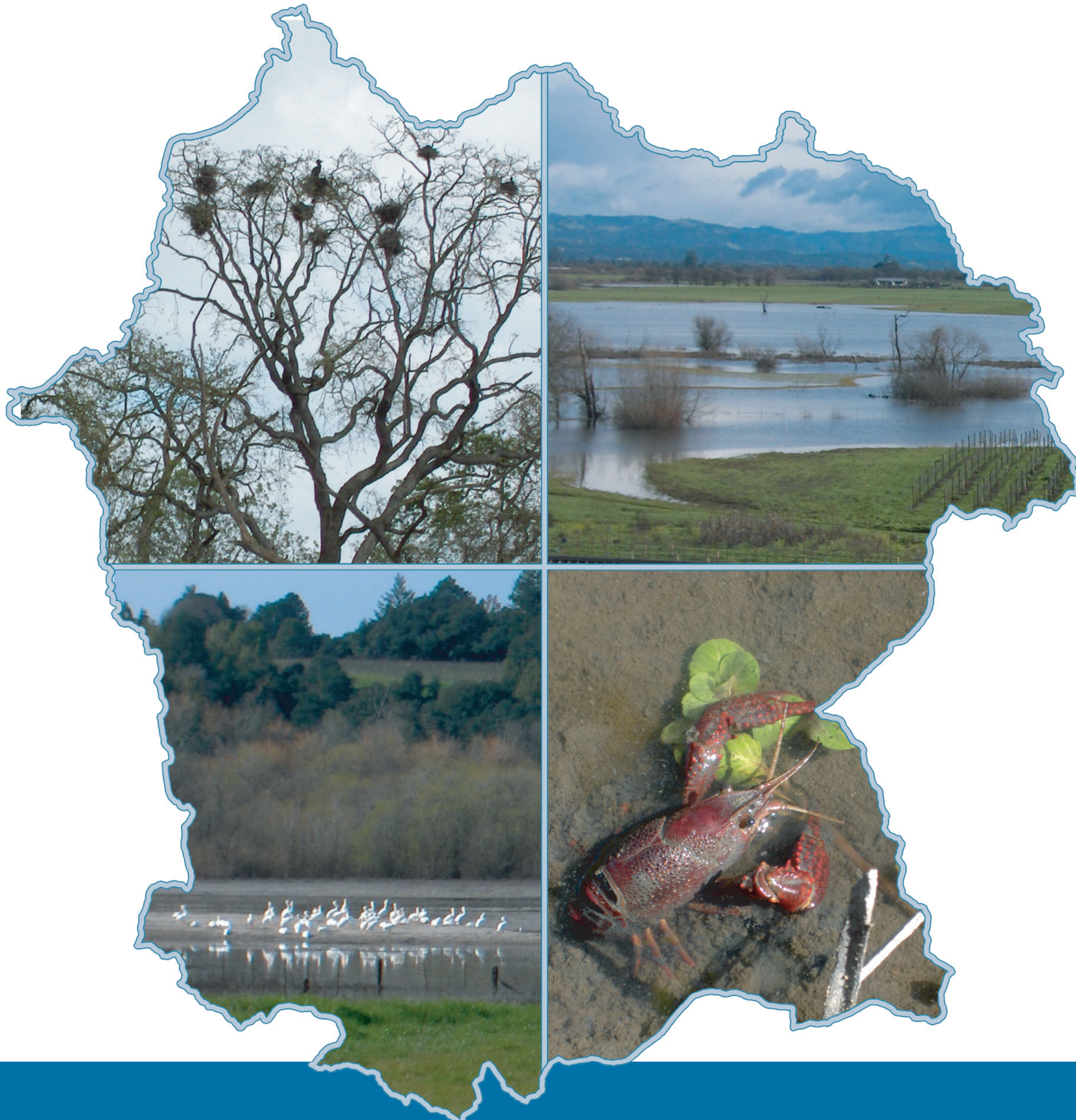
The Altered Laguna

A Conceptual Model for Watershed Stewardship



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A CONCEPTUAL MODEL

FOR WATERSHED STEWARDSHIP

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**A synthesis of current data on
sedimentation, water quality, and ecosystem impairments,
for planning and management of the
Laguna de Santa Rosa watershed,
Sonoma County, California**

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Laguna de Santa Rosa Foundation

Santa Rosa, California
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The Laguna de Santa Rosa Foundation
works to preserve, enhance and restore the
Laguna de Santa Rosa, and to inspire greater
public understanding and appreciation of its
magnificent natural areas.
For more information, visit www.lagunafoundation.org.

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Tetra Tech, Ltd. provides specialized management consulting and technical services in the areas of resource management, infrastructure, and communications, with specialties related to waterways, harbors, and coastal areas.

Philip Williams & Associates, Ltd. works on solutions to complex river, wetland, and water resource management problems through scientifically rigorous yet practical multi-objective engineering solutions.

The Laguna de Santa Rosa Foundation works to preserve, enhance and restore the Laguna de Santa Rosa, and to inspire greater public understanding and appreciation of the biodiversity and wildlife of its natural habitats.

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1.1 Project goals

The Laguna de Santa Rosa watershed embodies a complex system of physical, hydrological, chemical and biological processes that are closely linked to many direct and indirect impacts from the largest concentration of human settlements in Sonoma County. The Laguna is wedged between five expanding urban centers: Cotati, Rohnert Park, Sebastopol, Santa Rosa, and Windsor. Much of the Laguna de Santa Rosa and its watershed tributaries have been altered, and now reflect numerous historic and contemporary human caused modifications to natural processes. Many of these alterations have rendered the watershed as impaired, with negative impacts to natural hydrology, sedimentation, flood capacity, water quality and valuable ecosystem services for wildlife and humans. This degraded system, historically extremely rich and diverse, now performs at a sub-optimal level and active restoration is needed to turn the tide for improvement of "Beneficial Uses" identified in the North Coast Regional Water Quality Control Board Basin Plan.

The Laguna de Santa Rosa Foundation, in collaboration with Philip Williams and Associates (PWA) and Tetra Tech, and with guidance from North Coast Regional Water Quality Control Board and a Technical Advisory Group developed a conceptual framework to address the following goals:

1) Improve our understanding of the Laguna system for basin scale planning and management;
2) Gather and analyze available data;
3) Identify data gaps, appropriate system indicators, monitoring regimes, and restoration targets; and
4) Specify further modeling efforts focused on the watershed.

The impetus to this process is the project's important role in launching the Laguna Total Maximum Daily Load (TMDL) study to address water quality concerns, and to ensure that the appropriate watershed-scale scope is used for the TMDL-related work. This report addresses the following project objectives:

- Prepare a list of detailed management objectives to guide future restoration, model development and data collection activities;
- Establish a comprehensive project database to consolidate and organize existing information to support assessment and model development;

- Develop a suite of conceptual models to identify key factors and processes driving existing and future conditions within the basin with regard to hydrology and sedimentation, water quality, and ecosystem processes;
- Perform data gaps and uncertainties analysis to identify the information needed to complete an assessment and modeling analysis of the basin, including those assessments and tools needed for TMDL development;
- Develop model selection and development recommendations to ensure that the chosen approach addresses the needs of all of the modeling objectives;
- Prepare monitoring recommendations to provide a basis for data collection prioritization.

1.2 Role of conceptual models

In the highly complex Laguna de Santa Rosa watershed system, predictions are only possible by close examination of all system components. Our understanding of the linkages among these components is made tangible through a series of steps that progress from the conceptual model addressed in this report to dynamic modeling simulations in the near future:

- Conceptual models are developed to illustrate all system components and recognizes linkages between the initial drivers (stressors), the intermediate outcomes (response components or effects), and ultimate impacts (final outcomes or attributes);
- The conceptual models are developed in conjunction with a parallel process of identifying the important and relevant management questions and restoration priorities to be addressed;
- Preliminary restoration objectives and key uncertainties are then described, and data gaps and information needs are clarified and monitoring recommendations are developed;
- The conceptual models are used to guide selection of dynamic/fully automated simulation models that are capable of simulating all of the key components and linkages that have been identified;
- The monitoring plan is then implemented to address key uncertainties, data gaps, and to provide the dynamic model with the information necessary to simulate various management scenarios;
- The dynamic models are then calibrated to achieve an adequate level of predictability of outcomes according to specific input parameters. Model calibration is achieved when the model can successfully replicate a quality assured monitoring database of the targeted system (e.g., the Laguna);
- This final step ensures that the watershed stewards can use the model to explore various management options and that the model outcome is reasonably realistic and dependable.

This report mainly addresses the conceptual part of these modeling approaches and so serves as comprehensive summary of the current understanding of how the Laguna de Santa Rosa watershed system works, what is yet missing from our understanding and how we might go about filling data gaps and addressing key uncertainties. The conceptual models developed through this project describe key elements and processes of the Laguna ecosystem, such as hydrologic and sediment delivery processes, water quality functions and ecosystem dynamics. These preliminary conceptual models clarify how these processes potentially impact water quality and flood protection objectives and ecosystem function. We align these identified processes with management goals and identify key uncertainties and related data gaps that need to be addressed by future research and monitoring regimes. Additionally, we make suggestions of the types of fully automated and dynamic simulation models needed in the next step to realistically predict outcomes from our actions aimed at restoring system functions.

In short, the goal of the conceptual model method is to reduce the processes and stressors of the system to a collection of concepts or hypotheses that then can be more clearly and readily addressed. Taken together, these concepts form a representation, in reduced form, of how the system works. The attempt here is to develop a broader modeling framework by focusing the lens on all of the topics addressed separately in previous studies. This project therefore develops a basis for a comprehensive assessment, modeling, and preliminary planning framework to coordinate basin-scale activities for flood protection, ecosystem health, water quality (including development of TMDLs), and water management for the Laguna de Santa Rosa. Accordingly, it is a direct extension of the Laguna de Santa Rosa Foundation's (LSRF) watershed management plan (Honton and Sears 2006), and serves as a valuable technical basis to the North Coast Regional Water Quality Control Board's development of Laguna de Santa Rosa Total Maximum Daily Load (TMDL) regulatory thresholds for parameters currently on the 303(d) list of water quality impairments. This report thus represents the official initiation of the Laguna TMDL regulatory and implementation process.

1.3 Nexus with basin scale planning goals

While development and implementation of TMDLs are important components of an overall restoration strategy other planning components are needed in restoring Beneficial Uses in the Laguna watershed. Other components need to be addressed: flood management, sediment management, open space and biodiversity, and maintenance of a working landscape. It is clear that the surrounding communities have now begun to recognize the value of retaining the Laguna as a viable ecosystem to enhance water quality, flood protection, and ecological function. The 2007 Laguna Science Symposium included a brainstorming session of technical and public participants to identify future research and study needs and rank the importance of selected topics. To develop a comprehensive basin scale plan for the Laguna watershed was selected by more participants than any other single topic. This project is the first step in the development of this comprehensive plan by addressing the first three of the following basin scale goals:

- Flood protection
- Water Quality Planning (TMDL process)

- Ecosystem Restoration
- Water Management

This report was developed to provide a conceptual framework and current technical knowledge base to the following planning objectives:

Flood protection planning: Evaluation of current flood capacity, and informing plans for protecting and enhancing flood capacity for the future. The hydrology and hydraulics of the watershed are continuously changing due to increased storm water flow associated with development and to climate change, which is predicted to increase the severity of weather events (drought and storms). Models are needed to predict flood risk under different storm scenarios, sustainability of different engineered solutions (such as setting back levees). Good modeling tools, supported by good topographic, land-use and monitoring data, will be essential for robust long-range planning.

Water quality assessments: Assessment of the impact of pollutants from both point and non-point sources on the Beneficial Uses designated for the Laguna de Santa Rosa and on attainment of related water quality objectives. This would include studies of dissolved oxygen, temperature, nutrients, organic matter and sediments to identify which constituents impair Beneficial Uses in Laguna waters so that a Waste Load Allocation (WLA) can be performed. Once the has been completed the North Coast Regional Water Quality Control Board (NCRWQCB) will develop an implementation plan to achieve the allocation targets for each TMDL constituent. These studies will include pollution control planning that incorporates the relationship between land-use, pollutant loading, and water quality impairments; evaluate the capacity of the watershed to absorb or process pollution inputs; and prioritize remediation options for non-point source pollution and for point source pollution addressed through discharge permits. Of particular interest is the relationship between nutrient and sediment loads, physical habitat changes, and the nuisance levels of the invasive macrophyte water primrose (invasive *Ludwigia* sp). The planning and assessment framework needs models to describe baseline conditions, in-channel and surface-water flow rates under different land-use conditions and season, as well as sediment delivery and transport models.

Restoration planning: Developing ecological and physical baseline characterizations of the watershed, and preparing guidelines and success criteria for restoring environmental and ecological function of Laguna waterways and uplands to support biological diversity. Such guidelines and criteria would address physical improvements, such as stabilizing channels, and reducing sediment inputs, and biological enrichments such as restoring vegetative buffer zones, adjusting top-down aquatic food web dynamics to favor maximized nutrient uptake, controlling invasive species, and establishing and/or (re)connecting wildlife corridors. The focus would include interrelated basin-scale issues that are not adequately addressed with reach specific modeling efforts, describe baseline water and food web dynamics, predict future basin-wide conditions, and evaluate feasibility of engineered solutions (such as restoring channel contours and reconfiguring watersheds to reduce directly connected impervious areas).

1.4 Laguna function: past and present

The Laguna watershed is surrounded by two actively uplifting ranges in a Mediterranean climate. As such it is likely that it naturally had relatively high levels of sediment production prior to European settlement in the 19th century. However, although the Laguna watershed naturally generates large amounts of sediment, the natural drainage system that existed prior to European settlement ensured that much of that sediment was deposited on the alluvial fan surface of the upper Santa Rosa Plain, rather than in the lower Laguna waterways. Land use change and the creation of drainage and flood control channels, while making the Santa Rosa Plain more habitable and productive, has mobilized more sediment and shifted the focus of deposition to the lower tributaries and the Laguna itself. Figure 1-1 is a conceptual model of the physical processes affecting the Laguna prior to settlement; figure 1-2 is a conceptual model of the physical processes affecting the Laguna after settlement.

Through our analysis and discussion of hydrology and sedimentation in section 4 of this document, we anticipate that future land use changes in the watershed will further impact hydrologic and sediment processes by changing runoff volumes and peak discharges, and by increasing sediment production in the upper watershed and mobilization along the channels. The combined effect of increased sediment generation and transport capacity in the watershed and increased potential for deposition in the Laguna has several implications. Increased deposition of sediment causes an increase in flood elevation for any given water discharge. This increases flooding in low-lying areas of the Laguna and causes water to back up into the tributaries, creating increased flooding in the tributary watersheds. These changes threaten the Laguna both as a wetland and as a flood detention basin, with implications both in the Laguna and downstream in the Russian River.

With regard to water quality, historical accounts of the Laguna de Santa Rosa describe a productive low gradient system that included a mosaic of open channels, wetlands, and lake like features. The historic Laguna was likely a highly productive warm-water system, supporting wildlife and human use of the Laguna for fishing and recreation. The water quality conceptual model for the Laguna developed by the project team in section 5 of this document identifies the mainly anthropogenic drivers or stressors that have caused water quality conditions in the Laguna to decline over time. The water quality conceptual model focuses on two components, nutrients and organic matter which, in combination with other hydrologic and physical habitat factors, have resulted in conditions that have caused a degradation of Laguna ecosystem function that is unsupportive of "Beneficial Uses" that are assigned to the Laguna in the North Coast Basin Plan. The water quality conceptual model illustrates the linkage between the stressors and the Beneficial Use endpoints. Between these two model endpoints are a series of environmental conditions and responses that can be measured to assess the status of the Laguna's Beneficial Uses.

With focus on Laguna ecosystem function, historic accounts describe the Laguna de Santa Rosa watershed as containing extremely high levels of biodiversity, mainly due to an array of diverse community types rooted in an assortment of equally diverse underlying geology and microclimates. At present, the Laguna watershed is still host to a wide variety of plant communities providing habitat for a suite of other organisms that remain. In section 6 we sketched out a conceptual model of biological diversity over time (Figure 1-3) as a means to understand loss and gain of ecologic potential according to anthropogenic actions causing system degradation or improvement. Over the charted period from 1800 to

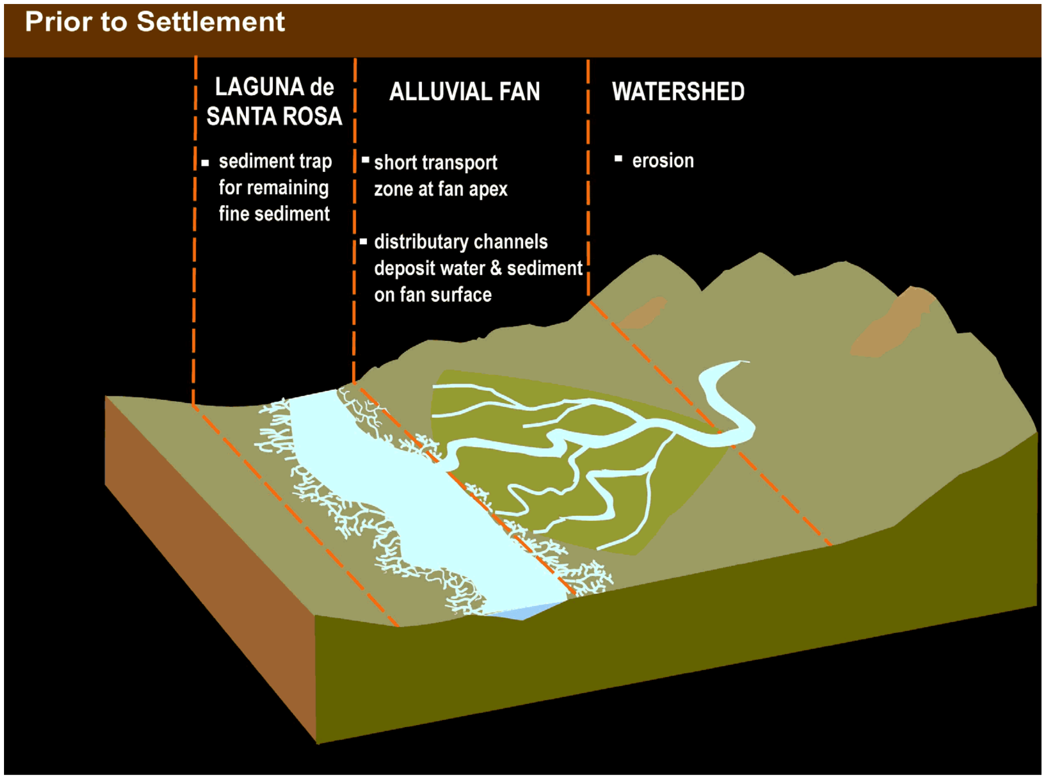

Figure 1-1 Conceptual model of physical processes affecting the Laguna prior to settlement

~2000 biodiversity loss has occurred in eight stages, with rapid declines occurring in five stages, each stage followed by a period of new stability at a lower level. At the very end of the 20th century, a reversal of the downward trend is shown in the last stage, with a hopeful upward trend beginning. Two projected trend-lines are plotted for the future, one at the existing plateau, the other at a slightly higher level. The lower trend line predicts a future based on the status quo; the upper trend line predicts a future based on the promulgation of Laguna TMDLs, implementation of the Santa Rosa Plain Conservation Strategy, and progress made towards the goals set forth in the Restoration and Management Plan.

1.5 Analysis of available data

In section 4, we present results of several recent and current studies on the hydrology and sedimentation in the Laguna system. These include the PWA (2004) study on the sedimentation, rate, and fate in the Laguna, the ongoing USGS study of the 2006 new year's flood, the ongoing NASA/AMES SWAT model development of the Laguna watershed, and the 2002 and 2003 US Army Corps of Engineers' studies on the hydrology of Santa Rosa Creek and Laguna de Santa Rosa watershed, respectively. We summarized available hydrologic and sediment data in the watershed and provided a comparative analysis of different sediment yield estimates. We presented our perspective on sediment yield in the Laguna based on several local and regional estimates and provided a rough sediment budget. The sediment budget is primarily based on the previous study on the rate of sedimentation in the Laguna (PWA, 2004) which had estimated a deposition rate and sediment yield in

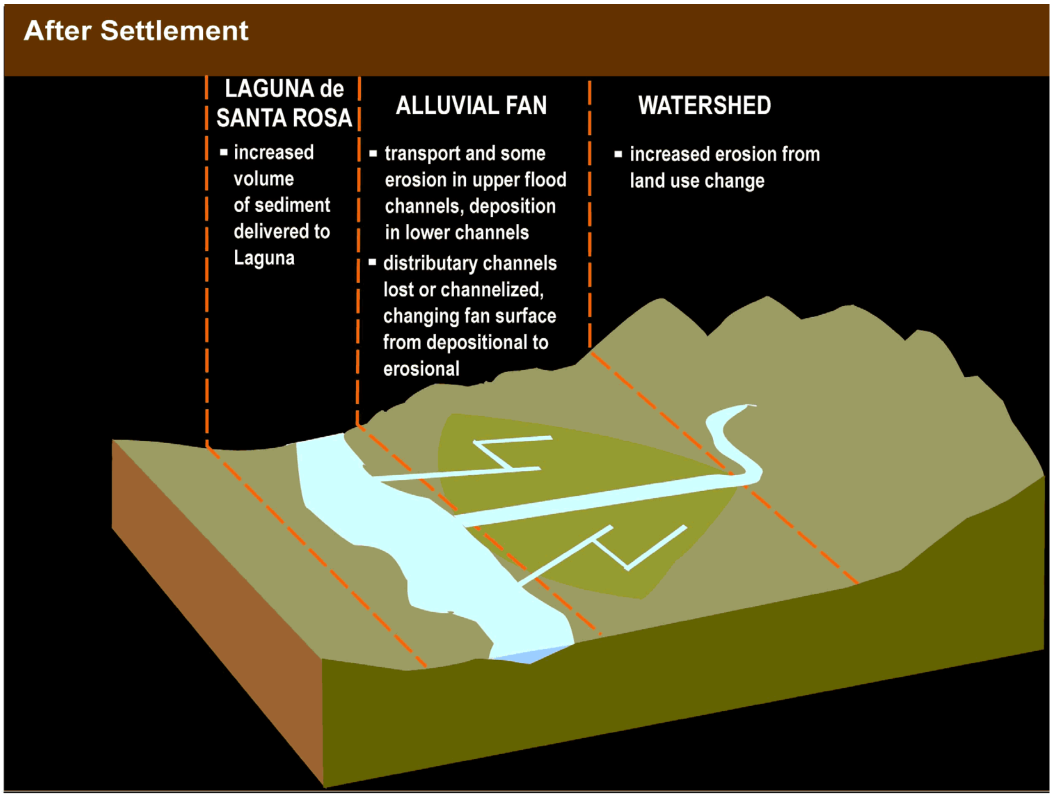

Figure 1-2 Conceptual model of physical processes affecting the Laguna after settlement

the watershed using multiple approaches: repeated floodplain cross-sections in the Laguna, measured sediment deposition in Matanzas Reservoir, other sediment yield estimates in the surrounding basins, PSIAC sediment yield estimations for the upper Laguna watersheds and turbidity sensors installed at three USGS gages during 2002-2003. Though all these sources had different types and degrees of error and uncertainty attached to them, there was an encouraging convergence of estimates for sediment yield in the Laguna.

The water quality section 5 evaluates two key elements of the conceptual model: 1) nutrient and organic loading, and 2) dissolved oxygen (DO). For the first time, datasets from different agencies and organizations were compiled to assess spatial and temporal trends for nutrients and dissolved oxygen in the Laguna for three time periods:

- 1989 to 1994: This period represents the Laguna prior to the implementation of the Waste Reduction Strategy
- 2000 to 2005: Monitoring during this period will capture the effect of the Waste Reduction Strategy
- 2004-2006: During this period the City of Santa Rosa reduced discharge to the Laguna de Santa Rosa from its wastewater treatment plant and diverted this discharge to the Geysers Project.

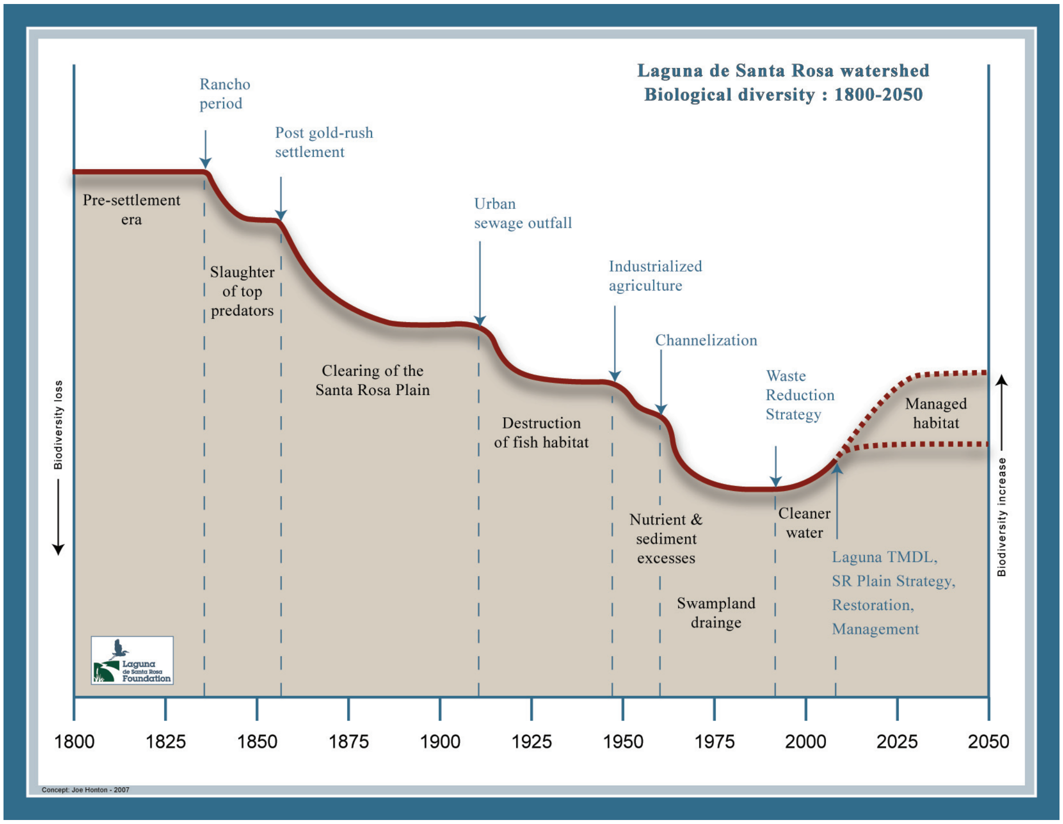

Figure 1-3 Conceptual model of biological diversity over time

The following organizations provided quality assured data, which was compiled into a consolidated project data set:

- City of Santa Rosa Wastewater Treatment Plant;
- City of Santa Rosa Stormwater Monitoring Program;
- Sonoma County Water Agency;
- North Coast Regional Water Quality Control Board – various projects;
- The Laguna de Santa Rosa Foundation - *Ludwigia* Abatement Project;
- California Department of Fish and Game.

Combining data from these various sources into an integrated database allowed the project team to assess temporal and spatial trends for nutrients and dissolved oxygen.

Efforts at compiling existing Laguna ecosystem data, presented in section 6 focused on the recently published reference sources within *Enhancing and Caring for the Laguna* (Honton and Sears 2006), and on available GIS layers in the Laguna Foundation geo-database. Additional information was obtained via the Russian River Interactive Information System (RRIIS), from the Sonoma County Water Agency website, and was made available to us by City of Santa Rosa staff and USDA/ARS researchers. Data analysis was focused on available Laguna de Santa Rosa watershed fish and aquatic habitat surveys from the Sonoma county water agency and California Department of Fish and Game, and biotic indicator surveys such as aquatic macroinvertebrates, and bioassays, performed by the City of Santa Rosa

Stormwater monitoring program. The United States Department of Agriculture- Research Service's invasive *Ludwigia* sp. research program and the Laguna de Santa Rosa Foundation's invasive *Ludwigia* sp. control program provided current data on the physiology, ecology and herbicide and mechanical removal control success of this invader.

1.6 Addressing management questions

With focus on basin plan Beneficial Uses and restoration goals recognized in the Laguna restoration and management plan (Honton & Sears 2006) we identified a suite of key management questions for sedimentation and hydrology, water quality and ecosystem processes. These key management questions are presented in section 3, and each question is followed by a discussion of the current key uncertainties and data gaps in order to guide the development of the Laguna TMDL study and implementation of the Laguna restoration goals.

Key data gaps related to hydrologic processes stem from uncertainties related to discharge estimates along the Laguna and its tributaries due to inadequate stage-discharge relationships, overbank flows, and presence of bi-directional flows and backwater effects both from the Russian River. The flood flow hydrology of the system is not well established and information on the frequency, duration, and seasonality of floodplain inundation along the Laguna de Santa Rosa does not presently exist. No evaluation of transport capacity has been developed that would allow estimation of the delivery of bedload and suspended load to the Laguna from each sub-watershed. Sediment transport along the mains tem Laguna has not been studied. Locations of sediment deposition and subsequent impairment of beneficial uses have not been catalogued. A critical uncertainty about the hydrologic and sedimentation processes in the Laguna is the lack of information on the volume and frequency of water and sediment received from the Russian River during high flow conditions.

For water quality, key data gaps and uncertainties remain mainly with regard to a significant geographical and temporal limitation in the available data for dissolved oxygen (DO) and nutrient dynamics in much of the Laguna. Thus, background/baseline DO conditions remain unknown, and the duration and magnitude of lethal to stressful DO level zones and the presence of refuge habitats remain uncertain. There is also uncertainty regarding the significance of each of the individual risk cofactors that each in part contribute to low DO conditions. How much of low DO conditions is due to sediment processes is still unknown. The relative importance of terrestrial and aquatic sources of organic carbon is difficult to determine without further study, and background loadings of BOD and organic carbon have not been determined. The relative contribution of aquatic sources to organic/inorganic nitrogen is not clear without reliable loading estimates. Nitrogen oxygen demand needs to be studied more broadly through the Laguna in order to verify the conceptual model prepared for one location (SEB3). The role of wind mixing and the location and magnitude of impoundments affecting oxygen dynamics in the water column need study. The absence of a reference site and knowledge about the direction and dynamics of the aquatic food web makes assessment of whether the Laguna DO objectives are achievable in the absence of human disturbance uncertain, necessitating development of a calibrated model to infer the expected DO regime under natural conditions.

With regard to nutrient loadings, it is yet unclear whether nitrogen and phosphorous ever become limiting to algal or macrophyte growth, and what the relative contributions are of food web dynamics and other cofactors. Appropriate levels of algal and macrophyte densities to support cold water fish are yet unknown in the Laguna. Realistic loading estimates from all possible sources (groundwater, atmospheric depositions, septic tanks, agriculture, urban runoff, internal nutrient cycling, and factors that affect bioavailability of nutrient loads) still need to be established for the Laguna. Internal nutrient loading rates and loading rates from wet and dry season groundwater sources are unknown.

The degree to which riparian buffer zones will reduce loadings still needs to be explored in more detail, and their current extent in the Laguna quantified. Fish biomass estimates for the Laguna and fish contribution to re-suspension of sediments in to the water column are data gaps. Whether or not the Laguna main stem can support anadromous fish passage, and how the Laguna aquatic and terrestrial food web communities are affected by levels of pollutant bioaccumulation, low DO conditions, high nutrient input, and invasive species such as invasive *Ludwigia* sp. is yet unclear. With regard to Laguna biodiversity, there is no clear understanding of aquatic, semi-aquatic and terrestrial food web dynamics due to the absence of a current ecological baseline. Without such a baseline and study of food web links that would aid in the understanding of community structure and ecosystem energy dynamics it will be impossible to predict how the watershed will be affected by changing climate patterns.

The contribution of factors such as hydrology, sediment delivery, degraded channel morphology, riparian degradation, and excess nutrients to the accelerated growth and spread of invasive *Ludwigia* sp. in the Laguna has not yet been quantified. How invasive *Ludwigia* sp. affects food web dynamics and other biotic processes is still unknown. Whether nutrient sources for invasive *Ludwigia* sp. originate from the sediment or the water column is as yet unquantified, as well as its specific contribution to mosquito growth and the spread of the mosquito associated West Nile virus.

1.7 Conceptual model development

Using the available data and preliminary estimates of rates and loadings within the context of management and restoration goals we developed a suite of conceptual models of the hydrologic and sedimentation, water quality and ecosystem processes within the Laguna watershed. For some cause-effect linkages, the nature and direction of the effect was identified within the model.

Sedimentation and Hydrology

The conceptual models were developed to describe the anthropogenic influences on sediment processes and surface water hydrology and their consequences. We explored the spatial variability in physical processes in different parts of the watershed by developing "Operational Conceptual Models" that delineate the cause-effect relationships by identifying the key anthropogenic drivers, linkages, and outcomes. These models were developed for two geomorphic domains in the watershed: the Lower Laguna Watershed and the Upper Laguna Watershed. The Upper Laguna Watershed consists of headwater zones of tributary channels to the Laguna and the main stem tributary channels and represents sediment production and transport zones. The Lower Laguna Watershed consists of the main channel of Laguna and its floodplain, including the lower reaches of the tributary channels and floodplains. We also explored the temporal variability of physical processes in the Laguna de

Santa Rosa watershed and articulated a temporal conceptual model of the Laguna, briefly summarizing the evolution of the system over time.

Ecosystem

An in-depth study of the interplay between functional ecosystems and clean water and the underlying physical and biological forces is provided in Enhancing and Caring for the Laguna (Honton & Sears 2006), and a brief summary is given in section 4 of this document, where we've developed two broad conceptual models of the relationships between physical and biotic processes related to water quality: again, one for the Upper Watershed (eastern and western mountain tributaries) and one for the Lower Watershed (the central Santa Rosa plain tributaries, main stem Laguna de Santa Rosa and its floodplain). We also addressed more detailed dynamics at a community scale by reviewing a suite of developed knowledge base logic networks and by developing a conceptual model of the invasive aquatic plant *Ludwigia* sp. (water primrose), having infested lower, nutrient-rich, slow-moving areas of the Laguna de Santa Rosa watershed. This model serves as a conceptual framework for aquatic nuisance species invading degraded water habitats. Showing the interrelated drivers and stressors of this invasion will aid in focusing research questions and adaptive management in controlling its impact and extent.

Water Quality

A conceptual model for nutrient loading (Figure 1-4) identified several sources that contribute nutrients and in some cases organic material to the Laguna.

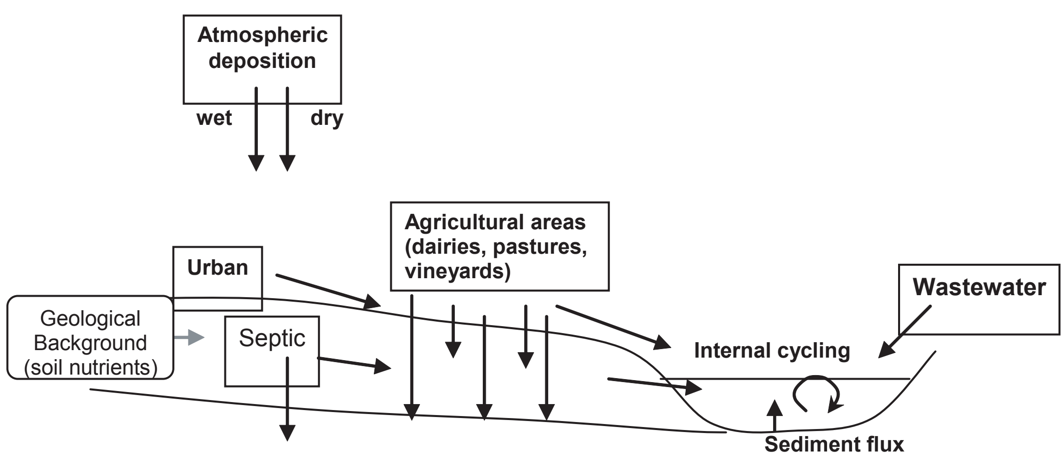

Figure 1-4 Potential point and non-point sources of nutrients/BOD in the Laguna watershed

Sources of nutrients include:

- Municipal wastewater discharge – is a point source that contributes to loadings of nitrogen, phosphorus and BOD during the winter discharge period;

- Stormwater runoff from urban area - carries pollutants such as sediments, nitrogen, phosphorus and BOD that build up on impervious areas and lawns and are transported to the Laguna during storm events;
- Runoff and erosion from agricultural areas – carries excess sediments, nutrients and BOD from agricultural lands that receive fertilization, manure application and irrigation using reclaimed water;
- Internal nutrient cycling and sediment fluxes – as a result of releases of nutrients from sediments and rapid turnover in the biological cycle can be potential sources;
- Atmospheric deposition – (particularly nitrogen deposition as a result of automobile uses and agricultural activities) can increase the background nitrogen levels;
- Groundwater input –is a potential source during summer dry season and can be influenced by the application of fertilizer, manure and reclaimed water on agricultural lands and recharge from septic systems;
- Septic effluents - can contribute to nutrient and BOD loadings; and
- Dry weather storm drain flows –capture runoff from incidental urban water uses (e.g., car washing, lawn watering, etc.) that also delivers sediment, nutrients, and BOD but perhaps more importantly extends wet season conditions within stream channels that were formerly dry during the summer season.

1.8 Findings

Based on a comparison of historic and current cross-sections surveyed at nearby locations, we estimated that the Laguna channel and floodplain filled in by approximately 1.5 feet between 1956 and 2002, representing a loss of flood storage of 54 ac-ft/yr (PWA, 2004). In a subsequent companion study, long-term floodplain accumulation was also assessed taking sediment cores along the Laguna floodplain northeast of Timberhill Road and analyzing them for ^{210}Pb activity (Aalto, 2004). The results indicated that annual sediment accumulation on the floodplain was approximately 2.5 millimeters up to 15 feet from the channel and was typically in the range of 1 to 2 millimeters. Although less than the approximately 10 millimeters per year of deposition rate estimated for the whole Laguna floodplain (PWA, 2004), the coring results are within an order of magnitude of deposition rates obtained from cross-section and sediment yield analyses. Estimates of sediment yield for the same system typically vary by an order of magnitude. In addition, coring analysis was performed for one location on the floodplain, and therefore, represents a higher resolution approach and spatial refinement of our system-wide deposition rates. Therefore, we propose that these estimates represent an approximate range of deposition rates along the Laguna floodplain and vary spatially. In terms of spatial patterns of deposition along the main stem Laguna, we hypothesize that the reach upstream of the Santa Rosa Creek and the Delta Pond had one of the highest deposition rates due to the backwater created by the confluence of flows and the constriction of the floodplain at this location. This hypothesis appears to be supported by the preliminary map of deposition potential currently being developed by the USGS (Lorraine Flint, pers. com.)

Our best estimate of the available data is that the average sediment yield in the Laguna watershed is approximately 150 to 200 ac-ft/yr or 0.6 to 0.8 ac-ft/sq-mi/yr. Approximately 50 percent of the sediment produced is stored in the watershed (mostly as coarse sediment in the headwaters or fine sediment in lower flood control channels), 25 percent settles out in the Laguna and 25 percent is delivered to the Russian River. Of the 50 percent of sediment stored in the watershed, a fraction is deposited as fine sediment along the downstream reaches of the majority of the Laguna tributaries including Blucher, Colgan, Bellevue/Wilfred, Five, Hinebaugh, and Copeland Creeks, as well as more upstream reaches of Windsor and Mark West Creeks (PWA, 2004). In terms of relative sediment contribution of each watershed, our analysis indicated that most sediment–approximately 40 percent of the total Laguna yield, consistent across the two different methods–comes from Santa Rosa Creek (PWA, 2004). This is anticipated since Santa Rosa Creek has the largest watershed area and its steep headwaters are underlain by erodable rocks on a tectonically active block. Sediment yield from the Mark West Creek watershed represents 20 to 35 percent of the total Laguna yield (PWA, 2004). Although Mark West Creek has the steepest gradient and appears to have a high level of natural erosion, it has also historically been one of the least developed areas in the watershed. Therefore, its relative sediment contribution has been less than the surrounding subwatersheds. However, given the recent urban and agricultural development in the watershed, it is also the most sensitive area to future land use changes. The Laguna watershed at Llano Road, which includes Gossage, Washoe, Bellevue/Wilfred, Hinebaugh, Crane, and Copeland Creeks, is estimated to contribute 10 to 25 percent of the total Laguna yield (PWA, 2004).

