of these other sources of sediment loading, especially the road, soil creep, and gully sources. Tetra Tech (2015) estimated that much of the channel degradation load originates on old alluvial fans in areas relatively downstream in the drainage network and nearer to the Laguna de Santa Rosa. Thus, the channel degradation source (estimated at 56 percent of the total sediment load) is likely to be largely omitted from the 2008-2010 monitoring results.

If the road, soil creep, and gully sediment loads are included within the monitoring results then the estimated sediment potencies would be more properly applied to the sum of these sediment sources plus the upland sediment load. This could increase the estimated total phosphorus load by a factor of about 2 or 3, but is highly uncertain.

Sediment derived from channel degradation will also have an associated phosphorus load. Concentrations associated with channel degradation in the watershed are not precisely known, but are likely approximated by the stream sediment samples for the area contained in the National Geochemical Survey Database (Grossman, et al., 2008). Five individual samples from the Laguna de Santa Rosa watershed range from 0.05% to 0.129% P by weight, with a median of 0.0895%. The average for Sonoma County as a whole is 0.07%. The median for the Laguna watershed converts to a sediment potency of 1.79 lb/ton. Based on the estimated channel degradation sediment load of 47,589 t/yr (Table 8-1 in Tetra Tech, 2015), this could account for an additional phosphorus load of up to 85,184 lb/yr. Compensating for this increase, there will also be decreases due to sediment removal associated with SCWA channel maintenance activities.

5.3 FLUX Analysis of Nutrient Loads in Santa Rosa Creek

The Sonoma County Water Agency (SCWA) has collected nutrient samples in Santa Rosa Creek at Fulton Road since 1997 in accordance with its municipal separate storm sewer system (MS4) stormwater permit. From 1997 to 2009 samples were collected on an annual basis during storm events. Since 2010, SCWA has collected samples on a monthly basis at a variety of flow conditions. The samples prior to 2010 are primarily of value for quantifying nitrogen species as there appears to have been a high detection limit for phosphorus (1 mg/L) between 1999 and 2009. Phosphorus was quantified at levels less than 1 mg/L in 1997 – 1998, but flow gaging is not available for those years. The one valid total phosphorus concentration from the 1999 – 2009 time period is incorporated into the analysis.

The drainage area upstream of Fulton Road (excluding the Matanzas Reservoir and Lake Ilsanjo drainages) contains 29,701 acres, or roughly one-sixth of the Laguna watershed area. Unfortunately, flow is not monitored directly at Fulton Road. The USGS gage on Santa Rosa Creek is located a short distance downstream, at Willowside Road; however, Piner Creek, which drains a significant portion of the western part of the City of Santa Rosa, enters between these two locations. This limits the ability to evaluate loads from the SCWA monitoring. An approximate estimate was made by combining the monitoring with USGS gaging of flows in Santa Rosa Creek at Willowside Road, prorated for the difference in drainage area (factor of 0.9579), to develop estimates of nutrient loading using the FLUX tool.

FLUX is an interactive program developed by the U.S. Army Corps of Engineers' Waterways Experiment Station and designed for use in estimating loads of nutrients or other water quality constituents from concentration monitoring data (Walker, 1999). The model may be used to estimate long-term load estimates or daily series based on relationships between concentration and flow. Data requirements include (1) point-in-time water quality concentration measurements, (2) flow measurements coincident with the water quality samples, and (3) a complete flow record (mean daily flows) for the period of interest.

Estimating constituent mass loads from point-in-time measurements of water-column concentrations presents many difficulties. Load is determined from concentration multiplied by flow, and while measurements of flow are continuous (daily average), only intermittent (e.g., monthly or tri-weekly grab) measurements of concentration are available. Calculating total load therefore requires "filling in" concentration estimates for days without samples and extrapolating point-in-time measurements to whole-day averages. The process is further complicated by the fact that concentration and flow are often highly correlated with one another, and many different types of correlation may apply. For instance, if a load occurs primarily as a result of nonpoint soil erosion, flow and concentration will tend to be positively correlated; that is, concentrations will increase during high flows, which correspond to precipitation-washoff events. On the other hand, if load is attributable to a relatively constant point discharge, concentration will decrease as additional flow dilutes the constant load. In most cases, a combination of processes is found.

Preston et al. (1989) undertook a detailed study of advantages and disadvantages of various methods for calculating annual loads from tributary concentration and flow data. Their study demonstrates that simply calculating load for days when both flow and concentration have been measured and using results as a basis for averaging is seldom a good choice. Depending on the nature of the relationship between flow and concentration, more reliable results may be obtained by one of three approaches:

1. *Averaging Methods:* An average (e.g., yearly, seasonal, or monthly) concentration value is combined with the complete time series of daily average flows;
2. *Regression Methods:* A linear, log-linear, or exponential relationship is assumed to hold between concentration and flow, thus yielding a rating-curve approach; and
3. *Ratio Methods:* Adapted from sampling theory, load estimates by this method are based on the flow-weighted average concentration times the mean flow over the averaging period and performs best when flow and concentration are only weakly related.

No single method provided superior results in all cases examined by Preston et al.; the best method for extrapolating from limited sample data depends on the nature of the relationship between flow and concentration, which is typically not known in detail. Preston et al. show that *stratification* of the sample data and analysis method, however, can reduce error in estimation. Stratification refers to dividing the sample into two or more parts, each of which is analyzed separately to determine the relationship between flow, concentration, and load. Sample data are usually stratified into high- and low-flow portions, allowing a different relationship between flow and load at low-flow (e.g., diluting a constant base load) and high-flow regimes (e.g., increasing load and flow during nonpoint washoff events). Stratification could also be based on time or season to account for temporal or seasonal changes in loading.

The FLUX package implements all three of the general approaches described by Preston et al., including a number of variants on the regression approach, and allows flexible specification of stratification. FLUX also calculates error variances for the estimates.