To address the temporal variability in sediment processes in the Laguna, we assessed sediment yield in the Laguna watershed for several historic land use conditions. We estimated that the pre-European sediment yield was approximately one quarter of the current sediment yield (PWA, 2004). Based on assumptions of a 20 percent growth in urban area and vineyard production over the next 50 years, we forecast a 30 percent increase in sediment yield (PWA, 2004). While modifications to the watershed have delivered more sediment to the Laguna, the Laguna main stem has also been modified. Over time the Laguna has been straightened and channelized in places, increasing its transport capacity locally. However, the fundamental control on the Laguna de Santa Rosa is the area approximately 1,500 feet north of the Trenton Road crossing–at Ritchurst Knob–where the channel is constrained by a bedrock outcrop and forced to take a circuitous route to its confluence with the Russian River. Making the Laguna system more efficient upstream does not overcome this bottleneck and therefore any measures to increase transport capacity along the main channel would be ineffective in removing sediment. Solutions to sediment accumulation in the Laguna will most likely succeed if they focus on controlling sediment sources and delivery into the Laguna system rather than attempting to increase delivery out of the system.

With regard to water quality, we developed preliminary loading estimates from the various source categories for several nutrient related parameters including ammonia, nitrate, total nitrogen, phosphate, total phosphorus, and BOD. Due to the lack of appropriate data estimates were not developed for all of the conceptual model source categories. In some cases the estimates were obtained from other studies conducted on the Laguna. The methodology for developing each source category loading estimate is provided. The estimates are preliminary and are meant for use to compare the approximate relative potential size of the various source categories. The loading estimates for the source categories developed by the project team are included in the table below:

Table 1-1
Summary of estimated pollutant loadings during winter by land uses

	Ammonia (lbs/yr)	Nitrate (lbs/yr)	Total Nitrogen (lbs/yr)	Phosphate (lbs/yr)	Total Phosphorus (lbs/yr)	BOD (lbs/yr)
Municipal wastewater	5,563	104,758	121,290	21,839	21,839	32,338
Dairies	37,273	782	66,857	1,434	--	187,201
Pasture on dairies	732	916	8,606	549	--	24,097
Urban stormwater*	80,437	69,380	562,591	12,915	31,053	657,994
Atmospheric deposition to urban areas	12,564	55,836	68,400			

* Calculated based on total urban area of 49 square miles (including the cities of Santa Rosa, Rohnert Park and Cotati).

The source loading table illustrates that the Laguna receives a large amount of nutrients and BOD from surrounding land uses and discharges into the Laguna. These sources have enriched the sediments and have likely contributed a higher level of eutrophication than would be expected under natural background conditions. No one category is consistently the largest contributor for all parameters. We were unable to develop estimates for categories that are likely significant contributors such as internal cycling from the sediments into the water column. We were also unable to develop estimates for total phosphorus from dairies and pastures which are likely sources to the Laguna. In addition, further analysis is needed to determine the actual impact of loading from each category. For example, urban stormwater via Santa Rosa Creek is estimated to be the single largest contributor of nutrients and BOD to the Laguna. However, the impact from Santa Rosa Creek stormwater loads may be less than other sources due to the location and conditions under which the loading occurs. That is, storm flows in Santa Rosa Creek are discharged into the Laguna below where the most problematic conditions exist and may pass through to the Russian River without depositing a significant fraction of the nutrients or organic load within the Laguna. These source loading estimates will need to be refined and further evaluated as part of the TMDL development process.

Results of the spatial and temporal nutrient analysis have been summarized in Table 1-2. The table presents longitudinal conditions along the Laguna channel from the upper Laguna above Llano Road, the middle Laguna on the western edge of the Santa Rosa plain to just beyond Delta Pond in the North, to below the confluence with Santa Rosa Creek (lower Laguna). To evaluate temporal trends, annual mean concentrations for each of these reaches are presented for three different time periods: 1) pre-Waste Reduction Strategy, 2) post-Waste Reduction Strategy, 3) reduced Laguna reclaimed water discharge due to Geyser project. For most parameters at most sites the temporal trend is decreasing concentrations from the earlier time period (1989–1994) through the latest time period (2004–2006). The longitudinal pattern suggests that the middle portion of the Laguna retains nutrients to a greater extent than the reach below Santa Rosa Creek. This suggests that the Waste Reduction Strategy and the diversion of the wastewater treatment plant discharge out of the Laguna to the Geysers have successfully reduced nutrient concentrations at most locations within the Laguna. However, the mean concentrations for each parameter from the 2004–2006 time-period remain well above the average concentrations for other waters within the region that are ecologically similar to the Laguna.

Table 1-2 Nutrient concentraiton trends for the upper, middle, and lower Laguna

Location / Sampling Period	Mean Total Phosphorus - mg/L		
	1989-1994	2000-2005	2004-2006
Above Llano Road - Upper Laguna	0.58	0.63	0.59
At Highway 12 - Middle Laguna	1.80	1.23	0.79
Below Santa Rosa Creek - Lower Laguna	0.73	0.80	0.65
Location / Sampling Period	Mean Nitrate (NO3) - mg/L		
	1989-1994	2000-2005	2004-2006
Above Llano Road - Upper Laguna	1.27	0.91	1.13
At Highway 12 - Middle Laguna	1.18	2.71	0.89
Below Santa Rosa Creek - Lower Laguna	1.43	1.18	0.75
Location / Sampling Period	Mean Ammonia (NH3) - mg/L		
	1989-1994	2000-2005	2004-2006
Above Llano Road - Upper Laguna	1.70	0.10	0.55
At Highway 12 - Middle Laguna	2.00	0.25	0.38
Below Santa Rosa Creek - Lower Laguna	0.20	0.07	0.28
Location / Sampling Period	Mean TKN - mg/L		
	1989-1994	2000-2005	2004-2006
Above Llano Road - Upper Laguna	1.14	1.10	1.20
At Highway 12 - Middle Laguna	7.60	1.40	1.38
Below Santa Rosa Creek - Lower Laguna	2.35	1.21	0.97

Data for dissolved oxygen (DO) for several locations and time periods were analyzed for the project. While results vary from year to year and between locations, a clear pattern of pervasive and severe low DO conditions are evident. Despite the positive trend in nutrient conditions within the Laguna, DO conditions continue to decline at several locations. For some stations there is no clear trend but conditions remain critical for significant periods of time each year. At times the diurnal pattern suggests that the photosynthesis and respiration cycle result in cyclic DO minimums that could be lethal to most aquatic life. At other locations, a persistent low DO suggest oxygen demand from decaying organic material and sediment processes is the dominant process. An example of the declining trend in DO conditions is illustrated below for the Laguna station near the Todd Road bridge.

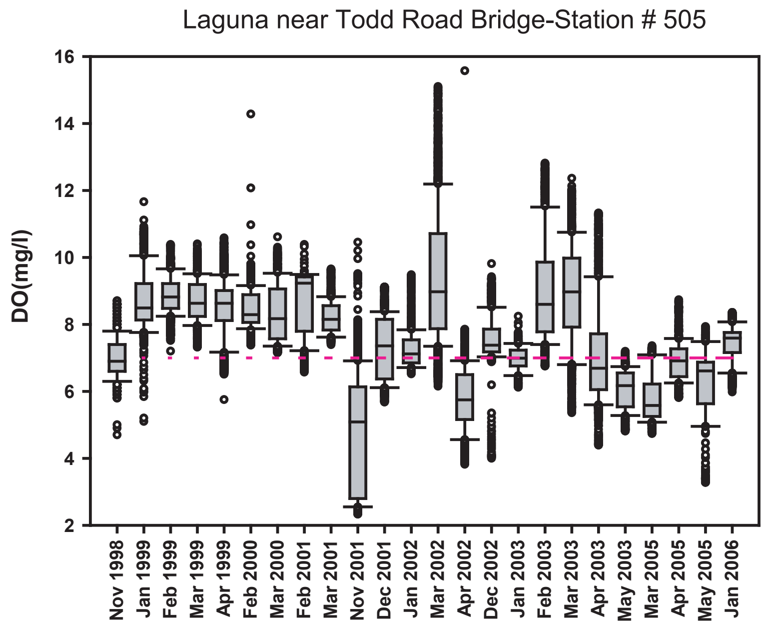

Figure 1-5 Range of DO concentrations at Laguna near Todd Road bridge

Various physical, chemical and biological factors contribute to the DO conditions within the Laguna. These factors include flow, temperature, channel geometry, channel morphology, riparian vegetation, wind fetch, organic and chemical oxygen demand, and biological food web dynamics (algal and macrophyte abundance). The relative contribution of each these factors are variable for different locations along the Laguna. The project team developed three different conceptual models to describe potential dissolved oxygen processes for three typical Laguna scenarios. The scenario for the Laguna at Occidental Road (LOR) is presented below.

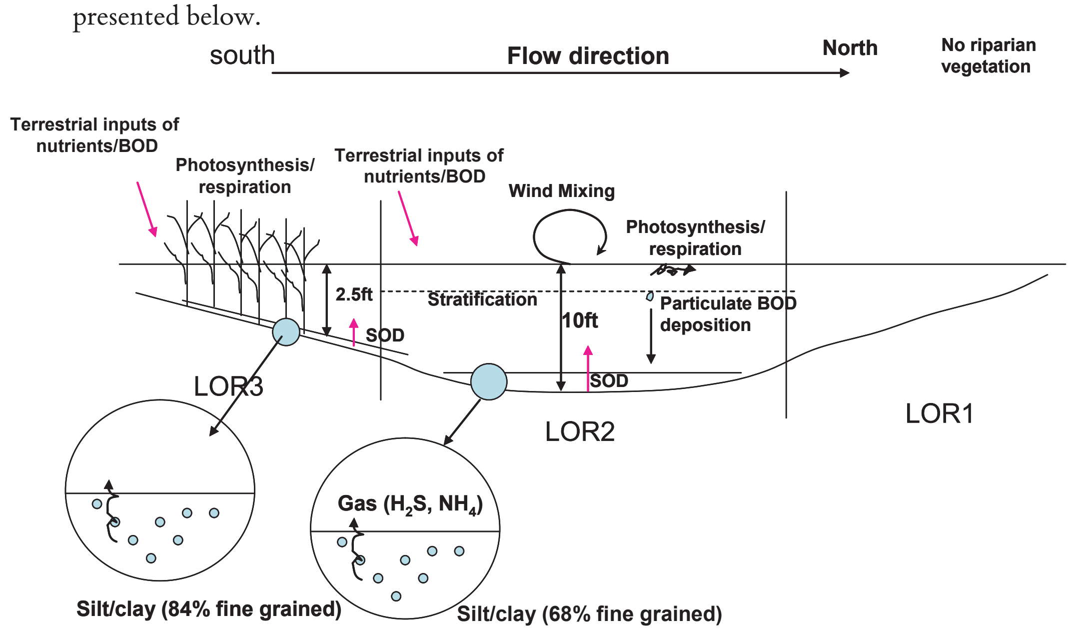

Figure 1-6 Preliminary conceptual model for the Laguna at Occidental Road (LOR)

The model illustrates two of the dominant factors contributing to low DO: macrophytes and algal photosynthesis and respiration; and oxygen consuming processes in the fine sediments. The unsheltered reach is also subject to periodic wind mixing which increases water column DO. A comprehensive map of conditions for the entire Laguna is not possible at this time but sufficient data is available to confirm a serious problem with DO relative to support of Beneficial Uses.

In section 6 we examine upland, riparian, and stream and other knowledge bases logic networks developed for the Russian River watershed, of which the Laguna is the largest tributary. These logic networks and our additional conceptual models make it clear that anthropogenic actions affect physical, hydrological, chemical, and biological factors in conjunction at all levels of investigation through various linkages and effect strengths. The complexity of these logic networks and conceptual models shows that an improvement in system function will likely result from an interplay of a few major or many minor factors (see, for example, figure 1-7). We here list the key drivers as they relate to the three conceptual models for the Upper and Lower Watershed and for invasive *Ludwigia* sp. persistence we described in section 6, in an attempt to illustrate this interplay of major and minor factors.

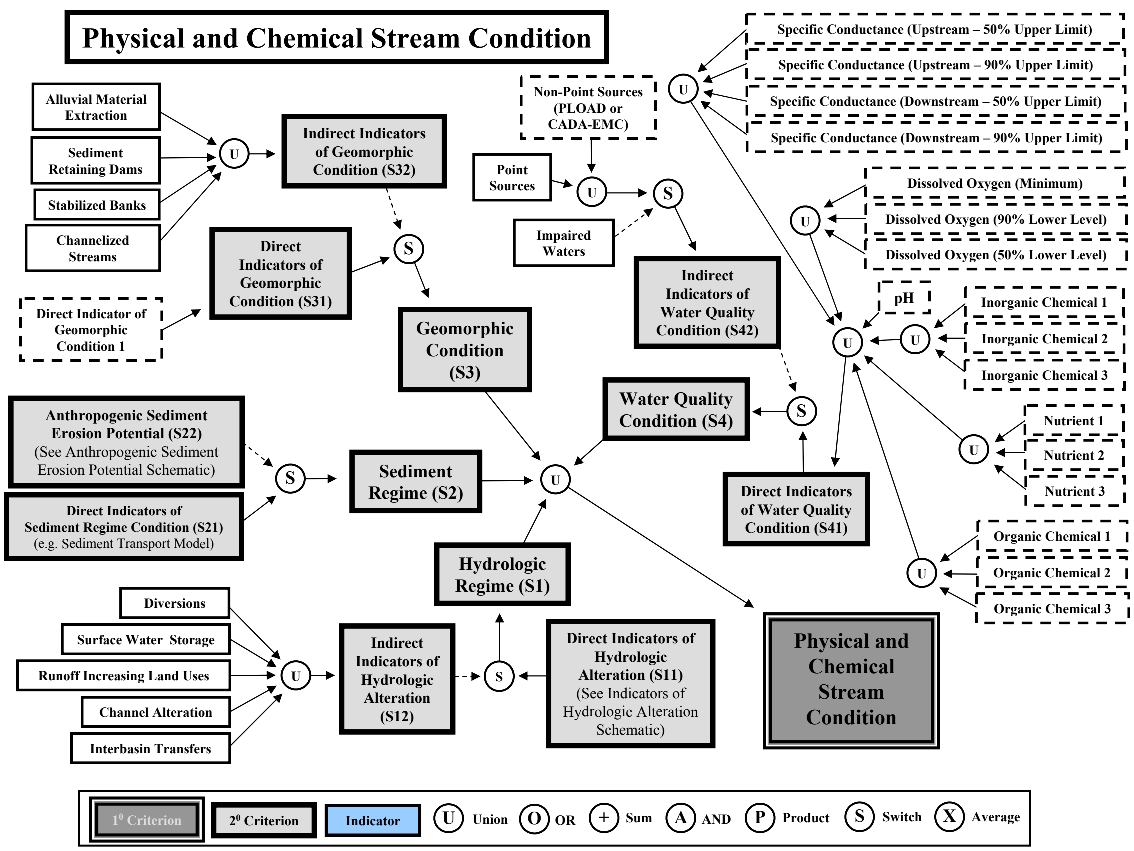

Figure 1-7
Physical and chemical stream condition knowledge base schematic
(Smith 2006)

The key drivers in the Upper Laguna Watershed include:

- A highly active geology, hillside grazing, unpaved roads and driveways where winter storms trigger landslides.
- Inadequately sized culverts that trigger sheet and rill erosion and cause fish passage barriers.
- Historic cinnabar mines and naturally occurring serpentine soils that leach mercury into the waterways.
- Exotic invasive species introductions that can cause shifts in native plant communities, the loss of natural competitive population checks, and the potential for local extirpation of species and extinction of endemics.
- Existing and planned recreational trails that can act as a repeated source for the introduction of new pathogens or invasive plants (from footwear and tire treads).
- Small ranches (ranchettes) that increase human presence in the rural parts of the watershed, so disrupting corridor dynamics, and adding pollutants to soil, air, and water.
- Fire suppression and change in fire regime, leading to the latent potential for large-scale catastrophic fires including the potential for massive erosion, and the certain shift in the diversity of upland communities.

The key drivers in the Lower Laguna Watershed include:

- Urban and rural residential encroachment that led to the loss of riparian buffer zones and the straightening and constricting of channels for flood control, resulting in elevated temperatures in oxygen poor waters, killing aquatic fauna and displacing fish and birds to cooler habitats, and causing a greater than normal reliance on the flood plain to buffer high winter flows.
- Flashy stream flows exacerbated by impervious soils, such as rooftops, streets, and parking lots, that also add oils, metals, and other car pollutants.
- Urban and rural backyard run off and road maintenance activities contributing pesticides, herbicides and other pollutants.
- Agricultural operations in the floodplain exacerbating the loss of riparian corridors, adding nutrients to the system, and keeping water in areas well past their normal drying period due to subsurface flow coming from nearby irrigated fields, negatively affecting species specially adapted to California's climate pattern.
- Recycled water discharged into the Laguna, leading to elevated nutrient levels in the water column and potentially including yet unregulated chemical compounds, such as estrogenic and other pharmaceuticals, and cosmetics that may harm humans and wildlife; the long-term accumulation of sediment phosphorus; and keeping water levels artificially high throughout the year.

- The introduction of non-native plants such as invasive *Ludwigia* sp., *Lepidium latifolium* and others, causing a shift in the native plant community and the loss of natural competitive population checks, potentially decreasing biodiversity.
- Sustained growth, spread, and novel introductions of invasive *Ludwigia* sp. and other macrophytes in the water column, thriving in high nutrient conditions and potentially exacerbating low dissolved oxygen conditions.

Key drivers in the invasion of non-native *Ludwigia* sp. are identified as:

- Altered hydrology, via increased water movement through the system, providing a suitable home for invasive aquatic macrophytes such as invasive *Ludwigia* sp.
- Altered hydraulics, via flood conveyance channels, providing higher than normal system velocities, causing floating living plant fragments to break free and be distributed downstream. These alterations allow the plant to reach new locales forming nascent populations that may eventually develop into vast monocultures.
- The recurrent introduction of invasive *Ludwigia* sp. into the system, via the re-distribution of plant fragments during floods downstream, through natural transport by wildlife (e.g. seeds or shoots get moved via birds), or via inadvertent human introductions from backyard ponds.
- Altered channels leading to sections with slow or stagnant flows, where, coupled with high nutrient levels in both water column and substrate and light availability, young invasive *Ludwigia* sp. plants take root and thrive, potentially causing explosive growth rates, causing large monocultures.
- Absence of associated invasive *Ludwigia* sp. herbivores and plant competitors from their native range causing a lack of a potential natural check to population expansion resulting in vast monoculture-like mats of invasive *Ludwigia* sp., and as an ecosystem engineer (Crooks 2002) completely change the dynamics of the system.
- Weather fluctuations, that may either favor invasive *Ludwigia* sp. growth during frost-free winters, or depress its growth during cold frosty winters. More investigation of this phenomenon is warranted.

A comprehensive modeling framework will be necessary to evaluate management strategies for improving hydrologic, sedimentation, water quality, and ecosystem conditions within the Laguna. The report recommends a multiple model framework because the number of factors that are affecting theses processes cannot be simulated using a single model.

1.9 Project recommendations and next steps

We developed preliminary responses for the most pressing management questions using available information, and identified substantial data gaps and key uncertainties. The conceptual models that we developed to evaluate these questions suggest that it is the cumulative effect of many factors that have led to the decline of environmental conditions within the Laguna. We reviewed the work of existing studies, which all reflect the general paucity of data available for the Laguna (e.g. watershed dynamics and history, water quality, hydrology, sedimentation, groundwater, biodiversity, among others), and outline the need for continued and expanded data gathering via standardized monitoring regimes and specified data collection efforts throughout the watershed. These data will further our understanding by better characterizing the complex dynamics of the Laguna system and will provide an improved level of predictability of the natural system fluctuations in the face of increasing urbanization and climatic change.

We provide general guidance on proposed monitoring activities. A more detailed Laguna monitoring and quality assurance plan is recommended as a priority next step. We recommend that the key data gaps and uncertainties related to hydrology and sedimentation in the Laguna are addressed primarily through monitoring and field work in order to establish an extensive baseline for all relevant processes. Hydrodynamic modeling initiatives in the Laguna proper should build on the current USGS and City of Santa Rosa models. However, we recommend that independent one-dimensional hydraulic and sediment transport models of the tributaries are initiated to address key questions on hydrology, sediment transport, and flood management in the Upper Laguna Watershed. Tributary models would provide further information on the hydrologic and sediment processes along the channels and on the hydrologic and sediment delivery to the Laguna. The first step of such an effort would involve refinement of hydrologic conditions in the tributary watersheds.

The recent 2006 New Year's flood presents a unique opportunity to calibrate existing or future hydraulic models for high flow conditions, and therefore to establish the flood hydrology of the tributaries. In addition, using data from the recently installed gauges, tributary hydraulic models can be used to establish the continuous and low flow hydrology of the tributary systems. Field surveys of channel and floodplain cross-sections and longitudinal profiles along the main stem Laguna, field surveys of rates of bed and bank erosion and aggradations along the tributary channels, continuous sampling of suspended sediment and bedload, as well as observations and measurements of sediment deposition along the mainstem Laguna and tributaries are identified as key indicators to assist in the development of a comprehensive management plan and a TMDL study. We also recommend preparation of a county- or city-wide hydrograph modification management plan that would regulate the future change in hydrologic and sediment delivery due to new developments with the goal of minimizing the potential channel instability and erosion along tributaries. Preparation of such a plan may involve more detailed field work on the relative sediment contribution from different processes and could lead to future efforts to trap sediment in the upstream watershed before it is transported down to flood control channels.

To reduce key water quality uncertainties for nutrient loading and DO conditions within the Laguna, a focused monitoring program will be required. A key to obtaining enough monitoring data to address key questions will be to better coordinate existing data collection activities through the development of a comprehensive monitoring plan. High priority monitoring activities for water quality and related aquatic food web dynamics are included in the list below:

- Longitudinal characterization of sediment conditions within the Laguna including mineral composition, organic content, nutrient content, and depth.
- Collection of information to better inform the dissolved oxygen conceptual models including DO measurements and the site factors such as macrophytes and algal densities, riparian cover, and channel conditions.

- Characterization of aquatic food webs in impaired lake-like and riverine sections of the Laguna. Addressing top-down food web dynamics within restoration may help shift abundance of certain trophic levels and so aid in faunal nutrient uptake and removal.
- Improved characterization of key loading categories including sediment cycling, stormwater sources, agricultural inputs (e.g., dairies, vineyards) and irrigation infiltration to base flow.
- Improved mapping of the Laguna floodplain including hydrologic connections to potential pollutant source areas.
- Biotic indicator monitoring at increased geographical and time scales in order to better establish the biotic potential at degraded and restored sites, so examining the underlying causes of decreasing Laguna biodiversity.
- Continued study of invasive *Ludwigia* sp. spread, population dynamics, physiology, and ecology, and its function in the altered food web.

As no single model can adequately capture the complexity of the watershed's hydrological, chemical, and ecological processes, a set of overlapping models will ultimately need to be developed to give decision makers a suite of tools that will enable them to make prudent and effective management decisions. The preliminary modeling framework includes the uplands or watershed processes that deliver sediment and pollutants to the stream network. The stream network will include flow conditions and channel processes. Finally, water quality and aquatic ecosystem processes will be addressed by another model. Such a dynamic modeling framework will so help to evaluate how different management scenarios will impact each component. Such an adaptive modeling framework is an iterative loop that guides long term management through a series of incremental modeling/decision-making steps. The conceptual models we developed help to clarify which stressors must be addressed to make meaningful progress in restoring ecosystem integrity. In order to help implement and evaluate the success of future adaptive management strategies we proposed relevant indicators for key system components and processes, and included monitoring recommendations to provide a basis for data collection prioritization.

The results of this report can be used to begin development of a suite of comprehensive basin scale planning activities. This will require that the following steps be taken in the next phase of this process:

Stakeholders and agencies partnerships:

- Support and develop an understanding among those that must play a role in the development of a comprehensive watershed plan.
- Create an integrated Laguna planning and implementation team that includes local stakeholders, and local, regional, state, and federal agencies.

Historical and baseline ecological analysis:

- Expand the current knowledge base on the physical and ecological history of the Laguna watershed and establish a contemporary ecological baseline for the Laguna to provide a better understanding of background conditions that can be used to develop scientifically defensible habitat restoration and water quality management objectives.

Targeted monitoring to addressing high priority data gaps

- Coordinate data gathering by stakeholders.
- Develop a monitoring program to address key uncertainties and component indicators identified within this report.
- Develop a monitoring and modeling grant to complement the TMDL framework to be developed by the North Coast RWQCB.

Preliminary restoration project recommendations

- Identify initial enhancement projects and strategies that can be implemented prior to the completion of the comprehensive modeling framework.
- Set restoration targets.
- Establish specific restoration success criteria.
- Prioritize component models for further development.

Adaptive Management

- Use long-term monitoring results to measure management and restoration success against set criteria and periodically adjust management strategies accordingly.

Project Background 2

2.1 Watershed setting

The Laguna de Santa Rosa watershed encompasses a 254 square mile basin that drains through the Russian River to the Pacific Ocean. The 30" to 60" inches of rain received annually over the basin is partially drained via surface flow, partially absorbed in the ground and partially captured and stored for later use. Additional water is added to the basin's water budget via its municipal supply system, and additional water is removed from the basin's water budget through external discharge of treated wastewater.

The watershed encompasses the cities of Santa Rosa, Rohnert Park, Cotati, Windsor and Sebastopol. The people that live and work in the urban areas of the watershed, draw water in part from the region's underground aquifer and in part from the Russian River; this urban population—for the most part—sends their sewage through pipes to a regional wastewater treatment facility located within the watershed. Much of the water from this treatment facility is sent by pipe to the Geysers where it is used to recharge the underground chambers that drive steam-powered electricity generators. A large portion of the remaining water, that is not sent to the Geysers, is sent by pipe to a distributed network of storage ponds: these are drawn down during the spring and summer and used to irrigate hay fields, grapevines, golf courses and urban parks. In wet years, the remaining treated water is discharged into the Laguna at points between Llano Road and Guerneville Rd; in dry years, this direct discharge is small to none.

A large rural residential population inhabits the mountainous regions in the east and draws its water from wells that tap into the aquifer; for the most part these people treat their sewage locally through septic systems. A rural residential population using wells and septic systems also inhabits the plain between the cities and the Laguna de Santa Rosa. Septic tank service companies discharge to the regional wastewater treatment facility. Rain that isn't absorbed locally runs off into storm drains or roadside ditches which discharge into local creeks. Outfall from these drainage systems is managed by the cities, the County of Sonoma and the Sonoma County Water Agency. Many of the natural drainage systems, both within the cities and in the rural areas, have been significantly altered to reduce flooding and to make more land available for homes, businesses and agriculture.

2.2 Recent history

From 1990 to 1998, the Laguna de Santa Rosa watershed was listed on the Clean Water Act Section 303(d) List due to impairment by seasonally high ammonia and low dissolved oxygen levels. A Waste Reduction Strategy was implemented in 1995 as a phased TMDL; this achieved good results and the watershed was removed from the list in 1998.

In 2000, the US Army Corps of Engineers (USACE), under the leadership of the Sonoma County Water Agency (SCWA), commissioned a geomorphic investigation of the watershed, which was completed by Philip Williams and Associates (PWA) in 2001.

In 2002 the watershed was again added to the 303(d) list, this time for phosphorus, nitrogen, low dissolved oxygen, elevated temperatures and excessive sediment. The most recent 2007 303(d) listing also includes elevated mercury levels.

Immediately after completing the geomorphic investigation, PWA was commissioned to expand their work into an analysis of sediment source, rate and fate within the watershed. That work was completed in 2004.

In 2004 the California Coastal Conservancy commissioned the development of a watershed scale restoration and management plan. The Sonoma County Water Agency and the City of Santa Rosa fiscally contributed to this plan, and the work—which was done by the Laguna Foundation—was published in 2006. This plan provided a valuable coarse historical ecological context for this project.

In 2006, the US Geological Survey was commissioned by SCWA through the USACE to conduct a multi-year study of the rate of sediment accumulation along the Laguna's floodplain from Occidental Road to Wohler Road. This work is expected to be completed in 2008.

In 2006 the City of Santa Rosa, at the prompting of the Laguna Foundation, agreed to commission the development of a conceptual model of water quality for the watershed. That work proceeded from late 2006 through 2007, and the results of that work are the subject of this report.

It is anticipated that the NCRWQCB will begin the development of a TMDL for the watershed sometime in 2008. The development process is expected to last through 2011.

2.3 Project participants

The development of this report has proceeded from the collaborative efforts of several groups. At the core, team members from Tetra Tech, Philip Williams & Associates, and the Laguna Foundation, joined together to conduct the bulk of this project's work. Added to this effort was the guidance of the NCRWQCB, which assisted in the strategic direction of the core team.

Tetra Tech: The professional staff at Tetra Tech, Inc. has experience in large multidisciplinary watershed studies. Recent work in this area was completed for the Santa Clara Valley Water District where a watershed stewardship plan was developed to provide a framework for protecting water supply, flood protection and ecosystem health. Tetra Tech staff have also been members of the technical support team for developing nutrient numeric endpoints for California and Nevada.

Philip Williams & Associates (PWA): The professional staff at PWA were the developers of the two SCWA-commissioned reports for the Laguna: the 2001 geomorphic investigation and the 2004 sediment study. Staff at PWA have also completed sediment transport and management analysis for the San Lorenzo River and the Pájaro River.

Laguna Foundation: The professional staff at the Laguna Foundation were the developers of the 2006 restoration and management plan for the watershed. Staff members were also responsible for the 2007 State of the Laguna Conference and Science Symposium.

The professional staff that contributed to this work from these three core groups were primarily: Clayton Creager and Limin Chen from Tetra Tech; Betty Andrews and Setenay Bozkurt from PWA; Dr. Christina Sloop and Joe Honton from the Laguna Foundation. Additional technical and administrative supports were provided by other staff members from each of these three organizations.

At three points during the work, the core team met with a Technical Advisory Group (TAG), to solicit feedback and to provide assistance with obtaining technical reports and data. The three Technical Advisory Group meetings were also attended by a small group of interested private citizens who were provided the opportunity to listen and observe, but who were not formally part of the process.

Members of the technical advisory group have come from a variety of backgrounds. They have served on the TAG without direct compensation, although many of them receive a salary from agency and city departments whose work is related to this project.

Colleen Ferguson, of the Department of Public Works at the City of Santa Rosa, is a civil engineer responsible for managing the city's storm water program which addresses storm water quality and quantity as well as stewardship and restoration of urban creeks.

Brock Dolman, of the Occidental Arts and Ecology Center, is an instructor and practitioner of watershed ecology, and has been instrumental in creating a network of community outreach programs within Sonoma County.

Dr. Lorraine Flint, of the US Geological Survey, is the hydrologist who is presently leading the investigation of sediment accumulation in the Laguna de Santa Rosa watershed.

Dr. Chris Kjeldsen, Biology professor Emeritus at Sonoma State University, has recently retired from teaching freshwater ecology; he is now in a private consulting practice. He has many years of first hand knowledge regarding the Laguna.

Rebecca Lawton, of the Sonoma Ecology Center, has expertise in geology and sedimentation, and has recently conducted a sediment source analysis for the nearby Sonoma Creek watershed.

David Lewis, of the UC Cooperative Extension, is a specialist in watershed water quality management.

Dr. Chris Potter, NASA Ames Research Center, is developing a watershed-scale model of the Laguna using the SWAT modeling program. He is an expert in modeling using remote sensing techniques.

Dr. David Smith, of Merritt Smith Consulting, is a private consultant to the City of Santa Rosa's wastewater treatment facility.

Tim Stevens, of the California Department of Fish & Game, is a biologist with professional expertise in water quality.

Sean White, of the Sonoma County Water Agency, is a biologist who has conducted fish studies in the Russian River and part of the Laguna.

2.4 Steps towards analysis and report development

The development of this report began by capturing management questions defining the goals envisioned for the watershed. The assembly of a collection of available publications, spreadsheets, and GIS shapefiles, then formed the basis for identifying what was currently known about the watershed.

The project team selected modeling tools and techniques that matched evolving industry standards while also matching the needs of the watershed itself, and presented them to the TAG showing drafts of the proposed models themselves. We developed overlapping models using very different approaches, since no single modeling technology fit the disparate needs of the three teams. A shortened form of these models was also presented to a large audience of knowledgeable professionals and the public at the 2007 State of the Laguna Conference and Science Symposium at Sonoma State University.

After selecting suitable temporal scales and geographic scales, for each modeling technique, the project team formulated the hypotheses behind each model and how each model captures the physical, chemical, or biological processes that occur within the watershed. Literature review yielded appropriate citations and general references, to justify the assumptions used and validate conclusions reached in the report.

Assessment and Management Questions 3

Early in the development of this report, the project team considered a wide field of assessment and management questions related to water quality and watershed processes. This early step in the analysis provided a framework for prioritization of what could be addressed in this report. Questions were asked along six lines:

- Hydrology
- Sedimentation
- Dissolved oxygen
- Nutrients, macrophytes, and algae
- Biological diversity
- Invasive *Ludwigia* sp.

For each question, a general narrative response is provided, with a discussion of the analysis of the data that was called upon to support that discussion. But in answering these questions, there were limits to the confidence that could be assigned to the analysis; thus, key uncertainties and "data gaps" are enumerated for each question. These key uncertainties provide an assessment of where new data collection efforts are needed. Within the limits of the available data, a working hypotheses is proposed for each question.

3.1 Hydrology questions

Management questions related to hydrologic and sediment processes in the Laguna, key uncertainties and data gaps to address these questions, and the hypotheses implicit in the questions are described in the following paragraphs.

Question 3.1.1 What are flood peaks, volumes, and durations throughout the watershed, and how do the interactions from subregions affect flood hazards?

Most recently, draft estimates for peak discharges, flood volumes, and flow hydrographs for the 2-, 10-, 25-, 50-, and 100-year flow events at Santa Rosa Creek at Willowside, Windsor Creek at Pool Creek, Mark West Creek at Old Redwood Hwy, Blucher Creek at Hwy 116, Colgan Creek at Llano Road, and Laguna de Santa Rosa at Llano Road have been developed by the USACE using hydrologic modeling. Updated estimates for several additional streams are expected from studies being conducted the City of Santa Rosa as part of the Southern Santa Rosa Drainage study Based on the simulations of watershed hydrology, there is significant interaction between the flood peaks of the Laguna de Santa Rosa and its tributaries. For the simulated storm conditions, this study suggested that in large flood events Santa Rosa Creek, Colgan Creek at Llano Road, and Blucher Creek peak first, quickly followed by the Laguna de Santa Rosa at Llano Road; then Windsor Creek at Pool Creek; and lastly, Mark West Creek at Old Redwood Highway. Because the peaks all occur within about a 4-hour period and the flood hydrographs extend over 16 to 36 hours, peak flows reach the lower Laguna within a narrow time period, which would result in a rapid rise in flood waters. In the December 2005 – January 2006 flood event, peak stages on Santa Rosa Creek, the Upper Laguna, and Colgan Creek were reached within 1.5 hours of each other.

The City of Santa Rosa is working with FEMA to initiate a new flood insurance study of many of the eastside drainages tributary to the Laguna upstream of Sebastopol. This study is expected to develop new hydrologic, hydraulic, and flood hazard information for a portion of the Laguna watershed. Completion of the study is expected within approximately the next two years (Lori Urbanek, pers. comm.).

The Sonoma County Water Agency is also in the process of updating its manual for flood control. This effort is expected to include updates of isohyetal maps for precipitation to include more recent rainfall records and revision of the intensity-duration-frequency relationships for precipitation in the County, including the Laguna de Santa Rosa watershed (Chris Delaney, pers. comm.).

Key Uncertainties and Data Gaps

The estimates for discharge along the Laguna de Santa Rosa and Santa Rosa Creek are subject to significant uncertainty because stage-discharge relationships are inexact due both to overbank flows and the presence of bi-directional flow or ponded water conditions. Backwater effects along the Laguna are significant during flood events. When water levels in the Laguna are high, these control the downstream water surface in the tributaries, affecting flood conditions upstream. The streamflow record at these stations for calibration of hydrologic modeling is also very short; the record at other locations is even shorter or non-existent. The USACE Draft Laguna Basin Hydrology Assessment (2003) did not develop estimates of peak discharge and volume information at other locations (e.g. confluences of other tributaries and points of interest along Laguna). Another unknown that will be key to understanding the interaction of the Laguna de Santa Rosa and the Russian River during flood events is the direction, timing, and magnitude of flow from and to the Russian River. Lastly, information on the frequency, duration, and seasonality of present-day floodplain inundation along the Laguna de Santa Rosa does not presently exist.

Hypothesis

Hydrologic and hydrodynamic simulation models will be capable of simulating flood conditions in the basin adequately once sufficient spatially-distributed calibration and verification data over a sufficiently long period is collected and interactions between the Russian River and Laguna de Santa Rosa are better understood.

Question 3.1.2 What is the present flood storage capacity of the Laguna, and what are the conveyance capacities of the tributary channels?

Relative to the estimated flood storage volume of 80,000 acre-feet provided by the Laguna during the 1964 flood, and assuming a loss of storage volume over a similar period of 54 acre-feet per year (PWA, 2004), we estimate a flood storage volume of approximately 77,500 acre-feet. New information on floodplain topography has been developed and it would be possible to develop a new stage-storage curve for the Laguna that would refine this estimate. Combined with a better understanding of interactions between the Laguna and the Russian River derived from future monitoring data, hydrodynamic modeling of the system would provide a still better estimate of the actual effect of storage in the Laguna on flood attenuation for downstream communities along the Russian River.

In addition, a better understanding of the hydrodynamics of the Laguna itself will be needed to fully understand its role in providing flood storage. Encroachments into the floodplain may limit the effectiveness of flood storage in the Laguna. One such encroachment may be the Delta pond just upstream of the confluence of the Laguna with Santa Rosa Creek. This holding pond creates an apparent bottleneck in the movement of floodwaters, and may thereby reduce the effectiveness of upstream flood storage in the Laguna.

We are aware of hydraulic modeling that has been conducted for Santa Rosa Creek, as well as Colgan and Roseland Creeks. Santa Rosa Creek was designed to convey the 16,500 cfs flow estimated in 1965 to be the 100-year peak flow at Willowside Road at the time of design with an additional 3-4 feet of freeboard in the leveed reach. (City of Santa Rosa, 1992). The present capacity of the channel given the development of extensive in-channel vegetation and deposition of sediment is unknown. The 2004 study of Colgan and Roseland Creeks (Winzler & Kelly, 2004) found that significant reaches of the channels were insufficient to pass their design discharges, an estimated 100-year peak flow at the time of their design. The City of Santa Rosa is working with FEMA to initiate a new flood insurance study of many of the eastside drainages in southern Santa Rosa, tributary to the Laguna upstream of Sebastopol. This study will develop new hydrologic, hydraulic, and flood hazard information for a portion of the Laguna watershed. Completion of the study is expected within approximately the next two years.

Key Uncertainties and Data Gaps

The flood flow hydrology of the system is not well established, and the dynamics of interaction between the Laguna and the Russian River is not well understood. Both of these elements will significantly affect the actual flood storage function of the Laguna de Santa Rosa.

Hypothesis

The flood storage volume of the Laguna continues to provide significant flood attenuation benefits to the communities downstream along the Russian River, though it has likely declined since the 1964 flood; part of this detention capacity is produced by overbank flooding along the lower reaches of the Laguna's tributary channels.

Question 3.1.3 Is it likely that present and/or expected future condition low flows, especially in the Lower Laguna Watershed do or will impair beneficial uses (e.g., habitat, invasive species, species of concern, etc.)?

Summer season flows in the Laguna system appear to be elevated compared to historic conditions. One potential source of this runoff is irrigation of urban and agricultural lands upstream. There may be linkages between the abundance of some species and the changed habitat conditions triggered by the presence of elevated summer flows. The spread of *Ludwigia*, for example, may be fostered in part by the growth of persistently wetted channel area.

Shallow groundwater aquifer conditions can interact with streamflows, augmenting them if the water table is higher than water levels in the stream, and lowering them if the water table is lower. A 1958 investigation by the USGS suggested that groundwater was contributing to streamflows in the Santa Rosa Plain. Shallow groundwater levels may have declined from historic conditions as a result of the history of extraction in the Santa Rosa Basin and the urbanization of significant portions of the high recharge areas in the watershed, but the present interaction of these two systems is unknown.

Key Uncertainties and Data Gaps

The recorded data on historic summer low flows is limited to a short record at a single station along Santa Rosa Creek. Historic descriptions of the waterways of the Laguna may provide another source of information to help evaluate the probability of an increasing trend in summer low flows. The current USGS groundwater study may also provide insight on the present-day interaction between surface and groundwaters within the portion of the watershed occupying the Santa Rosa Plain.

Hypothesis

Summer low flows in the Laguna are elevated over historic conditions and contribute to a decline in certain beneficial uses, including the spread of *Ludwigia*.

Question 3.1.4 How will future modifications within the watershed affect flood conditions and the future hydrologic regime?