SCWA monitoring, coupled with area-adjusted USGS gage records for Santa Rosa Creek, enables the estimation of annual loads for total phosphorus, total Kjeldahl nitrogen (organic nitrogen plus ammonium nitrogen), nitrate nitrogen, and ammonium nitrogen. Total nitrogen estimates can be assembled as the sum of Kjeldahl nitrogen and nitrate nitrogen (nitrite nitrogen concentrations are typically minimal in oxygenated waters). For each constituent, a reasonable fit was obtained (based on analysis of the residual coefficient of variation) using FLUX method 6 with stratification at or near median flow. Method 6 is a bias-corrected regression of concentration on flow, implemented on a daily basis.

Results of the FLUX analysis, based on flows for WY 1999-2014 and using interpolation to residuals on a 15-day time window, are shown in Table 5-11.

Table 5-11. FLUX Estimates of Annual Nutrient Loads in Santa Rosa Creek at Fulton Road based on SCWA Monitoring for 2010 - 2014

Parameter	Interpolated Load (lb/yr)	Flow-weighted Concentration (mg/L)
Total Phosphorus	29,920	0.172
Nitrate-N	80,757	0.473
Total Kjeldahl-N	212,628	1.225
Ammonium-N	39,826	0.235
Total N	293,384	1.698

5.4 Comparison of Loading Estimates for Santa Rosa Creek

The FLUX analysis provides an independent estimate of loading in Santa Rosa Creek passing Fulton Road, although, as described above, the estimate is imprecise because the flow gage is not at the same location. The FLUX estimates can be combined with estimates using the LCLM and sediment potency approaches (Sections 5.1 and 5.2) calculated using only the area upstream of Fulton Road and omitting the area upstream of Matanzas Reservoir and Lake Ilsanjo, which are likely to trap most phosphorus load.

The various load estimates for total P and total N above Fulton Road are compared in Table 5-12. For total phosphorus, the load estimates based on upland sediment potency are less than those obtained from FLUX and from the LCLM using median concentrations, while estimates from the LCLM using mean concentrations are much higher. The FLUX estimates of total N load fall about midway between those obtained from the LCLM using median concentrations and those obtained using average concentrations. The fact that the sediment potency estimates of phosphorus load are lower than the other estimators may be due to the omission of dissolved phosphorus loads as well as phosphorus associated with other sources of sediment load, such as channel degradation. As discussed in Section 5.2.2, phosphorus associated with road, soil creep, and gully sediment loads could increase the upland sediment-associated phosphorus load estimate by a factor of about 2.3, while additional loads may come from channel erosion. These additional loads would likely increase the estimate from the upland sediment potency method to be somewhat greater than the estimate based on LCLM with median concentrations and FLUX.

Table 5-12. Comparison of Annual Loading Rate Estimates for Santa Rosa Creek above Fulton Road

	LCLM, Average Concentration	LCLM, Median Concentration	Upland Sediment Potency Method	FLUX, 1999 - 2014
Total P (lb/yr)	115,650	27,125	19,655	29,920
Total N (lb/yr)	437,252	103,214	NA	293,384

Note: LCLM and Upland Sediment Potency Method estimates omit land area upstream of Lake Ilsanjo and Matanzas Creek Reservoir.

In sum, estimates of nonpoint source nutrient loading in Santa Rosa Creek and in the Laguna de Santa Rosa watershed as a whole are highly uncertain. Several lines of evidence suggest that the LCLM provides a reasonable, if imprecise, order-of-magnitude estimate of nutrient loads. FLUX analysis of SCWA monitoring at Fulton Road suggests that the actual nutrient loads may lie between the LCLM estimates based on median concentrations and those based on average concentrations. Additional monitoring in small watersheds with relatively homogenous land use would likely improve the accuracy of the LCLM and would also provide data that could in the future support calibration of a process-based nutrient delivery model.

5.5 Loading Rates prior to European Settlement

Regional Board staff performed a detailed analysis to estimate land use coverage in the watershed prior to European settlement (Butkus, 2011b). Under pre-settlement conditions, about 18 percent of the watershed area was in oak savanna. Representative nutrient loading rates for this land use were assigned by Butkus (2010) based on data from an un-grazed watershed near the town of Hopland in 1999-2000 reported by Dahlgren et al. (2001).

Using land use coverage provided by Butkus (2011b) we recalculated nutrient loads for pre-settlement conditions using both the median and average annual load rates (Table 5-13). The median loads differ slightly from those presented by Butkus (2013), but we agree that pre-settlement loads were likely an order of magnitude less than those under current conditions.

Table 5-13. Nutrient Loads for Conditions prior to European Settlement Estimated by the LCLM

Pre-Settlement Land Cover	Land Cover Area (acres)*	Median Annual P Load (lb/yr)	Average Annual P Load (lb/yr)	Median Annual N Load (lb/yr)	Average Annual N Load (lb/yr)
Open Water	2,963	0	0	0	0
Perennial Wetland	16,964	0	0	0	0
Riverine Wetland	5,058	0	0	0	0
Rangeland	24,182	17,471	80,262	63,902	256,124
Oak Savanna	28,832	2,499	6,327	11,831	30,148
Forest	83,076	10,118	51,667	60,522	334,681
Total	*161,075*	*30,088*	*138,256*	*136,255*	*620,953*

* Excluding drainage area below Ritchurst Knob.

Butkus (2013) notes that loads of nutrients from the watershed that were actually delivered to the Laguna de Santa Rosa under conditions prior to European settlement were likely much less than the loads estimated by the LCLM. In contrast to current conditions in which flood control channels are designed to move water off the Santa Rosa Plain, the pre-settlement land coverage (Butkus, 2011b) contained many disconnected channels that discharged into seasonal wetlands on alluvial fans, and there were extensive amounts of both riparian and permanent wetlands.