Development of presently undeveloped lands and an increase in impervious area in the watershed upstream of the Laguna is expected. The apparent increase in summer low flows will therefore likely grow in the future as one potential source of this runoff is irrigation of developed lands upstream. Flood flows are also expected to increase, as development is associated with increased runoff peaks and volumes. If encroachments are allowed in the 100-year floodplain, or tributary flood flows are contained within levees or similar structures, particularly in their currently flood-prone lower reaches, flooding may increase as a result of lost flood attenuation. Containment of tributary flows also has the potential to increase the ability for those flows to transport sediment to the Laguna as shear stresses increase.

New land, stormwater, and sediment management requirements and programs may reduce the effect of these anticipated changes, as would creation or restoration of flood detention storage. Increasing scarcity or cost of delivered water may also result in limiting the growth of or even reducing the use of water for irrigation, thereby potentially limiting the anticipated increase in summer low flows.

Key Uncertainties and Data Gaps

Projecting development levels or management decisions into the future is always highly uncertain. The potential for future development to increase summer low flows is unknown. The extent and magnitude of future flooding conditions under potential development scenarios are non-existent.

Hypothesis

Flood storage capacity in the Laguna de Santa Rosa will decline while flood peaks are increase; summer low flows will increase.

Question 3.1.5 How will climate change affect flood conditions and the hydrologic regime in general?

Climate change is expected to shift California's precipitation earlier in the year; such a change would similarly shift the peak of a typical annual hydrograph earlier in the year.

Key Uncertainties and Data Gaps

Regionally-specific rainfall intensity and quantity projections are not available.

Hypothesis

Climate change will result in change in the hydrologic regime, triggering evolution of the habitats in the Laguna and ecosystem functions and services provided by the Laguna.

3.2 Sedimentation questions

Management questions related to sediment processes in the Laguna, key uncertainties and data gaps to address these questions, and the hypotheses implicit in the questions are described in the following paragraphs.

Question 3.2.1 What is the magnitude of bedload contribution from each source (e.g., roadside ditches, landslides, gullies, creek banks, etc.) and each geographic subregion, and how are these expected to change in the future?

PWA (2004) found that the largest source of bedload inflow to the lower Laguna is from the Santa Rosa Creek subbasin, followed by the upper Laguna and its tributaries above Llano Road, Mark West Creek, Windsor Creek, Blucher, and Colgan Creek subbasins. Increases in peak flows or changes in climate may increase sediment supply from each of these features.

Key Uncertainties and Data Gaps

No data has been collected that would allow analysis of these contributions by feature and subbasin. No evaluation of transport capacity has been developed that would allow estimation of the delivery of bedload to the Laguna from each subbasin. Projecting development levels or management decisions into the future is always highly uncertain. Regionally-specific rainfall intensity and quantity projections are not available.

Hypothesis

The magnitude of bedload contributions by source varies by subwatershed. For the lower gradient eastside stream crossing the Santa Rosa Plain, sediment delivery to the lower Laguna from each subbasin is transport-limited.

Question 3.2.2 Where are the present sediment deposition areas within stream channels and the floodplain that impair other beneficial uses, and how are these expected to change in the future?

Sediment deposition occurs in locations where supply exceeds transport capacity, such as upstream of hydraulic constrictions and at reductions in channel gradient. Beneficial uses may be affected by deposition in that flood hazards may be aggravated or desirable habitat features may be changed or lost (e.g., upstream of Delta Pond, significant aggradation may have enhanced ponding, creating more favorable conditions for the growth of *Ludwigia*.) As reported in PWA (2004), only a very short record of sediment removal quantities and locations by the SCWA exists. Anecdotal reporting from SCWA maintenance staff may help to focus on apparent depositional areas; these would then need to be assessed for their potential impairment of beneficial uses. It is likely that the growth of in-channel vegetation in the channels that cross the Santa Rosa Plain has reduced their sediment transport capacity and thereby increased sedimentation rates. It is possible that this shift has decreased delivery to the Laguna itself.

Key Uncertainties and Data Gaps

Locations of sediment deposition and impairment of beneficial uses resulting from such deposition have not been broadly catalogued. Nor has the effect of increased growth of in-channel vegetation on sedimentation and transport capacity been evaluated. Changes in future deposition patterns in the Laguna de Santa Rosa and its tributaries in the future will most likely be the result of site-specific land management decisions, which are extremely difficult to project.

Hypothesis

Areas that are presently depositional and where deposition impairs beneficial uses will likely persist into the future except where site-specific intervention is sufficient to alter the hydraulic conditions at that location.

Question 3.2.3 What management interventions would most effectively address sediment sources of concern without impairing other beneficial uses?

PWA (2004) recommends the use of sediment traps at the apex of the alluvial fans feeding sediment into the tributaries of the Laguna. The clearest impairment of downstream beneficial uses is the result of excess, not limited, sediment supply, and management of a specific site for sediment removal would cause far less habitat disturbance compared to sediment removal along an extended reach of creek. It would also avoid the flood hazards that might be created if sediment-laden water were routed onto the floodplain, as occurred under natural conditions. However, such sediment traps may not be the most effective or cost-effective way to address sedimentation conditions at distant locations, such as the Laguna itself. They may also be impractical if they could not be sized to capture a sufficient portion of the sediment that would be delivered over the course of a rainy season.

Key Uncertainties and Data Gaps

To address impairment at a given site by source or upstream controls, an understanding of the source of sediment at that location must be developed. If the largest sources of sediment causing beneficial use impairment at a given site could be identified, then management interventions could be evaluated for effectiveness and cost relative to benefit.

Hypothesis

A better understanding of the relative contribution of the sources of sediment causing impairment would allow prioritization of management measures by cost-effectiveness.

3.3 Dissolved oxygen

Management questions related to dissolved oxygen, as an impairment to beneficial uses of the watershed,together with key uncertainties and data gaps to address these questions, and the hypotheses implicit in the questions are described in the following paragraphs.

Question 3.3.1 Where in the watershed (which stream sections) and when (what time period) and where (in the water column) does the DO impairment occur?

Based on the limited data, DO impairment was observed above Santa Rosa Creek with critical sections between the Laguna at Occidental and above Santa Rosa Creek, and the Laguna near Stony Point Road and above D Pond discharge. DO impairment can occur in both the winter and summer months. The lowest DO is usually observed in deeper water near the sediment/water interface. In extreme cases, an anoxia zone of several feet was developed in deeper water. However, more systematic continuous monitoring of DO is needed. Dissolved oxygen is likely to be negatively impacted under existing conditions; however, background or baseline potential is unknown.

Key Uncertainties and Data Gaps

The dissolved oxygen monitoring program was not comprehensive and it is not known whether there are other locations or time periods where DO is below desired objectives. There is also uncertainty regarding the spatial extent and the completeness (channel cross-section) of the depressed dissolved oxygen zones. Background/baseline DO conditions within the Laguna remain somewhat uncertain, but this could be better evaluated using a dynamic watershed/water quality model.

Hypothesis

Reduced nutrient and BOD loading, improved hydraulic flow, and improved habitat conditions, would improve DO conditions in the Laguna.

Question 3.3.2 To what extent does the DO impairment impact the Beneficial Uses? Do dissolved oxygen concentrations reach stressful or lethal levels for salmonids and other aquatic life in the Laguna watershed, at time periods when the fish are likely to be present?

The DO impairment most likely impacts Beneficial Uses related to aquatic life because low DO is observed both in winter and summer months throughout the Laguna. In the Laguna main channel during the summer, minimum DO as low as 0.03 mg/l was observed, and as low as 0.21 mg/l in the winter months in the main channel and 2.29 mg/l in the tributaries. These represent lethal to stressful conditions for most forms of aquatic life.

Key Uncertainties and Data Gaps

The duration and magnitude of these zones and the presence of refuge habitats is unknown. Therefore, more detailed information on when and where the aquatic species may be present is needed. It is also not known to what degree that low dissolved oxygen zones could potentially serve as migration barriers to cold-water fish for access to upper tributaries where DO impairment occurs. Steelhead migration to and from Santa Rosa Creek does not appear to be impacted.

Hypothesis

The current dissolved oxygen conditions within the Laguna represent a serious threat to the viability of several of the Laguna's designated Beneficial Uses.

Question 3.3.3 What is the cause of the DO impairment? What physical, chemical and biological factors control the DO impairment?

As indicated in the previous question, various factors contribute to low DO in the Laguna. Among these, the significant factors include low flow, low gradient of water, channel morphology, high loadings of nutrient and organic carbon, high sediment oxygen demand and an abundance of algae and macrophytes.

Key Uncertainties and Data Gaps

There is uncertainty about the significance of each of the individual risk cofactors listed above in creating low dissolved oxygen conditions.

Hypothesis

It is possible to mitigate the impacts of the various risk cofactors on dissolved oxygen through a series of management actions including reductions in nutrient and organic carbon loading, restoration of riparian habitat, and removal of hydrologic restrictions.

Question 3.3.4 What are the relative contributions of DO consumption due to algae and macrophyte respiration and the decomposition of organic material (e.g. dead algae) in water and sediment?

As indicated in the previous sections, large DO swings indicate the influence of algae and macrophytes respiration; however, the low baseline DO, even in winter months, indicates that there is a large oxygen demand in the lower water column and sediments, possibly due to organic carbon and reduced forms of nitrogen. The relative contribution of DO consumption due to algae or microbes may vary with season. However, prolonged depressed DO observed in summer months indicates a large influence of bacterial activity.

Key Uncertainties and Data Gaps

Sediments and sediment processes within several sections of the Laguna are not well understood. It is not known how much oxygen consumption is due to sediment processes.

Hypothesis

In the Laguna during the summer DO consumption is dominated by algae and macrophytes respiration as well as sediment oxygen demand, and in the winter most of the DO consumption is due to BOD loadings from external sources.

Question 3.3.5 What are the relative contributions of organic carbon originated from terrestrial and aquatic sources to oxygen demand in the Laguna?

It is clear that organic carbon from both the terrestrial sources (e.g. urban/agricultural/forest runoff) and aquatic sources (decay of macrophytes and detritus of algae) contribute to the loading of organic carbon in the Laguna. Organic carbon loads from aquatic sources are possibly more dominant during the summer when primary production is high and are likely to be more bio-available and is more easily decomposed and may contribute to short-term oxygen demand. Such loads may be particularly high following die-back of macrophyte beds. Organic carbon from terrestrial sources is probably more dominant in the winter and not as rapidly decomposed and therefore may be contributing to the long-term prolonged depression. *Ludwigia* continues to be a significant contributor of organic carbon in the Laguna despite progress made by the *Ludwigia* eradication program. Preliminary loading estimates as described in section 3.2 indicate that urban stormwater and agricultural lands contribute to loadings of BOD that could potentially be impacting DO conditions within the Laguna.

Key Uncertainties and Data Gaps

The relative importance of terrestrial and aquatic sources of organic carbon is difficult to determine without further study. High algal density has been observed during 1990 to 1994 (*e.g.*, average of 78.7μg/l of chlorophyll a at the Laguna at Occidental Road – Table 3-16); however, information on current algal levels has not been reviewed by the project team. In addition, background loading of BOD and organic carbon has not been determined. Therefore, the estimates provided in this document must be considered preliminary.

Hypothesis

Within the Laguna organic carbon contributions during the summer and fall are dominated by aquatic sources, while in the winter organic carbon sources are dominated by terrestrial sources.

Question 3.3.6 What are the relative contributions of organic/inorganic nitrogen originated from terrestrial and aquatic sources to oxygen demand in the Laguna.

Nitrogen loads to the Laguna have an important indirect effect on oxygen dynamics by supporting growth of algae and macrophytes. The direct contribution of nitrogenous oxygen demand is less clear. Relatively high organic nitrogen and inorganic nitrogen (ammonia) concentrations were observed in sections of the Laguna. Oxygen demand due to nitrification could be significant. The main terrestrial TKN sources include runoff from dairies and other agricultural activities. Nitrogen sources in water include possible ammonia releases from sediment and organic nitrogen released from decomposition of dead algae and plant tissue. In the nutrient and dissolved oxygen dynamic study (Otis, 2006), TKN in the water column at SEB3 was found to increase with depth (from 1.3 to 6.9 mg/l from surface to bottom), indicating a possible aquatic source. The importance of this question is to determine whether any additional effort should be directed to managing terrestrial sources of nitrogen or rather that aquatic sources that are not easily managed are dominant.

Key Uncertainties and Data Gaps

Without a loading estimate for aquatic sources, the relative contribution is not clear.

Hypothesis

It is most likely that the largest portion of the reduced forms of nitrogen comes from agricultural sources in close proximity to the Laguna and if controlled would significantly reduce the overall nitrogen oxygen demand. Reduced algal and macrophyte abundance will also reduce the aquatic portion of nitrogen oxygen demand.

Question 3.3.7 Does nitrogenous oxygen demand contribute to DO consumption in the water column?

Yes, there is evidence that nitrogenous oxygen demand does contribute to DO consumption in the water column. It is likely that BOD is a more significant demand than nitrogen. As indicated previously high TKN concentrations were observed in sections of the Laguna result in increasing levels of oxygen demand due to oxidation of TKN. TKN concentrations have been measured at 6.9 mg/l in the lower water column at SEB3 on July 21, 1998 (Otis, 2006).

Key Uncertainties and Data Gaps

The extent of nitrogen oxygen demand in locations other than SEB3 has not been assessed and it is uncertain whether other locations exhibit the same profile as SEB3. Additional monitoring is necessary to determine how broadly the conceptual model developed for SEB3 applies within the Laguna.

Hypothesis

While there are indications of nitrogen oxygen demand in the water column, organic carbon imposes a larger oxygen demand within the Laguna.

Question 3.3.8 Are there impoundments that reduce travel time, promote settling, promote stratification, and promote oxygen consumption?

Yes. There are several reaches in the Laguna where the channel is wide and have a reduced flow velocity that contributes to settling, stratification and oxygen demand (Otis, 2006). These factors contribute to the low DO in the bottom layer of water.

Key Uncertainties and Data Gaps

The location and magnitude of these impoundments is uncertain and the overall impact on water quality within the Laguna is also uncertain.

Hypothesis

Eliminating unnatural impoundments (e.g., constrictions due to bridge abutments) would result in improved water quality conditions within the Laguna.

Question 3.3.9 How and where does wind mixing affect DO concentrations in the water column?

It has been proposed that due to the low gradient, high heat, and lack of canopy, wind mixing is one of the few possible mechanisms for reaerating some reaches of the Laguna's depleted water column. However, there is little information upon which to evaluate the overall importance of this mechanism.

Key Uncertainties and Data Gaps

Additional information on DO diurnal monitoring in association with channel morphology and riparian cover is needed to determine whether, when, and where wind mixing contributes significantly to reaeration of the water column. An important question is the extent to which dense macrophyte beds reduce natural reaeration rates.

Hypothesis

Under current conditions wind mixing is inadequate to overcome excess oxygen demand and respiration effects within the Laguna.

Question 3.3.10 What are physical, biological, and chemical characteristics of the photic zone in various reaches of the Laguna?

The photic zone is usually open without riparian vegetation and therefore receives full sunlight. There is not enough data to quantitatively address the question. In photic zones, excess algal growth can occur as indicated by observed large DO swing. In shallow photic zones, macrophytes such as *Ludwigia* may also grow. A detailed survey of *Ludwigia* cover or algae density has not been reviewed by the project team.

Key Uncertainties and Data Gaps

A detailed survey of *Ludwigia* cover or algae density has not been reviewed by the project team.

Hypothesis

Currently the photic zone is dominated in sections by *Ludwigia*. In sections not dominated by *Ludwigia* the water column frequently has algal biomass (measured as chlorophyll a) exceeding 25 µg/, which also impacts Beneficial Uses.

Question 3.3.11 Is the Basin Plan minimum DO objective of 7.0 mg/l achievable at all times and places within the LSR watershed?

Preliminary data analysis based on limited data suggested that the Basin Plan minimum DO objective was not met at any locations within the main Laguna channel. Santa Rosa Creek meets the DO objective in the winter months but does not meet the basin plan objective in the summer months. Some tributaries downstream of waste water discharge points also do not meet the basin plan objective. More systematic continuous DO monitoring is needed to more completely characterize existing conditions within the Laguna. Clearly under existing conditions, the LSR can not achieve the Basin Plan minimum. This may be due to excess inputs of nutrients and organic materials and restricted flow. Given reduced levels of nutrients and organic inputs, and improved flow conditions (low flow channel) DO conditions would be dramatically improved. However, it is not possible at this time to determine whether these improvements will result in pervasive achievement of the Basin Plan minimum DO objective. It is also important to note that legacy sediment quality effects will likely delay improvements in water quality conditions. Low gradient, flow volume and elevation would probably result in marginal DO conditions during the dry season. This question of DO could be reasonably well addressed through the use of dynamic simulation model to determine the implementation strategies that could result in the achievement of the basin plan objective throughout the Laguna. There is uncertainty regarding the feasibility of achieving desired DO conditions under restored conditions during the summer season.

Key Uncertainties and Data Gaps

Because of the unique nature of the Laguna, there is no known reference site with which to assess the question of whether the DO objectives are achievable in the absence of human disturbance. Development of a calibrated model would allow evaluation of the expected DO regime under natural conditions in the Laguna.

Hypothesis

Using a calibrated model a background simulation will present marginal but acceptable DO conditions within a hypothetically un-impacted Laguna.

3.4 Nutrients, macrophytes and algae

Management questions related to nutrients, macrophytes and algae are discussed here, together with the key uncertainties and data gaps that limit these discussions. To the extent possible, working hypotheses are provided for each management question.

Question 3.4.1 Do nutrient (N, P) loadings contribute to excess algal and macrophytes growth in the Laguna? What are other contributing risk cofactors that contribute to excess growth? For N and P, which one is the controlling factor for algal and macrophytes growth? Is either controlling or are both present in sufficient quantity that there is no limiting nutrient? How will reducing N and P loadings result in improvement in water quality conditions? To what levels will the N and P loadings need to be reduced?

This question is a concern in part because nutrient concentrations in the Laguna are well above other water bodies within Ecoregion 6 (which includes the Laguna de Santa Rosa). Mean nitrate concentrations range from 0.52 – 2.96 mg N/l at different sampling locations in the Laguna. The mean nitrate concentration for minimally impacted waterbodies (N=112) within Ecoregion 6 is 0.16 mg/l. The range of nitrate concentrations from this same Ecoregion 6 sample is .05 mg/l to 2.85 mg/l. Mean TP concentrations in the Laguna range from 0.11- 1.22 mg/l. The range within the Ecoregion 6 survey of minimally impacted waters is 0.03 mg/l to 0.30 mg/l. The mean is 0.08 mg/l. In addition this question may have a different outcome depending on whether macrophytes or algae are being considered limited by nutrients.

The project team recently received a technical memorandum dated March 19, 2007 developed by Dennis J. Brown of LSA Associates as a contribution to the City of Santa Rosa IRWP Discharge Relocation Project Draft EIR. The memorandum evaluates factors controlling the colonization and growth of *Ludwigia* sp. within the Laguna de Santa Rosa. The memorandum states that the availability of propagules and habitat conditions are the main controls on *Ludwigia* infestation. The review suggests that nitrogen in the water column may play a role in limiting growth of *Ludwigia* and that phosphorus concentrations in the water column are unlikely to be limiting, as ample P can be obtained from the sediments via the roots. While external inputs of P clearly increase the sediment store it is unlikely to be a limiting factor since P is mobile under anaerobic conditions and the native sediment is likely to contain enough P to support macrophytes growth. These results would suggest that in addition to mitigating the hydrologic and habitat factors contributing to the infestation that any nutrient management strategy would need to address both N and P over the long-term to have a measurable impact in reducing the abundance of *Luwigia*.

In addition to this most recent study there is additional information to consider relative to this key management question. The effect of nutrients on growth of phytoplankton and other plants is typically represented by Michaelis-Menten kinetics, in which $G = Gmax \cdot C/(K+C)$, where G is the growth rate, $Gmax$ is the maximum potential growth rate (absent any other limitations on growth potential), C is the available nutrient concentration, and K

is the half-saturation constant. Growth limited by a nutrient is then G/Gmax = C/(K+C). In this formulation, nutrient limited growth asymptotes towards 1 as *C* becomes large relative to *K*. As summarized in Thomann and Mueller (1987, p. 427): "If a nutrient control program is initiated, but the reduction in input load only reduces the nutrient concentration to a level of about two to three times the Michaelis constant, then there will be no effect on the phytoplankton growth. This is equivalent to the notion of the limiting nutrient. Removing a nutrient that is in excess will not have any effect on growth until lower concentrations are reached." In fact, the statement of "no effect" is a bit misleading, as the Michaelis-Menten formulation is asymptotic, implying that some potential limitation persists at any concentration, but that it becomes exceedingly small as concentrations become much greater than the half-saturation constant.

Determining at what point nutrient limitation becomes "insignificant" depends on the specification of the half-saturation constants, as well as the decision as to what represents a significant effect. Thomann and Mueller cite typical half-saturation constants for phytoplankton growth of 10-20 µg/L for [inorganic] N and 1-5 µg/L for [inorganic] P. Other authors have suggested somewhat different values.

The Michaelis-Menten formulation indicates that when concentration is 4 times the half-saturation constant growth will be 80 percent of the maximum potential rate, implying only a minor limitation. The upper ranges on the Michaelis-Menten half-saturation constants suggest that minimal limitation on phytoplankton growth by nutrients will occur until inorganic N concentrations fall below 80 µg/L or inorganic P concentrations fall below 20 µg/L or less. In contrast, inorganic N concentrations in the Laguna appear to be around 450 µg/L and inorganic P concentrations around 900 µg/L – suggesting that N is likely to limit phytoplankton growth by less than 5 percent and P by less than 1 percent of the maximum potential rate. Of course, algal growth may be limited by other factors, including light, temperature, settling, and grazing.

In a paper in which he reviews the eutrophication status of streams Dodds (2006) states that in an excess of threshold values of total N and total P there are no increases in mean benthic chlorophyll a. Dodds suggests that this indicates that nutrient limitation is overcome when water column nutrient concentrations are great enough. 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.

Listed below are some the key summary points from the Dodds (2006 and 2006a) that relate to this management question:

- There is a relationship between TN/TP with primary production (particularly for benthic, and planktonic algae);
- The relationship to macrophytes is less clear but it is still considered to be a factor for most species;
- When nutrients in the water column reach a high level, nutrient limitation can be overcome;

- Organic carbon input (both allochthonous and autochthonous) can increase heterotrophic activity and lead to net heterotrophic status;
- Nutrients enrichment can stimulate both autotrophic and heterotrophic activity;

Dr. Eugene Welch has commented on this question for the Laguna stating that N/P ratios have little meaning if concentrations for both are high, citing studies that suggest that light will become the limiting factor before nutrients (Saas et al. 1989; and Cooke et al. 2005 – page 93). In general he states that phosphorus control leads to more efficient biomass control.

The project literature review included a reference to an Algal Growth Potential (AGP) assay conducted by the City of Santa Rosa in waters collected from the Laguna de Santa Rosa and presented in their findings in the "1996 City of Santa Rosa EIR" (Wickham, 2000). The AGP results suggested that the Laguna is a nitrogen limited system. Tetra Tech conducted a review of the AGP procedure and prepared the following review:

The City of Santa Rosa (City) examined the Algal Growth Potential (AGP) in waters collected from the Laguna de Santa Rosa and presented their findings in the "1996 City of Santa Rosa EIR" (Wickham, 2000). According to Wickham (2000), the City collected an aliquot of water from a particular station and isolated and held it for 14 days. They monitored algae production and measured nutrient uptake to see which nutrients were depleted first. Their premise being that the limiting nutrient would be depleted before the non-limiting nutrient.

Although the description of the specific procedures used in the City's AGP test as presented in Wickham (2000) are not reported, and, therefore, cannot be commented upon, some general uncertainties about the procedure can be discussed. The following sections provide a discussion about these general uncertainties. An alternate method for evaluating nutrient limitation is provided in Section 9 "Monitoring Recommendations".

1. The test method cited used "raw" water and resident algal species. This procedure incorporates several uncertainities:
    a. Raw water contains not only nutrients and algae, but bacteria, rotifers, zooplankton, and detritus.
    b. Rotifers and zooplankton graze on the algae, making accurate quantification of growth/lack of growth impossible. It also impedes the ability to identify the limiting nutrient(s) because the nutrients are constantly being assimilated by algal growth and released as metabolic by-products.
    c. Raw water samples can contain a mixture of algae species, the health of which is unknown. Unhealthy algae can add bias into the test results.
    d. Detritus can provide a surface upon which nutrients can sorb, thus adding bias into the test results.
2. The City's AGP test method was unable to differentiate between nutrients that were assimilated by the algal cells vs. those assimilated by bacteria or sorbed onto particulate detritus. Since the City's method used a chemical quantification of the

remaining nitrogen and phosphorus, there exists the potential for some methodologically derived uncertainties:

e. If the sample was not filtered through a 0.45 micron sterile filter prior to chemical quantification of nitrogen and phosphorus, the analytical procedure would result in lysing the cells, releasing all of the nutrients back into solution. Thus making it very difficult to quantify which nutrients were assimilated by algae and bacteria or sorbed onto particulate detritus.

f. If the sample was filtered through a 0.45 micron sterile filter, and the filtrant analyzed for nutrients, the results would provide only the amount of nutrients assimilated by whatever was living in the test solution (algae, bacteria, etc.) or sorbed by particulate detritus.

3. There is no indication that the City examined seasonal nutrient limitation. For example, what is limiting during the summer dry months might not be limiting during the wetter winter and spring months.

The management question is linked to the potential impact of organic matter in two ways. First that nutrients are not the only potential stressor resulting from external loading sources; and secondly that the primary impact is the internal production of organic matter that then leads to low dissolved oxygen conditions. For the Laguna, the high organic carbon load suggests that there should be high heterotrophic activity. The role of organic carbon as a stressor upon beneficial uses is likely to be important. A key aspect regarding organic matter is whether the main source of organic carbon is originated from the water column or from terrestrial input.

As defined by Dodds in the 2006 paper, the Laguna has the situation where the autotrophic and heterotrophic state coexist (one may dominate according to season). If the heterotrophic state dominates and the main carbon source is allochthonous, then controlling carbon should help limit heterotrophic activity. However, as nutrients can stimulate primary production (which can provide and internal carbon source) and heterotrophic activity, controlling carbon only without controlling nutrients will still result in heterotrophic activity and high DO demand.

High turbidity in Laguna water may lead one to believe that algal growth is limited. However, as the diurnal cycle illustrated in the DO analysis indicated that in open water there is substantial algal activity. Tetra Tech did obtain and summarize algal data for the period of 1989-1994 (Table 3-16). The values in Table 3-16 must also be evaluated in light of a potentially successful *Ludwigia* removal program. If turbidity is not the dominant light limiting factor the removal of the shading effects of the macrophytes could lead to nuisance levels of algal growth. Monitoring for algal concentrations in *Ludwigia* control reaches should be undertaken to investigate the potential for this possibility. In summary:

- N and P loadings likely contribute to excess algal and macrophytes growth in the Laguna, however other factors must be considered;
- Under current conditions it is unlikely that either N or P are a controlling or limiting factor for algal or macrophytes growth;

- Reducing nutrient loading for the long-term will reduce growth rates of both algae and macrophytes that will lead to improved DO and habitat conditions; and
- It is not clear how much or how long nutrient loading will need to be reduced to see measurable improvement in water quality conditions.

Key Uncertainties and Data Gaps

It is unclear whether nitrogen and phosphorus ever become a limiting nutrient to algal or macrophyte growth in the Laguna. What is the relative contribution of other risk cofactors to excess levels of algae and macrophytes? The assessment of nutrient targets or loading reduction must be done in association with other risk cofactors, which can be best accomplished through the use of a dynamic water quality/watershed simulation model(s).

Hypothesis

A reduction of nitrogen and phosphorus loading to the Laguna in conjunction with the strategy to mitigate risk cofactors will reduce excess algal and macrophyte growth within the Laguna to acceptable levels.

Question 3.4.2 To what extent do the macrophytes (including *Ludwigia* and other nuisance invasive species) and algae growth impact the beneficial uses?

As illustrated in the overview conceptual model (Figure 3-1), macrophytes and algal growth and decay processes significantly impact water quality conditions (DO, pH, etc.) causing impairment to all beneficial uses. The respiration phase of the diurnal cycle results in lower DO that would be harmful to fish and other aquatic life. Decay of macrophytes and algal material consumes oxygen and also results in low DO. The physical density of macrophytes is also likely to impair beneficial uses (migration, recreation, etc.). Unaesthetic odor and slime also impair recreation uses. Macrophytes (specifically *Ludwigia*) provide ideal breeding habitat for mosquitos, which impacts public health. Hypotheses demonstrating impacts of other beneficial uses can be developed using the overview conceptual model in Figure 5-1.

Key Uncertainties and Data Gaps

Tetra Tech (2006) recommended a maximum algal density of less than 10 µg/L chlorophyll a in lakes and reservoirs to support cold water aquatic life uses without impairment and 25 µg/L chlorophyll a to support warm water aquatic life uses without impairment. It is not clear if these lake targets are applicable to the Laguna. It is also not clear what the threshold density for macrophytes should be to ensure that impacts to Beneficial Uses do not occur. No targets have been recommended for macrophyte density at this time.

Hypothesis

Specific targets for macrophytes density and coverage or algal concentrations have not been developed. However, it will require a comprehensive management strategy that includes habitat restoration and nutrient reduction strategies to reduce the impact of nuisance invasive species and algal growth and to restore the beneficial uses to the Laguna de Santa Rosa.

Question 3.4.3 What are the sources of nutrient loadings? What are the relative contributions of the following sources: urban storm water runoff; agricultural storm water runoff; agricultural irrigation return flows; municipal wastewater discharge; sediment flux; atmospheric deposition; and groundwater? For external nutrient loadings, what is the relative contribution from point and various non-point sources? Can we reasonably estimate the amount of nutrient loading from each source? What are the largest sources of nutrient loading (both N and P) in the watershed? Can the identified sources be effectively managed?

Various sources exist in the Laguna contributing to nutrient loadings, including all the sources listed above. Based on preliminary loading estimates, main sources of nutrient loadings vary with season and constituents. During winter, urban storm water runoff, agricultural storm runoff and municipal wastewater discharge are the main sources of nutrients. Phosphorus has a tendency to bind with sediments. Therefore, transport of phosphorus is more associated with sediments, which are mobilized by storm flows. Release of phosphate from anoxic bottom sediments can be a large source of phosphorus during the dry season. As summarized in Section 2.3.4, shallow groundwater may interact with streams and therefore be a potential source of loadings. Currently there is limited information on the connectivity between surface and deep groundwater, but generally deep groundwater may not be a significant source

For nitrate, point source of municipal wastewater discharge remains as a main source. Urban storm water runoff is also a main source. For ammonia, urban storm water runoff and agricultural runoff from dairies are the main sources. For nitrate, both municipal wastewater and urban stormwater runoff are the significant sources. For phosphorus, municipal wastewater discharge and urban storm water runoff are main sources for phosphate. However transport of phosphorus is closely associated with sediments, and therefore non point sources of runoff from various land uses (e.g. agricultural lands, urban) should be a larger source for total phosphorus.

Municipal wastewater discharge remains as one of the main nitrate sources and phosphate. However, runoff from urban storm water and agricultural lands contribute more significantly to ammonia, organic nitrogen, and total phosphorus. For non-point sources, some best management practices (BMPs) such as riparian cover are necessary for reducing loadings to streams.

Key Uncertainties and Data Gaps

The loading estimates we developed are based on assumptions that need to be further evaluated and without detailed model calculations, the estimates are preliminary. The following uncertainties and data gaps must be addressed before a meaningful loading analysis can be completed:

- Ground water discharges need to be better mapped and quantified.
- Estimates of dry and wet atmospheric deposition of ammonia and nitrate need to be further refined.
- Contributions of nutrients from septic tanks through infiltration during wet and dry periods need to be monitored.
- Overall loadings from agricultural operations (e.g. manure application, slurry rates, and irrigation, fertilizer use in vineyards) need to be updated.
- A comprehensive estimate of urban runoff needs to be developed.
- Factors that affect the bioavailability of nutrient loads to algae and macrophytes needs to be further evaluated.
- Loading from internal nutrient cycling and sediment flux needs to be better quantified.

Hypothesis

Atmospheric deposition is likely to be a minor source of nutrients during storm events when compared to other source categories. Groundwater, as shallow infiltration, is an uncertain but likely source of nutrients during storms and from irrigation infiltration; however, it is also a smaller source when compared to surface runoff from agricultural operations, urban stormwater, and point source discharge during winter storms. During the summer dry season, urban incidental runoff, sediment flux and internal cycling in the Laguna could be major sources of nutrients.

Question 3.4.4 Are nutrient loadings greater from external or internal origin? What are the primary nutrient loadings under high flow and under low flow conditions? Are nutrients being released from sediment during low flow, and is it a significant source? To what extent does internal sediment contribute to the loading of nutrients? What management intervention for sediment control would have the most significant effect on nutrient loading?

Even without accurate estimates of internal loading rates it is likely that during the winter months external loads are greater than internal loads. During the dry season internal loading rates could be greater than the external loading rates–but most of the internal load ultimately derives from external sources. External sources during the dry season include: infiltration to base flow from irrigation and septic systems, and urban storm drain discharge from incidental water use. It is unclear during the dry season whether external or internal sources are larger.

Even though they are smaller, summer loads (including cycling of deposited wet season nutrients) may be more important to nuisance growth of algae and macrophytes. That is, nutrients can also accumulate in the sediments that are transported to the Laguna from urban stormwater and from wastewater discharges. Sediment flux and internal nutrient cycling can be significant sources of nutrients during low flow season. As shown in previous studies, sediments in the Laguna have accumulated large pools of nutrients and organic matter in the sediments.

The most effective management intervention for reducing nutrients in the sediment is to reduce overall nutrient loading to the Laguna and allow natural hydrologic processes to either transport the nutrients out of the Laguna or bury them until they are no longer biologically available. The hydrologic transport of nutrients out of the Laguna may take many years. Increasing DO at the sediment-water interface will also reduce cycling into the water column through the formation of insoluble ferric hydroxides. Dredging is likely to be too expensive to be a practical option and could have significant adverse impacts on habitat. Other management strategies should be evaluated regarding their feasibility including reaeration and alum treatments. In addition, limited restoration of low flow stream channels should be considered.

Key Uncertainties and Data Gaps

Internal loading rates are unknown. Loading rates from wet and dry season groundwater sources are also unknown. Are nutrients introduced during high flow events available for uptake by biota?

Hypothesis

Overall nutrient loading to the Laguna exceeds the ecosystem's capacity to assimilate and process these nutrients and maintain the integrity of Beneficial Uses. During the summer sediments are a significant source of nutrients for biological productivity and excess nutrients that have accumulated in the sediments will remain as a significant source for a long period of time.

Question 3.4.5 What impact does irrigation and surface discharge of treated wastewater on agricultural lands have on water quality? Can loading from this source be reduced through enhancement of vegetated buffers? How have groundwater nutrient concentrations been impacted by wastewater irrigation and application programs? To what extent are the Laguna surface waters under the influence of this ground water source?

The irrigation with treated wastewater has the possibility of exceeding nutrient demand of crops (mostly pastures), but should be operated in a manner that agronomic rates are not exceeded. Riparian forest has been found to remove nitrogen more efficiently than pastures. Therefore enhanced vegetated buffers may reduce the potential loading from this source. Previous monitoring data suggest that groundwater from agricultural lands that received irrigation from reclaimed water can have nitrate concentrations greater than 10 mg/L. As suggested in Section 4.3.4, shallow groundwater is likely to influence surface water quality. The magnitude of loading from this potential pathway is unknown. However limited information is available to assess the connectivity between deep groundwater and surface water except in the vicinity of the confluence of Santa Rosa Creek and the Laguna.

Key Uncertainties and Data Gaps

The impact of restored riparian buffer with developing woody species is difficult to predict, but previous studies indicated that the buffer can serve to intercept and trap nutrients before they reach the aquatic ecosystem and serve as a filter for sediment and organic matter. The degree to which this will reduce these loadings will need to be further developed and explored using a dynamic watershed model.

Hypothesis

A restored riparian canopy can benefit water quality conditions though uptake of nutrients and trapping sediment loads being transported to the stream both overland and through infiltration.

Question 3.4.6 To what extent does fish biomass affect internal nutrient cycling?

Internal nutrient cycling in the Laguna transforms nutrients between different forms and different pools. Inorganic nitrogen and phosphate are taken up by algae, macrophytes, bacteria and fungi. Nitrogen and phosphorus (both organic and inorganic) can be leached or excreted from the living biomass or released through decaying from non-living biomass. Particulate forms of nutrients can be settled to bottom sediment and released through decay processes mediated by bacteria. Fish can take up nutrients through consumption of phytoplankton or ingestion of particulate forms of nutrient and excrete nutrients in various forms. As discussed in Section 3.2 internal cycling can be a significant source of nutrients during summer. However, it is unclear how important fish biomass can be relative to the vegetative biomass that includes macrophytes and algae. Certain fish populations (carp) disturb bottom sediments during mating and feeding, thus resuspending nutrient laden sediment into the water column.

Key Uncertainties and Data Gaps

Fish biomass estimates for the Laguna were not available to the project team. The extent to which fish bioturbation contributes to the resuspension of sediments into the water column is not known.

Hypothesis

The Laguna fish population community has shifted to low DO tolerant species such as carp, who through their feeding and mating activities (bioturbation) significantly contribute to internal nutrient loading.

Question 3.4.7 How did the changes in hydrology, sediment delivery, channel morphology and riparian degradation over time contribute to macrophyte growth? Do the nutrient sources for *Ludwigia* growth originate from the sediment or water column or both?

A previous sediment study indicated sediments yields have increased compared to historical conditions,as a result of flashier runoff, increased permeable area, and increased disturbance of soils (PWA, 2004). Channelization also results in more delivery of sediments to the Laguna channel instead of on the alluvial fan. Previous studies suggest that the Laguna main channel has accumulated approximately 1.5 feet of sediments between 1966 and 2002. The accumulated sediments have reduced channel depth. This reduced average depth has increased the area that can be colonized by macrophytes because they are now within the reach of their rooting zone. Enriched nutrients in sediments also provide nutrients for macrophytes growth. It is not clear to what extent the *Ludwigia* infestation has led to the decline of the riparian canopy or rather that the decline of the riparian canopy has contributed to the spread of *Ludwigia*. It is also possible that *Ludwigia* has also impacted the Laguna hydrology by reducing flows due to increased channel roughness.

Nutrient for *Ludwigia* growth can originate from both sediments and water column. The USDA-ARS study of *Ludwigia* growth indicated that soil nutrients are more significantly related to growth in early life stage (highly significant across all response variables; Dr. Brenda Grewell 2007 workshop report to Foundation) and is the primary sources of nutrients during the early stage of development. Water nutrients are also significant for rooting nodes (vegetative reproduction interaction effect). At high water nutrient levels there is more rooting node growth. Elevated nitrogen in the water column can enhance *Ludwigia* growth rates.

Key Uncertainties and Data Gaps

The contribution of factors such as hydrology, sediment delivery, degraded channel morphology, riparian degradation, and excess nutrients to the accelerated growth and spread of *Ludwigia* in the Laguna has not been quantified.

Hypothesis

Ludwigia has benefited from excess sediment delivery to the Laguna's channel and has impacted the Laguna hydrology by reducing flow rates. The *Ludwigia* infestation has impacted riparian cover through over saturation of soils causing sections of riparian forest to be drowned. Elevated nitrogen in the water column is not the sole cause of the *Ludwigia* infestation but exacerbates the problem.

Question 3.4.8 What are the natural factors/processes that contribute to the excess macrophytes and algae growth? To what extent can the system recover given the natural conditions? Are there natural attenuation processes of N and P in the Laguna?

The Laguna historically has been a productive ecosystem that is in some parts lake, wetland, and stream. The low gradient and low elevation characteristics lead to naturally low flow rates and high temperatures. This has made the Laguna more susceptible to accelerated nutrient and sediment loading related to development activities. One common characteristic of wetland ecosystems is the presence of macrophytes. The surrounding clay soils may have resulted in higher than average phosphorous concentrations within the Laguna.

The Laguna retains significant portions of its original natural biological communities. Through proper stewardship a significant portion of the naturally functioning conditions should be able to be restored. Access to tributaries will be critical to restoring facultative use by a cold water aquatic community. No disturbed ecosystem can ever fully recover its original trajectory; however, given adequate commitment large components of lost integrity can be recovered.

Some natural attenuation processes in the Laguna may include nutrient removal by riparian vegetation and wetlands before reaching the streams. Riparian vegetation and wetlands can remove nutrients through uptake and denitrification processes which convert nitrate into gases. However, riparian vegetation and wetlands have decreased (Smith, 1990).

Key Uncertainties and Data Gaps

The Laguna is a unique ecosystem for which no reference condition exists. Historical records indicate a productive ecosystem that supported the designated Beneficial Uses. Ecosystem recovery is difficult to predict.

Hypothesis

The Laguna will remain as a productive ecosystem once nutrient loading and other risk cofactors have been addressed due to natural conditions that define it as a marginally euthrophic wetland/lake/riverine ecosystem. Pervasive low dissolved oxygen episodes will become infrequent to rare. Nutrient concentrations will significantly decline over a period of years.

3.5 Biological diversity

Management questions related to biological diversity are discussed here, together with the key uncertainties and data gaps that limit these discussions. To the extent possible, working hypotheses are provided for each management question.

Question 3.5.1 What are the ecosystem engineers of the Laguna, and what are their 'roles?' What are the highest priority habitat restoration targets for improving water quality? How would enhanced riparian habitat conditions improve water quality and the status of beneficial uses? How does habitat degradation influence beneficial uses, water quality, flooding capacity, water supply?

Riparian zones

Trees in riparian buffer zones can be viewed as "ecosystem engineers," as they fundamentally change ecosystem function. Riparian zones could thus be viewed as 'keystone' communities. Areas where historical riparian vegetation have been lost are sure indicators of habitat loss/degradation, negatively affecting the entire associated aquatic and terrestrial communities. Terrestrial streamside communities are mainly impacted through the loss of cover, foraging and nesting habitat (Pearson and Manuwal 2001). Stream habitat degradation could be in the form of increased run-off and stream bank erosion, lack of shade along stream banks causing increased water temperatures, and loss of fish cover or spawning habitat. Lack of riparian vegetation may also allow adjacent livestock to enter the water, causing bank erosion, degrading the stream bottom through trampling and the introduction of increased nutrients into the stream via direct and indirect input of livestock excrement.

The loss or degradation of vegetation along streams also reduces the effectiveness of riparian buffers to improve water quality through processing and removal of excess anthropogenic nitrogen from surface and ground waters. To maintain maximum buffer effectiveness, buffer integrity should be protected against soil compaction, loss of vegetation, and stream incision (Mayer et al 2006). Restoring degraded riparian zones, and stream channels may improve nitrogen removal capacity of the stream system, making riparian buffers a 'best management practice' (Mayer et al 2006). While there is not one generic riparian corridor width to keep water clean, stabilize banks, protect wildlife, and satisfy human demands, generally the larger the width of vegetation, the better the impact on ecosystem services and biodiversity (Kreitinger & Gardali 2007, Semlitsch and Bodie 2003, Pearson and Manuwal 2001).

Invasive *Ludwigia* sp.

Invasive exotic plants can also act as 'ecosystem engineers,' negatively impacting the ecosystem (Crooks 2002). As exotic invasive plants, such as invasive *Ludwigia* sp., increasingly take hold in native plant communities, they threaten native biodiversity by changing the native vegetation structural diversity, often completely 'taking over,' not only out-competing native plants and establishing an extensive and expanding mono-culture, but in the process permanently changing the habitat structure and function. This process so fundamentally changes the original native ecosystem, causing the local extinction of organisms tightly linked to the original community structure and function (National Invasive Species Council 2001). A large proportion of noxious invasive plants were brought to their new range by humans and initially established in disturbed sites (Mack et al 2000).

Key Uncertainties and Data Gaps

Riparian zones

Extant riparian areas in the Laguna de Santa Rosa have been mapped in the lower watershed via aerial photo interpretation in 2000 (Laguna de Santa Rosa: Resource Atlas and Protection Plan 2000), and modeled in 2006 on a watershed scale in Enhancing and Caring for the Laguna (Vol. II, Plate 2). In order to expand on these baseline efforts, the Laguna de Santa Rosa Foundation is currently engaged in a comprehensive mapping effort of the entire watershed using aerial photography. This effort aims to address current data gaps in the watershed.

Invasive *Ludwigia* sp.

Some of the factors influencing invasive *Ludwigia* sp. growth may include: changes in hydrology of the Laguna, sedimentation and siltation of channels and streams, and nutrient loads in sediment and/or water column. There are several pathways for the capture of nutrients by invasive *Ludwigia* sp. via trimorphic roots: floating nodes on the gas-filled, rhizomatous shoots are able to absorb nutrient from the water column directly, while subsurface roots take up nutrients from the sediment. Studies of the relative contribution of each pathway towards plant vigor have not been completed. Preliminary data from a completely randomized, full factorial growth experiment by USDA/ARS (Dr. Brenda Grewell, pers. comm.) suggest that soil nutrient loadings may be more significant in affecting early invasive *Ludwigia* sp. growth (highly significant across all response variables) than nutrients in the water column. Continuation of this USDA/ARS research program will likely shed more conclusive light on this question in the near future.

At this time the specific relationship between nutrient loadings, habitat factors and invasive *Ludwigia* sp. growth is still unclear, and no conclusive inferences can be drawn from currently available data.

Hypotheses

Relationship of terrestrial and aquatic fauna to riparian habitat loss and fragmentation. Riparian zones provide foraging and nesting habitat for migratory and resident birds and territory and corridors for terrestrial vertebrates and invertebrates. They further provide stream bank structure and reduce water temperature for aquatic fauna and flora. The size and complexity of the riparian vegetation is positively correlated with the amount of terrestrial and aquatic biodiversity.

Relationship of native woodland/wetland/riparian/grassland communities to exotic invasive species. A number of the more aggressive exotic invasive species are ecosystem engineers and so have the potential to permanently alter species composition and structure of native communities. They also modify the ecological processes operating on a site and may lead to local extinction of species and loss of endemics. Spread of exotic plants is often related to disturbance, and invasive animals may be tied to invasive plant communities. Noted in more detail in the invasive *Ludwigia* sp. model description.

Relationship of the absence of herbivores and competitors to invasive Ludwigia sp. *local establishment and spread*. In their new range, most noxious invasive plants are usually released from their native range predators and competitors. This absence of their natural population check allows them to establish and spread more quickly in open suitable habitat.

Question 3.5.2 Can ecological restoration occur to support anadromous and other native fish species? Where are barriers to fish passage? What are current levels of bioaccumulation of toxins in fish? Mercury/heavy metals: where in the watershed were the quarries, mines, gravel mines that are now leaching?

Fish community data of the Laguna de Santa Rosa watershed are at present only available for a small number of its tributaries: Mark West Creek, Santa Rosa Creek, Millington Creek and Copeland Creek. The available data show that a number of introduced fish species occur in the surveyed reaches and that there are areas with vast mats of invasive *Ludwigia* sp. that could potentially impair fish passage.

Key Uncertainties and Data Gaps

While anecdotal reports exist of juvenile Steelhead in Copeland creek, several key uncertainties exists in 1) how well adults leave and reach these upper watershed spawning and rearing grounds, as they have to swim through the more seriously impaired (e.g.: low dissolved oxygen, high temperature) sections of the lower watershed in order to reach either the Russian River on their way to the ocean, or when returning to their spawning grounds in the upper watershed; leading to 2) how abundant and demographically healthy Steelhead and other anadromous fish populations are within the entire watershed; and to 3) whether there are structural impairments (e.g. culverts, extensive mats of invasive *Ludwigia* sp., etc.) preventing fish movement into certain upper watershed reaches. Fish community composition in both WARM and COLD habitat types, coupled with a better understanding of the components of the aquatic faunal food web and potential impacts to native fauna from introduced fish species are critical to assess past and future anthropogenic, and impending climate change impacts on the ecosystem.

Further, the level of pollutant bioaccumulation in high-level consumers (e.g., predatory fish and birds) is a water quality key uncertainty. Currently, fish bioassays are conducted by surveying only one species (Rainbow trout–not native to the watershed) within the City of Santa Rosa storm water monitoring program. This program could be expanded and improved by incorporating other reaches and species that tolerate different levels of contaminants, and so allow for a more comprehensive coverage, and a higher confidence level in assessing the water as non-toxic to more than just one species. This would also be beneficial in determining the source of toxicity. Fish bio-assays address levels of known contaminants but should potentially be extended to yet unregulated pollutants, such as endocrine disruptors, pharmaceuticals and other toxic substances in the future.

Hypotheses

Relationship of aquatic fauna to elevated summertime temperatures. Salmonids and other cold water fish require cool water for reproduction success. Increased temperatures are negatively correlated with the amount of dissolved oxygen in the water column, since the solubility of oxygen is affected by temperature and by the partial pressure of oxygen over the water. The solubility of oxygen is so greater in colder water than in warm water. Increased water temperatures thus negatively affect respiration of aquatic fauna.

Relationship of floodplain aquatic community distribution to increased seasonal stream flow velocities. Increased seasonal stream velocities cause a spatial shift in sediment deposition zones, in turn causing a shift in aquatic community distribution within the floodplain at a frequency rate that exceeds natural levels. Increased stream velocity also negatively affects availability of foraging and breeding habitat for aquatic fauna causing a decrease in species diversity and abundance.

Relationship of aquatic fauna to landslides and sediment erosion. Excessive sediment erosion negatively affects aquatic fauna, in particular endangered Salmonid habitat, through potential barriers to fish passage and high turbidity in the water column, the former preventing passage and the latter inhibiting successful spawning and rearing of juvenile fish.

*Relationship of aquatic fauna to mercury a*nd other pollutants. The presence of high levels of toxic pollutants in the water column negatively affects the health of the aquatic fauna. Bioaccumulation is the build up of poisons in the body of an organism. If pollution levels are sustained over time bio-magnification occurs within the food web causing an increase in the concentration of toxins as they pass through successive levels of the food web, particularly affecting top-level predators.

*Relationship of fauna and flora to the introduction of path*ogens. In line with exotic invasive species, the spread of pathogens throughout the system will negatively impact the health of wildlife, which can alter native community composition and structure.

*Relationship of human and wildlife health to unregulated s*ynthetic hormonally active agents. Hormonally active agents have been found in surface waters worldwide and may cause adverse health effects in humans and wildlife and thereby contribute to environmental degradation. Treated wastewater and livestock feedlots may act as source of such compounds in the Laguna watershed.

Question 3.5.3 What are the early biotic indicators of impaired ecosystem function? What are the current levels of habitat complexity & biodiversity in the Laguna watershed?

Benthic macroinvertebrates, amphibians, and periphyton are some of early biotic indicators of impaired ecosystem function (see section 5 on indicators). Habitat complexity and biodiversity in the Laguna watershed have been degraded and reduced, respectively, however neither has been directly quantified to date (Honton and Sears 2006).

Key Uncertainties and Data Gaps

With the exception of six creek reaches within the Santa Rosa urban boundary, benthic (macroinvertebrate) community data are missing for the majority of creek and stream habitats in the Laguna de Santa Rosa watershed. Given that current available data indicate very poor biological condition of these urban reaches, the level of biological conditions in the rest of the wadeable streams in the watershed is a key uncertainty. Adding permanent monitoring sites in the upper and lower parts of the watershed to the on-going data from the Santa Rosa urban creeks, will outline, water quality and habitat conditions on a watershed scale. This will aid in determining areas within the entire watershed where water quality is impacted by either point or non-point sources, and will provide more comprehensive causal connections between the upper and lower reaches. In cases where specific indicator species have not yet been defined, comparisons of biotic functional groups may be an appropriate way to assess stream health in comparison to reference conditions.

Current monitoring programs in the Laguna de Santa Rosa watershed do not include amphibians, except for California Tiger Salamanders *(Ambystoma californiense)*, that breed in vernal pools on the Santa Rosa plain (D. Cook, pers. comm.). The reduced numbers of endangered California red-legged frogs *(Rana aurora draytonii)* and Foothill yellow-legged frogs *(Rana boylii),* species of special concern, in the watershed signify that habitat loss and deterioration are potential causes for their decline. Populations of these frogs are not monitored regularly, but data on these species are periodically entered into the California Natural Diversity Database. Amphibians can serve as early indicators for water quality impairments for Laguna de Santa Rosa waterways, and the distribution, species composition and abundance of amphibians in the watershed are critical uncertainties.

There are no periphyton monitoring programs in the Laguna de Santa Rosa watershed. Periphyton surveys could serve to get a better understanding of lower watershed processes, in the slow flowing- lake-like areas of the Laguna de Santa Rosa. The aquatic species composition and abundance of the flooplain reaches represent key uncertainties that would allow a better evaluation of water quality on ecosystem processes. The objectives of a rapid bioassessment protocol for periphyton could include, but are not limited to, assessment of biomass (chlorophyl a or ash-free dry mass), species, composition and biological condition of periphyton assemblages. The strength of biological assessments is optimized by using algal data in association with macroinvertebrate and fish data (USEPA 2006).

Hypothesis

Relationship of biological indicators to impaired ecosystem function. Biological indicators are characteristics or processes that serve to assess the condition of different areas in the watershed with respect to one or more criteria.

Question 3.5.4 How does wetland diversity and habitat loss and fragmentation affect biodiversity?

The Laguna de Santa Rosa floodplain represents important breeding and foraging habitat for migratory and wetland birds along the Pacific Flyway. Water birds feed in a variety of foraging habitats and the needs for individual species can be quite specific (Kushlan et al 2002). In order to restore a biologically rich bird fauna in the Laguna de Santa Rosa it is important to have a variety of aquatic habitats in the region, many of which are degraded to varying degrees and represent opportunities for restoration, that can serve the needs of many different bird species. Birds are excellent indicators of ecosystem health, and if bird diversity will decrease, it likely indicates an overall decrease in faunal and floral diversity.

In winter 2004/05 and summer 2005, PRBO Conservation Science completed a one-time point count survey of bird distribution, breeding status, abundance, richness, and diversity along the Laguna de Santa Rosa floodplain, between Todd Road to the south, and just to the north of Occidental Road. The study was designed to inform the Sonoma County Agricultural Preservation and Open Space District of potential negative impacts on birds from a proposed trail system for this area. This study represents a very valuable baseline dataset, but as was outline in the study's final report (PRBO 2005), a one-time survey is not sufficient to determine natural fluctuations of all parameters measured from those caused by trail construction or use or other anthropogenic actions, such as impaired water quality. The Laguna Foundation is currently continuing this program in the short-term and is developing ways to continue the effort in the long-term.

Key Uncertainties and Data Gaps

No specific Laguna watershed bird survey exists at this time (B. Burridge, pers com.). Standardized long-term surveys are needed along the lower reaches of the watershed in order to assess how impaired water quality affects 1) the role of the floodplain as an important stopover habitat for migratory birds along the Pacific Flyway, 2) regional waterfowl population dynamics, and 3) wetland and riparian bird breeding success. Once baseline data are established changes in hydrologic factors, sedimentation, turbidity, and pollutants can be identified as extreme departures from normal data distributions in long-term abundance, breeding, distribution, richness, and diversity datasets.

Waterfowl and wading birds are also highly suitable for inclusion in bioassay studies, due to their top rank as consumer in the aquatic food web. Toxic substances can bio-accumulate in bird tissue and affect their health or their reproductive success. The levels of toxic substances in wetland birds represents a key uncertainty.

Hypothesis

Relationship of terrestrial and aquatic fauna to wetland habitat loss and fragmentation. The decline of wetland habitat is directly correlated with the loss of associated species diversity, including both resident and migratory species. Wetland loss along the Laguna floodplain directly affects birds along the Pacific Flyway migratory route.

The diversity of birds is positively correlated with habitat and faunal diversity. Bird diversity indicates the functional health of their associated faunal and floral communities.

Question 3.5.5 How will global climate change affect the Laguna ecosystem function in the short-and long-term?

Global climate change is predicted to affect rainfall periods and storm/flood frequencies and magnitudes. This may have a measurable impact on sediment transport, temperature and inundation regimes that will likely negatively affect biodiversity.

Key Uncertainties and Data Gaps

How the Laguna de Santa Rosa watershed will be affected by impending climate change remains a key uncertainty. Storm frequency and strength may increase, causing an increase in flooding frequency and levels. Temperature fluctuations may become more extreme. Mediterranean climate summers may change from dry and hot to wetter and colder, over time bringing with it potentially severe changes in the floral and faunal components of the ecosystem. Some periods may also get dryer and hotter, increasing the fire danger. Current levels and dynamics of habitat complexity and biodiversity of the watershed are still largely unknown, and so a multitude of scales need to be investigated. Therefore a holistic, multi-scale approach to long-term management of the resources in the watershed is imperative.

Hypotheses

Relationship of native grassland species richness to summer rainfall. The typically long summer droughts of the Mediterranean climate in California severely constrain plant growth during this period, supporting drought adapted grassland communities. Consistent long-term summer inundation within the Laguna floodplain negatively impacts these native grassland ecosystems, causing reduced plant and invertebrate richness over time. Species typically favored by summertime inundation include annual grasses and non-nitrogen fixing forbs, while nitrogen-fixing forbs may initially increase, but then return to lower levels (Suttle et. al. 2007).

*Relationship of biodiversity to multi-decadal bui*ld up of fuel loads. High intensity catastrophic fires will negatively impact the native natural communities through a shift in community types, favoring exotic species, and will so induce native biodiversity loss.

Relationship of temperature to invasive Ludwigia sp. persistence and spread. Ideal growing conditions for invasive *Ludwigia* sp. represent warm temperatures (above freezing point), while extended periods in conditions below freezing will inhibit its growth. Its aquatic habitat may effectively buffer extremely low air temperature conditions and so prevent massive dye-offs during the winter months.

3.6 Invasive *Ludwigia* sp.

Management questions related to invasive *Ludwigia* are discussed here, together with the key uncertainties and data gaps that limit these discussions. To the extent possible, working hypotheses are provided for each management question.

Question 3.6.1 What are the natural factors/processes that contribute to excess macrophyte growth? How did the changes in hydrology, sediment delivery, channel morphology and riparian degradation over time contribute to invasive *Ludwigia* sp. growth? To what extent does the growth of invasive *Ludwigia* sp. impact the beneficial uses?

Macrophytes are emergent, submergent, or floating aquatic plants that grow in or near water. Macrophytes provide cover for fish and substrate for aquatic invertebrates and are so beneficial to lakes. They produce oxygen, which assists with overall lake functioning, and provide food for some fish and other wildlife. Crowder and Painter (1991) indicate that a lack of macrophytes in a system where they are expected to occur may suggest a reduced population of sport and forage fish and waterfowl. In addition, the absence of macrophytes may also indicate water quality problems as a result of excessive turbidity, herbicides, or salinization. In contrast, an overabundance of macrophytes can result from high nutrient levels and may interfere with lake processing, recreational activities (e.g., swimming, fishing, and boating), and detract from the aesthetic appeal of the system (USEPA 2006).

Key Uncertainties and Data Gaps

The relative contributions of historic changes in hydrology and hydraulics affecting channel depth and shape, and nutrient levels in both the water column as well as accumulated levels in the sediment on invasive *Ludwigia* sp. growth and spread remain key uncertainties at this time. USDA/ARS research is underway to address the ecology, physiology, and growth dynamics of this invasive. The literature on macrophyte growth shows that in artificial stream experiments macrophyte *(Potamogeton pectinatus,* a rooted pondweed) biomass was enhanced by the addition of phosphorous, and unaffected by addition of nitrogen (Carr and Chambers 1998). *Ludwigia* species have been used in constructed wetlands due to their ability to tolerate nutrients enriched waters. Greenway (1997) showed that *Ludwigia peploides* had the highest tissue nutrient concentrations (both P and N) of eight macrophytes, with P and N concentrations double that of the other macrophytes under natural and experimental conditions. This indicates that *Ludwigia* species are extremely tolerant to high nutrient conditions and, in this case floating leaves are able to extract a large amount of nutrients from the water.

The extent to which invasive *Ludwigia* sp. changes the aquatic chemistry and food web-community in invaded areas, and how directly or indirectly it promotes mosquito growth are key uncertainties. While the Marin/Sonoma Mosquito and Vector Control District shows an overall reduction of adult mosquitoes at sites where invasive *Ludwigia* sp. populations have been reduced (Marin Sonoma Mosquito and Vector Abatement District unpublished data), more comprehensive studies directed at the aquatic larval lifestage of mosquitoes and on potential aquatic food web impacts are needed.

Another aquatic plant of note is the native mosquito fern *(Azolla filiculoides)*. While not a macrophyte, it also forms dense mats in stagnant water such as lakes and ponds, and has been observed in the Laguna de Santa Rosa (C. Sloop pers. obs.) and in the upper watershed at Fairfield Osborne Preserve: (http://www.sonoma.edu/Org/Preserve/species_lists/plants_at_fop.pdf). It can impact water quality directly through input of nitrogen, since this tiny floating aquatic water fern has a symbiotic relationship with a nitroxen-fixing microscopic filamentous blue-green alga or cyanobacterium *(Anabaena azollae)*. A major invasive in South Africa, *Azolla filiculoides,* has severely affected the biodiversity of aquatic ecosystems and had implications for all aspects of water utilization (Gratwicke and Marshall 2001). In South Africa these effects were also severe in the agricultural sector, where the weed increased siltation of dams and rivers, reduced the quality of water for agricultural and domestic use, clogged irrigation canals and pumps, and caused drowning of livestock that were unable to differentiate between pasture land and a weed covered dam (Hill 1997). The effect of nitrogen input by mosquito fern on Laguna de Santa Rosa water quality and its effect on the aquatic biodiversity are key uncertainties.

Areas with high levels of sedimentation (accrued over the past decades, having absorbed a large amount of available phosphorous and nitrogen), represent prime habitat for invasive *Ludwigia* sp. This is not only because these areas represent shallow conditions ideal for invasive *Ludwigia* sp. to take root, but also due to the potential availability of nutrients that are taken up through plant roots in the sediment. Enriched sediments can accelerate the growth rate of macrophytes (Carr and Chambers 1998), and it is therefore likely that all factors including habitat formation from sedimentation, altered hydrology, channel modifications, and nutrient enrichment have played a role in the infestation All factors will need to be addressed in any effective control program. Ongoing research will determine the best strategy for each factor within the Laguna.

The relative contributions of historic changes in hydrology and hydraulics affecting channel depth and shape, and nutrient levels in both the water column as well as accumulated levels in the sediment on invasive *Ludwigia* sp. growth and spread remain key uncertainties at this time.

Hypotheses

Relationship of altered stream hydrology and hydraulics to invasive Ludwigia sp. *introduction and establishment*. The introduction and establishment of exotic invasive species is facilitated by anthropogenic habitat disturbance. Altered flow regimes, causing more stagnant conditions and decreased water depth due to sediment build-up represent ideal macrophyte growing conditions: the roots have increased anchoring space (not just along the shore), and low-energy flow prevents wash-out during most of the year. This means that under these conditions large dense mats can form that completely cover vast areas of previously open water.

Relationship of periodic high-energy flow in invasive Ludwigia sp. *invaded areas to its recurrent spread to and establishment at new sites downstream*. Severe winter storm events drastically increase water velocity through areas where invasive *Ludwigia* sp. occurs. High-energy flow causes invasive *Ludwigia* sp. shoots to break off and get carried downstream, where they eventually settle out alongshore and re-establish, increasing the geographic range of the invasion.

Relationship of invasive Ludwigia sp. *invasion to anadromous fish passage*. Extensive mats of invasive *Ludwigia* sp. can grow several feet thick, consisting of thin and thick (0.1 to 1.5 inch diameter) floating rhizomes that are intertwined with each other and large leaves. Fish passage can only occur below these mats. In areas where channels are shallow, invasive *Ludwigia* sp. may also root directly in the bottom sediment, making passage of large salmonids impossible.

Relationship of invasive Ludwigia sp. *invasion to native aquatic food web community*. Extensive mats of invasive *Ludwigia* sp. shade the water column and reduce the availability of open water habitat. While increasing the amount of cover, *Ludwigia* sp. floating mats cause open water habitat to be reduced or lost, resulting in a potential shift in the native food web community from limnetic to littoral marsh.

Relationship of invasive Ludwigia sp. *mats to availability of dissolved oxyg*en. While macrophytes generally fix oxygen within the water column, extensive mats prevent surface influx, and massive decomposition of *Ludwigia* sp. vegetation in turn takes up oxygen through bacterial decomposition.

Relationship of invasive Ludwigia sp. *to sediment deposition*. The roots and rhizomes of extensive mats of invasive *Ludwigia* sp. inhibit the movement of suspended particles in the water column increasing the potential for local deposition of sediment.

Relationship of invasive Ludwigia sp. *to loss of structural habitat diversity. Ludwigia* has the potential to grow into low diversity monoculture-like mats. These floating mats eliminate the historic open-water habitat that was previously there.

Question 3.6.2 Do the nutrient sources for macrophytes and algal growth originate from the sediment or water column or both?

Some of the factors influencing invasive *Ludwigia* sp. growth may include: changes in hydrology of the Laguna, sedimentation and siltation of channels and streams, and nutrient loads in sediment and/or water column. There are several pathways for the capture of nutrients by invasive *Ludwigia* sp. via trimorphic roots: floating nodes on the gas-filled, rhizomatous shoots are able to absorb nutrient from the water column directly, while subsurface roots take up nutrients from the sediment. Studies of the relative contribution of each pathway towards plant vigor have not been completed. Preliminary data from a completely randomized, full factorial growth experiment by USDA/ARS (Dr. Brenda Grewell, pers. comm.) suggest that soil nutrient loadings may be more significant in affecting early invasive *Ludwigia* sp. growth (highly significant across all response variables) than nutrients in the water column. Continuation of this USDA/ARS research program will likely shed more conclusive light on this question in the near future.

Key Uncertainties and Data Gaps

At this time the specific relationship between nutrient loadings, habitat factors and invasive *Ludwigia* sp. and other macrophyte growth is still unclear, and no conclusive inferences can be drawn from currently available data. Correlations between water-column nutrient concentrations and invasive *Ludwigia* sp. vigor that do not account for the contribution from sediment-bound phosphorus may not be tracking the true signal. It is therefore premature to determine habitat as a more important factor over that of nutrient loadings, since these are closely inter-connected, and long-term sediment nutrient loadings may play a more important role in invasive *Ludwigia* sp. growth as currently understood. Please refer to the water quality section of this report for more in depth discussion on this topic.

Hypotheses

Relationship of nutrient levels to invasive Ludwigia sp. *persistence and spread*. Rapid and extensive expansion of invasive *Ludwigia* sp. populations are fueled by the high availability of nutrients in the water and sediment. Invasive *Ludwigia* sp. can tolerate and thrive on extremely high levels of available nitrogen.

Relationship of aquatic flora (algae, macrophytes) and fauna to increased nutrients (nitrates & phosphates). Aquatic plants and algae need sunlight, water, carbon dioxide, and nutrients-including phosphorous, nitrogen, and potassium to grow. Increased levels of available nutrients will generally increase aquatic plant growth. Excessive growth of algae or macrophytes can lead in turn to large diel (24-hour) swings in pH and dissolved oxygen concentrations. Excessively low dissolved oxygen concentrations and excessively low or high pH levels can reduce the diversity of animal life in a stream by stressing the physiological systems of most organisms and reducing reproduction.

Relationship of aquatic fauna to run-off pollutants (pesticides, oils, heavy metals, etc.). The presence of high levels of toxic pollutants in the water column negatively affects the health of the aquatic fauna. Bioaccumulation is the build up of poisons in the body of an organism. If pollution levels are sustained over time bio-magnification occurs within the food web causing an increase in the concentration of toxins as they pass through successive levels of the food web, particularly affecting top-level predators.

Question 3.6.3 To what extent does invasive *Ludwigia* sp. and other aquatic flora promote mosquitoes (vectors of West Nile virus)?

Invasive *Ludwigia* potentially contributes to a public health threat as it creates protective habitat for mosquito species that can carry West Nile virus (WNV), which reached Sonoma County in 2004. Dense invasive *Ludwigia* sp. mats sharply inhibit current mosquito control efforts by inhibiting larvicide applications; and several *Ludwigia*-infested areas have been observed to produce mosquito populations more than 100 times greater than normally considered acceptable (Marin/Sonoma Mosquito and Vector Control District, unpublished data). 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. If larvicide 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 invasive *Ludwigia* sp. appear to favor ‘foul-water’ mosquito species that are superior vectors for West Nile virus (in the genus *Culex*).

Key Uncertainties and Data Gaps

After year two years of the *Ludwigia* control program there has been a notable reduction in adult mosquitoes captured near invasive *Ludwigia* sp. infested areas (Marin/Sonoma Mosquito and Vector Control District, unpublished data) in 2006. While adult mosquito traps can indicate the relative abundance and types of mosquito species in a general area, they fail to give detailed information on the larval origin of these mosquitoes. Comparative studies aimed at the aquatic larval stage of mosquitoes within and outside of the invasive *Ludwigia* sp. mats are needed to ascertain a more direct relationship of mosquito abundance and invasive *Ludwigia* sp.

Hypotheses

Relationship of invasive Ludwigia sp. *invasion to mosquito abundance*. Extensive mats of invasive *Ludwigia* sp. prevent application of mosquito control agents to the invaded water body via surface application. Therefore mosquito abatement efficacy is reduced by invasive *Ludwigia* sp. biomass, resulting in localized mosquito population growth.

Hydrology and Sedimentation 4

The Laguna de Santa Rosa watershed, set in a Mediterranean climate, has a complex and variable hydrology. The watershed includes numerous tributary streams, the majority of which drain west from the Sonoma Mountains across the Santa Rosa Plain towards the northwest trending Laguna wetland ecosystem (see figure 4-1). The uplands are drained by high-gradient, high-energy, coarse-bedded mountain channels, which flow down the hillsides to the broad, flat, vernal pool-dotted Santa Rosa Plain. The main stem Laguna is a slow-moving channel that has a unique character, which was once described as: "neither river, nor pools, nor floodplain, nor marsh, nor vernal pool – but with the characteristics of all, plus other characteristics, and a distinct type of watercourse related to physical feature, but a rare one" (LAC, 1988).

The character of Laguna watershed channels reflects underlying geological structures. The Santa Rosa Plain is surrounded by two actively uplifting ranges: The Santa Rosa block in the east (underlying the Mayacamas and the Sonoma Mountains) and the Sebastopol block in the west (underlying the Gold Ridge). The boundary between these two blocks is the western edge of the Laguna floodplain, near Sebastopol. The blocks are oriented on roughly a northwest-southeast axis, and both tilt towards the Laguna (Hitchcock and Kelson, 1998). The Santa Rosa block has a major laterally displaced slip-strike fault system (the Mayacamas-Rodgers Creek faults) that forms the topographic boundary between the gently sloping Santa Rosa valley and the steep slopes of the Mayacamas and Sonoma Mountains. As these blocks have tilted and uplifted erosion has acted on the exposed surfaces, washing sediment into the syncline occupied by the Laguna in the form of an alluvial fan. This configuration of basin, ranges and alluvial fans is very common in the American west. On the east side of the Laguna, the main tributaries (Windsor Creek, Mark West Creek, Santa Rosa Creek, etc.) have eroded valleys into the block or range, transporting sediment downstream. There is a marked break of slope that forms a distinct topographic boundary between the eroding block and its depositional apron, along the line of the Healdsburg and Rodgers Creek faults. In the Laguna watershed this line is broadly defined by Calistoga Road and Yulupa Avenue in the north and by Petaluma Hill Road in the south of the watershed. On the west side, the headwaters of Blucher Creek are eroding into the rising center of the Sebastopol block in a similar fashion. Channels cut in rapidly uplifting blocks tend to have characteristic 'V' shaped incised valleys, and experience rapid erosion as they attempt to stay in equilibrium with their surroundings. In addition to channel erosion, such fluvial systems often have steep and landslide-prone valley sides, as the channel cuts slopes steeper than their angle of limiting stability. Therefore naturally high levels of sediment transport from the hills on both east and west sides of the Laguna watershed.

The Laguna watershed has been significantly altered by anthropogenic processes since European settlement in the 1840s. Key stages in the basin land use history include the following:

- 1837 - Start of intensive ranching. The Santa Rosa Plain was converted to cattle grazing. We anticipate that this led to changes in vegetation from perennial bunch grasses and annual forbs to Mediterranean grasses, with soil compaction and increased runoff and erosion, and the clearance of some woodland.
- 1853 - Conversion of some grazing to wheat farms. This land use change led to the start of large-scale land drainage to convert wetland areas to productive farmland. In addition the first large scale oak wood clearance began around this time. It has been suggested that this land use conversion released large amounts of sediment from the hillsides to the lower Laguna.
- 1940s - Start of rapid urbanization. From the 1940s onwards agricultural land was converted to urban as population increased exponentially. At the same time the type of agriculture varied, with dairy farming peaking in the early 20th century, orchards and row crops peaking in the 1950s, while irrigated farming has expanded since its introduction in the 1960s.
- Current trends. Growth in urban and vineyard area, with decline in crops and grassland. The current trend is for greater urbanization/suburbanization, mostly at the expense of cropland and especially pasture. At the same time agricultural land is being converted to vineyards.

This landscape evolution has had several general effects on hydrologic and sediment processes:

- Reduced canopy interception and evapotranspiration leading to more and flashier runoff, and therefore, greater erosivity of runoff and increased sediment transport capacity;
- Increased impermeable area, decreased permeability, and extended drainage channel network leading to greater volume and flashier channel flows, increasing erosion potential and sediment transport capacity;
- Increased area of disturbed and bare earth leading to greater soil erodibility and sediment yield;
- Increased storage of sediment; and
- Morphologic and topographic changes;

Thus more sediment is generated from the ground surface, and the drainage system is generally more effective at transporting the sediment. Within this broad picture there have been some more subtle changes, however. The initial conversion of the landscape to grazing is likely to have had a dramatic effect, releasing large volumes of fine sediment from the alluvial fan surface as grazing compacted the ground surface, reducing infiltration capacity and increasing surface erosion. Subsequent conversion to row crops is expected to have reduced erosion where it involved the same land surface area (though not to pre-disturbance levels) by increasing surface roughness and infiltration capacity compared with grazing.

On the other hand woodland clearance associated with large-scale farming released large amounts of additional sediment, especially on the hillsides. Assuming it followed the patterns observed elsewhere in northern California, development will have increased erosion in the channel network, and temporarily increased sediment yield from construction plots, while permanently increasing yield through the development of bare earth ditches and unpaved roads. Conversion of grazing and arable land to vineyards is likely to have increased sediment yield due to soil erosion, especially where rows are orientated downslope.

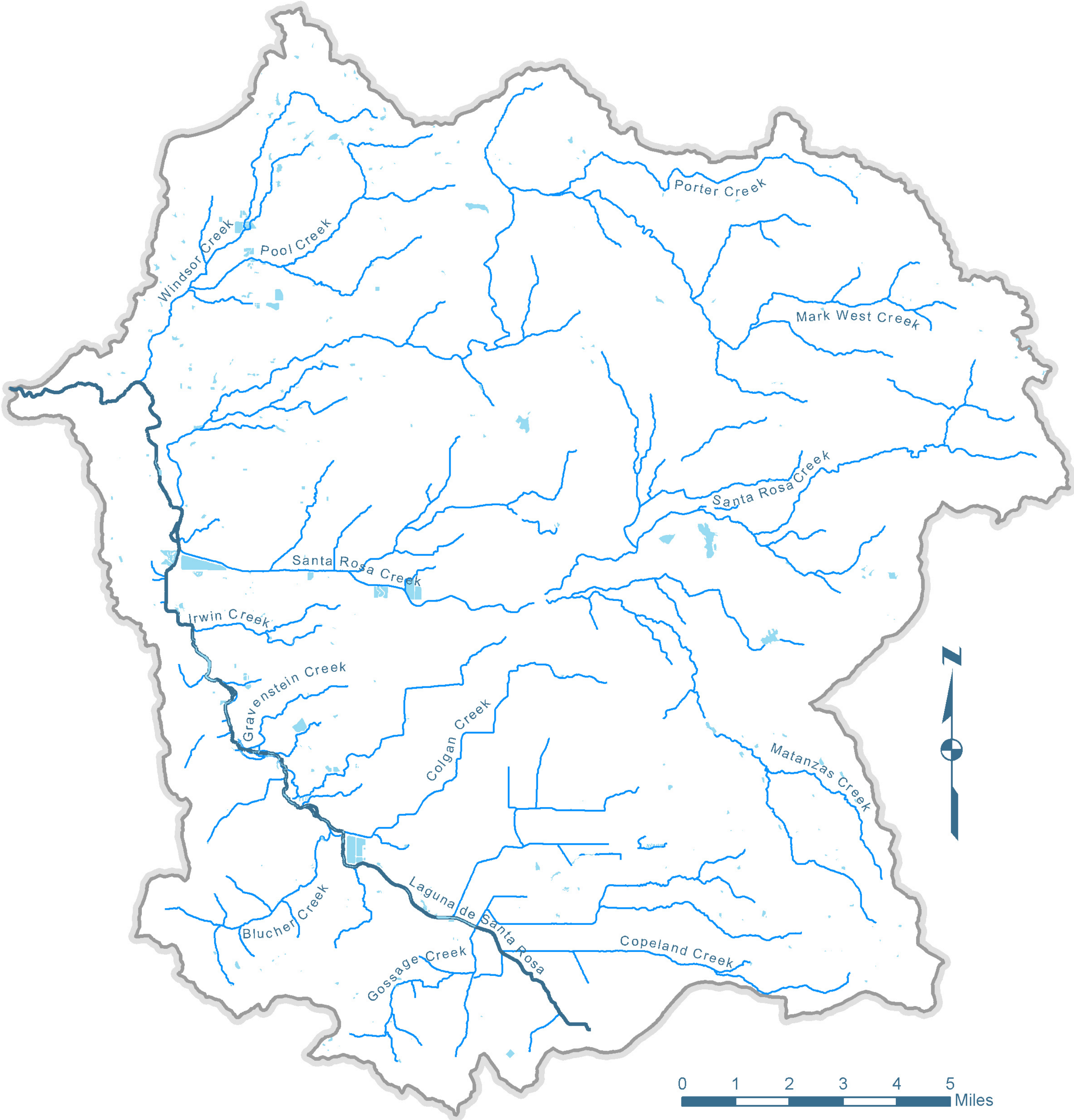

Figure 4-1 Laguna watershed and tributaries

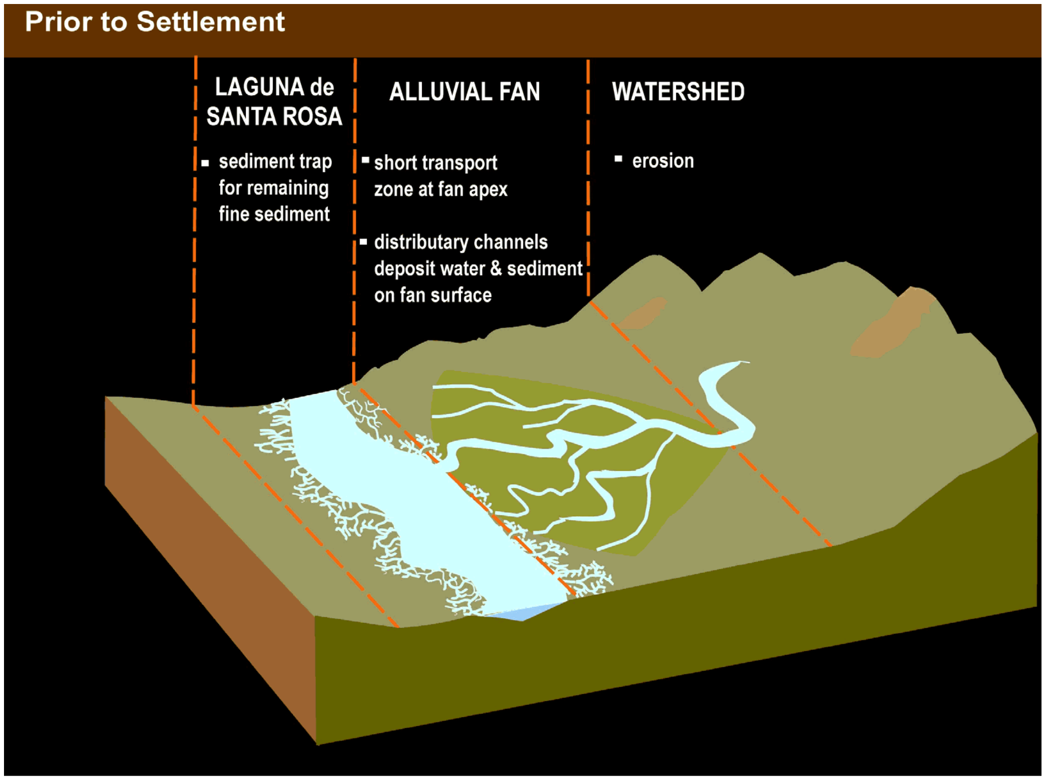

Figure 4-2 (a) Conceptual model of physical processes affecting the Laguna prior to settlement

In addition to watershed land use changes, natural stream channels in the watershed were progressively replaced with larger, straighter channels that were designed to make the alluvial fan more habitable and productive for farming and that are better suited for efficient flood conveyance. Channel modifications have essentially moved the focus of sediment deposition away from the fan surface and towards the Laguna. By eliminating overbank flows and channel avulsions and by connecting distributary channels to the Laguna, the modified drainage network has had three effects:

- Sediment that would previously have traveled down dispersed distributary channels and been deposited on the fan surface is now either concentrated in drainage channels or transmitted to the Laguna.
- When channels work effectively to transport flood flows in-channel (typically hydraulically smooth channels during large flow events) sediment that would previously have been carried out of bank and deposited on the alluvial fan is now transported to the Laguna and either deposited there or washed out to the Russian River.
- When channels do not work efficiently (typically vegetated, hydraulically rough channels or channels that are oversized for small events) sediment is deposited in-channel, eventually requiring removal to preserve flood conveyance capability.