Regional Board staff estimated that a total of 73 percent of the upland phosphorus load and 87 percent of the upland nitrogen load was likely “assimilated” in wetlands prior to reaching the Laguna mainstem under pre-settlement conditions (Butkus, 2013). These estimates appear highly speculative as they are based on estimates reported in EPA compilations of the median removal efficiency of riparian wetland buffers for nitrogen (USEPA, 2005) and riparian buffers in general for phosphorus (USEPA, 1993), along with application of the simple PREWet model of nutrient removal in perennial wetlands (Dortch and Gerald, 1995). These references primarily address removal efficiencies through managed riparian buffers and constructed wetlands in a modern landscape and may differ significantly from the performance of the natural system that existed pre-settlement. Removal efficiencies are likely to have been lower because the source strength in runoff was lower. Reported percent removal in BMPs is strongly dependent on source water concentration, and many treatments exhibit an “irreducible concentration” below which net removal is essentially non-existent (Wright Water Engineers and Geosyntec Consultants, 2007). In addition, trapping of nutrients in wetlands is in large part not permanent as nutrients that settle out or are converted to biomass can later be remobilized in large flow and scour events or converted back to dissolved form in hypoxic sediments. The only pathways for permanent removal in a wetland or riparian area would be through removal of sediment or biomass (which would by definition be non-existent or minor under pre-settlement conditions) or denitrification that converts nitrogen compounds to nitrogen gas. It appears clear that the large area of wetlands present under pre-settlement conditions would reduce the rate of nutrient transport into the Laguna mainstem, but the net effect would likely be smaller than the estimates provided above, which can be considered to provide an approximate upper bound on removal. Even without accounting for assimilation by wetlands, phosphorus loads under pre-settlement conditions are estimated to be only 18 percent of present day loads (using the LCLM median-basis analysis).

6 Nutrient Numeric Endpoints Analysis

6.1 THE CA NNE APPROACH

Evaluating nutrient concentrations within a waterbody alone is not an effective means of assessing the impacts of eutrophication on beneficial uses. The State Water Resources Control Board has not yet adopted a final policy on nutrient criteria for streams, but is in the process of developing a Nutrient Numeric Endpoints (NNE) approach. In support of this process, Tetra Tech (2006) developed a draft technical support document for California NNE. The proposed CA NNE approach is based on an evaluation of the risk of impairment of beneficial uses in response to nutrient loading, rather than assigning fixed nutrient concentration targets. Such an approach recognizes that many site-specific factors influence the expression of impacts of nutrients on uses, and also that nutrient-caused impairment may be due to a combination of ongoing water column loads and previously loaded nutrients stored in waterbody sediment.

The CA NNE approach also addresses natural background nutrient concentrations: Nutrients occur naturally, and vary in relationship to soils, geology, and land cover. It is inappropriate to set a nutrient criterion that is lower than natural background for a specific waterbody, as could occur through application of ecoregional statistical criteria.

The CA NNE approach recognizes that there is no clear scientific consensus on precise levels of nutrient concentrations or response variables that result in impairment of a designated use. To address this problem, waterbodies are classified in three categories, termed Beneficial Use Risk Categories (BURCs). BURC I waterbodies are not expected to exhibit impairment due to nutrients, while BURC III waterbodies have a high probability of impairment due to nutrients. BURC II waterbodies are in an intermediate range, where additional information and analysis may be needed to determine if a use is supported, threatened, or impaired. The BURC categories and CA NNE assessment process are summarized in Figure 6-1.

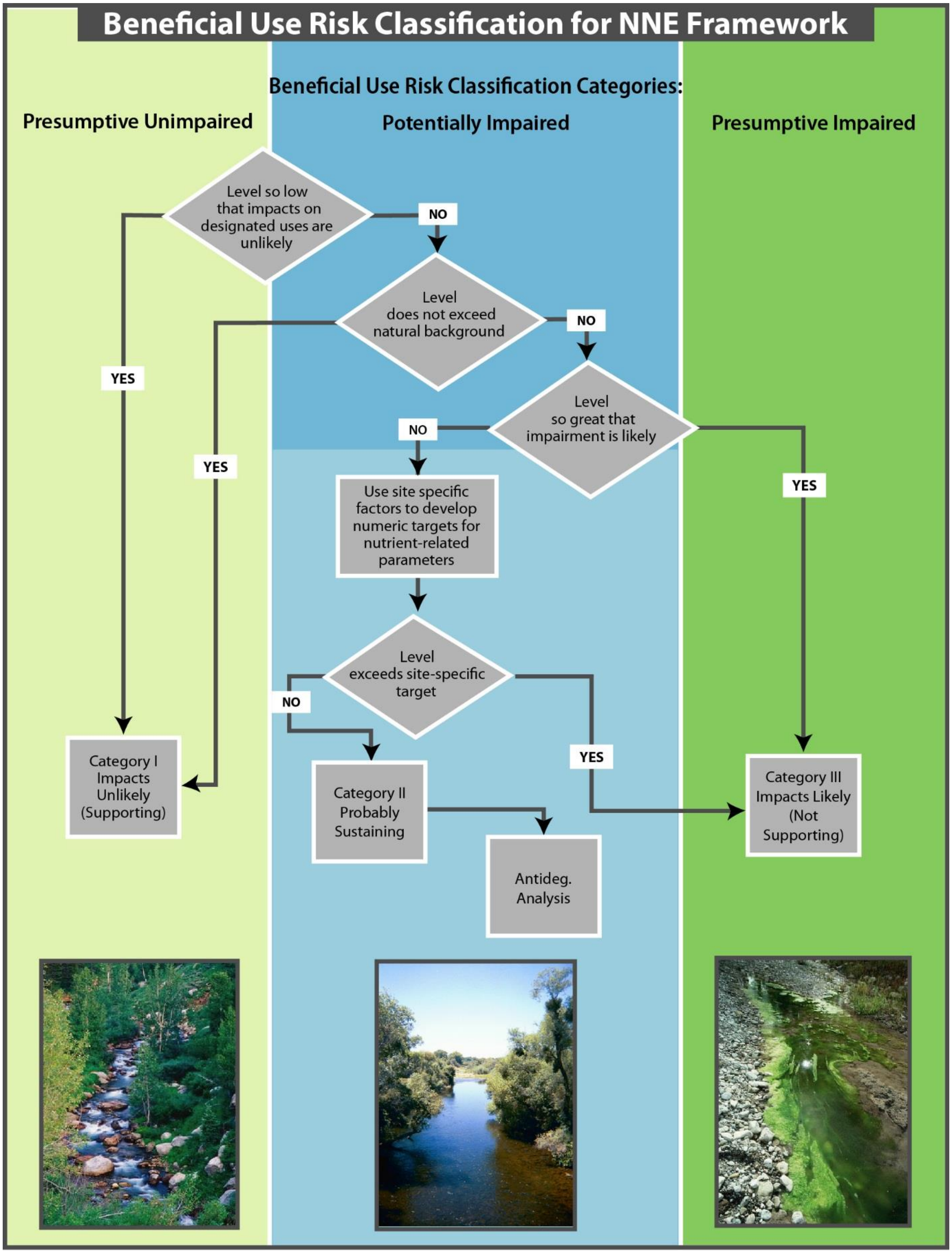

Figure 6-1. Beneficial Use Risk Classification (BURC) Categories and Nutrient Assessment Process (from Tetra Tech, 2006)

Tetra Tech (2006) lists consensus targets for response indicators defining the boundaries between BURC I/II and BURC II/III. These were generally defined as measures of effect and include DO, pH, and chlorophyll *a* concentrations (benthic and planktonic). For DO and pH, the numeric criteria in the local Basin Plan apply and can be considered as equivalent to the BURC II/III boundary. The proposed numeric endpoints for algal biomass indicators are shown in Table 6-1.

Table 6-1. Nutrient Numeric Endpoints for Algal Biomass Indicators – Beneficial Use Risk Category (BURC) Boundaries: I / II and II / III (adapted from Tetra Tech, 2006)

RESPONSE INDICATOR	RISK – CATEGORY BOUNDARY	BENEFICIAL USE and NUMERIC ENDPOINT						
		COLD	WARM	REC-1	REC-2	MUN[1]	SPWN	MIGR
Benthic Algal Biomass in streams/rivers (mg chl-*a*/m^2) -Maximum	I / II	100	150	**C**	**C**	100	100	**B**
	II / III	150	200	**C**	**C**	150	150	**B**
Planktonic Algal Biomass in Lakes and Reservoirs (as µg/L chl-*a*)[2] – summer mean	I / II	5	10	10	10	5	**A**	**B**
	II / III	10	25	20	25	10	**A**	**B**

A = No direct linkage to impairment of beneficial use

B = More research needed to quantify linkage; not applicable at this time

C = Addressed by Aquatic Life Criteria

[1] For application to zones within waterbodies that include drinking water intakes

[2] Reservoirs may be composed of zones or sections that will be assessed as individual waterbodies

The CA NNE development team evaluated macrophyte density as a potential endpoint, but concluded that measures of macrophyte density were “not useful as a general numerical effect measure” to address nutrient numeric endpoints due to the many factors controlling macrophyte growth and the general lack of models that are able to accurately predict macrophyte responses to nutrients.

Tetra Tech (2006) also documents a set of relatively simple spreadsheet tools to assist in evaluating the translation between response indicators and nutrient concentrations or loads. These simplified tools were intended to provide a starting place for the estimation of site-specific nutrient endpoints, and are intended to be superseded by calibrated site-specific models where available. The two spreadsheet tools respectively address benthic algae in wadeable streams and planktonic algae in lakes and reservoirs. Neither tool simulates the response of macrophytes to nutrient eutrophication, and neither is fully appropriate to the slow-moving and macrophyte-dominated waters of the Laguna de Santa Rosa.

The State Board in 2007 issued a staff report containing recommendations on screening levels of nutrient and chlorophyll *a* concentrations for use in the 303(d) listing process (SWRCB, 2007). Values selected for rivers and streams were based on four case studies conducted by Tetra Tech using the benthic biomass spreadsheet described in Tetra Tech (2006); values for lakes and reservoirs are taken from recommendations compiled from the literature in Welch and Jacoby (2004). We do not recommend using the screening levels for streams derived in this way for detailed analyses of specific individual streams because:

- The results are derived from a small set of applications with widely varying environmental conditions, ranging from the Klamath River to Malibu Creek;
- The benthic biomass tool on which the numbers are based is still under review, and more recent research suggests the nutrient levels predicted by the tool as consistent with attaining measures of effect, such as target benthic algal biomass, may need to be revised (e.g., Fetscher et al., 2014);

- The benthic biomass tool contains multiple model options that provide differing results;
- Results are likely not applicable to the slow-moving, macrophyte-dominated waters of the Laguna de Santa Rosa.

In contrast, the lake and reservoir targets summarized by Welch and Jacoby (2004) represent a broad consensus in the literature as to the approximate boundary between eutrophic and hypereutrophic conditions. These correspond to a total nitrogen (TN) concentration of 1.2 mg/L and a total phosphorus (TP) concentration of 0.1 mg/L, intended to correspond to a chlorophyll *a* target of 25 µg/L (all values expressed as growing season median or geometric mean concentrations).

6.2 Lines of Evidence

6.2.1 Water Quality Monitoring

Water quality monitoring in the Laguna de Santa Rosa through 2010 is described in detail by Fitzgerald (2013) and those details are not reported here. Data (for some nutrients) goes back to 1972 and appears to show large declines in both nitrogen and phosphorus concentrations up until the late 1990s. Sloop et al., (2007, Ch. 5) provide an extensive discussion of nutrient concentrations in the Laguna de Santa Rosa based on samples from 1985 – 2005. Their summary documents highly elevated nutrient concentrations, but also shows decreases over time that are likely reflective of improvements to wastewater treatment and reduction in nutrient loads from dairies. Key points in this summary include the following:

- *Very high total NH_3 and TKN concentrations (e.g., average of 6.8 mg/l at certain locations) were observed for the period of 1989 to 1994.*
- *Total NH_3, TKN, NO_3, and TP have shown different degrees of decreases from 1989 to 1994, 1995 to 2000, and 2000 to 2005. The largest decreases are in total NH_3 and TKN concentrations. Among the three sampling periods, 1995 to 2000 has the lowest nutrient concentrations.*
- *Current nutrient concentrations for the Laguna main channel during 2000 to 2005 are quite uniform for total NH_3, with median concentrations in the range of 0.3-0.5 mg/l. Median NO_3 concentrations remain high at 1-3 mg/l and show larger variations. Organic nitrogen is relatively uniform and generally below 2 mg/l with median values around 1 mg/l at many sampling locations. Median TP concentrations are generally between 0.5- 1 mg/l with a few locations showing median TP above 1 mg/l.*
- *For the main channel of the Laguna, nutrient concentrations are generally lower at the upstream station… increase downstream to [Occidental Road]… then further decrease downstream of [Occidental Road]… Santa Rosa Creek generally has lower nutrient concentrations. Dilution from Santa Rosa Creek decreases nutrient concentrations further downstream.*
- *Generally higher nutrient concentrations are observed during winter/spring months. Low NO_3 concentrations are observed in summer for all the locations. However, relatively high TP concentrations (0.3-0.5 mg/l) have also been observed in summer months, suggesting contribution from other sources rather than wastewater discharge.*