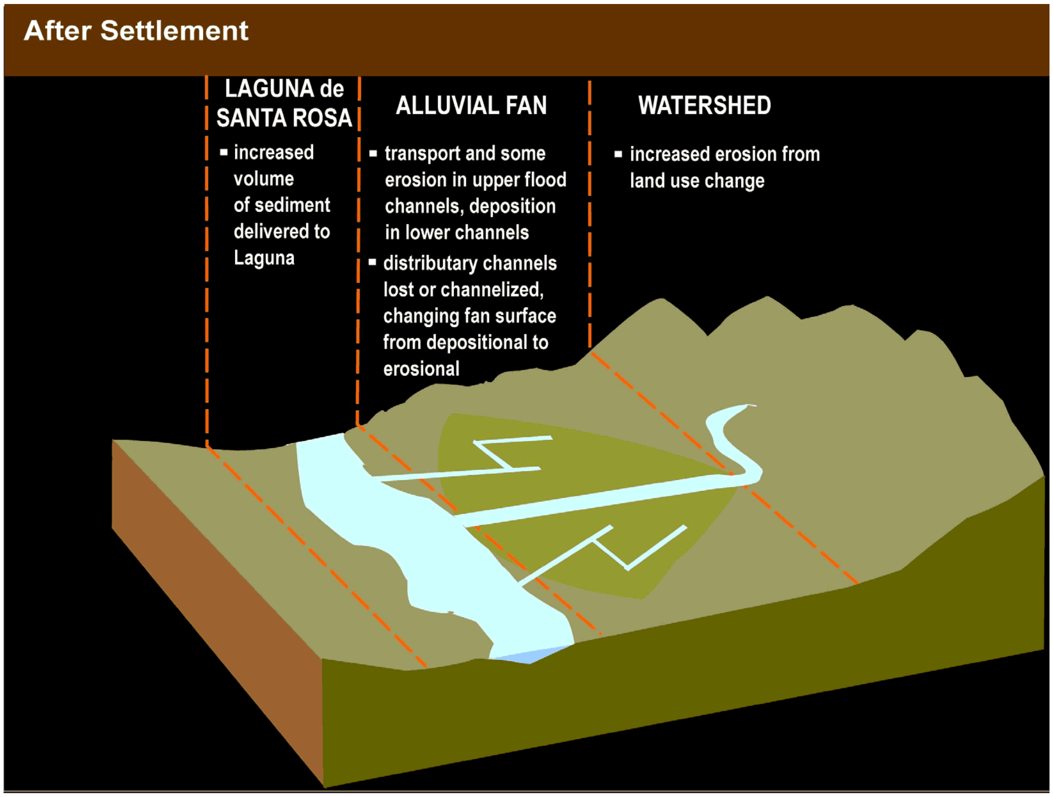

Figure 4-2 (b) Conceptual model of physical processes affecting the Laguna after settlement

Thus channel modification has reduced sediment deposition on the fan and concentrated it in the channel network and in the Laguna. In addition, some of the modified channels have themselves become sources of sediment due to accelerated erosion. Straight, hydraulically effective channels with low width to depth ratios and little bank vegetation have in some cases suffered bank and bed erosion, contributing sediment into the Laguna.

The combined effect of these processes has been to increase sediment generation and transport capacity to the Laguna, resulting in increased potential for deposition.

Figure 4-2, a simple conceptual model for sediment processes in the Laguna, presents a conceptual model that describes key changes in the main hydrologic and sediment processes due to anthropogenic impacts.

4.1 Summary of recent and current studies

Results have been presented in five main recent or current studies on the hydrology and sedimentation in the Laguna system. The USGS is presently conducting a sixth study that will characterize flow and sedimentation processes within the study area. The study includes development of a conceptual model of floodplain processes and sedimentation, a sediment budget, measurement of floodplain sedimentation and inundation, and extrapolation of the results throughout the basin in GIS in order to evaluate the changes in flood storage capacity over time. A 1-D calibrated hydrodynamic model will be developed for an approximately 1.5 mile stretch of the Laguna for sediment transport simulations. Another study presently being conducted by the USGS is focused on groundwater hydrology within the Santa Rosa Plain, the main aquifer underlying the Laguna watershed. No findings from that study have yet been released, but its goals are described below in the section describing groundwater conditions.

The Army Corps of Engineers conducted two studies developing hydrologic models for the Santa Rosa Creek and Laguna de Santa Rosa watersheds. There is a draft report summarizing the results of the former study. However, the results of the Laguna de Santa Rosa hydrology assessment have not been formally reported. Three additional studies have recently produced hydrology and sedimentation findings with respect to the Laguna de Santa Rosa. PWA (2004) summarized the results of a 5-year long study on the hydrologic and sedimentation characteristics of the Laguna. Another study by the NASA AMES is currently investigating key hydrological and sediment yield characteristics of the Laguna de Santa Rosa watershed. Results of these studies have not yet been published. However, brief summaries of their findings as presented in the State of the Laguna Conference are included below (Santa Rosa, March 29 to April 1, 2007).

4.1.1 PWA 2004 study on the sedimentation, rate, and fate in the Laguna

PWA estimated the rate and effect of sedimentation processes in the Laguna watershed and articulated on the implications of these processes on flood conveyance through the Laguna and in flood channels. PWA investigated sediment delivery to the Laguna calculating sedimentation rates using several lines of evidence, including a field-based geomorphic assessment, empirical models of soil erosion to predict sediment yield (Pacific Southwest Interagency Committee [PSIAC] and the Modified Universal Soil Loss Equation [MUSLE]), aerial photographic interpretation, and comparison of historic and current floodplain cross section surveys. PWA supported these results with data from reservoir surveys and a network of three continuous suspended sediment monitors that were installed along the main stem Laguna (2 stations) and Santa Rosa Creek (1 station) for the runoff season of 2002-2003. The study identified the main sediment source areas, sediment yield, and the rate at which the Laguna is filling. The study found that the Laguna has filled an average of approximately 1.5 feet between 1956 and 2002, representing a loss of flood storage of 54 acre feet (ac-ft) per year. The study estimated that the current sediment yield in the watershed is approximately 153 ac-ft per year, of which approximately 50 percent is stored in the watershed, 25 percent settles out in the Laguna, and 25 percent is delivered to the Russian River. The study found that most sediment is contributed by Santa Rosa Creek (42 percent of the total Laguna yield), followed by the upper Laguna tributaries upstream of Llano Road, near Cotati (24 percent), Mark West Creek (18 percent), Windsor Creek (9 percent), Blucher Creek (4 percent), and Colgan Creek (3 percent). The study also estimated the historic sediment yield rate before European settlement of the watershed and future rates based on hypothetical built-out conditions informed by the county general plan. Historic sediment yield rate was estimated as approximately one quarter of the current rate. Based on assumptions of a 20 percent growth in urban area and vineyard production over the next 50 years, an increase in sediment yield to approximately 200 acre feet per year was predicted. At this rate, the flood storage capacity of the Laguna would be reduced by approximately 50 to 60 acre feet per year (4 percent of the current storage volume of the Laguna over 50 years) and result in 2.5 to 3.0 feet of increased flood elevation in the Laguna over 50 years.

4.1.2 USGS study of the 2006 New Year's flood

The USGS is studying the 2006 New Year's flood in the Laguna floodplain. The objectives of the study are to measure and map the inundation extent of the New Year's flood of 2006 on the Laguna de Santa Rosa and analyze the precipitation intensities causing these high peak flows. This study also investigates the conditions under which the floodplain deposition occurred during and after the flood and developed a deposition potential map of the area for this precipitation event to provide an upper boundary for floodplain sedimentation conditions.

On December 31, 2005 and January 1, 2006, the lower Laguna experienced flooding with peak flows of over 6,500 cfs based on the USGS streamflow gage near Sebastopol (#11465750), (see photograph below). Median flows at this location are typically less than 500 cfs. The high peak flows resulted in overbank flows at many channel locations for several periods of time between December 12 and January 6.

Hourly precipitation data for the December 29 to December 31 storm period were spatially distributed using regression equations and a digital elevation model (DEM) to map total accumulation amounts through the storm. Field observations of inundation levels as evidenced by debris lines on hillslopes, trees, vegetation, buildings, and fences were made. Elevation measurements were extrapolated on the basis of contours of the DEM. The study found that maximum flood inundation approached the 100-year flood elevation boundary in the downstream reaches of the Laguna (Figure 4-4). It also revealed that although this storm was approximately equivalent to a 20- or 30-year event, inundation elevations in the eastern uplands were not significant.

Figure 4-4 is a map of elevation for the Laguna de Santa Rosa floodplain, between the Russian River and State Highway 12. The map illustrates the estimated inundation levels reached during the 2006 New Year's flood, identified by the red line. Points on the map illustrate the observation locations.

Figure 4-3 Laguna in flood

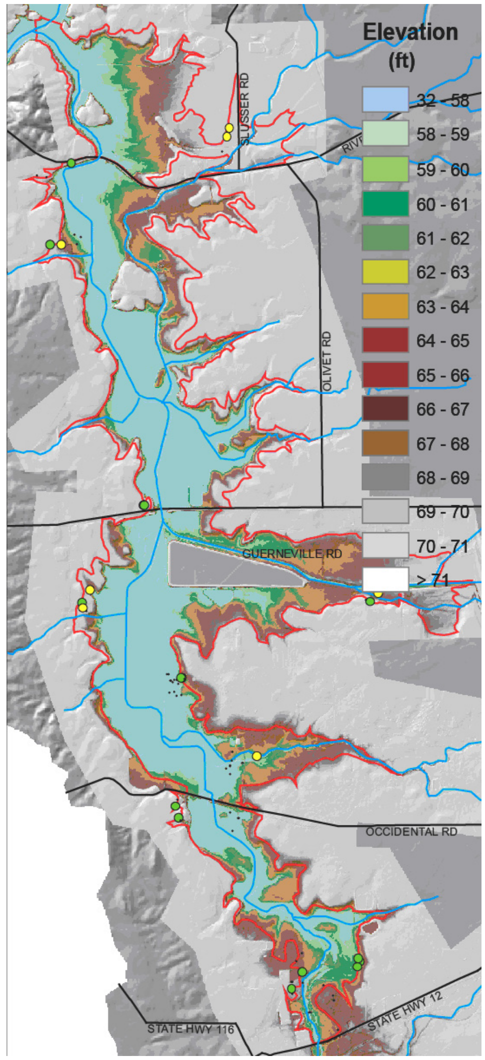

Figure 4-4 Laguna floodplain elevation map

4.1.3 NASA/AMES study

The NASA/AMES is modeling non-point source nutrient input to the Laguna incorporating sediment yield assessment from different land uses. The study is developing a SWAT model (USDA's Surface Water Assessment Tool) to address the role of certain land use practices or changes such as agriculture, woodland conversions, and (sub)urban runoff sources in water quality, flood frequency, soil erosion, and sedimentation of the Laguna floodplain. The study produced an updated land cover map of the Laguna watershed. The map merged the USGS 30-meter resolution National Land Cover Dataset with the California Department of Water Resources crop type polygons and the Sonoma County Assessor's parcel descriptions. National Agricultural Imagery Program's digital orthographic imagery data were used to confirm the merged land cover product in key areas of uncertainty. The study also updated climate station records to 2007 and added data from precipitation stations at Graton, Windsor, and Sonoma. This study is still on-going and no report has yet been published. The findings reported here are derived from personal communication with Chris Potter (NASA/AMES) or from Laguna Conference and Science Symposium proceedings.

The NASA/AMES SWAT model was calibrated using gage data along Santa Rosa Creek. The model required minimal (re)calibration to match daily and monthly measured gage discharge rates ($r^2 > 0.9$; for years 2001-2006). Laguna de Santa Rosa discharge rate predictions explained 85 percent of the measured discharges. The SWAT model also estimated sediment yield in the Laguna watershed using MUSLE. Sediment yield estimates were not presented at the Laguna Symposium. However, preliminary results indicate that the estimates are within 5 percent of PWA's PSIAC estimates, which are estimated to represent sediment yield in the Laguna watershed (PWA, 2004; pers. comm. Chris Potter).

4.1.4 USACE Santa Rosa Creek basin hydrology assessment

The Army Corps of Engineers conducted a hydrologic modeling study of the Santa Rosa Creek watershed and published a draft report (USACE, 2002). The study was conducted using the Hydrologic Modeling System, HMS, to simulate precipitation versus runoff process in the Santa Rosa Creek watershed. The only other hydrology study for the Santa Rosa Creek watershed was done by the NRCS for their Central Sonoma Watershed Study (1960).

The study used 12 precipitation stations and divided the watershed into 29 subbasins. There is little data on streamflows in the watershed. The USGS has operated three stream gages in the watershed since 1940 but for short periods of time only. Two stations in the watershed had only been recently activated. Since there are only scattered streamgaging records available, a curve of peak discharge versus frequency was developed using a synthetic unit-hydrograph approach.

Since most flood-producing storms in the region last from one to two days, the study used a storm duration of 24 hours. Time distribution of rainfall was based on an actual 24-hour event during the historic storm of 3 to 5 January 1982. The maximum discharge at the outlet from a storm over the Santa Rosa Creek watershed usually occurs within a few hours following the most intense period of rainfall.

Peak flows for the one-percent chance flood event computed by the HMS model for existing watershed conditions are presented in Table 4-1.

Table 4-1
Discharges during 1-percent (100-year) flood event

Location	Drainage Area (sq-mi)	Peak Discharge (cfs)
Above Diversion	20.8	8,250
Below Diversion	20.8	3,030
Below Spring Lake Outlet	22.4	4,280
Below Brush Creek	33.2	8,300
Below Matanzas Creek	55.7	13,400
Below Piner Creek	71.1	17,900
At Mouth	78.5	19,600

The study concluded that the one-percent peak flow at the Santa Rosa Creek outlet as well as other key locations throughout the watershed has increased significantly. Results also suggested that the four major flood control reservoirs in the watershed will experience significant spilling during the 100-year flood event. Assuming that the Santa Rosa Creek flood control channel is adequately maintained, it appeared to offer protection for a 25- to 50- year flood with the design freeboard. Proposed development in the watershed by the year 2020 according to the General Plan is unlikely to increase runoff significantly. Currently approximately 50 percent of the total watershed (mostly in the upstream areas) is undeveloped and unanticipated significant development in the upper watershed could significantly increase runoff. The study recommended that any major improvements should look beyond the General Plan time frame (beyond 2020).

4.1.5 USACE Laguna de Santa Rosa basin hydrology assessment

The Army Corps of Engineers San Francisco District (USACE) conducted a basin hydrology assessment of the Laguna de Santa Rosa watershed (2003). This study has not yet been published. PWA's 2004 sedimentation analysis relied on draft results of this assessment for sediment yield analysis. The summary of the basin hydrology assessment presented here is derived from our communication with the USACE in 2002 through 2004 and from spreadsheets depicting the peak flows and volumes of simulated events that were provided to PWA.

- The study developed flood hydrographs of various flow-frequencies at the following locations:
- Windsor Creek at the confluence with Pool Creek
- Mark West Creek at the Old Redwood Highway
- Blucher Creek at Highway 116
- Colgan Creek at Llano Road
- Santa Rosa Creek at Willowside Road
- Laguna de Santa Rosa at Llano Road.

Flood hydrographs for the study were developed based on a synthetic unit-hydrograph approach that transforms excess rainfall directly into runoff. Unit hydrographs were derived from an S-curve hydrograph developed by the USACE. The HMS software, which was used in conjunction with Geospatial Hydrologic Modeling Extension (Geo-HMS), simulated the precipitation-runoff process for the Laguna de Santa Rosa watershed. The unpublished results of flood frequency analysis are presented below in Table 4-2 and Table 4-3. The hydrographs for the simulated events are illustrated in Figure 4-5 through Figure 4-9.

Table 4-2
Estimated peak runoff rates during several events

Location	Drainage Area (sq mi)	Peak Flow Rates in cfs				
		2-year	10-year	25-year	50-year	100-year
Laguna de Santa Rosa at Llano Road	44.12	4,590	8,400	10,290	11,570	12,810
Blucher Creek at Highway 116	7.40	940	1,700	2,070	2,320	2,570
Colgan Creek at Llano Road	6.84	710	1,300	1,600	1,800	1,990
Santa Rosa Creek at Willowside Road	75.83	7,560	13,220	15,550	17,330	19,160
Mark West Creek at Old Redwood Highway	42.75	3,900	8,040	10,300	11,820	13,270
Windsor Creek at Pool Creek confluence	17.32	2,020	3,980	5,020	5,730	6,420

Table 4-3
Estimated runoff volumes during several events

	Runoff Volumes in ac-ft				
	2-year	10-year	25-year	50-year	100-year
Laguna de Santa Rosa at Llano Road	3,456	6,857	8,592	9,750	10,883
Blucher Creek at Highway 116	583	1,155	1,447	1,643	1,833
Colgan Creek at Llano Road	480	975	1,229	1,397	1,586
Santa Rosa Creek at Willowside Road	8,352	16,147	19,179	22,007	25,516
Mark West Creek at Old Redwood Highway	4,644	9,995	13,019	15,008	16,926
Windsor Creek at Pool Creek confluence	1,746	3,647	4,725	5,453	6,160

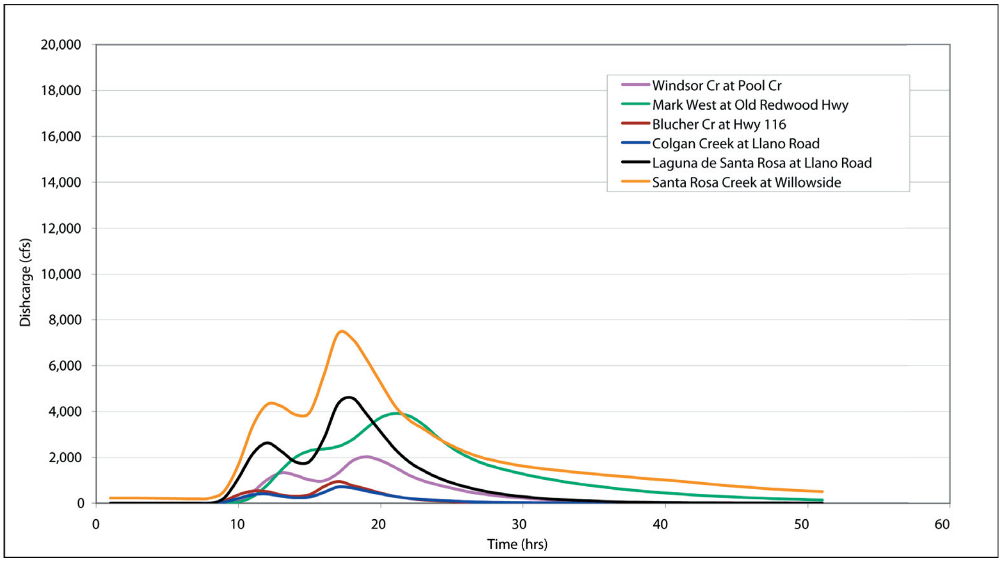

Figure 4-5 Laguna de Santa Rosa 2-year flow hydrographs
(Source: USACE. 2003. Draft Laguna de Santa Rosa Basin Hydrology Assessment. Unpublished Report)

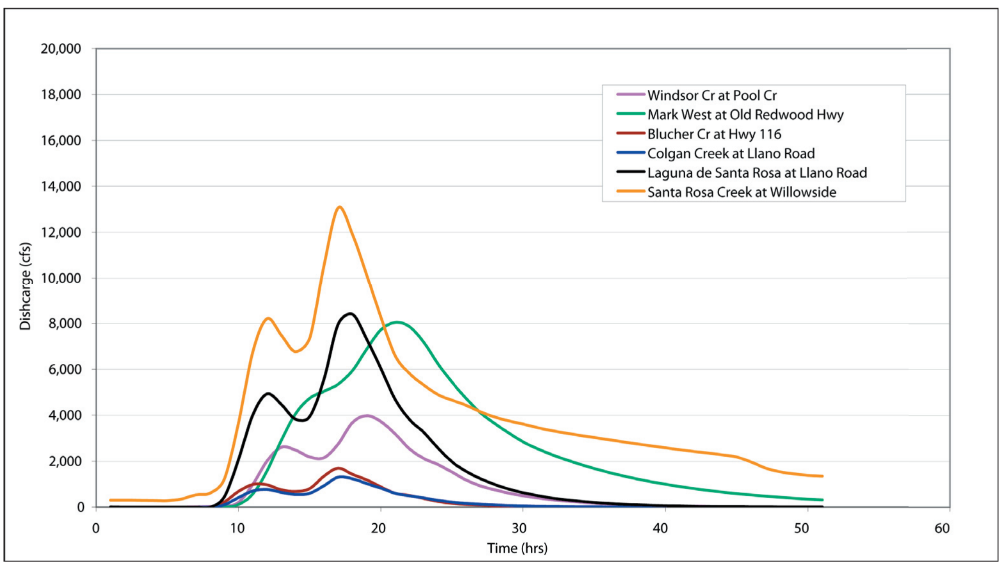

Figure 4-6 Laguna de Santa Rosa 10-year flow hydrographs
(Source: USACE. 2003. Draft Laguna de Santa Rosa Basin Hydrology Assessment. Unpublished Report)

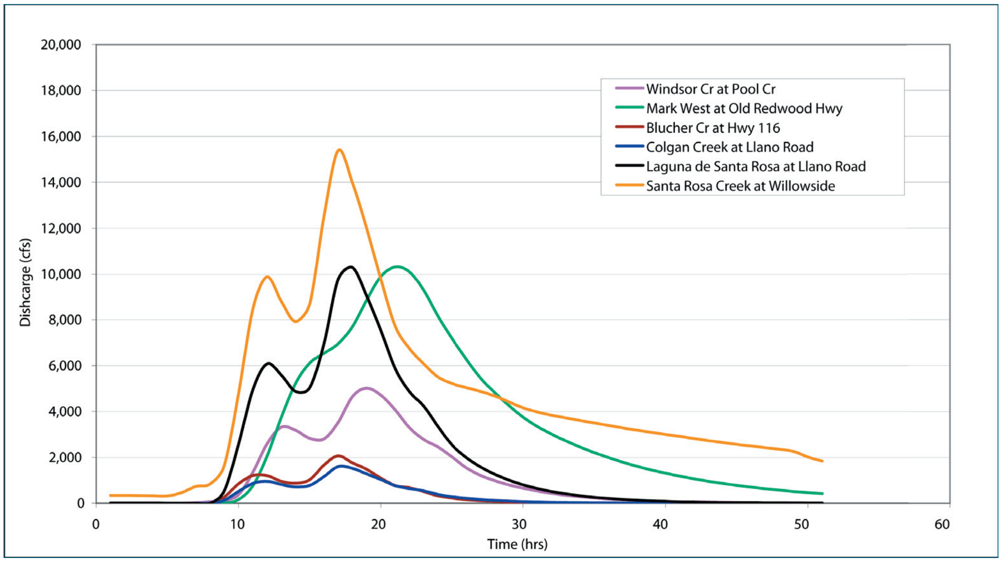

Figure 4-7 Laguna de Santa Rosa 25-year flow hydrographs
(Source: USACE. 2003. Draft Laguna de Santa Rosa Basin Hydrology Assessment. Unpublished Report)

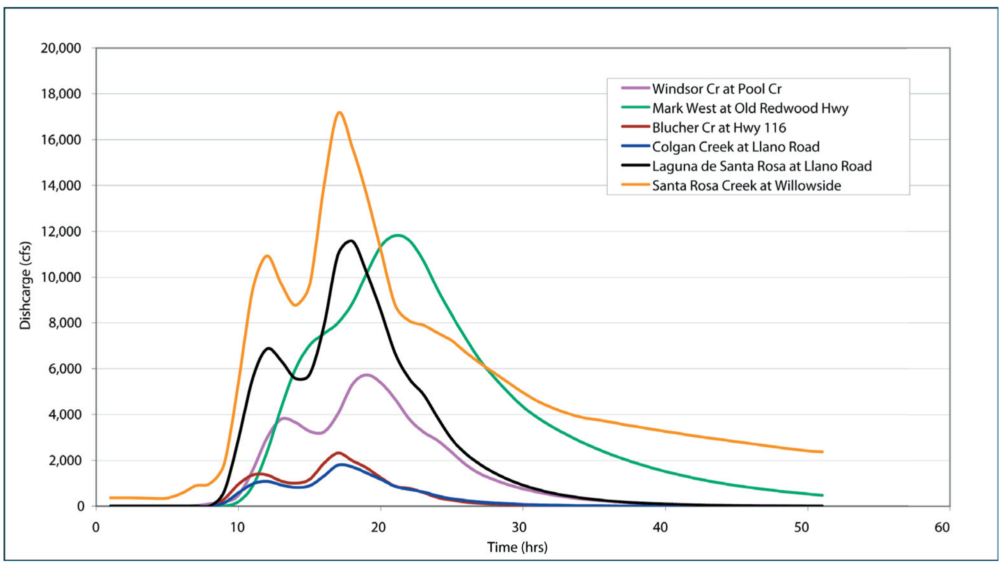

Figure 4-8 Laguna de Santa Rosa 50-year flow hydrographs
(Source: USACE. 2003. Draft Laguna de Santa Rosa Basin Hydrology Assessment. Unpublished Report)

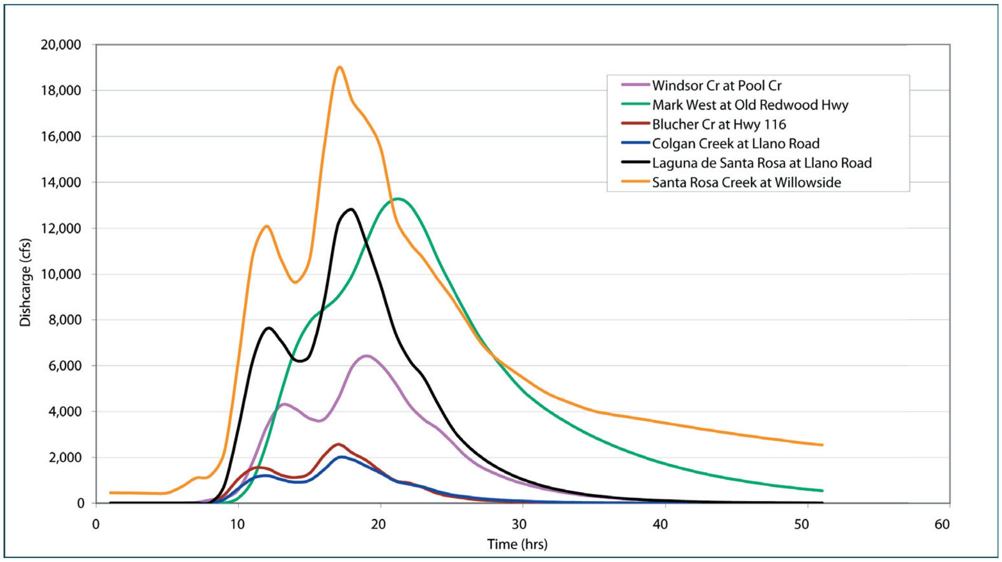

Figure 4-9 Laguna de Santa Rosa 100-year flow hydrographs
(Source: USACE. 2003. Draft Laguna de Santa Rosa Basin Hydrology Assessment. Unpublished Report)

4.2 Data analysis: characterization of sedimentation and hydrology

There is scarce data on water flows and sediment movement through the Laguna de Santa Rosa watershed. The USGS has, over the years, operated peak flow, real time, and daily flow stations at approximately twenty locations. The data from these stations were used to develop hydrologic conceptual models for the current effort. In terms of sediment processes in the Laguna watershed, a recent study on sediment transport, rate, and fate in the Laguna (PWA, 2004) constituted the basis of conceptual models of sediment transport and deposition.

4.2.1 Hydrologic data

Understanding water input and movement through the Laguna can be achieved through analysis of precipitation and flow gage data. We compiled available records from one precipitation gage operated by CIMIS and one operated by Sonoma County and from approximately fifteen flow gages operated by the USGS. Available records from precipitation and flow gages were analyzed and used to quantify, where possible, key hydrologic processes included in the conceptual models.

Precipitation

There are several precipitation gages within and in the vicinity of the Laguna de Santa Rosa watershed (Figure 4-6). Precipitation records of one station were compiled to inform the hydrologic budget we prepared as part of our conceptual model development: CIMIS Station ID 83. The CIMIS station in the watershed is located between Llano Road and Laguna de Santa Rosa, south of Highway 12. The station was activated on January 1, 1990 and has an elevation of 80 feet.

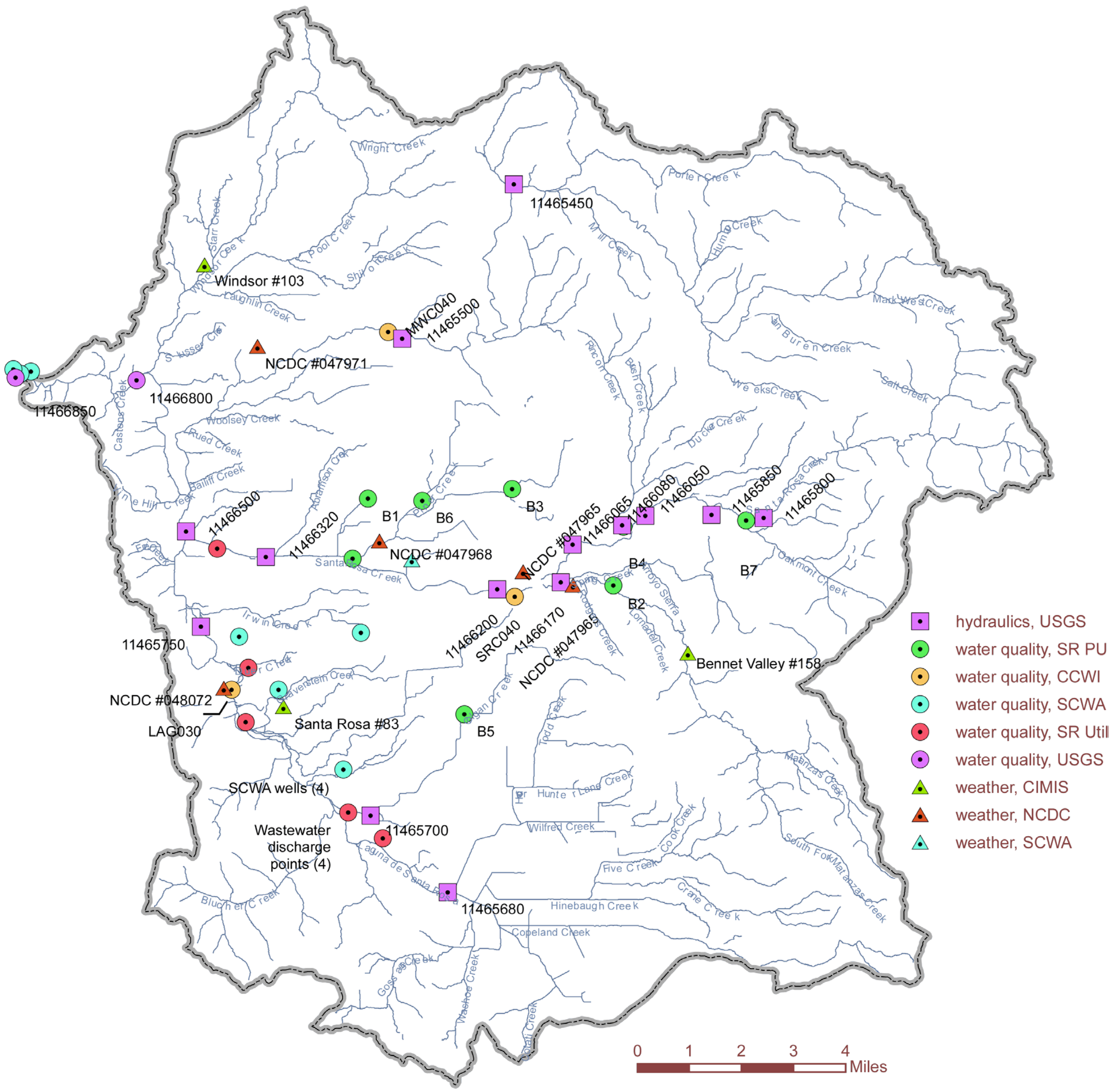

Figure 4-10 Weather and water gaging stations

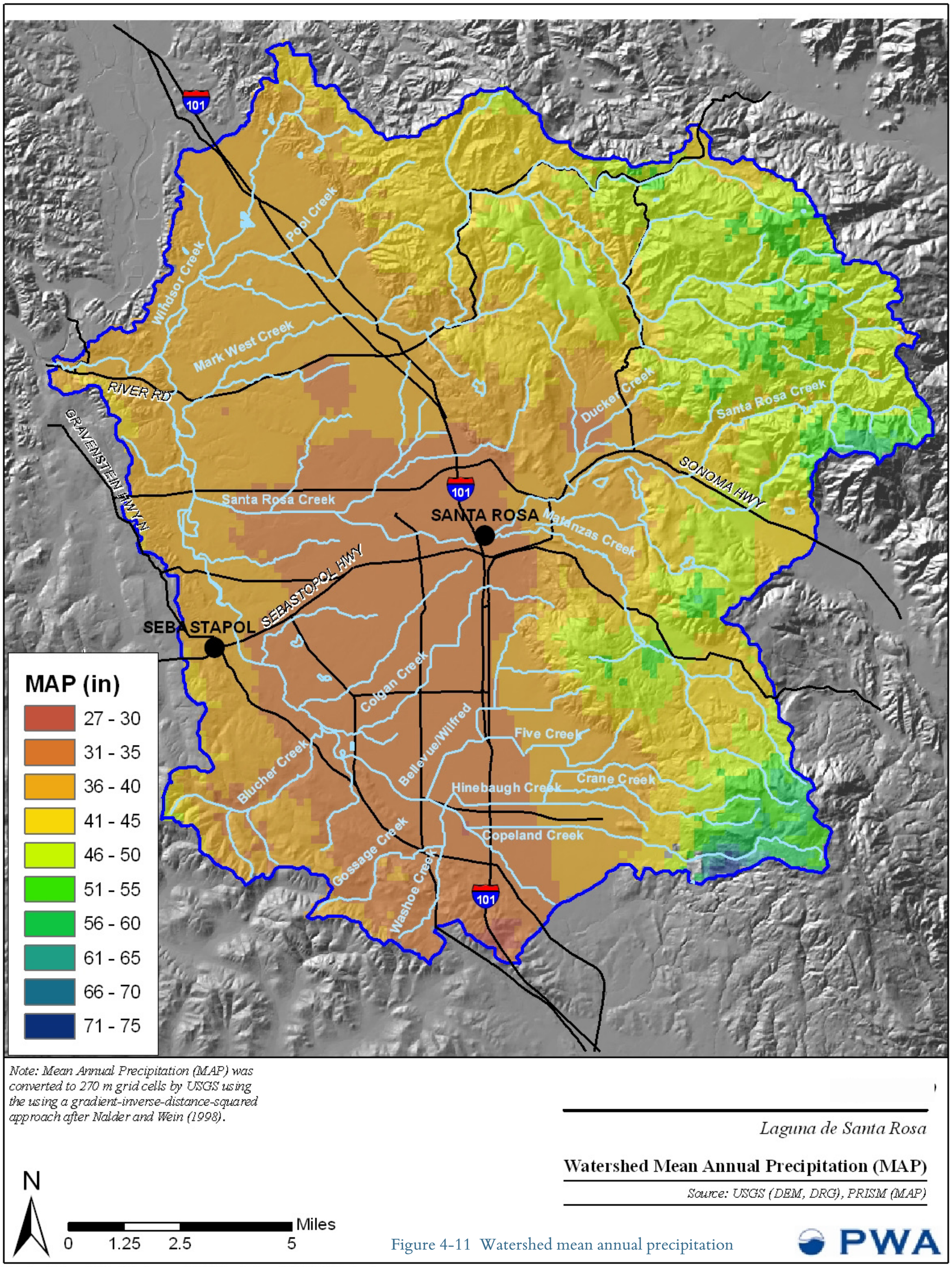

Figure 4-11 Watershed mean annual precipitation

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The mean annual precipitation is strongly affected by elevation and varies considerably in the watershed. A mean annual precipitation for the watershed was created using the 4-kilometer PRISM data (average of 1970-2004) that has been downscaled to 270-meter using a gradient-inverse-distance squared approach (PRISM data and analysis from L. Flint, USGS). The mean annual precipitation in the Laguna watershed ranges from a low of approximately 30 inches in the lowlands near the Laguna to a high of 60 inches in the higher elevations of Mayacamas Mountains (Figure 4-11). Average annual precipitation in the Laguna watershed is 39 inches based on the PRISM data for the Laguna watershed.

Surface water hydrology

One major constraint with hydrological analysis of the Laguna de Santa Rosa is the lack of long-term flow gaging in the watershed. The paucity of the hydrological records for the Laguna have been partially addressed through the installation, in late 1998, of four USGS gages recording 15-minute stage data, that is converted to discharge estimates. Two of these gages are on the Laguna de Santa Rosa (at Stony Point Road [11465680] and Occidental Road ["near Sebastopol" 11465750]); one is on Santa Rosa Creek at Willowside Road (11466320) and one on Colgan Creek (11465700) (Figure 2-8). In addition, there are two daily streamflow gages on the Russian River, upstream and downstream of the Laguna confluence: near Healdsburg (11464000) and near Guerneville (11467000), respectively. These stations constitute the most functional records to quantify hydrologic processes in the Laguna watershed. There are a dozen additional USGS gages within the Laguna watershed that only report water surface elevations or peak flows or have been discontinued. Table 4-4 below details all the gaging stations and their period of record.

Table 4-4
USGS gaging stations withinor near the Laguna watershed

Station No	Station Name	Available Data
11465680	Laguna de Santa Rosa at Stony Point Rd.	Daily Streamflow Values for 11/6/98-9/30/05 Unpublished Streamflow Data for 10/1/05 - 5/18/07
11465750	Laguna de Santa Rosa near Sebastopol	Daily Streamflow Values for 11/18/98-9/30/05 Unpublished Streamflow Data for 10/1/05 - 5/18/07
11465700	Colgan Creek near Sebastopol	Daily Streamflow Values for 11/7/98-9/30/05 Unpublished Streamflow Data for 10/1/05-5/18/07
11466320	Santa Rosa Creek at Willowside Rd	Daily Streamflow Values for 12/9/98-9/30/05 Unpublished Streamflow Data for 10/1/05-5/18/07
11466500	Laguna de Santa Rosa near Graton	Elevation above sea level, recorded only above 55.0 ft Published data for 2/40-9/49 and 10/64 to 2005
11466050	Santa Rosa Creek at Mission Boulevard, at Santa Rosa	Elevation above sea level, from October 1 to May 31 Published data for 11/97 to 2005

11466080	Santa Rosa Creek at Alderbrook Drive, at Santa Rosa	Elevation above sea level, from October 1 to May 31 Published data for 10/97 to 2005
11465850	Spring Lake at Santa Rosa	Elevation above sea level, recorded only above 291.50 ft, from October 1 to May 31 Published Data for 10/97 to 2005
11466200	Santa Rosa Creek at Santa Rosa	Elevation above sea level, from October 1 to May 31 Published Data for 12/39-9/41 and 10/01 to 2005
11466065	Brush Creek at Santa Rosa	Elevation above sea level, from October 1 to May 31 Published Data for 11/02 to 2005
11466170	Matanzas Creek at Santa Rosa	Elevation above sea level, from October 1 to May 31 Published Data for 11/02 to 2005
11467000	Russian River near Guerneville	Daily Streamflow Values for 10/1/39-9/30/05 Unpublished Streamflow Data for 10/1/05-5/18/07
11464000	Russian River near Healdsburg	Daily Streamflow Values for 10/1/39-9/30/05 Unpublished Streamflow Data for 10/1/05-5/18/07
11465200	Dry Creek near Geyserville	Daily Streamflow Values for 10/1/59-9/30/05 Unpublished Streamflow Data for 10/1/05-5/18/07
11465359	Dry Creek near mouth, near Healdsburg	Daily Low Flow Values, recorded only below 200 cfs Published Data for 11/80 to 2005
11465450	Mark West Creek at Mark West Springs	Peak Flows Between 1958-1962
11465500	Mark West Creek near Windsor	Real-time Site
11466800	Mark West Creek near Mirabel Heights	Real-time Site

Two issues constrain the use of these data sources. First, many of the gages have not yet undergone sufficient calibration to allow high confidence in the readings. The lake-like conditions in high stage on the Laguna make the calibration of stage and discharge at many of the Laguna-area gages uncertain. The two daily flow stations along the Laguna were rated "poor" by the USGS due to its lake-like behavior during high-flows and frequent overbank conditions, resulting in poor stage-discharge rating curves. The Santa Rosa Creek station (11466320) is the only station that was rated as "fair". Second, the gage records are not yet of long enough standing to allow construction of meaningful flood-frequency relationships. The only available flood-frequency relationships from a finalized study are reported in the FEMA Flood Insurance Study (1997) and are detailed in Table 4-5 below.

Flood flows in the Laguna de Santa Rosa are strongly influenced by the backwater effect of coincident high flows from the Russian River. FEMA (1997) notes that "the maximum stage on Laguna de Santa Rosa has a high correlation with the maximum stage of the Russian River downstream from its confluence with the Laguna de Santa Rosa. As a result of completion of Warm Springs Dam on Dry Creek, the 100-year flood stage on Laguna de

Santa Rosa has been reduced to an elevation 75 feet NGVD." Flood levels for the 100-year flow are given as a constant from the confluence with the Russian River to Slusser Road on Mark West Creek (38,600 feet upstream of the Russian River confluence) and to Blucher Creek on Laguna de Santa Rosa (46,000 feet upstream of the Mark West confluence). The 10-year flood elevation is reported as 67.5 feet and is level upstream to the railroad tracks east of Sebastopol. The 1986 flood on Laguna de Santa Rosa (slightly influenced by Russian River flooding) plots at slightly over 74 feet (FEMA, 1997). The peak stage reported by USGS for the Laguna at Guerneville Road (11465750) in the 2005-6 New Year's Eve Flood was 72.6 feet.

The ability of the lower Laguna de Santa Rosa-Mark West system to provide flood storage both of its own waters and those incoming from the Russian River is recognized. It is estimated that without the Laguna-Mark West system's flood storage in the 1964-65 flood, levels in Guerneville may have been up to 14 feet higher, and that the Laguna detention reduced Russian River flows by a maximum of 40,000 cfs (SCFCWCD, 1965). Flood inundation extent during the 1964-5 floods was estimated at 7,400 acres (SCFCWCD, 1965), although the total flooded area recorded by individual streams is estimated at 8,080 acres (Laguna = 5,600 acres, Mark West Creek = 1,430 acres, Santa Rosa Creek, 1,050 acres).

SCWA (1997) estimate the storage capacity provided by flood inundation at various flows using staff gage readings from February 7, 1940 – April 15, 1941, near Graton. The Laguna basin is expected to provide 79,000 acre-feet of water storage at the 100-year (75 feet NGVD29) flood level.

Table 4-5
Flow details from Sonoma County unincorporated areas flood insurance study
(Source: FEMA 1997)

		Drainage Area	Peak Discharges (cfs)			
		(sq mi)	10-yr	50-yr	100-yr	500-yr
Laguna de Santa Rosa	Upstream of confluence with Mark West Creek	170.0	21,100	30,300	35,100	44,900
	Downstream of confluence with Santa Rosa FCC	166.0	16,800	23,900	28,000	35,700
	Upstream of confluence with Santa Rosa FCC	87.4	14,000	20,100	23,300	30,800
	Upstream of confluence with Colgan Cr	n/d	7,710	11,200	12,850	17,100
	At Stony Point Rd	n/d	7,170	10,400	11,950	15,900
	Upstream of confluence with Copeland Cr	n/d	977	1,410	1,630	2,120
	Upstream of confluence with Hinebaugh Cr	n/d	2,280	3,250	3,800	5,000
	Downstream of confluence with Hinebaugh Cr	n/d	5,550	7,900	9,250	12,000
Mark West Creek	Upstream of confluence with Windsor Cr	227 *	29,602	42,248	47,900	62,318
	Upstream of confluence with Laguna de Santa Rosa	52.1	8,172	11,000	12,085	15,000
Santa Rosa Flood Control Channel	Upstream of confluence with Laguna de Santa Rosa	78.6	9,900	14,500	16,500	22,000

* estimated
n/d = not determined

To support PWA's sedimentation study, the Army Corps of Engineers prepared a draft basin hydrology assessment for the Laguna de Santa Rosa watershed (USACE, 2003) as well as having completed a separate draft hydrologic analysis of the Santa Rosa Creek watershed (USACE, 2002). Neither study has been finalized by the USACE and should not be used for any hydrologic or sediment-related processes without the USACE's permission. The runoff volumes and peak discharge rates for 2-, 10-, 25-, 50-, and 100-year flows at six locations throughout the watershed were provided by the USACE and are presented in Table 4-2 and Table 4-3. Notably, the estimated 100-year peak flow for Santa Rosa Creek at the mouth is approximately 16% higher and for the Laguna at Llano Road is approximately 10% higher than the rate reported in FEMA (1997).

Dames and Moore (1988, in CH2MHill, 1989) estimated average monthly flows for the Laguna de Santa Rosa at Guerneville Road. Flows were assembled using rainfall statistics (a weighted average of daily precipitation at the National Weather Service (NWS) gage near St Helena (NWS station 047643) and SCWA Santa Rosa gage 1014) and calibrated against 11 years of daily streamflow data (August 1959 – September 1970; 134 months) for USGS streamflow gage station 11465800 on Santa Rosa Creek near Santa Rosa. Potential evaporation (PE) estimates were generated using pan evaporation data from the Santa Rosa Wastewater Treatment Plant (West College). Monthly values were converted to 6-hour precipitation values and daily PE values with simulated-to-observed differences of less than 6 percent. A synthetic unit hydrograph was calculated via HEC-1, the earlier version of the HMS software developed by the USACE. Flows were compared to flows recorded at the Guerneville gage from January 1958 – December 1987. Table 2-6 shows the flows thus estimated.

Table 4-6
Average monthly Laguna de Santa Rosa flows at Guerneville Road

Month	Average Monthly Streamflow (cfs)
October	20
November	117
December	352
January	645
February	657
March	368
April	173
May	32
June	11
July	4
August	4
September	5

4.2.2 Sediment data

There is very little data on sediment movement through the Laguna system and very few reports dedicated to quantify sediment production, transport, or deposition processes across the watershed. We summarized existing studies on the sediment processes in Section 4-1. This section will present the detailed results of sediment yield estimates of PWA's previous study. It will summarize the selected estimates by subwatershed and by time scale to quantify key processes included in the hydrologic and sediment conceptual models. It should be noted that all the recent studies have addressed sediment production and delivery in the Laguna watershed; no analysis of sediment transport conditions through the system is available to incorporate into the conceptual models.

Sediment yield estimates from empirical models

PWA used the Pacific Southwest Interagency Committee (PSIAC) and the Modified Universal Soil Loss Equation (MUSLE) methods to estimate the average annual sediment yield and event sediment yield due to sheet and rill erosion, respectively. MUSLE was also used to provide an estimate of annual sediment yield by taking the weighted average of soil loss from individual events.

The sediment yields estimated using these two methods represent the total amount of sediment delivered to stream channels at the selected outlets. The sediment yields within the Laguna de Santa Rosa system were estimated at the following locations:

- Windsor Creek below confluence with Pool Creek
- Mark West Creek at Old Redwood Highway
- Santa Rosa Creek at Willowside Road
- Laguna de Santa Rosa at Llano Road
- Colgan Creek at Llano Road
- Blucher Creek at Highway 116

The PSIAC method provides sediment yield estimates in acre feet per square mile per year (ac-ft/sq-mi/yr). A unit weight of 90 pounds per cubic feet (lb/ft^3) (approximately 1,400 kilogram per cubic meter) was used to convert the results to tons/sq-mi/yr. The sediment yield estimates for the above subwatersheds using the PSIAC methodology are provided in Table 4-7.

The total annual load to the mainstem Laguna system from all subwatersheds is approximately 153 ac-ft/yr or 272,916 tons/yr. This estimate does not take into account Matanzas Reservoir, the largest reservoir in the watershed, as well as several smaller reservoirs such as those along Paulin Creek and Brush Creek. Therefore the sediment yield estimate also includes the volume of sediment that would be trapped by the reservoir.

Table 4-7
Annual sediment yield estimates by PSIAC

	Annual Sediment Yield (ac-ft/sq-mi/yr)	Annual Sediment Yield (ton/sq-mi/yr)
Laguna at Llano Road	0.84	1,495
Blucher at Hwy 116	0.78	1,388
Colgan at Llano Road	0.61	1,089
Santa Rosa at Willowside Road	0.85	1,513
Mark West at Old Redwood Highway	0.66	1,182
Windsor at Pool Creek confluence	0.78	1,385

The event sediment yields calculated by MUSLE for 2-, 10-, 25-, 50-, and 100-year flows are given in Table 4-8.

Table 4-8
Event-based sediment yields estimated by MUSLE

	Drainage Area (mi²)	2-year (tons/mi²)	10-year (tons/mi²)	25-year (tons/mi²)	50-year (tons/mi²)	100-year (tons/mi²)
Laguna at Llano Road	44.1	557	1,146	1,457	1,670	1,880
Blucher Creek at Hwy116	7.4	1,134	2,317	2,935	3,359	3,783
Colgan Creek at Llano Road	6.8	174	363	465	533	600
Santa Rosa Creek at Willowside Road	75.8	1,609	3,182	3,837	4,404	5,061
Mark West Creek at Old Redwood Hwy	42.8	1,701	3,919	5,220	6,106	6,968
Windsor Creek at Pool Creek confluence	17.3	1,196	2,642	3,478	4,058	4,631

Event sediment yields can be weighted according to their incremental probability, resulting in a weighted storm average. To compute the annual yield, the weighted storm yield is multiplied by the ratio of annual water yield to an incremental probability-weighted water yield. The results of annual sediment yield estimates thus computed are provided in Table 4-9.

Table 4-9
Mean annual sediment yield estimated by MUSLE

	Mean Annual Runoff (in)	Mean Annual Runoff (ac-ft)	Annual Sediment Yield (ac-ft/sq-mi/yr)	Annual Sediment Yield (ton/sq-mi/yr)
Laguna at Llano Road	10	23,531	2.23	3,857
Blucher Creek at Hwy116	10	3,947	4.51	7,789
Colgan Creek at Llano Road	12	4,378	0.93	1,610
Santa Rosa Creek at Willowside Road	14	56,620	6.38	11,017
Mark West Creek at Old Redwood Hwy	18	41,040	9.01	15,551
Windsor Creek at Pool Creek confluence	18	16,627	6.77	11,698

2002-2003 turbidity measurements

PWA collected water surface and turbidity measurements at three locations along the Laguna de Santa Rosa and Santa Rosa Creek suitable for developing sediment rating curves. The monitoring locations along the Laguna de Santa Rosa and Santa Rosa Creek that are currently gaged for stage and streamflow by the USGS were chosen for monitoring turbidity/suspended sediment. The monitoring locations included:

- Santa Rosa Creek at the Willowside Road Bridge
- Laguna de Santa Rosa at the Occidental Road Bridge
- Laguna de Santa Rosa at the Stony Point Road Bridge

Sediment loading (lbs/sec) was computed from the sediment concentration data and discharge data (Figure 4-12 through Figure 4-14). Sediment loading and cumulative sediment yield computations at the Willowside Road monitoring location on Santa Rosa Creek and at the Stony Point Road monitoring location on the Laguna de Santa Rosa do not include the major storm events that occurred during mid-December. Rating curves relating sediment loading and discharge for each monitoring location indicate that suspended sediment concentration is dependent on several parameters and partially a function of discharge.

Our turbidity records for Santa Rosa Creek during 2002-2003 (a relatively average year in terms of rainfall and runoff) show a load of 96,993 tons, compared with a PSIAC-estimated yield of 114,722 tons. The measured load missed the first large event of the season, but by comparing the Santa Rosa Creek and Laguna at Occidental Road loads we can estimate that Santa Rosa Creek delivered approximately 40-50,000 tons of sediment during this storm, giving a total yield for the year of approximately 150,000 tons. For 2002-2003 (all storms) the measured suspended sediment load for the Laguna de Santa Rosa at Occidental Road was 385,297 tons (compared with a PSIAC-estimated yield of 222,000 tons). The rating curve for the Laguna de Santa Rosa at Occidental Road is considered 'poor,' while Santa Rosa Creek is considered 'fair'; discharge estimates were used in our computation of suspended load. In both comparisons of values presented, estimated sediment yield was compared with calculated suspended sediment load. Sediment yield would be expected the to be higher than the suspended sediment load since there will be additional load carried as bedload (especially in Santa Rosa Creek) and some sediment yield that does not reach the channel (especially in Laguna de Santa Rosa).

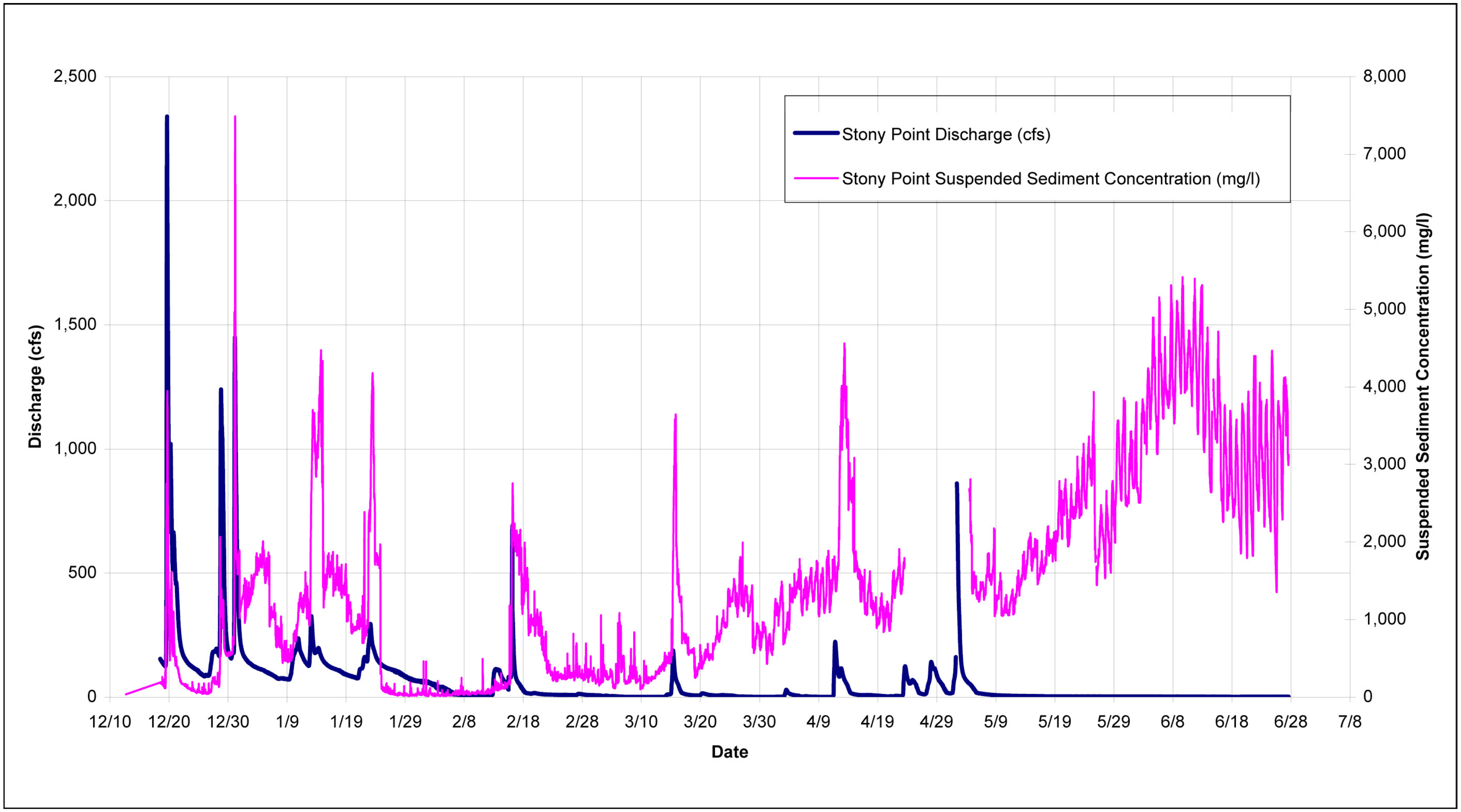


Figure 4-12
Laguna de Santa Rosa at Stony Point Road discharge and suspended sediment concentration 2002-03

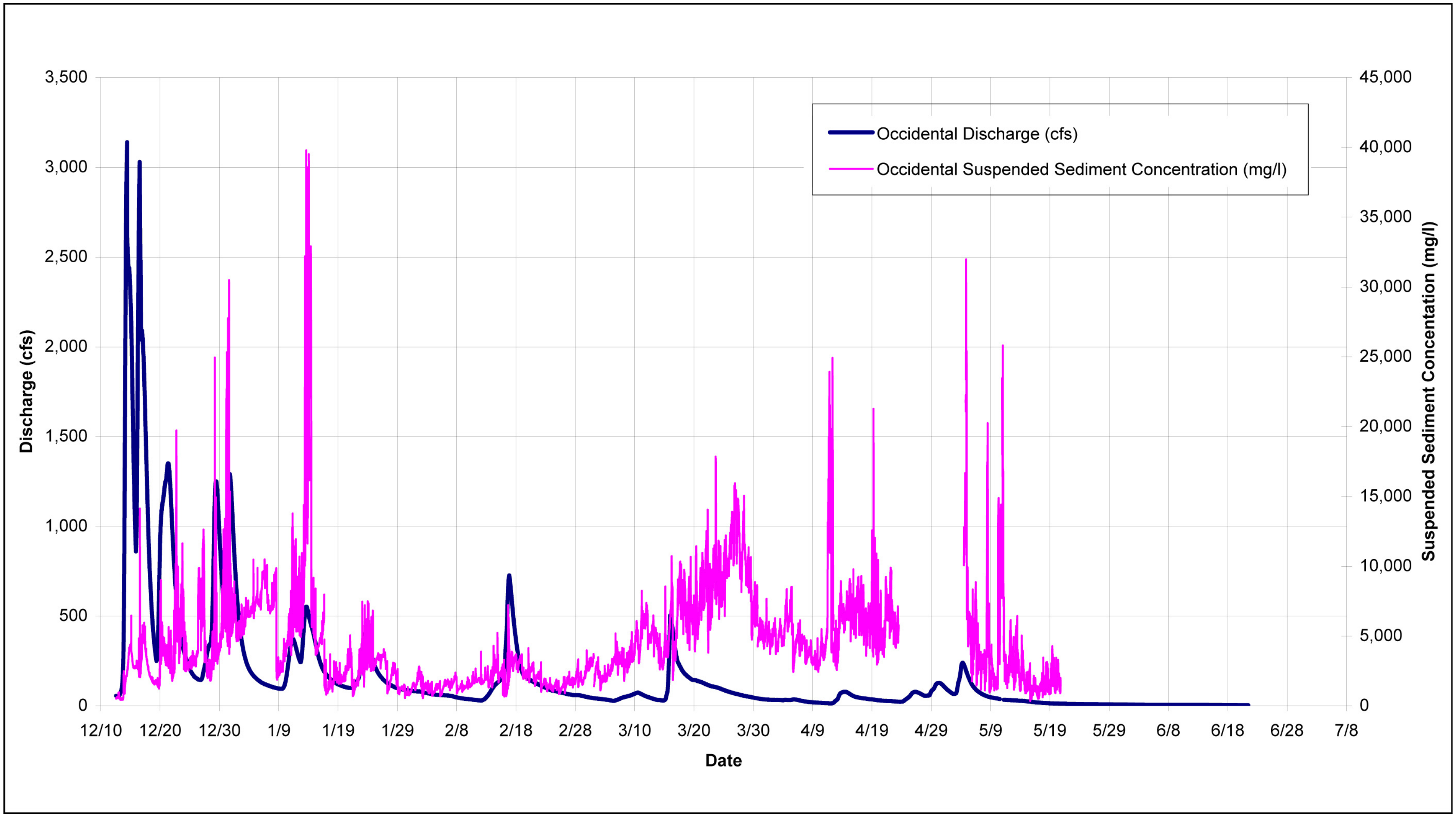


Figure 4-13
Laguna de Santa Rosa at Occidental Road discharge and suspended sediment concentration 2002-03

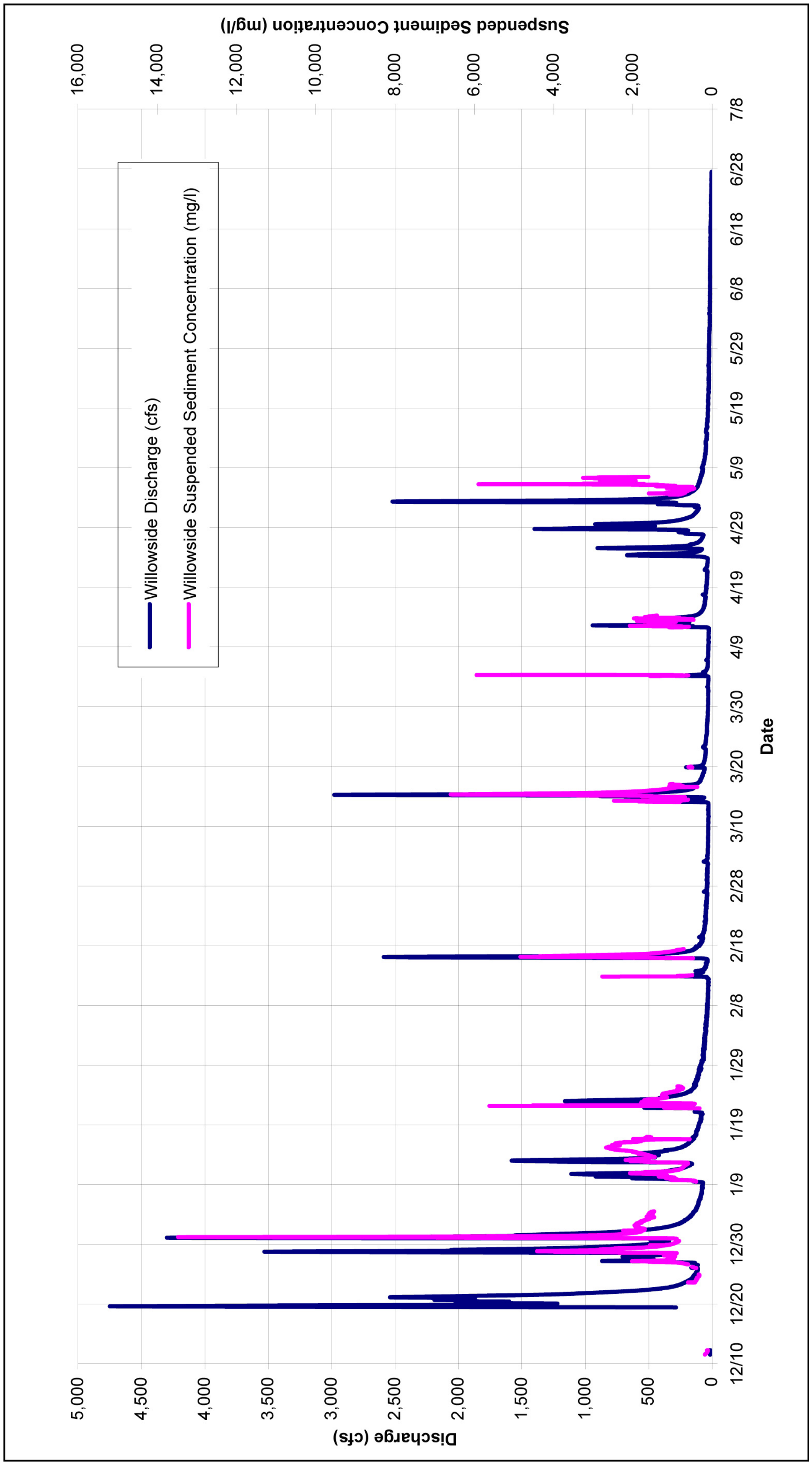


Figure 4-14
Santa Rosa Creek at Willowside Road discharge and suspended sediment concentration 2002–03

Reservoir sedimentation studies and sediment yields in nearby watersheds

Matanzas Creek is the southern tributary of the Santa Rosa Creek and drains an area of 11.5 mi^2. Matanzas Reservoir was built in the early 1960s as a part of the Central Sonoma Watershed Project. The Soil Conservation Service initially surveyed the reservoir in 1964, and then 1972 and 1982. The storage capacity reduction in the reservoir was reported for the two periods between the surveys, and an average annual sedimentation rate was estimated. Table 4-10 below presents the survey information and the annual sedimentation estimates.

Table 4-10
Loss of storage volume in Matanzas Reservoir, 1964-1982

Date of Survey	Period between surveys (years)	Storage Capacity (ac-ft)	Specific Weight	Average Annual Sedn (per sq-mi) Ac-ft Tons		Agency Supplying Data
Jun 1964	--	1,500	--	--	--	SCS
Mar 1972	7.8	1,411	90	1.0	1,960	Not specified
Aug 1982	10.4	1,324	90	0.7	1,423	Not specified

The loss of storage capacity shown above represents an average sediment volume of between 0.7 and 1.0 ac-ft/sq-mi/yr. The actual sediment yield of the watershed will be higher because not all generated sediment will be delivered to the channel network and the reservoir. However, because Matanzas Reservoir is close to the steep headwaters and forms a very effective sediment trap, we assume that these figures are relatively close to the actual sediment yield of the watershed. The Matanzas Creek watershed is very similar to the larger Santa Rosa Creek watershed in terms of soils, geology, land cover, and hillslope gradients. Therefore, the annual sediment yield estimates of between 1.0 and 0.7 ac-ft/sq-mi/yr derived from the reservoir surveys are believed to be representative of sediment yields in the Santa Rosa Creek watershed, albeit slight underestimations. In addition, due to the similarities of watershed characteristics draining the Sonoma Mountain range in the Laguna de Santa Rosa watershed, the estimates are expected to approximate sediment yields in other subwatersheds as well.

Milliman and Syvitski (1992) quoted a study by Janda and Nolan that estimated the annual sediment yield in the Russian River watershed. Their estimate was 680 t/km^2/y or 1760 t/mi^2/y. Assuming a unit weight of 90 lb/ft^3 or approximately 1400 kg/m^3, the annual sediment yield in the Russian River watershed would be 1.02 ac-ft/sq-mi/yr, consistent with the estimates from Matanzas Reservoir. Ritter and Brown (1971) evaluated suspended sediment transport in the Russian River basin. For the years 1965 to 1968, Ritter and Brown found a suspended load of 1,150 to 14,000 tons/sq-mi/year, the highest being in the very wet 1965 year. Griggs and Hein (1980) estimated average erosion rates for a number of Northern California watersheds based on off-shore sedimentation studies. Their study suggested an erosion rate of approximately 1,600 tons/sq-mi/yr for the Russian River watershed. Sonoma Ecology Center has published a sediment budget of the Sonoma Creek watershed in which, an annual sediment yield of approximately 1,100 tons/sq-mi was estimated. California Geological Survey (CGS) prepared a technical memorandum that concluded that from a review of the literature and analysis of recent studies conducted by the CGS watersheds underlain by Franciscan mélange are likely to have natural/background sediment loads of approximately 1,000 tons/sq-mi/year or greater (Bedrossian and Custis, 2002).

Sediment inputs to the Laguna from the Russian River

In addition to sediment from within the watershed, the Laguna occasionally receives sediment-rich water from the Russian River. During flood events where the Russian River backs up into the Laguna, some fine sediment is carried upstream to the Laguna and would deposit especially where the water from both systems meet, around the Mark West Creek confluence. There are no estimates of the amount of sediment that is contributed by the Russian River. Good long-term flow records for the lower Laguna channel, including flow direction, and sediment and flow records for the Russian River around the Laguna confluence are required to estimate the amount of sediment contributed and deposited by the Russian River in the Laguna.

Grain size analysis

PWA collected 32 bulk samples from channel beds along the Laguna tributaries. The samples were collected by hand at strategic positions around the watershed. Each sample was collected from a riffle or riffle-equivalent position (in modified channels) and consisted of approximately 25-40 lbs of sediment from the near sub-surface layer of the channel bed. Efforts were made to ensure that the samples were collected from exposed bed sites, to clear obvious armor layer deposits and to minimize the loss of fine materials during collection, but it should be expected that each sample somewhat underestimates the fine sediment proportion. Particle size analysis was performed on all samples. Summary statistics for the bulk samples are provided in Table 4-11, organized by sample number.

Table 4-11
Particle size distribution of bed material samples in Laguna tributaries

Sample Location	Description	% Gravel	% Sand	% Fines
Mark West @ Porter Creek	Gray poorly- graded gravel with sand	56	39	5
Mark West @ Calistoga	Gray poorly- graded gravel with sand	51	47	2
Mark West @ MW Springs (Redwood Hill)	Gray poorly- graded gravel with sand	54	45	1
Mark West @ MW Springs	Gray well- graded gravel with sand	77	21	2
Mark West @ Old Redwood Hwy	Gray poorly- graded sand with gravel	48	51	1
Mark West @ Laughlin	Gray poorly- graded gravel with sand	50	49	1
Mark West @ Slusser	Gray well- graded gravel with sand	67	33	0

Sample Location	Description	% Gravel	% Sand	% Fines
Santa Rosa@ Wildwood	Gray poorly- graded gravel with sand	70	30	0
Santa Rosa @ Montgomery	Gray poorly- graded gravel with sand	62	38	0
Brush Cr. @ Hwy 12	Gray poorly- graded gravel with sand	64	35	1
Spring Cr. @ Park Trial	Brown well-graded gravel with silt and mud	64	28	8
Manzinitas CR. @ Yulupa	Gray well-graded gravel with sand	70	28	2
Santa Rosa @ Sonoma	Gray well-graded gravel with sand	72	28	0
Pauline Cr @ Lomitas	Gray well-graded gravel with sand	68	30	2
Santa Rosa @ Fulton	Gray poorly- graded gravel with sand	52	47	2
Piner Cr. @ Fulton	Gray poorly- graded gravel with sand	64	36	0
Santa Rosa @ Willowside	Gray brown well-graded gravel with sand	59	40	1
Colgan Cr. @ Victoria	Brown silty sand	0	62	38
Colgan Cr. @ Stony Point	Gray well-graded gravel with sand	55	44	2
Colgan Cr. @ Llano	Olive gray clay with trace sand	4	10	86
Blucher @ Canfield	Gray sand with clay	2	87	11
Blucher @ Lone Pine (Hwy 116)	Gray sand with clay	1	93	6
Bellevue/Wilfred @ Petaluma Hill	Gray brown well-graded gravel with sand	58	38	4
Bellevue/Wilfred @ Todd	Gray well-graded sand with gravel	42	56	2
Bellevue/Wilfred @ Wilfred	Dark grayish brown silt with sand	2	19	79
Crane Cr. @ headwaters	Light brown silty gravel with sand	66	21	13
Crane Cr. @ Petaluma Hill	Gray poorly graded gravel with sand	60	38	2
Hinebaugh Cr. @ Petaluma Hill	Dark brown & gray poorly-graded sand with silt and gravel	28	61	11

Sample Location	Description	% Gravel	% Sand	% Fines
Hinebaugh Cr. @ Redwood	Gray poorly-graded sand with silt and gravel	19	75	6
Copeland Cr. @ Lichau	Gray brown well-graded gravel with sand	70	28	2
Copeland Cr. @ Snider	Gray well-graded gravel with sand	64	36	0
Copeland Cr. @ trailer park	Gray well-graded sand with silt	3	87	10
Pool Cr @ Windsor Road	Brown poorly- graded gravel with sand	62.5	35.8	-
Windsor Cr @ Windsor Road	Brown well- graded gravel with sand	58.1	40.9	-
Pool Cr @ Pleasant Ave	Brown poorly- graded sand with gravel	34.2	63.9	-
Windsor Cr @ Arata Ln	Brown well- graded gravel with sand	56.6	41.1	-
Windsor Cr @ Brooks Rd N	Brown poorly- graded sand with gravel	43.7	53.6	-
Windsor Cr @ Conde Ln	Brown poorly- graded sand with gravel	48.4	50.1	-
Pool Cr @ Conde Ln	Brown well- graded gravel with sand	58.3	40.1	-
Pool Cr @ Leslie Rd	Brown well- graded sand with gravel	48.4	50.0	-
Windsor Cr @ MW Station Rd	Brown poorly- graded gravel with sand	52.2	46.6	-

4.3 Conceptual models

Development of conceptual models of complex ecological systems such as Laguna de Santa Rosa is fundamentally important to define the scope of problems being considered and to describe the causes, interactions, and effects underlying environmental change (National Research Council, 1995). Conceptual models also serve as the foundation of a comprehensive modeling effort and subsequent restoration program. Our conceptual models are developed to explain a general state of understanding about the Laguna system and its physical and ecological processes and to present the rationale for selecting and developing subsequent modeling studies. The conceptual models of hydrologic, sediment, water quality, and ecologic processes will be coupled to provide the linkages between these different parts of the system and to provide the basic structure for future computational models.

We explored the temporal and spatial variability of physical processes in the Laguna de Santa Rosa watershed in the previous section. Section 4.3.1 presents a temporal conceptual model on the Laguna and briefly summarizes time dependent equilibrium states of the system. We also developed two different types of spatial conceptual models to express our present state of understanding about hydrological and sediment processes in the Laguna de Santa Rosa watershed. These models are described in Sections 4.3.2 and 4.3.3. Our definition of conceptual model components is derived from CALFED's Delta Regional Ecosystem Restoration Implementation Plan (DRERIP) Framework (DRERIP, 2005).

The first type of conceptual model is an Operational Conceptual Model, or a model that clearly delineates the cause-effect relationship by identifying the key anthropogenic drivers, linkages, and outcomes in the Laguna ecosystem (DRERIP, 2005). These models were developed for two geomorphic domains in the watershed: the Lower Laguna Watershed and the Upper Laguna Watershed. Each domain is represented by a qualitative schematic that illustrates how drivers influence relationships among processes that lead to outcomes. In our conceptual models, an ecosystem element refers to a basic component or function and can be categorized as a process, habitat, stressor, or species. As specified in these models, a driver is a human-induced element with a known or hypothesized important effect on another element. In coupled models, a driver in a model can be the outcome from another model. A linkage is a cause-effect relationship among ecosystem elements. An outcome or intermediate outcome is a result, effect, or consequence (DRERIP, 2005). For each cause-effect linkage, the nature and direction of the effect is identified. A positive effect or a negative effect is represented by + or – sign, respectively. A response curve effect is represented by a bell-shaped curve and is an effect that is generated most strongly within a limited range of conditions.

The second type of conceptual model is a Budgetary Conceptual Model that summarizes the directions and known magnitudes of hydrologic and sediment delivery processes from subwatersheds to the Laguna de Santa Rosa. Data for Budgetary Conceptual Models have been derived from hydrologic information acquired from USGS gauging stations in the Laguna watershed and from PWA's previous analysis on sediment sources and rates in the Laguna (PWA, 2004).

4.3.1 Temporal variability

The Laguna de Santa Rosa and its watershed are part of an integrated physical system in which cascading arrangements of mass (i.e. sediment) pass through the morphological components of the system (i.e. landforms) over varied time scales. The components mutually adjust to changes in inputs of mass, frequently with negative feedback arrangements, which allow the system to be self-regulating. Self-regulation is usually directed toward an equilibrium state where the inputs of energy and mass are equal to the outputs from the system. There are several forms of equilibrium state including static, stable, unstable, metastable, steady-state and dynamic (Chorley and Kennedy, 1971). The time scale of interest strongly influences the view of system stability and the cause of any induced change.

In the short term (e.g., one to one hundred years), there may be unceasing adjustment between the system components. Variable conditions produce fluctuations about an average value (i.e., stable equilibrium). The long term (e.g., one hundred to several hundred years) can involve the establishment and maintenance of a characteristic set of landforms within a system that persist through time, although individual components will be evolving and the pattern and interrelationships of these features will be continuously changing (i.e., steady-state equilibrium). In the very long term (e.g., a thousand to several hundred thousand years), progressive or major episodic changes become more apparent (i.e., dynamic or metastable equilibrium, respectively).

The temporal variability of hydrologic and sediment delivery to the Laguna de Santa Rosa can be explored within two different contexts: before and after the European settlement of the area, approximately 150 years ago. Prior to European settlement, hydrologic and sediment delivery from tributary channels were likely in a state of dynamic equilibrium: variations year to year were driven by the natural processes of rainfall and stream flow and the production of sediment in the subwatersheds. Gradual progressive changes in sediment delivery would have resulted from tectonic processes. Since the European settlement of the Laguna de Santa Rosa watershed, there has been a series of land use changes in the watershed that have had significant impacts on sediment yield at an unprecedented rate. Specific land uses that influenced hydrologic and sediment delivery in the Laguna de Santa Rosa watershed are grazing, agriculture, urbanization/ suburbanization, drainage modifications and flood control projects. How a particular change may have affected sediment delivery to the Laguna over time cannot be specified due to insufficient historic data and the impacts that legacy land use features have on past, present, and future hydrologic and sediment dynamics. The Operational Conceptual Models were developed for the short term and represent a snapshot view of the processes for the present and near future conditions.

In the long term and the very long term, the Laguna de Santa Rosa watershed is subject to numerous external natural forces that affect its evolution. Sea level rise, a function of climate change, will alter the base level condition for Russian River, which in turn will decrease the overall slope and associated conveyance characteristics of Laguna. Sea level rise creates significant increases in the accommodation space, or volume available to act as a sediment sink as sea level rises further above the current base level. At the opposite ends of the watershed, tectonic uplift raises the upper watershed, increasing slopes and probably sediment delivery. In the lower reaches of the watersheds, subsidence – both tectonically and anthropogenically-induced – may alter slopes and increase accommodation space as land levels drop relative to sea level. Hydrologic change, a function of both climate change and anthropogenic influence, will also be reflected in the morphology and sediment budgets of the Laguna watershed. There are considerable uncertainties about precise impacts of climate change on California hydrology and water resources. Kiparsky and Gleick (2005) reviewed existing literature on the impacts of climate change on water resources in California. The following discussion provides a brief summary of their review as specifically related to the impact of climate change on precipitation and runoff. Several recent regional modeling efforts conducted for the western United States indicate that overall precipitation will increase (Giorgi et al. 1998; Kim et al. 2002; Snyder et al. 2002). Studies conducted by Giorgi et al. and Kim et al. reported that precipitation increases will be centered in Northern California and in winter months. Variability of the hydrologic cycle also increases when mean precipitation increases, possibly accompanied by more intense local storm and changes in runoff patterns (Noda and Tokiaka, 1989; Hennessy et al. 1997). Large-scale general circulation studies produce various results on storm volumes, but increased storm intensity is consistently forecast (Carnell and Senior, 1998; Hayden, 1999; Lambert, 1995), along with a shift in runoff toward earlier in the season. Estimates of changes in runoff due to climate change have also been produced for California. Such estimates are based on anticipated, hypothetical, or historical changes in temperature and precipitation (Kiparsky and Gelick, 2005). In addition to prediction models, several studies investigated precipitation and runoff trends in the last century. Karl and Knight (1998), updated by Groisman et al. (2001) analyzed long-term precipitation trends in the United States and determined that precipitation over the contiguous US has increased by approximately 10 percent since 1910 (with most of the increase in the highest annual one-day precipitation event), that the intensity of precipitation has only increased for very heavy and extreme precipitation days, and that the proportion of total precipitation from heavy events has increased at the expense of moderate precipitation events. To the extent that all of these external forcing functions occur, thereby triggering adjustments in the landscape, they will produce gradual but important changes in the subwatersheds of the Laguna de Santa Rosa.

4.3.2 Operational conceptual models

The geographic scope of our Operational Conceptual Model is twofold: the Upper Laguna Watershed and the Lower Laguna Watershed. These different geomorphic domains in the system are characterized by different drivers, linkages, and outcomes based on the dominant anthropogenic influences and consequent geomorphic processes in each domain. The temporal scope of the models is "ahistorical" and represents a snapshot view of the current Laguna watershed.

The Lower Laguna Watershed consists of the main channel of Laguna and its floodplain, including the lower reaches of the tributary channels and floodplains. The Lower Laguna Watershed represents the depositional zone in the Laguna system where stream channels act as sediment sinks and where sediment transported from the Upper Laguna Watershed is stored for different periods of time along the channels or the Laguna floodplain. The Operational Conceptual Model of Anthropogenic Influences on Sediment Processes and Surface Water Hydrology in the Lower Laguna Watershed is illustrated in Figure 4-15.

The Upper Laguna Watershed consists of headwater zones of tributary channels to the Laguna and the main stem tributary channels and represents sediment production and transport zones. This domain is the source for sediment through hillslope processes but also serves as the transport link between headwater zones and the Lower Laguna. Once sediment is delivered to the channels in the Upper Laguna Watershed, it moves downstream to the Laguna with reduced channel and valley bottom storage due to channel modification activities in the lower parts of tributary systems. The Operational Conceptual Model of Anthropogenic Influences on Sediment Processes and Surface Water Hydrology in the Upper Laguna Watershed is illustrated in Figure 4-16.