Sloop et al. noted that mean TN and TP concentrations within the Laguna are considerably higher than the mean of minimally impacted waters sampled within Ecoregion 6 (Southern and Central California Chaparral and Oak Woodlands; Omernik, 1987), and noted that concentrations may be sufficiently high that nutrients are not limiting growth. They also noted:

It is possible neither nitrogen nor phosphorus ever becomes limited in the Laguna due to the availability of these nutrients released from the sediments. It would be necessary to further control N and P loadings to begin to address excess algal and macrophyte growth in the Laguna. However, other risk cofactors including shallow water depth, lack of riparian cover, low flow, altered flow regime, and high water temperature also contribute to excess algal and macrophytes growth. A nutrient management strategy will have limited success in controlling excess algal growth without also addressing other risk cofactors.

Three compliance stations on the shallow, lake-like Laguna mainstem were established as a result of the Waste Reduction Strategy (Morris, 1995): at Stony Point Road (LSR), at Occidental Road (LOR), and at Guerneville Road (LGR) (Figure 6-2). (The Waste Reduction Strategy also established a compliance station on lower Mark West Creek at Trenton-Healdsburg Road. This station is downstream of Ritchurst Knob and not necessarily representative of lentic conditions within the Laguna mainstem, and so is not further evaluated here.) Water quality sampling within the Laguna de Santa Rosa over the last 10 years (since 2005) has been limited, but does include efforts at all the compliance stations in 2008 and 2013, plus samples at Occidental Road (only) in 2005. Statistics for the recent data are presented in Table 6-2, while the TN and TP data are summarized in the form of box plots in Figure 6-3 and Figure 6-4, respectively.

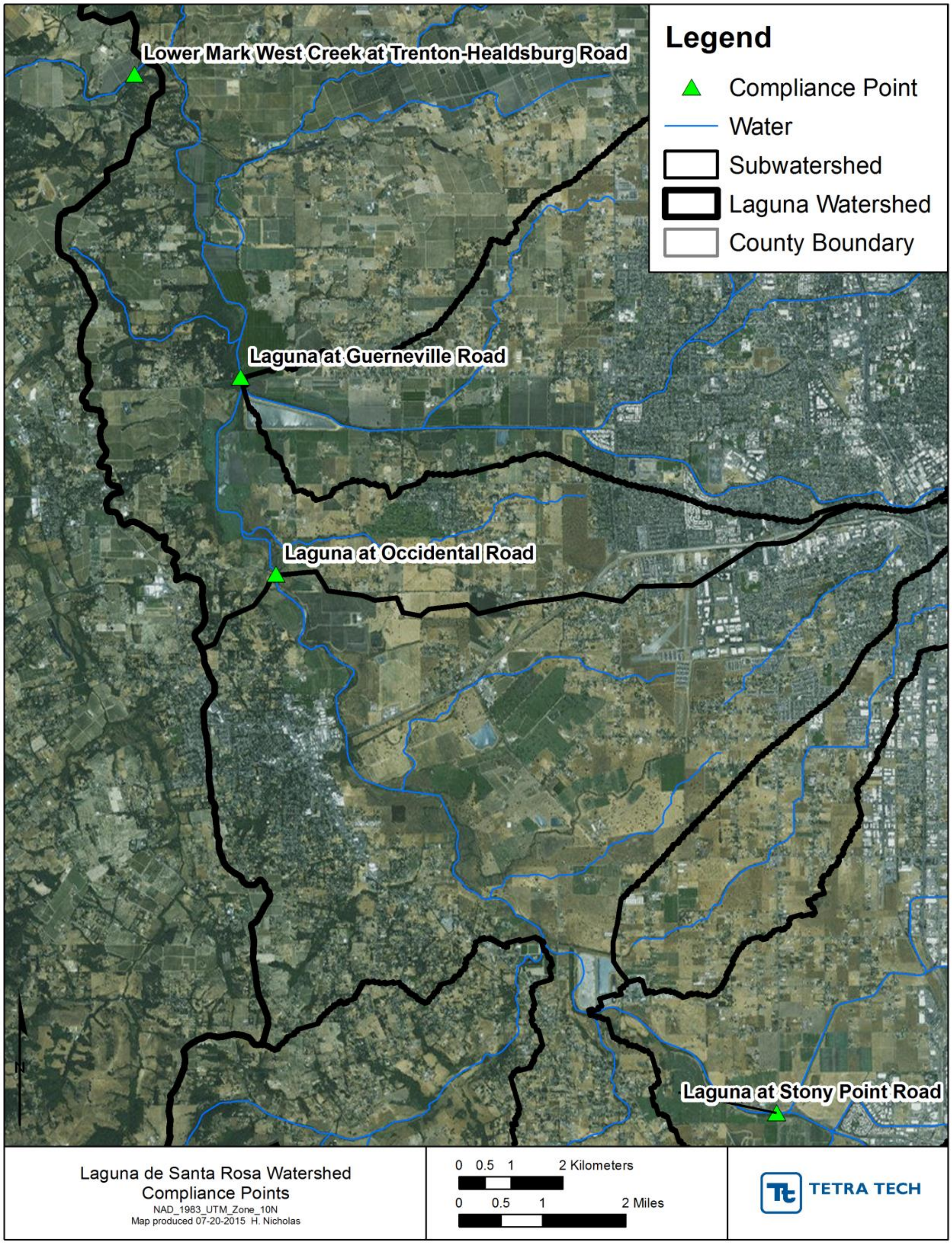

Figure 6-2. Nutrient Compliance Monitoring Points in the Laguna de Santa Rosa

Table 6-2. Nutrient and Chlorophyll *a* Concentrations within the mainstem Laguna de Santa Rosa, 2005 - 2013