We identified the key anthropogenic drivers, linkages, and outcomes in the Laguna ecosystem and the nature and direction of the cause-effect relationships. The cause-effect relationships are brief summaries of the anticipated effects that watershed and flow characteristics have on sediment loads. Our approach to develop conceptual models was to first identify outcomes that have been recognized as key management concerns and referred to in the proposal development. These outcomes were identified in the Lower Laguna Watershed since this zone is the key area of concern from hydrologic, water quality, and habitat standpoints. The key drivers that would have an impact on these outcomes were then identified. The cause and effect linkages between these two groups that were termed "intermediate outcomes" were explored and described subsequently. Although presented here as fragmented geomorphic units, the Upper and Lower Laguna Watersheds are coupled: outcomes from the former are drivers for the latter. Therefore, once the drivers and outcomes for the Lower Laguna Watershed were recognized, the outcomes for the Upper Laguna Watershed were consequently identified. The process of exploring the drivers and linkages for the Upper Laguna Watershed was then pursued.

Lower Laguna watershed operational conceptual model

The Lower Laguna Watershed conceptual model of anthropogenic influences on sediment processes and surface water hydrology (see Figure 4-15) is derived from the following outcomes that signify key management concerns: water quality issues, flood hazard issues, and *Ludwigia*. These outcomes have arisen as critical components related to hydrology and sediment processes that need to be addressed by the on-going and planned efforts such as comprehensive watershed plan, restoration planning and TMDL development. Our model's structure is based on the understanding that urbanization, agricultural development, oversized channels, inflow hydrology, and sediment inflow affect the hydrology and sedimentation characteristics in the Lower Laguna.

Urbanization and suburbanization (referred to as (sub)urbanization) have had significant impacts on the hydrologic and sediment transport processes in both the Upper and Lower Laguna Watersheds. (Sub)urbanization is accompanied by increases in impervious surfaces, which reduce the area of infiltration, surface storage, and connectedness of drainage channels. These in turn impact the pathways and the timing of runoff and change the relative proportions of overland flow and groundwater flow to the channels. The natural storage of water in the watershed is reduced. In addition, irrigation and other outdoor uses of water in a (sub)urban area increase summer low flows in a semi-arid watershed where irrigation volumes are significant compared to the pre-urbanization dry season flows. These hydrologic modifications result in increased runoff volumes and peak flow rates and reduced time lags. Increased runoff volumes and rates result in increases in fine sediment and coarse sediment supply rates, respectively (explained below).

Agricultural development, which predominantly involves hay fields and row crops in the Lower Laguna Watershed, is typically accompanied by drainage reconfiguration, homogenization of land surface, vegetation removal, irrigation, water diversions, or channelization of streams and swales. The hydrologic effects of these modifications are decreases in infiltration rates, depression storage, and evapotranspiration, which in turn result in increases in peak flow rates and flashiness of flows. Similar to the impacts of (sub)urbanization, irrigation and water diversion practices typically lead to increased low flow conditions in summer. Physical removal of riparian and in-channel vegetation coupled with drainage reconfiguration reduces the extent of bank vegetation, which subsequently increases the amount of fine and coarse sediment supply to the channels.

Increased summer low flows raise the shallow water table elevations through recharge along the bed and increase the outflow of shallow ground water to streamflow. In Mediterranean climates where the stream ecology has adapted to a season cycle of water supply (that is typically dry conditions in summer), increased summer low flows enhance the emergence and survival of in-channel vegetation. Changes in the shallow water table have created condition favorable to a number of non-native species including *Ludwigia* (explained in more detail in Section 6).

As the population increased in the Laguna watershed, the urban extent and agricultural development increased. Floods became more damaging as development increased and resulted in the first efforts for flood control. To make the alluvial fan more habitable and productive for farming, natural channels were replaced with larger, straighter channels better suited for flood conveyance. Channelized streams are designed to increase conveyance capacity and efficiency. Therefore, they typically are large, straight channels with steep gradients. In addition to hydrologic changes, channel modifications moved the focus of sediment deposition away from the alluvial fan surface that characterizes the lowest part of the Upper Laguna region, at the margin of the Santa Rosa Plain, and towards the Laguna. By eliminating out-of-bank flows and channel avulsions and by connecting distributary channels to the Laguna, the new drainage network has reduced sediment deposition on the fan and concentrated it in the channel network and in the Laguna. In addition, some of the modified channels have themselves become sources of sediment due to accelerated erosion. Straight, hydraulically effective channels with low width to depth ratios and little bank vegetation have in some cases suffered bank and bed erosion, contributing sediment into the Laguna. The combined effect of these processes has been to increase sediment generation and transport capacity to the Laguna, resulting in increased potential for deposition.

Inflow hydrology is separated into two distinct components that have different impacts on different sediment processes: runoff volume and peak flow rate. The effect of inflow hydrology on the hydrology of the Lower Laguna is explicit: the latter is proportional to the former. Hydrologic modification due to anthropogenic impacts typically implies increased runoff volumes and peaks. Increased runoff volumes result in increases in fine sediment supply. Fine sediment transport is typically supply-limited: the magnitude of transport is constrained by the availability of sediment to the stream and not by the transport capacity of the stream. Moreover, since fine sediment is easily mobilized and initiation of transport is not primarily dependant on flow competence (flow necessary to mobilize sediment), volumes are more relevant than flow rates to fine sediment transport. On the other hand, coarse sediment transport is typically transport-limited: the ability of flow to entrain and transport sediment controls the magnitude of coarse sediment transport. Therefore, increased peak flow rates result in increases in velocities and shear stresses, which in turn lead to increased coarse sediment transport.

Due to these anthropogenic changes in physical processes in the Laguna watershed that have resulted in increases in the amount of fine and coarse sediment supply and in-channel vegetation, the magnitude and the geographic extent of fine and coarse sediment deposition have increased. In-channel deposition and associated reduction in channel capacity in turn lead to increases in potential flood hazards that are of paramount concern to watershed managers and all stakeholders. Deposition in the Lower Laguna channels also impact habitat conditions for *Ludwigia*. We hypothesize that deposition would have a threshold effect on *Ludwigia*: favorable conditions as deposition increases until an optimum substrate and water level elevation is reached. Subsequent increases in deposition and associated bed levels would negatively affect *Ludwigia* habitat.

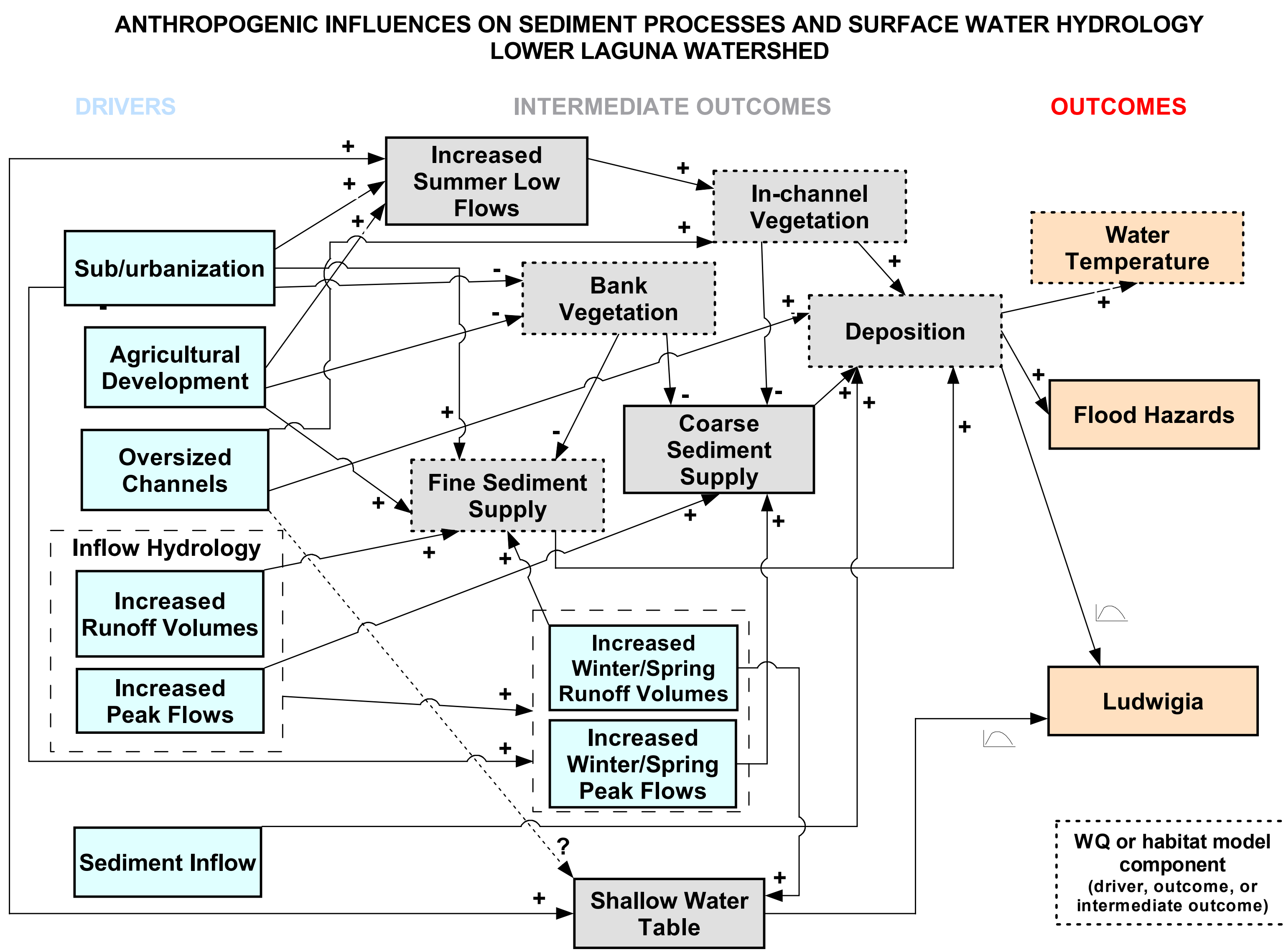


Figure 4-15
Anthropogenic influences on sediment processes and surface water hydrology in lower Laguna watershed

Upper Laguna watershed operational conceptual model

The Upper Laguna Watershed conceptual model of anthropogenic influences on sediment processes and surface water hydrology (see Figure 4-16) is coupled with the Lower Laguna model and controls the water and sediment inflow to the lower Laguna. Therefore, the outcomes from the Upper Laguna are outflow hydrology and sediment outflow.

We included physical watershed characteristics of the uplands as input to the Upper Laguna Model without articulating on their impacts on the drivers in this domain. Physical characteristics such as relief, precipitation, and geology inherent to the upland areas, where the main process is sediment production, have a direct impact on the Upper Laguna Watershed. These characteristics are not significantly modified due to anthropogenic impacts, and therefore are identified as upstream inputs.

Topography has a direct effect on hydrologic and sediment processes. Steeper slopes lead to faster delivery of runoff. Watersheds with a larger percentage of steeper slopes produce more sediment in transport-limited situations (Montgomery and Dietrich, 1994; Wohl et al., 1998). Steeper slopes initiate more frequent mass wasting events and contribute to the transport of loose particles on the hillslope and in the channel.

Precipitation is the main driver for all the hydrologic processes in any watershed. The magnitudes of all components of the hydrologic budget are directly proportional to precipitation. Sediment processes also depend on precipitation, which acts as a driver for natural erosion processes. Under otherwise equivalent conditions, higher rates of precipitation and higher precipitation variability result in higher rates of erosion from slopes, incision by streams into valley sides, and the transport of supplied sediment to the basin outlet (Hooke, 2000). Higher rainfall increases the likelihood of sediment-producing events, and therefore a higher sediment load. As a first approximation, mean annual precipitation is a measure of the differing amounts of rainfall throughout the Laguna watershed.

The effect of geology and soils on the hydrologic and sediment processes is evident. Impervious lithology and soils with low infiltration capacities would generate more runoff than permeable geology and soils that have higher infiltration capacities. Sediment yields from basins underlain by resistant rocks and compacted soils (such as clays) would be less than those underlain by weak rocks and loose, granular soils.

Similar to the Lower Laguna, the inflow hydrology, sediment inflow, (sub)urbanization, and agricultural development are identified as the main drivers in the Upper Laguna Watershed.

Hydrologic and sediment processes as drivers are directly proportional and linked to the outflow hydrology and sediment outflow as outcomes.

The hydrologic modification impacts of (sub)urbanization on winter/spring and summer flows are summarized in the preceding section. In addition, (sub)urbanization also lead to alteration of land cover and stream channels. Urban development brings about loss of tree cover and paving of land surface, resulting in the reduction of resistance to erosional forces and subsequent land degradation. (Sub)urbanization is typically accompanied by channelization, bank hardening, and drainage works. Straighter, larger channels are built to efficiently convey large floods. This results in elimination of overbank flows and channel avulsions and concentration of runoff in the stream channels, leading to in-channel and bank erosion. Sediment that would previously have traveled down dispersed distributary channels and been deposited on the alluvial fan surface is, with these changes, either con-

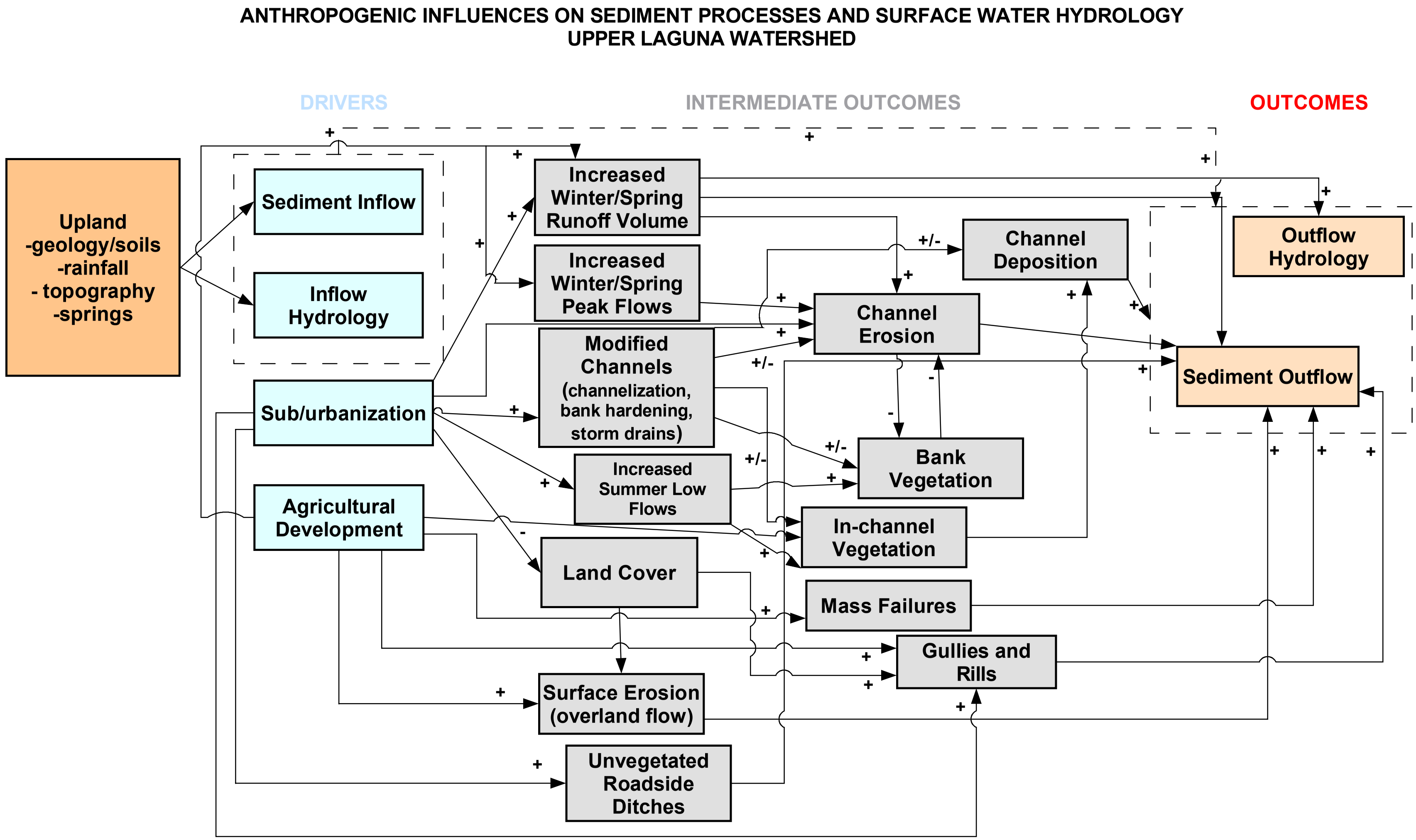


Figure 4-16
Anthropogenic influences on sediment processes and surface water hydrology in upper Laguna watershed

centrated in drainage channels or transmitted to the Laguna. When channels are oversized, they cannot efficiently carry their sediment load during low flows, resulting in sediment deposition after low flow events. To alleviate the impacts of hydrologic modification due to (sub)urbanization, channel bed or banks are typically hardened to reduce erosion. Urbanization also often involves putting entire channels, tributaries, or stream reaches into storm drains or box culverts. These systems are usually connected to impervious surfaces above ground that might supply negligible amounts of sediment, causing the downstream channel to become sediment-starved and prone to destabilization and erosion. (Sub)urbanization can also increase drainage density through the creation of road shoulders and ditches, making it easier for overland flow to reach stream channels in a short period of time. If such ditches are unvegetated, they are prone to erosion by clear overland flow, and thus contribute to increased sediment outflow from this geomorphic domain.

Vineyard and orchard development in the Upper Laguna Watershed have included direct physical impacts such as vegetation removal, tillage, compaction of land surface, and impacts on the hydrologic system such as drainage reconfiguration, water diversions, and irrigation. All of these processes either directly or indirectly affect the delivery of water to and interaction of ground water and surface water. The direct physical impacts of agriculture coupled with indirect impacts through hydrologic changes, result in increases in mass failures, and gullies and rills.

Intermediate outcomes of hydrologic and sediment processes in the Upper Laguna Watershed are increased channel erosion and altered depositional characteristics due to anthropogenic influences. These intermediate outcomes directly impact the outcomes from this domain: outflow hydrology and sediment outflow.

4.3.3 Budgetary conceptual models

The Budgetary Conceptual Models present the summary of information on the hydrologic and sediment budgets of the Laguna de Santa Rosa. A budget in this context is an accounting of the sources and disposition of water or sediment as it travels from its watershed of origin to its eventual exit from the Laguna. The hydrologic and sediment budget for the Laguna watershed is relatively incomplete due to the scarcity of data on flow and sediment.

We developed an annual hydrologic budget for the Laguna de Santa Rosa for Water Year 2005. Figure 4-17 presents a schematic illustrating hydrologic contributions from each subwatershed in the Laguna and annual runoff values for the period from October 2004 to September 2005. This period was chosen because 2005 annual flows are comparable to average conditions in this region. Annual runoff values for gaged subwatersheds were augmented by deriving runoff values from several ungaged subwatersheds using a network of monitored locations nearby. A list of USGS stations that were used to develop the hydrologic budget is presented below in Table 4-12.

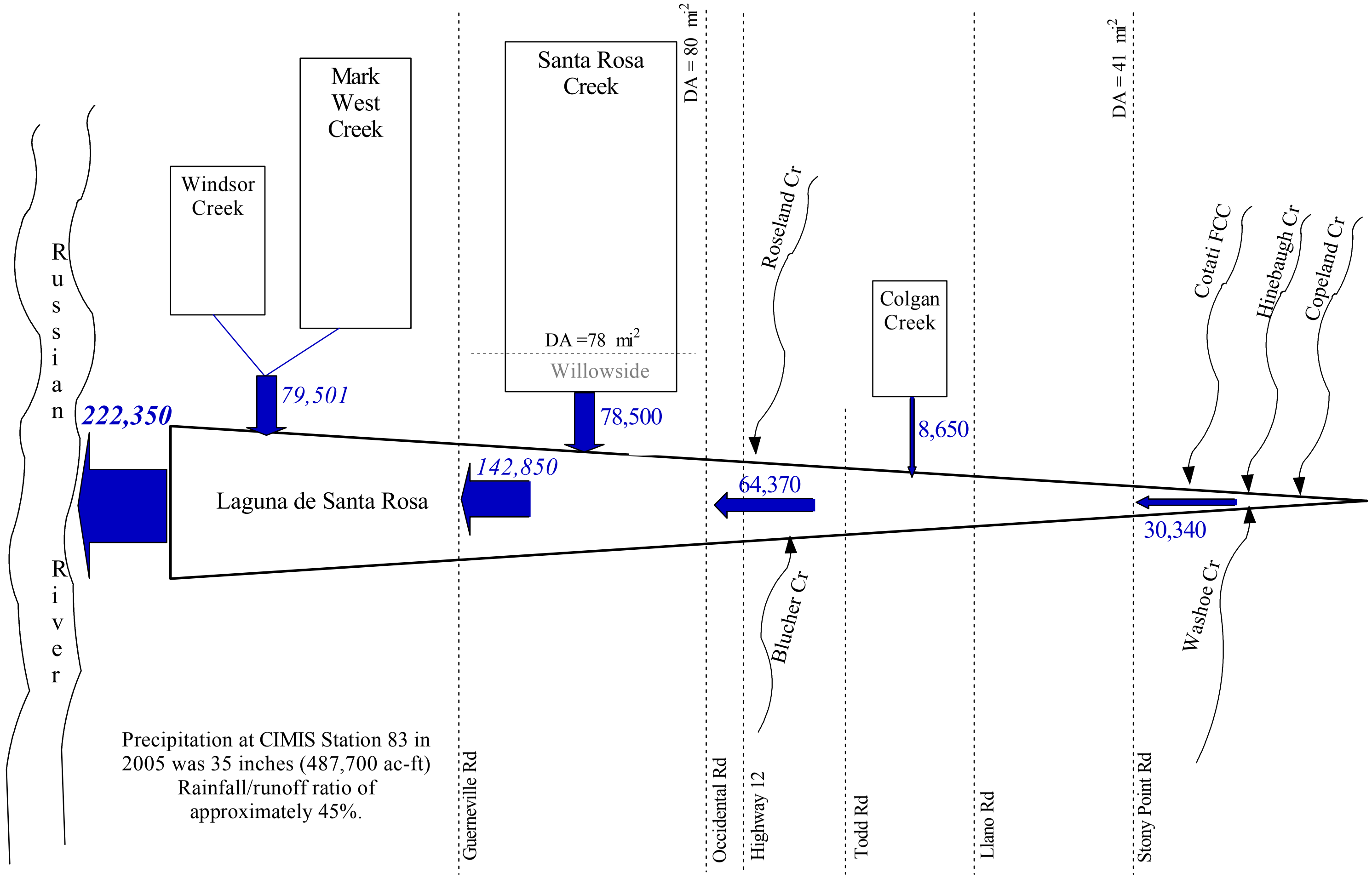
Table 4-12
Summary of USGS gauging stations in the Laguna de Santa Rosa watershed and vicinity

USGS Station Number	Station Number and Name	Record	Period of Record	WY 2005 Runoff (ac-ft)	Average Annual Runoff (ac-ft)
11465700	Colgan Creek near Sebastopol	Discharge	Nov 1998 to current year	8,640	6,780
11466200	Santa Rosa Creek At Santa Rosa	stage and discharge	Dec 1939 to Sep 1941 and Oct 2001 to May 2004 for discharge		
11466320	Santa Rosa Creek At Willowside Road near Santa Rosa	discharge	Dec 1998 to current year	78,480	69,170
11465750	Laguna De Santa Rosa near Sebastopol	discharge	Nov 1998 to current year	64,370	57,850
11465680	Laguna De Santa Rosa at Stony Point Road near Cotati	discharge	Nov 1998 to current year	30,340	23,210
11466500	Laguna De Santa Rosa near Graton	stage	Feb 1940 to Sep 1949, Oct 1964 to current year.		
11465500	Mark West Cr near Windsor	real time	?		
11466800	Mark West C near Mirabel Heights	real time	?		
11465200	Dry Creek near Geyserville	discharge	Oct 1959 to current year	196,900	211,000
11465350	Dry C Nr Mouth near Healdsburg	discharge	Oct 1981 to current year		
11467000	Russian River near Guerneville	discharge	Oct 1939 to current year	1,456,000	1,654,000
11464000	Russian River near Healdsburg	discharge	Oct 1939 to current year	969,900	1,035,000

The total precipitation in the Santa Rosa Plain based on the CIMIS station was approximately 35 inches for the year 2005. The CIMIS station precipitation totals do not represent precipitation conditions in the upland areas such as the Mayacamas Mountains, where the mean annual precipitation is expected to be much higher (see Figure 4-11). We assumed an annual precipitation total of approximately 488,000 ac-ft based on the CIMIS station record. This is an underestimate of the total precipitation amounts in the watershed. However, it is an adequate estimate to get a rough understanding of different components of the 2005 budget for surface water hydrology.

We also developed a sediment budget for the Laguna de Santa Rosa (Figure 4-18). The sediment budget summarizes average annual sediment delivery volumes to the Laguna based on the Pacific Southwest Interagency Committee method (PSIAC) that were described in our previous report on sediment sources, *Rate and Fate in the Laguna de Santa*

SURFACE HYDROLOGY BUDGET FOR LAGUNA DE SANTA ROSA FOR WATER YEAR 2005 (~AVERAGE YEAR)



Annual runoff for Water Year 2005 (in acre feet). *Runoff values in italic are calculated based on monitored locations nearby.*

Arrow size ~ Total Discharge

Rectangle area ~ Watershed area

Figure 4-17
Surface hydrology budget for Laguna de Santa Rosa for water year 2005
(~Average Year)

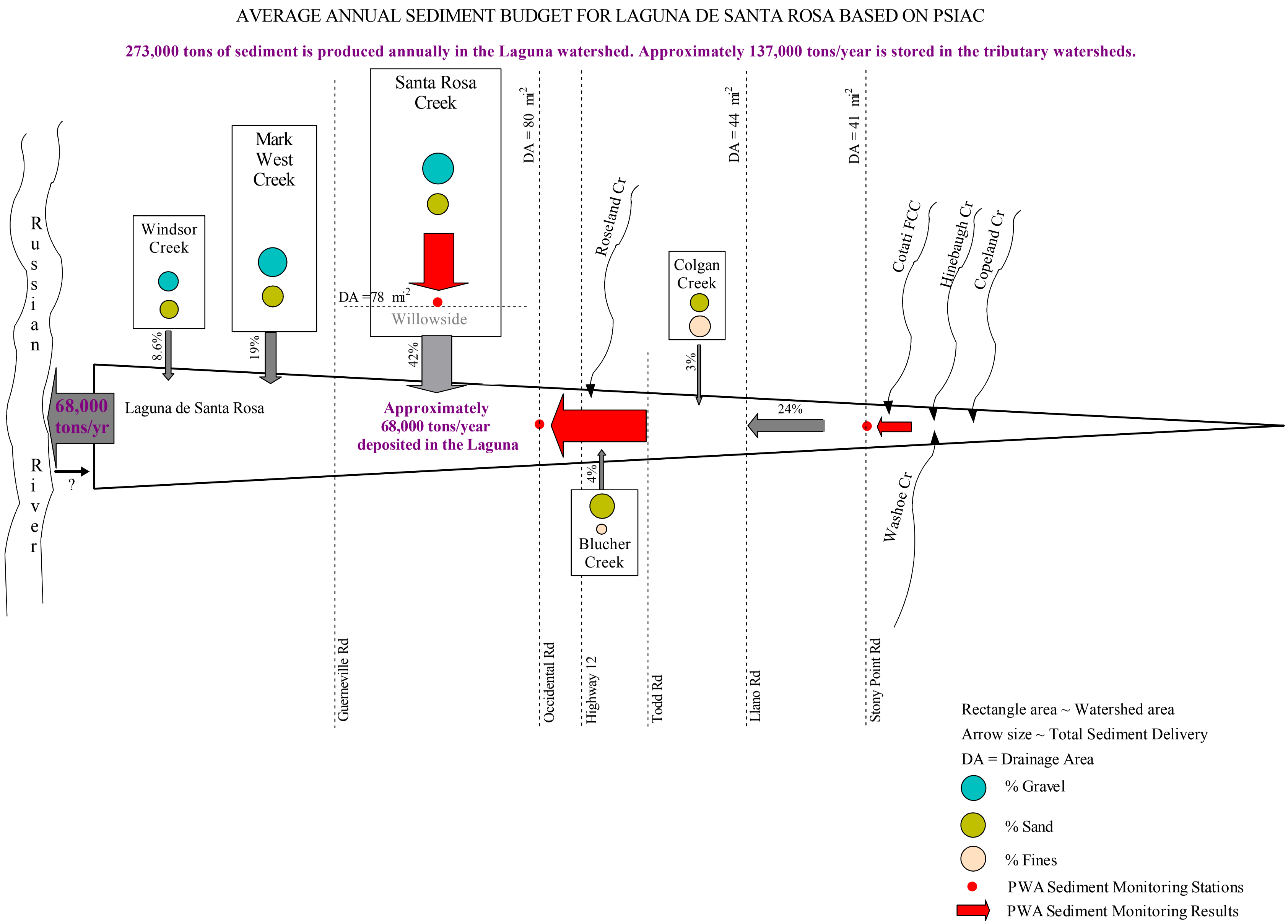


Figure 4-18 Average annual sediment budget for Laguna de Santa Rosa based on PSIAC

Rosa (PWA, 2004). PSIAC uses nine factors to determine the sediment yield classification for a watershed which then is assigned a range of sediment yield by class. These sediment yield estimates were based on qualitative rankings of physical characteristics for PSIAC and on USACE's draft hydrology analyses. The absolute amounts of sediment yield should be viewed as a rough estimate using the best available data and professional judgment. The relative contribution of sediment yield from each watershed, as predicted by PSIAC, would be expected to provide a relatively accurate understanding of the sediment budget of the Laguna.

In addition to empirical methods, PWA's sedimentation study (PWA, 2004) also used other lines of evidence to estimate sediment yield and deposition rates. These were comparison of historic and current floodplain cross sections along the Laguna, measured sediment deposition in Matanzas Reservoir, and discharge turbidity measurements for the 2002-2003 runoff season. The results of these analyses are presented in Table 4-13, as well as the results of analyses that have become available since that report was completed.

Table 4-13
Sediment yield estimates for the Laguna watershed and other watersheds nearby

Method	Annual Sediment Yield (in tons/mi2)	Total Annual Sediment Yield (in tons)
MUSLE	7,644	1,940,000
PSIAC	1,406	273,000
Turbidity Measurements (yielding SSC) at Santa Rosa Creek; Laguna at Occidental; and Laguna at Stony Point	1,250 4,850 840	96,993 385,297 34,241
Matanzas Reservoir sedimentation (1964-1982)	1,420 – 1,960	
Preliminary Matanzas Reservoir sedimentation (1988-2006) based on SCWA's planned dredging project	7,000	
Russian River Watershed	1,760	
Sonoma Creek Watershed	1,100	110,000

Perspective on sediment yield estimates

Table 4-13 illustrates the fact that estimates of sediment yield typically vary by orders of magnitude. This is especially true when the hydrologic conditions are above average, which was the case in 2006. Estimates of sediment yield for the same system made using different methods typically vary by up to an order of magnitude. Therefore, when estimates from several methods converge on a similar value, it is likely that these estimates are reliable. The PSIAC estimate for total sediment yield over the whole watershed is 153 ac-ft/yr or 272,916 tons/yr (using a specific weight of 90 lb/ft3). This corresponds to 0.8 ac-ft/sq-mi/yr or 1,400 tons/sq-mi/yr. These estimates have recently been supported by the results of the NASA AMES study, which indicated that the sediment yield results of their SWAT model are comparable to PWA's PSIAC analysis and are within 5 percent of our annual sediment loads (Chris Potter, pers. comm..). The PSIAC results are also close to the sediment yields measured for both the Matanzas Reservoir watershed (1,423 tons/sq-mi/yr) and the Russian River watershed (1,760 tons/sq-mi/y). In our previous study (2004), we concluded that MUSLE values were high, possibly due to high runoff peaks and volumes estimated by the USACE hydrology analyses.

An additional line of evidence supporting the use of the PSIAC estimate is the measured suspended sediment load from Santa Rosa Creek and the Laguna de Santa Rosa at Occidental Road during 2002-2003 season (a relatively average year in terms of rainfall and runoff). Our turbidity records for Santa Rosa Creek show a load of 96,993 tons, compared with a PSIAC estimated yield of 114,722 tons. The measured load missed the first large event of the season, but by comparing the Santa Rosa Creek and Laguna at Occidental Road loads we can assume that Santa Rosa Creek delivered approximately 40-50,000 tons of sediment during this storm, giving a total yield for the year of approximately 150,000 tons. The PSIAC estimate for the area of the Laguna upstream of Occidental Road is 221,949 tons/yr. For 2002-2003, measured suspended sediment load was 385,297 tons. It should be remembered that the rating curve for the Laguna de Santa Rosa at Occidental Road is considered 'poor,' while Santa Rosa Creek is considered 'fair'; discharge estimates were used in our computation of suspended load. For this reason, we attribute greater credibility to the estimate of measured suspended load from Santa Rosa Creek than the estimate for the Laguna at Occidental Road.

The two most recent studies on sediment yields in the Laguna watershed and the adjacent Sonoma watersheds corroborates our conclusion that the PSIAC estimates best represent sediment yields in the Laguna. The final report on the Sonoma Creek watershed yields (Trso, 2006) and the SWAT model results (on-going study by NASA/AMES) are within 20 and 5 percent of the PSIAC predicted yields, respectively.

On the basis of these multiple converging lines of evidence we believe we can tentatively accept the PSIAC figures as the best estimate for current sediment yield and infilling rate for the Laguna watershed, with the caveat that they probably represent a slight underestimation of sediment yield. Additional data to augment the record on suspended sediment delivery to the Laguna (such as continuous monitoring of turbidity data at the USGS gauges and monitoring or periodic sampling of sediment in other key tributaries) would further improve our understanding on sediment yields and trends in the watershed and would support future TMDL studies.

A recent newspaper article on the planned dredging of Matanzas Reservoir supported a substantially higher estimate of sediment deposition than previous periods, which are shown in Table 4-10. If this article is based on the actual sedimentation volume (as opposed to being in error or representing estimated excavated volume), further review of conditions during the sedimentation period and a potential update of our previous analysis and assumptions may be warranted.

4.3.4 Conceptual model of the groundwater hydrology within the Laguna de Santa Rosa watershed

This section broadly describes the role of groundwater hydrology within the Laguna de Santa Rosa watershed with respect to surface water hydrology and water supply. It is derived primarily from information contained within the 2005 Urban Water Management Plan published by the Sonoma County Water Agency (SCWA) in December 2006. A 5-year effort was initiated in December 2005 by the SCWA and the USGS to develop a refined conceptual model of the groundwater aquifer in the Santa Rosa Plain; this conceptual model will be used together with monitoring data to develop a numerical model (MODFLOW) of the groundwater hydrology of the basin.

The Laguna de Santa Rosa watershed overlays the majority of the groundwater basin identified as the Santa Rosa Valley Basin, including the component subbasins referenced as the Santa Rosa Plain, Rincon Valley, and Healdsburg Area. The Santa Rosa Plain is the largest subbasin in the County and in the Laguna watershed, and underlies its most populated areas as well as the Laguna itself. The Santa Rosa Plain Subbasin drains northwest toward the Russian River. To the south lies the Petaluma Valley Groundwater Basin; south of Rohnert Park, this basin drains to the southeast, towards San Francisco Bay.

For the Santa Rosa Plain Subbasin, average annual natural recharge from 1960 to 1975 was estimated to be 29,300 ac-ft (DWR, 2003). Natural recharge occurs east of Santa Rosa, primarily along stream beds, at the heads of alluvial fan areas, and in some parts of the Sonoma Volcanics. Recharge areas in the subbasin were evaluated and reported by DWR in 1982; these are shown in Figure 4-19. As part of the five-year study presently underway by the USGS, the location of significant recharge areas in the subbasin are again being evaluated; the results of this effort are anticipated to be available in 2010 or 2011 (Tracy Nishikawa, USGS, pers. com.).

General water level contour trends in the Santa Rosa Plain groundwater subbasin as reported in the last report published by DWR (1982) are generally declining to the west, following the land slope to the Laguna de Santa Rosa channel. A review of spring 2006 data from DWR (CDEC, 2007) shows that the typical depth of groundwater below the ground surface in the Santa Rosa Plain is approximately 25 feet, with a range of approximately 0-86 feet below ground surface. A 1982 California Department of Water Resources (DWR) study concluded that groundwater levels in the northeast part of the Santa Rosa Plain Subbasin had increased, while groundwater levels in the south had decreased (DWR, 1982). Groundwater storage capacity in the Santa Rosa Plain is estimated by the USGS to be 948,000 ac-ft (Cardwell, 1958, cited in DWR, 1982).

The following description of the geology of the Santa Rosa Plain is excerpted from the SCWA 2005 Urban Water Management Plan (SCWA 2006).

The geology of the Santa Rosa Plain Subbasin is complex and the stratigraphic relationships are the subject of recent and continuing studies, including mapping by the USGS and others (USGS, 2002). The subbasin is cut by many northwest-trending faults that influence groundwater flow. Most of the groundwater is unconfined, but in some locations can be confined where folding and faulting exists (DWR, 2003). The water-bearing deposits underlying the basin include the Wilson Grove Formation, the Glen Ellen Formation, and a younger and older alluvium (DWR, 2003). The Wilson Grove Formation is the major water-bearing unit in the western part of the basin and ranges in thickness from 300 feet to

1,500 feet (Winzler and Kelly, 2005; DWR, 2003). Deposited during the Pliocene, it is a marine deposit of fine sand and sandstone with thin interbeds of clay, silty-clay and some lenses of gravel. Interbedded and interfingered with the Wilson Grove Formation are Sonoma Volcanic sediments in the eastern basin separating the water-bearing units. Aquifer continuity and water quality are generally good according to Cardwell, 1958, which is still the most detailed reference on the hydrogeology.

The Glen Ellen Formation overlies the Wilson Grove Formation in most places and is Pliocene to Pleistocene in age (DWR, 2003). At some locations, the two formations are continuous and form the principal water-bearing deposits in the basin (Cardwell, 1958). The Glen Ellen consists of partially cemented beds and lenses of poorly sorted gravel, sand, silt, and clay that vary widely in thickness and extent (Cardwell, 1958; DWR, 1982). The formation is used for domestic supply and some irrigation (DWR, 2003). The Pliocene Petaluma Formation is exposed at various localities in Sonoma County, from Sears Point northward nearly to Santa Rosa. The formation consists of folded continental and brackish water deposits of clay, shale, sandstone, with lesser amounts of conglomerate and nodular limestone and occasional thick beds of diatomite are present. The Petaluma Formation has been defined as being contemporaneous in part and interfingering with the Merced Formation. The Petaluma Formation is noted for its low well yields.

Quaternary deposits include stream-deposited alluvium, alluvial fan deposits, and basin deposits (Todd Engineering, 2004). The younger alluvium (Late Pleistocene to Holocene age) overlies the older alluvium (Late Pleistocene age). The alluvium deposits consist of poorly sorted sand and gravel and moderately sorted silt, fine sand, and clay. The upper and mid-portion of the alluvial fan deposits are on the eastern side of the Santa Rosa Plain and are permeable and provide recharge to the basin. The basin deposits overlie the alluvial fan materials and have a lower permeability (Todd Engineering, 2004; Cardwell, 1958).

Vertical connections from the ground surface and shallow groundwater aquifer to intermediate and deeper groundwater aquifers vary significantly across the subbasin due to geologic variability. The 1982 DWR report on groundwater conditions in the Santa Rosa Plain indicated that water quality testing of surface and groundwaters suggested the presence of vertical connectivity in the vicinity of the confluence of Santa Rosa Creek and the Laguna de Santa Rosa. There was little suggestion of vertical connectivity in other locations within the subbasin from similar testing.

Groundwater extraction in the Santa Rosa Plain subbasin occurs at wells with depths ranging from shallow (less than 100 feet below ground surface) to deep (more than 400 feet below ground surface). Wells are owned and operated by both private and public entities, and serve such varied uses as individual residences, agricultural operations, and municipal water supplies. Average annual pumping during the period 1960 to 1975 has been estimated at 29,700 ac-ft. Well yields range from 100 to 1,500 gallons per minute (DWR, 1975).