Parameter	Statistic	Laguna at Stony Point Rd.	Laguna at Occidental Rd.	Laguna at Guerneville Rd.
Ammonia as N (mg/L)	count	7	7	16
	median	0.15	0.23	0.27
	range	0.07 - 0.51	0.045 - 0.68	0.015 - 0.6
Total N (mg/L)	count	7	7	16
	median	0.92	1.68	1.91
	range	0.69 - 4.61	0.74 - 6.01	0.31 - 5.3
Total P (mg/L)	count	7	7	16
	median	0.59	0.48	0.63
	range	0.35 - 0.749	0.322 - 0.67	0.31 - 0.94
Dissolved P (mg/L)	count	4	4	0
	median	0.30	0.33	
	range	0.25 - 0.52	0.25 - 0.42	
Chlorophyll *a* (µg/L)	count	0	15	0
	median		401	
	range		40 – 2,480	

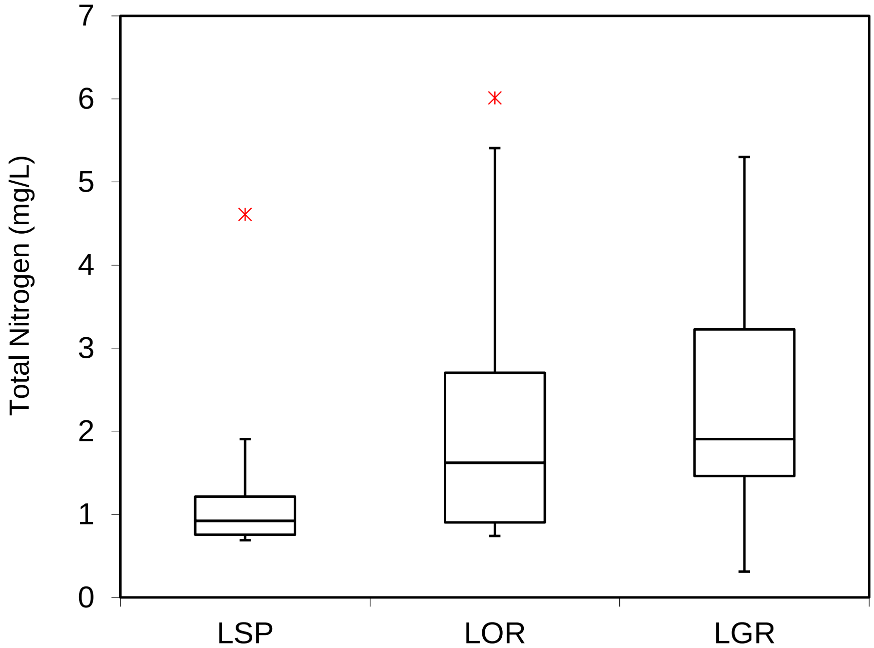

Figure 6-3. Boxplot for Total Nitrogen Concentrations in the Laguna de Santa Rosa, 2005 – 2013

Note: Central box shows median and interquartile range, while the whiskers are set at 1.5 times the interquartile range or the observed maximum (minimum) if smaller (larger). Outliers beyond the whiskers are plotted individually.

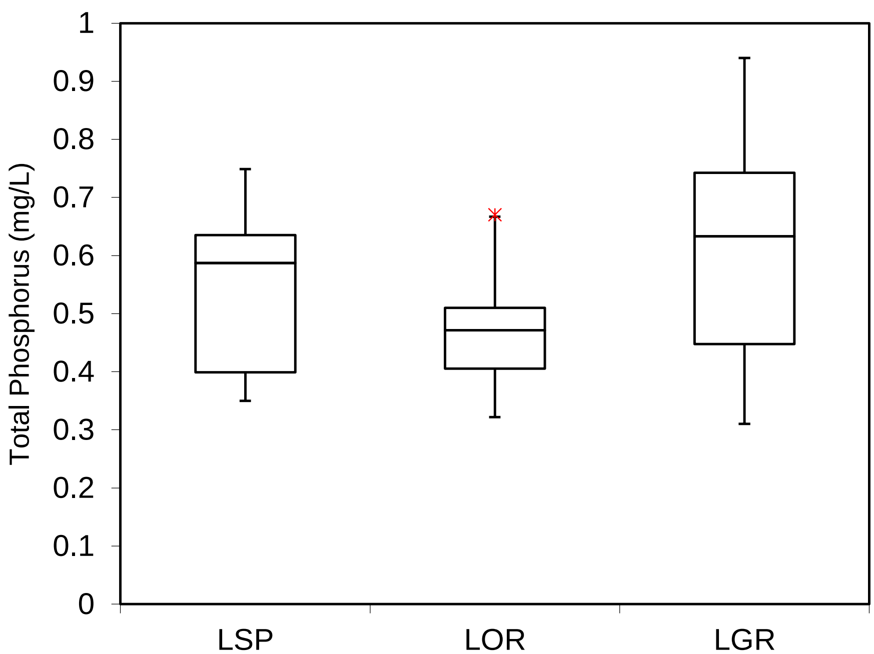

Figure 6-4. Boxplot for Total Phosphorus Concentrations in the Laguna de Santa Rosa, 2005 – 2013

Note: Central box shows median and interquartile range, while the whiskers are set at 1.5 times the interquartile range or the observed maximum (minimum) if smaller (larger). Outliers beyond the whiskers are plotted individually.

The monitoring data confirm a high degree of nutrient enrichment in the Laguna de Santa Rosa. For comparison, USEPA's (2001) analysis of nutrient distributions in lakes and reservoirs within Aggregate Nutrient Ecoregion III (which includes the Laguna de Santa Rosa watershed) documented the 25th percentile of the data distributions (inferred to approximate unimpaired conditions) as 0.40 mg/L total nitrogen and 0.017 mg/L total phosphorus.

The sample size is small, but suggests that total P concentrations are relatively consistent across the mainstem Laguna de Santa Rosa and in the neighborhood of 0.5 mg/L. This is consistent with the findings of Fitzgerald (2013), who calculated the median across all the compliance stations as 0.43 mg/L for 1995 – 2000 and 0.70 mg/L for 2001 – 2010. These concentrations are far above the 0.1 mg/L total P recommended as the boundary between eutrophic and hypereutrophic lentic waters cited above.

Total N concentrations appear to increase from around 1 mg/L upstream at Stony Point to around 2 mg/L at Guerneville Road. These median concentrations are again generally consistent with the medians reported earlier for total N by Fitzgerald (2013) of 1.5 mg/L for 1995-2000 and 3.2 mg/L for 2001 – 2010 and above the eutrophic – hypereutrophic boundary concentration of 1.2 mg/L reported by Welch and Jacoby (2004).

The Occidental Road (LOR) station on the Laguna mainstem is coincident with the remnants of historical Lake Jonive, an open water area near the center of the Laguna de Santa Rosa mainstem. Recent chlorophyll *a* data are available only for this station, and range up to 2,480 µg/L with a median of 401 µg/L, suggesting a hypereutrophic system. It should be noted, however, that the chlorophyll *a* data consist of 15 observations collected on only three days (in August, September, and October of 2008) to support development of a low-flow critical conditions application of the QUAL2Kw model, and the results may thus be biased high relative to the growing season average. Nonetheless, these observations from Lake Jonive provide an indication of the high algal growth potential that is present in the system in areas not shaded out by macrophytes.

Earlier year-round observations from 1990-1994 at the Occidental Road station showed chlorophyll *a* concentrations ranging from 2 to 564 µg/l, with an overall median of 61.8. The median for April – Oct was 75.8. These median concentrations are lower than those reported in 2008, although nutrient concentrations were higher in the latter period. They are still indicative of hypereutrophic conditions.

6.2.2 BATHTUB Analysis of Planktonic Chlorophyll

The Laguna de Santa Rosa contains areas of lentic, open water, such as the remnants of Lake Jonive near Sebastopol. During low flow conditions, this area behaves like a shallow lake; however, on a year-round basis it is part of the stream network, with a relatively short residence time as compared to most lakes. The tools developed for CA NNE analysis by Tetra Tech (2006) include a simple spreadsheet calculator for lakes and reservoirs based on the BATHTUB modeling tool (Walker, 1986; 1999). As noted above, this tool is not fully appropriate for analysis of Lake Jonive due to the shallow depth in summer (averaging approximately 0.34 m), which is outside the range of test sites (primarily U.S. Army Corps of Engineers reservoirs) upon which the empirical BATHTUB model equations were built and because of the short residence time of water on an annual basis. BATHTUB is a steady-state model that predicts growing season average concentrations of nitrogen, phosphorus, and chlorophyll *a* in lake surface waters based on watershed loading rates and morphometry of the lake. It can be applied to lakes with short residence times, but it is challenging to determine what the appropriate period for evaluating antecedent loading should be if most of the winter flow quickly washes through the system, and the general assumption that a steady-state approximation of summer conditions is appropriate is suspect in shallow water bodies with short residence times. Nonetheless, some insight can be gained through examination of the relationships between nutrients and algal response provided by BATHTUB.

The QUAL2Kw model of Lake Jonive developed by Regional Board staff was discussed above in Section 4. Detailed bathymetry of this segment was not available, but a growing-season BATHTUB model of

Lake Jonive was constructed with volume, depth, and surface area consistent with the QUAL2Kw model based on the hydraulic geometry assumptions provided in Butkus (2011a), resulting in a volume of 12,426 m^3 and a surface area of 35,914 m^3.

Average annual flow through Lake Jonive (based on records for 1998-2014 for USGS gage 11465750, Laguna de Santa Rosa near Sebastopol) is 74.4 cfs (the gage records outflow from the remnant Lake Jonive segment, but this is assumed to be equal to inflow). This is equivalent to a residence time of only 0.00019 years. The May – October average flow is 5.4 cfs (residence time 0.03 years). In contrast, at the extreme low flows evaluated in the QUAL2Kw model (0.0001 m^3/s), the residence time would be 3.94 years.

Given the short residence time even for the seasonal (May – October) representation, it is not clear what watershed loads are relevant to a steady-state prediction of response. We can, however, adjust the influent loads to replicate the observed median concentrations at Occidental Road of 0.48 mg/L total P and 1.68 mg/L total N (see Section 6.2.1), using default values of 1 for the BATHTUB calibration factors. These observed concentrations can be matched by the model if the May – October load is set to 310 kg total P and 735 kg total N based on an average flow of 5.4 cfs (total volume of 0.40 hm^3 in the units used by BATHTUB). The corresponding flow-weighted inputs are 0.78 mg/L total P and 1.84 mg/L total N. The BATHTUB tool predicts a median chlorophyll *a* concentration of 106 μg/L for these conditions. For the extreme low flow conditions evaluated in the QUAL2Kw run, a load of only 55 kg total P and 31.5 kg total N (over an undefined but brief antecedent time period) is needed to reproduce the median nutrient concentrations observed at Occidental Road, resulting in a predicted median chlorophyll *a* concentration of 120 μg/L.

The observed chlorophyll *a* concentrations at Occidental Road are higher than those predicted by BATHTUB, with a median of 401 and interquartile range of 240 – 468 μg/L, although, as noted above, the sampling is biased toward extreme low flow conditions. The chlorophyll *a* samples are also not coincident in time with nutrient samples. If the loads are adjusted to match the maximum instream concentrations observed during summer 2008 of 0.67 mg/L total P and 6.01 mg/L total N, the resulting uncalibrated BATHTUB prediction of chlorophyll *a* is 367 μg/L, approximately consistent with observations. Under these extreme low flow conditions, reducing the predicted chlorophyll *a* from the uncalibrated BATHTUB application to the target concentration of 25 μg/L would require reducing the total P concentration to around 0.03 mg/L or the total N concentration to around 0.58 mg/L. In the application with average growing season flows of 5.4 cfs, the median chlorophyll *a* concentration target of 25 μg/L can be achieved with an approximately 65 percent reduction in current median concentrations to 0.16 mg/L total P and 0.59 mg/L total N.

The experiments with the BATHTUB model are of limited value as quantitative predictions because the conditions in remnant Lake Jonive are clearly outside of the intended range of applicability of the BATHTUB tool. They do, however, reinforce the conclusion that significant reductions in current summer nutrient concentrations would be needed to achieve a planktonic chlorophyll *a* goal of 25 μg/L, as is recommended in the CA NNE draft approach (Tetra Tech, 2006), or an equivalent amount of macrophyte growth.

6.3 Potential Numeric Nutrient Endpoints for the Laguna de Santa Rosa

The previous sections of this report contain a variety of analyses relative to the nutrient balance and the linkage between nutrients and eutrophication in the Laguna de Santa Rosa. There is no single definitive analysis that yields a quantitative estimate of appropriate nutrient concentration or loading targets that will result in attainment of beneficial uses. Yet, there are multiple lines of evidence that together help constrain appropriate endpoints. The information discussed above is summarized in the following bullets:

- Investigations of the physiology of *Ludwigia* (Section 3.3) indicate that its dominance is promoted by shallow depths (associated with sedimentation) and elevated phosphorus loads and concentrations. Reducing phosphorus concentrations (in water and sediment) can reduce *Ludwigia* growth, but experimental information is not available to establish a quantitative target. Work of Gerard et al. (2014) suggests that water column phosphorus concentrations may need to decrease to around 0.03 mg/L to achieve substantial reductions in growth rate.
- QUAL2Kw modeling (Section 4) indicates that DO impairments are most strongly related to SOD, which is derived from a combination of macrophyte biomass accrual and loading of organic matter from the watershed.
- The QUAL2Kw modeling also shows strong sensitivity to reaeration rate, which is likely depressed by coverage of the water surface by *Ludwigia*.
- Estimates of present day nutrient loading rates by various methods are in general agreement for Santa Rosa Creek and confirmed by the results of MS4 monitoring. Phosphorus loads in Santa Rosa Creek are on the order of 0.84 lb/ac/yr and LCLM median-basis loads for cropland, pasture, orchards/vineyards, residential, and commercial land are between 1 and 2 lb/ac/yr (Table 5-1). These loads are significantly elevated relative to natural loading rates from forest and rangeland.
- Estimates of nutrient loading rates under conditions prior to European settlement (Section 5.5) suggest that anthropogenic activities have greatly increased nutrient loading to the Laguna de Santa Rosa. Total phosphorus loads under present-day conditions appear to be at least 5 times and possibly as much as an order of magnitude higher than pre-settlement loads. In accordance with CA NNE recommendations (Tetra Tech, 2006) the pre-settlement loading rate should be interpreted as a baseline that defines the maximum possible reduction target.
- Welch and Jacoby (2004) suggest a total phosphorus concentration of 0.1 mg/L (as a growing season average) is needed to prevent hyper-eutrophication in lentic waters. The median phosphorus concentrations from recent monitoring at three compliance stations within the mainstem of the Laguna de Santa Rosa (Table 6-2) range from 0.48 to 0.63 mg/L by station, suggesting a need for a reduction of up to 84 percent in phosphorus loads. Extremely high chlorophyll *a* concentrations observed for the open water section of the Laguna at Occidental Road ("Lake Jonive") support the need for a large reduction in nutrients that support excess algal growth.
- Recent observations of total phosphorus concentration at Occidental Road have a median of 0.48 mg/L. In contrast, USEPA (2001) recommendations for lentic waters suggest a phosphorus concentration of 0.017 mg/L as an approximate upper boundary for unimpaired sites. This represents a reduction of 96 percent; however, the target is likely overly strict for a waterbody such as the Laguna de Santa Rosa that would likely be naturally enriched in nutrients, although not to the extent observed under current conditions.
- BATHTUB modeling of remnant Lake Jonive (Section 6.2.2) suggests that growing season median total phosphorus and total nitrogen concentrations need to be reduced by about 65 percent to achieve the CA NNE proposed target growing season median of 25 µg/L chlorophyll *a*.

The 303(d) listing process and supporting analyses have identified the Laguna de Santa Rosa as impaired by phosphorus, and addressing eutrophication by control of nitrogen concentrations is believed to be infeasible due to the presence of nitrogen-fixing aquatic plants that can derive nitrogen from the atmosphere. The weight of evidence suggests that phosphorus loading reductions on the order of 65 percent (based on the BATHTUB analysis of Lake Jonive) to 84 percent (to attain the recommended total P recommendation of 0/1 mg/L in the Laguna de Santa Rosa mainstem) are needed to address nutrient-related impairment in the Laguna de Santa Rosa. It is important to remember, however, that phosphorus concentrations within the Laguna have a significant component due to legacy loading from past management practices. For this reason, a concentration based target may be preferable for TMDL development.

Because the most recent 303(d) List removes nitrogen as a cause of impairment in the Laguna de Santa Rosa it is not necessary to develop a specific nitrogen loading target to directly address eutrophication-related impairments, although it will be important to control both phosphorus and nitrogen loading. Regional Board staff (Butkus, 2012e) have developed a loading capacity analysis for total nitrogen based on preventing instream toxicity due to ammonia nitrogen (NH_3-N). The analysis establishes a relationship between NH_3-N and total N concentrations measured at the compliance points within the Laguna de Santa Rosa. The result is a recommended concentration target of 0.885 mg-N/L. As shown in Table 6-2, the median of recent (2005-2013) total nitrogen concentration measurements at the Guerneville Road compliance station (near the downstream end of the Laguna) is 1.91 mg/L. The proposed concentration target thus represents a reduction in nitrogen of about 54 percent.

The conceptual model (Sloop et al., 2007; see Figure 2-1 in this report) makes clear that impairments of the Laguna de Santa Rosa arise from the complex interactions and combined effects of nutrient loads, organic matter loads, sediment loads, and alterations to hydrology. An effective implementation plan will need to address these issues together through management activities that control peak flows and summer low flows, reduce erosion and sediment transport, and reduce both dissolved and sediment-attached phosphorus loads.

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