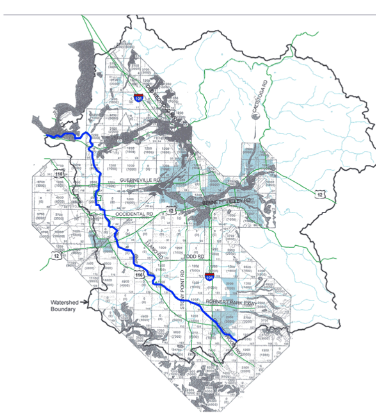


Figure 4-19
Available storage capacity and areas of natural recharge
(see full-sized inset)

In recent years, the SCWA has obtained 3 to 9 percent of its annual supply from wells it operates near Sebastopol within the Santa Rosa Plain Subbasin. Future extractions by the SCWA are anticipated to represent just under 4,000 acre-feet annually, presently representing about 5% of its total water supply. Other SCWA contractors, such as the Cities of Rohnert Park, Santa Rosa, and Cotati also pump water from the subbasin. Including the North Marin Water District, which draws on supplies outside of the subbasin, total groundwater and local surface water supplies (including recycled water) provided by these contractors are presently close to 7,500 acre-feet per year and projected to rise to nearly 10,000 acre-feet in 2015 before declining to a projected rate of less than 3,000 acre-feet annually by 2030 (SCWA 2006).

As described in the 2005 Urban Water Management Plan (SCWA 2006), recent investigations of groundwater elevations have reached different conclusions as to whether groundwater levels are generally increasing or decreasing over time. Increasing demand for groundwater led to declining groundwater levels at least until the importation of additional surface water began in about 1990. However, numerical modeling simulations completed as part of one study found that storage would continue to decline under current conditions; other studies indicated an expected increase in groundwater storage that is more consistent with the stable to slightly increasing groundwater level trends observed in area wells.

In 1958, USGS analysis of water levels in creeks in the Santa Rosa Plain were generally lower than levels in nearby wells, suggesting the groundwater was flowing to the creeks. But as of 1982, DWR reported that insufficient recent data was available to allow a similar comparison (DWR 1982). The USGS study currently underway will help to establish the nature of stream-aquifer interaction that exists and will exist under various management scenarios.

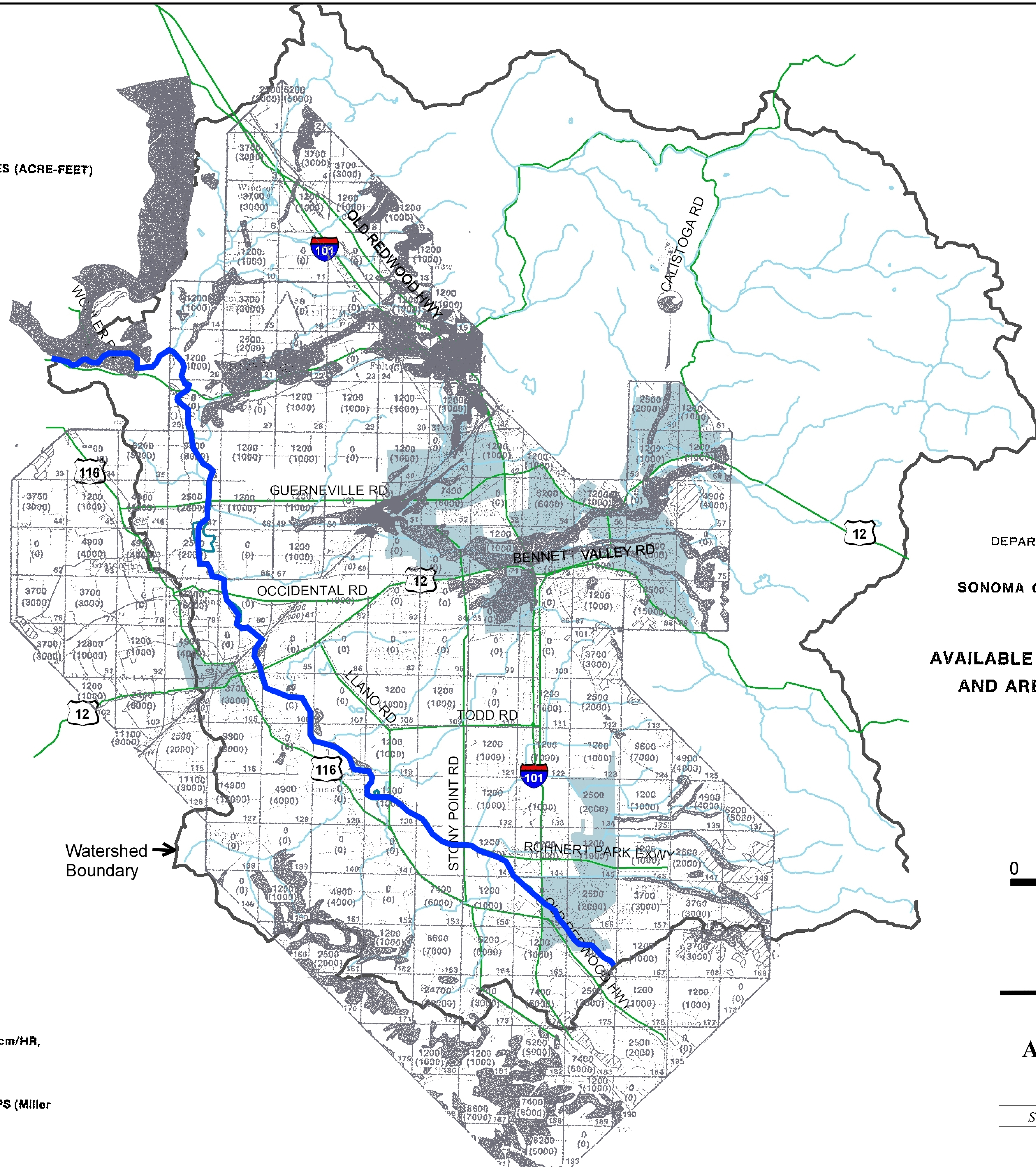
EXPLANATION

AVAILABLE STORAGE CAPACITY - SPRING 1980

1200 (1000) — AVAILABLE STORAGE CAPACITY IN CUBIC DEKAMETRES (ACRE-FEET)

19 — CELL NUMBER

AVAILABLE STORAGE CAPACITY NOT CALCULATED IF 1) NONWATER-YIELDING FRANCISCAN COMPLEX 2) COMPOSED OF SONOMA VOLCANICS WITH HIGHLY VARIABLE WATER-YIELDING CHARACTERISTICS.



NATURAL RECHARGE AREAS

- RECHARGE AREA (SOIL INFILTRATION RATE GREATER THAN 1.5 cm/HR, SLOPE LESS THAN 15%)
- POTENTIAL RECHARGE AREA (IF SLOPE DOES NOT EXCEED 15%)
- SLOW RECHARGE AREA (SOIL INFILTRATION RATE LESS THAN 1.5 cm/HR, OR SLOPE GREATER THAN 15%)

RECHARGE AREAS DETERMINED USING U.S. SOIL CONSERVATION SURVEY MAPS (Miller 1972), AFTER Muir AND Johnson (1979)

STATE OF CALIFORNIA
THE RESOURCES AGENCY
DEPARTMENT OF WATER RESOURCES
CENTRAL DISTRICT

SONOMA COUNTY GROUND WATER STUDY
SANTA ROSA PLAIN

AVAILABLE STORAGE CAPACITY PER CELL AND AREAS OF NATURAL RECHARGE

N

0 — 5 MILES

figure 2-18

Laguna de Santa Rosa

Available Storage Capacity and Areas of Natural Recharge

Source: California Department of Water Resources, 1982

PWA

Water Quality 5

5.1 Overview of water quality conceptual models

The purpose of the water quality conceptual model is to identify the probable linkages between key stressors (e.g., nutrients) and impacts on selected outcomes (e.g., support of Beneficial Uses). Conceptual models are used in other portions of this report to describe specific processes that are occurring in the Laguna. The water quality overview conceptual model (Figure 5-1) is an overarching illustration that incorporates most key water quality components and linkages to other ecosystem elements (e.g., hydrology and terrestrial ecosystem). The water quality overview conceptual model can also be used to identify key linkages within the Laguna that would be simulated using a dynamic model to support development of management strategies to protect and restore the Laguna.

In general we organized the conceptual model 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) that is linked to changes in the descending categories for physical habitat and water chemistry changes. The changes could potentially impact the integrity of biological community and other use categories. The Beneficial Uses assigned to the LSR represent a broad spectrum of ecosystem attributes that are included in the mission of Laguna Foundation to maintain, protect and restore the Laguna.

This initial conceptual model is not a complete representation but it will identify key linkages among processes that might be measured to evaluate trends within the Laguna which affect the goal of ecosystem restoration. The purpose of this model is not to describe the internal dynamics of the Laguna, rather it is to describe the linkages between those components in a generalized form. With this approach, we can identify those primary processes and linkages that require further investigation and will need to be represented more completely in any future modeling effort. Improving management of primary stressors and selective risk cofactors can improve conditions in key response categories and thus lead to restoration of the beneficial uses.

Nutrients and organic matter were identified as the primary external stressors for this conceptual model due to high concentrations and external loadings of nitrogen, phosphorus, and organic matter to the Laguna ecosystem as discussed below in Section 5.2 and as identified in previous studies (Smith, 1990; Otis, 2006). Risk cofactors (such as channel modification) are also stressors that in combination with nutrients can result in degraded conditions for the impact of assessment variables. The impact assessment variables that have been identified for the conceptual model are most of the beneficial uses listed in the North

Coast Regional Water Quality Control Board Basin Plan and represent most elements of the comprehensive Laguna ecosystem. Not all known processes and linkages have been included in the conceptual model illustration. Rather, those linkages that are believed at this time to most profoundly impact beneficial uses are included.

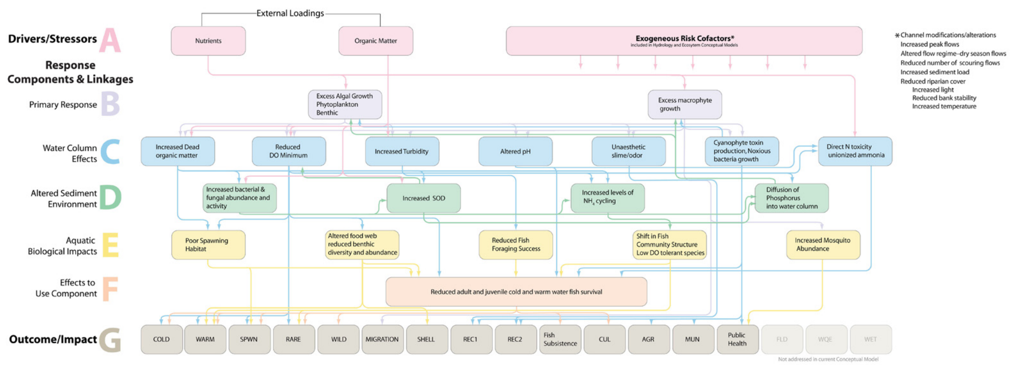


Figure 5-1 Water quality overview conceptual model
(see full-sized inset)

5.2 Data analysis

This section presents the results of the initial analysis of existing water quality data obtained from several sources. This analysis was conducted to provide information for the response to management questions and to further refine the conceptual model. This section consolidates analysis and information from several technical reports and studies.

5.2.1 Sources and loadings of nutrients and BOD

Historical accounts describe the Laguna as a productive low gradient system that included a mosaic of open channels, wetlands, and lake like features. Nutrient and BOD loadings associated with increased development within the watershed were important contributing factors to low dissolved oxygen conditions. The purpose of this section is to better characterize the relative magnitude of various source loading categories, and the timing of those loadings. The results have been incorporated into the overview water quality conceptual model and a series of other illustrations included below to begin the process of assigning priorities for managing nutrient and BOD loadings to the Laguna.

Potential pollutant sources and loadings

Various point and non-point sources exist within the Laguna watershed. They contribute excess nutrients and BOD loads that in combination with other factors contribute to water quality and ecosystem impacts (Figure 5-2). The categories that were used in this initial analysis to develop an improved understanding of the location, relative magnitude, timing, and potential impact on Laguna water quality are provided below.

- *Municipal wastewater discharge* – is a point source that contributes to loadings of nitrogen, phosphorus and BOD during winter discharge period;

- *Stormwater runoff from urban area* - carries pollutants such as sediments, nitrogen, phosphorus and BOD that build up on impervious areas and lawns and are transported to the Laguna during storm events;
- *Runoff and erosion from agricultural areas* – carries excess sediments, nutrients and BOD from agricultural lands that receive fertilization, manure application and irrigation using reclaimed water;
- *Atmospheric deposition* – (particularly nitrogen deposition as a result of automobile uses and agricultural activities) can increase the background nitrogen levels;
- *Groundwater input* –is a potential source during summer dry season and can be influenced by the application of fertilizer, manure and reclaimed water on agricultural lands and recharge from septics;
- *Septic effluents* - can contribute to nutrient and BOD loadings;
- *Internal nutrient cycling and sediment fluxes* – as a result of releases of nutrients from sediments and rapid turnover in the biological cycle can be potential sources; and
- *Dry weather storm drain flows* –capture runoff from incidental urban water uses (e.g., car washing, lawn watering, etc.) that also delivers sediment, nutrients, and BOD but perhaps more importantly extends wet season conditions within stream channels that were formerly dry during the summer season.

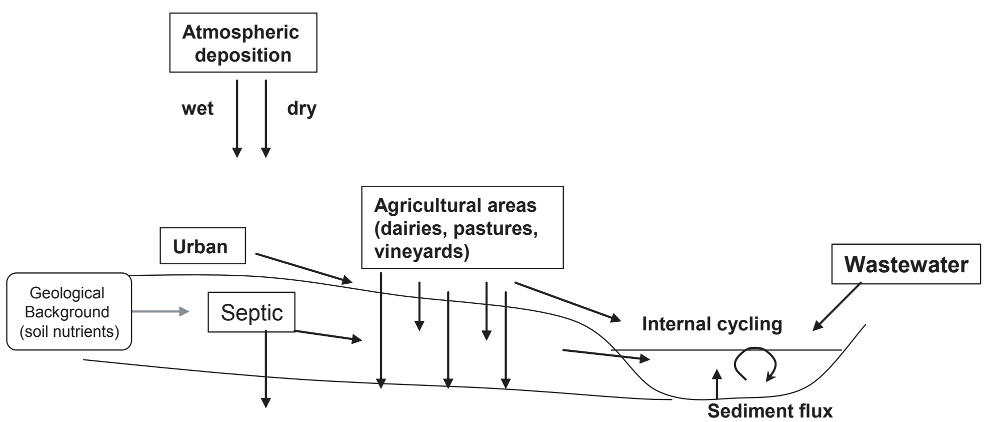


Figure 5-2 Potential point and non-point sources of nutrients/BOD in the Laguna watershed

Municipal wastewater discharges

Within the watershed, the Laguna Treatment Plant is the major source of municipal wastewater discharges. The plant is allowed to discharge in winter months only and the discharge volume in 2006 is around 2,127 million gallons to the river (http://cisanta-rosa.ca.cs). The discharge has nitrate concentrations of 8-10 mg/l, phosphorus concentrations 1.5-2.5 mg/l and BOD of 2-5 mg/l (Table 5-1).

Daily flow data and weekly concentrations are available at http://ci.santa-rosa.ca.us. Loadings from the plant were estimated by multiplying monthly total discharge volume and monthly average concentrations of the constituents. Discharge from May 15 through

September 30 is prohibited and generally occurs in January through March. The estimated average loadings for 2004-2006 are around 121,000 lbs/yr for nitrogen, 22,000 lbs/yr for phosphorus and 32,000 lbs/yr for BOD (Table 5-2). Calculated discharge volume and loadings for 2002 and 2003 (before off-watershed Geyser disposal project) are also included for comparison.

Table 5-1
Discharged effluent characteristics

Based on self monitoring report data for 2006 and 2007 available at http//ci.santa-rosa.ca.cs

Parameter	Value
Ammonia (mg N/L)	<0.2-0.5
Unionized Ammonia (mg N/L)	<0.1
Nitrate (mg N/L)	8.0-10.0
Organic Nitrogen (mg N/L)	<0.2-1.9
Phosphorus (mg P/L)	1.5-2.5
Chlorine	<0.1
BOD (mg/L)	<2.0-5.0
Dissolved Oxygen (mg/L)	8.7-13.6
pH	7.2-8.1
+Turbidity (NTU)	2.3-17.0
Conductivity (umhos/cm)	447-589
Temperature (F)	58-70
Non Filterable Residue (mg/L)	3.8-42.0

Table 5-2
Volume of treated wastewater discharged to the Laguna and the estimated pollutant loadings

Water Year	Volume (million gallon)	Ammonia (lbs N/yr*)	Nitrate (lbs N/yr)	Organic Nitrogen (lbs N/yr)	Phosphorus (lbs P/yr)	BOD (lbs/yr)
2006	2,122	6,490	141,500	18,062	24,581	48,563
2005	899	4,670	62,879	5,930	17,275	16,493
2004	1,522	5,528	109,895	8,916	23,660	31,958
Average	1,515	5,563	104,758	10,969	21,839	32,338
2003	4,091	16,647	288,930	38,743	61,305	94,672
2002	3,693	12,168	258,388	32,528	68,214	107,645

* Although the load is expressed on an annual basis, the discharge occurs only for a few months in winter.

Urban stormwater runoff

The main urban areas in the Laguna watershed include the cities of Santa Rosa, Sebastopol, Cotati, Rohnert Park, and Windsor. Storm event sampling by the City of Santa Rosa at Santa Rosa Creek indicated generally higher nutrients, fecal coliform, and total suspended sediment (TSS) concentrations downstream of the urban area compared to upstream sampling locations (Tables 5-3 and 5-4). For the sampling period of 1997-2006, two to four storm events were sampled each year, including some first flush events (Figure 5-3). A large portion of the nitrogen is in the organic form.

Table 5-3
Range of nutrients, BOD, TSS and bacteria concentrations at Site C1
(downstream of the City of Santa Rosa) for storm events sampled during 1998-2006

Parameter	Median	Average	Minimum	Maximum
Ammonia (mg N/L)	0.38	0.36	<0.20	0.68
Nitrate (mg N/L)	0.41	0.49	0.03	2.10
Nitrite (mg N/L)	0.2	0.2	<0.2	0.2
TKN, Total Kjeldahl Nitrogen (mg N/L)	1.35	1.91	0.28	5.40
Total Nitrogen (mg N/L)	2.3	2.3	0.44	5.0
Dissolved Phosphorus (mg P/L)	0.008	0.185	<0.002	1.00
Total Phosphorus (mg P/L)	0.114	0.251	<0.01	1.20
BOD (mg/L)	5.2	6.9	<5.0	15.0
TSS (mg/L)	70	84	<4	370
Fecal Coli. (mpn /100ml)	20000	555224	>1600	5000000
Fecal Strep (mpn /100ml)	25000	118680	920	1300000

Table 5-4
Range of nutrients, BOD, TSS and bacteria concentrations at Site C2
(upstream of the City of Santa Rosa) for storm events sampled during 1998-2006

Parameter	Median	Average	Minimum	Maximum
Ammonia (mg N/L)	0.20	0.23	<0.20	0.33
Nitrate (mg N/L)	0.24	0.60	<0.20	5.00
Nitrite (mg N/L)	0.2	0.2	<0.2	0.2
TKN (mg N/L)	0.77	1.19	0.21	4.60
Total Nitrogen (mg N/L)	0.59	0.69	<0.50	1.20
Dissolved Phosphorus (mg P/L)	-	-	0.2	0.2
Total Phosphorus (mg P/L)	-	-	0.11	0.25
BOD (mg/L)	6.5	7.4	<5.0	12.0
TSS (mg/L)	11	79	1.0	1500
Fecal Coli. (mpn /100ml)	17000	144416	170	2400000
Fecal Strep (mpn /100ml)	3000	99781	13	1800000

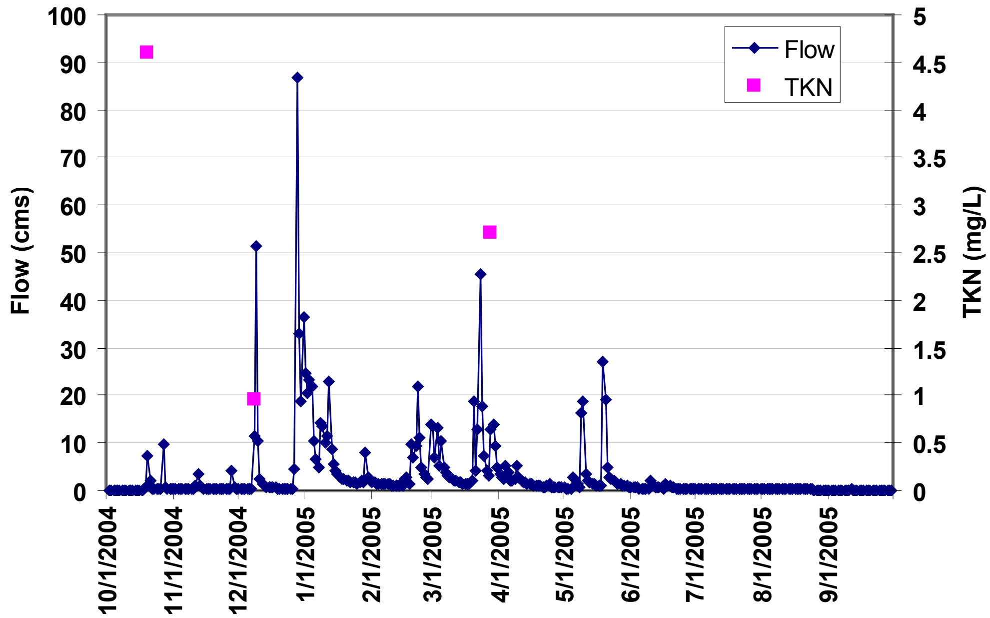


Figure 5-3 Flow at Santa Rosa Creek at Willowside Road with TKN concentrations Sampled during storm events of 2005

To calculate pollutant loadings from urban stormwater runoff, flow monitoring data at Santa Rosa Creek at Willowside Road (USGS 11466320) was used. Based on the flow record, we assumed storm event runoff to be greater than 75 cfs, which results in an average of 92 days each water year with flow greater than this criterion (C. Ferguson, personal communication). Records from the City of Santa Rosa's weather station at 69 Stony Circle average 82 days a year with rain > 0.01 inches. Therefore the assumption of 75 cfs flow should be reasonable. Pollutant loadings were estimated as runoff multiplied by the observed median storm event concentrations downstream of the City of Santa Rosa, subtracted by loadings from upstream rural area (C2 watershed and Matanzas Creek). Loadings from upstream were calculated by multiplying flow and medium concentrations observed at C2. Flow from Santa Rosa Creek above C2 was assumed to be proportional to watershed area. Based on the limited flow data from Matanzas Creek (USGS 11466170), flow at Matanzas Creek is about 24% of the flow at Santa Rosa Creek at Willowside. Concentrations from Matanzas Creek were assumed to be the same as the C2 site (both forested areas). Estimated pollutant loadings show large variations across the years due to amount of runoff (Table 5-5). Total urban areas in the watershed are 49 square miles. Loadings from all urban areas can be calculated by scaling the loadings in Table 5-5 to the total urban areas. Some of the loadings from urban areas are originally from atmospheric deposition. Loadings reported in Table 5-5 will include contribution from the atmospheric deposition. Atmospheric deposition to urban areas was estimated and included in Table 5-9 for comparison.

Table 5-5a
Estimated urban storm runoff and pollutant loadings of Santa Rosa Creek at Willowside Road downstream of the City of Santa Rosa

Water Year	Volume (million gallons)	Ammonia (lbs N/yr)	Nitrate (lbs N/yr)	TKN (lbs N/yr)	TN (lbs N/yr)	Total Phosphorus (lbs P/yr)	BOD (lbs/yr)
2004	10,442	44,918	46,644	155,668	314,163	17,341	367,438
2005	12,466	53,624	55,685	185,842	375,059	20,702	438,660
2006	23,687	101,893	105,810	353,126	712,665	39,336	833,516
Average	15,532	66,812	69,380	231,546	467,295	25,793	546,538

Table 5-5b
Loadings normalized to area[1,2]

Water Year	Volume (million gallons)	Ammonia (lbs N/acre/ yr)	Nitrate (lbs N/acre/ yr)	TKN (lbs N/acre/ yr)	TN (lbs N/acre/ yr)	Total Phosphorus (lbs P/acre/ yr)	BOD (lbs/acre/ yr)
2004	10,442	1.72	1.79	5.98	12.06	0.67	14.11
2005	12,466	2.06	2.14	7.13	14.40	0.79	16.84
2006	23,687	3.91	4.06	13.56	27.36	1.51	32.00
Average	15,532	2.56	2.66	8.89	17.94	0.99	20.98

1. Calculated based on urban areas of 40.7 square miles.

2. http://www.epa.gov/waterscience/ftp/basins/training/b4lec15.pdf

Frink's export coefficients (lb/ac/yr)

	TN	TP
Urban	12.0±2.3	1.5±0.20

CTWM loading rates (lb/ac/yr)

	TN	TP
Urban-pervious	8.5 (5.6-15.7)	0.26 (0.20-0.41)
Urban –impervious	4.9 (3.7-6.6)	0.32 (0.18-0.36)

Agricultural storm runoff

The main agriculture land uses in Laguna include vineyards, pastures, and dairies. Dairies can be sources of nutrients and BOD to streams since dairies contain many loading units such as waste management areas where elevated nutrients and organic matter were found (Lewis et al. 2005; Meyer et al. 1997). Application of manure and slurry to pastures has the potential of increasing nutrients in runoff if excess nutrients beyond crop demand are applied (Bellows, 2001). Many of the dairies are located near streams, and therefore poor management can result in loadings to streams. As summarized in Decker (2007), vineyards and pastures that receive fertilization can be potential sources of nutrients due to over-fertilization or asynchrony with crop demands. Long-term fertilization can also result in accumulation of nutrients in the soils and therefore results in elevated nutrient concentrations in runoff.

Table 5-6
Agricultural types in the Laguna watershed
Determined from GIS layers provided by J. Honton

Agricultural type	Acres
Vineyard	5536
Pasture	3955
Dairy	2815
Beef Cattle	468
Corn	287
Orchard	278
Truck (small row crop production)	263

A typical dairy in California contains flushed freestalls in open barns (Meyer et al. 1997). Manure in freestall is flushed and liquid manure is stored in holding ponds. Solid and liquid manure is usually used to fertilize and irrigate crops or pasture lands nearby. Liquid manure is used for irrigation, spread as slurry or transported off the farm. Solid manure is spread on farm land, used for bedding, composted or transported off the farm.

Potential nitrogen loadings from 31 dairies during winter storms were estimated earlier by CH2M Hill and Merritt Smith Consulting (1994). In that study, dairy survey data were used to rank the management practices as poor, fair or good. Over half of the dairies surveyed were ranked to have poor practices. Manure and nitrogen production were calculated based on numbers of animals and typical manure and nitrogen production rates per body weight of animal. The loss of the produced manure nitrogen to streams was estimated based on management practices and excess nitrogen beyond requirements of irrigated crops. The estimated total nitrogen and organic matter (OM) loadings from dairies in winter storms was 179,000 lbs N/yr and 6,050,000 lbs/yr OM. With the waste reduction strategy, the management practices have been significantly altered and improved, although load estimates have not been updated so the beneficial effect is unquantified.

Without detailed information on current dairy operations and animal population, we estimated nutrient and BOD loadings based on a dairy runoff study conducted in Tomales Bay watershed (Lewis et al. 2005). In that study, fecal coliform and nutrient concentrations and flow were measured for different dairy loading units and upstream and downstream of dairies and were used to estimate instantaneous and storm loadings from dairies and the adjacent pastures. We attempted to extrapolate the results to Laguna watershed by taking the estimated nutrient loadings per storm (Table 5-7) and multiplied by typical numbers of storms and total areas of dairies in the Laguna watershed. Dairies in Tomales Bay watershed are just beginning to implement improved waste reduction and management practices that were established in the Laguna as a result of the waste reduction strategy. Therefore the Tomales Bay estimates are likely to have a higher per capita loading rate. It is also assumed that dairies in the Tomales Bay watershed produce more runoff due to steeper slopes and possible higher rainfall. Therefore the extrapolation developed for this analysis represents an upper bound of actual loadings to the Laguna from Laguna watershed dairies. On average, there are 21 runoff events per year with an average 1.25 inch rainfall per event (CH2M Hill and Merritt Smith Consulting, 1994). The estimated mean loadings from dairies and pastures during storms are presented in Table 5-8.

Table 5-7
Mean storm loads for nutrients
(Lewis et al. 2001)

Loading Unit	Ammonium (kg/acre/storm)	Nitrate (kg/acre/storm)	Total Nitrogen (kg/acre/storm)	Phosphate (kg/acre/storm)
Pasture	0.004 (0.001)	0.005 (0.001)	0.047 (0.031)	0.003 (0.001)
Downstream of dairies	0.286 (0.158)	0.006 (0.001)	0.513 (0.275)	0.011 (0.005)

Table 5-8
Estimated loadings of nutrients and BOD loadings from pasture and dairies

Loading Unit	Ammonium (lbs/yr)	Nitrate (lbs/yr)	Total Nitrogen (lbs/yr)	Phosphate (lbs/yr)	BOD (lbs/yr)
Pasture	732	916	8606	549	24,097
Downstream of dairies	37,273	782	66857	1434	187,201

Erosion from agricultural lands increases transport of pollutants associated with sediments, particularly for phosphorus. Here loadings of particulate phosphorus are not yet quantified. Information on vineyard fertilization or runoff quality is not available at this point and therefore we have not attempted to derive loadings for vineyards. Locations of these vineyards are mostly downstream of Santa Rosa Creek.

Atmospheric deposition

Atmospheric deposition can be a large non-point source of nitrogen. Atmospheric nitrogen deposition occurs both in inorganic (both ammonia and nitrate) and organic forms. To estimate atmospheric deposition loadings, data from the National Atmospheric Deposition Program (NADP) in station CA 45 (Hopland, Mendocino County, CA) were used. Another nearby station CA 88 (Davis, CA) also exists. Mendocino/Hopland was selected because the Davis station is more distant from the Laguna and is not as consistent with conditions found around the Laguna. For example, the Davis station has higher ammonia loadings (~ 4kg N/ha-yr) suggesting possibly larger influence from more intensive agriculture operations characteristic of the Central Valley. For CA 45 only wet deposition of ammonia and nitrate were available through the NADP network. Wet ammonia loading at CA 45 averaged 0.45 kg N/ha-yr and wet nitrate loading averaged 2 kg N/ha-yr at this station. Although total atmospheric deposition loadings can be large, the deposited loads will be retained partially by the watershed and runoff from various land uses will include contributions from atmospheric deposition. Direct deposition to water body however, was estimated to be 368lbs N /yr for ammonia and 1633 lbs N/yr for nitrate based on total area of water (371.2 ha).

Dry deposition of nitrogen occurs both in gaseous and particulate forms. Dry deposition of nitrogen can be as high as wet deposition and often higher than wet deposition. Wet deposition as well as dry deposition intercepted by forests and grasses can be washed off by precipitation and infiltrated into soils. Infiltrated nitrogen can be taken up by various types of vegetation. Nitrogen deposited to impervious areas can be directly washed off by overland flow and reaches the streams. Riparian vegetation provides a mechanism of nitrogen removal before reaching the streams. Stormwater monitoring data shown in Tables 5-3 and 5-4 indicated the range of concentrations from forested areas and urban areas. Runoff from other natural areas such as annual grass lands may also contribute to nitrogen loadings to streams. Figure 5-4 provides an overview of nitrogen transformation in the water column and sediments which illustrates that naturally occurring processes can introduce bio-available to the system should it become a limiting nutrient.

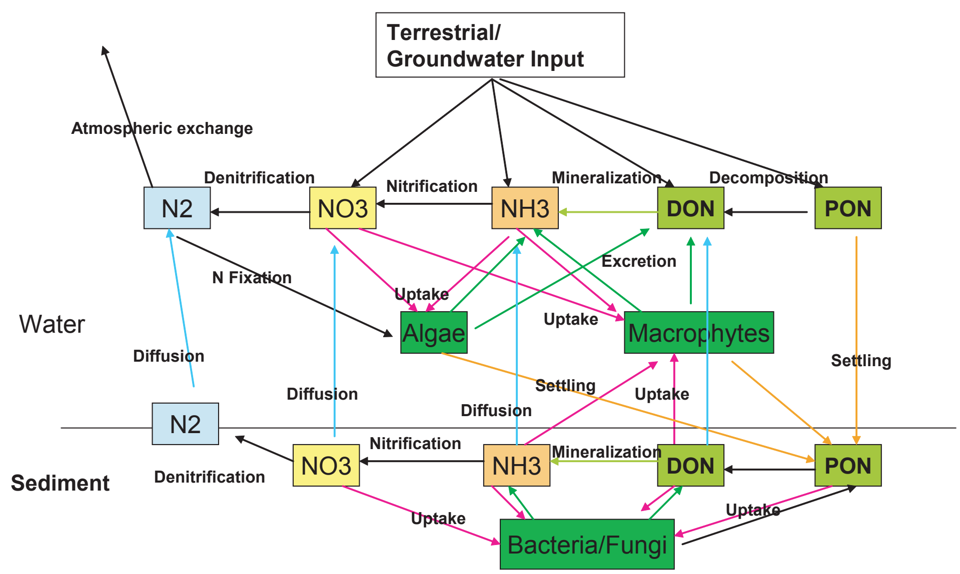


Figure 5-4 Nitrogen transformations in the water column and sediments

Groundwater

As summarized in section 4.3.4, shallow groundwater in Santa Rosa plain ranges between 0-86 feet below ground surface. During storm events, shallow ground water is likely to recharge the streams and therefore influence stream water quality, although it is not clear whether irrigation during summer seasons produces enough shallow groundwater that recharges to the streams. There is also evidence suggesting vertical connection of deep groundwater and surface near the confluence of Santa Rosa Creek and the Laguna de Santa

Rosa (as described in Section 4.3.4). Therefore the interaction between ground and surface water needs to be further evaluated. Summer base flow is generally very low for upper Laguna and the Laguna near Sebastopol when compared to Santa Rosa Creek, where incidental urban discharges occur more often during summer.

Various pollutant sources exist in the Laguna that could potentially influence ground water quality. These include dairies, irrigated pastures, and septic systems. Due to the low relief of the Santa Rosa floodplain, there is a large possibility that rainfall and septic effluents will recharge the groundwater when soil conditions permit. Current practices dictate that irrigated water be applied at rates that are less than rates of evapotranspiration. If irrigated water is applied at rates that exceed evapotranspiration it could also become a source.

Dairies can be an important nitrogen source to groundwater. Studies in the San Joaquin Valley suggested groundwater nitrogen concentrations were elevated by 40 mg/L down gradient of dairies (Harter et al. 2001). Currently there is an estimated total of 2,815 acres of dairies in the watershed (Table 5-6). Assuming 2 cows per acre and based on typical manure production rates by confined animals, these result in a total nitrogen production of 700,000 lbs/yr. Assuming half of the manure is transported off-farm, 350,000 lbs/yr is left within the watershed. Nitrate removal efficiencies in pasture were found to be around 15 lbs/acre/yr (Lowrance, 1992). In 2006, a total of 2,086 million gallons of reclaimed water was irrigated on agricultural/urban lands. Assuming an average nitrate concentration of 8 mg/L, this will result in a total surface nitrogen loading of 139,000 lbs/yr and a loading rate of 23.5 lbs/acre/yr. Phosphorus on the other hand is more easily adsorbed by soil and therefore is less susceptible to leaching to groundwater.

Septic systems

There are large numbers of septic units in the watershed. According to the 1990 census data, there are a total 19,901 septic units in the watershed. Due to the soil conditions in Laguna, septic failing rates might be high in certain areas. However, currently there is not enough information for evaluating the loadings from septics both during storms and under baseflow conditions due to septic failing. CH2M Hill and Merritt Smith consulting (1994) estimated a total nitrogen loading of 274,164 lbs/yr could be recharged into groundwater. However there is not enough information to verify this estimate.

Internal nutrient cycling in the Laguna

Wickham (2000) suggested a hypothesized mechanism of sequestering soluble reactive phosphorus from the wastewater treatment plant (SRP, mostly phosphate) in the Laguna with sediment deposition. Since phosphate is readily adsorbed to clay particles, elevated concentrations of phosphate can be adsorbed to and settle with sediments. Due to the high clay content of the Laguna soils, sediment eroded from various land uses contains phosphorus and can contribute to a phosphorus pool in the sediments. Sediment erosion and animal wastes transported from dairies have been found to accumulate in the bottom sediments of the Laguna (CRWQCB, 1992).

As a result, high concentrations of phosphorus were found in the sediments of the Laguna (as high as 2,400 mg P/kg, Otis 2006). High concentrations of organic carbon and nitrogen were also found in sediments (TN of 4,600 mg/kg). Sediment accumulation in certain sections of the Laguna is also significant (as much as 3 or 4 feet south and north of the confluence of Santa Rosa Creek; PWA 2004). These nutrient pools in the bottom sediments can serve as sources of nutrients through decomposition under aerobic and anaerobic conditions (releases of NH_3 and CH_4) and diffusion to the water column. The mixing of water, scour of sediments, and bioturbation can also immobilize nutrients from sediments to water column (Wetzel, 2001). Moreover, as the redox conditions changes to more anaerobic conditions, phosphate can be released from the sediment as the ferric ion (Fe^{3+}) that binds to phosphate is changed to ferrous form (Fe^{2+}). These processes are particularly important in summer as conditions favor the developing of anaerobic zones.

The uptake and turnover of phosphorus in an aquatic ecosystem is usually fast during summer; therefore, the cycling of phosphorus through aquatic community is also important. As shown in Figure 5-5, nutrients taken up by algae, plants and animals can be excreted or deposited to bottom sediments and can be quickly decomposed by bacteria and released back to water column.

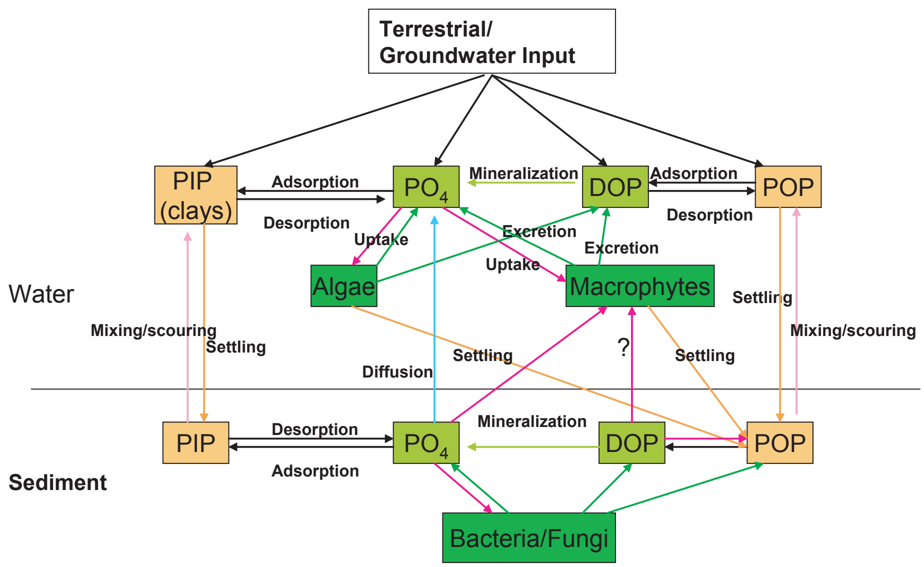


Figure 5-5 Phosphorus transformations in the water column and sediments

Quantifying sediment nutrient fluxes is very difficult without using models or real measurements. The mobility of phosphorus in particular depends on sediment redox conditions and the formation and stability of complexes with iron hydroxides. To make an attempt at an order-of-magnitude evaluation of this source, we estimated phosphorus releases from sediment due to diffusion only using simple equations derived from the WASP and QUAL2K model:

$$P\ flux = Edif/h * (Csw-Cw)$$

where Edif is eddy diffusion coefficient, h is active sediment depth, Csw is concentration in sediment water, and Cw is concentration in water column.

Nutrient concentrations in pore waters have not been reported for the Laguna. Therefore we estimated pore water concentrations using a partition coefficient of 1,000 as reported in literature (WASP, 2007) and the observed sediment phosphorus concentration of 2,400 mg/kg, which results in a concentration of dissolved phosphorus in sediment porewater of 2.4 mg/l. Using eddy diffusion coefficient of 2 x 10^{-4} m^3/sec reported in the literature (WASP, 2007) and an active depth of 2 cm, results in a sediment phosphorus flux of 0.02 g/m^2/day, which is near the center of the range of release rates reported by Nurnberg (1984) for lakes with anoxic sediment-water interfaces. Assuming LOR pond has a width of 250 feet and a length of 0.75 miles, results in a phosphorus loading of an order of 671 lbs/yr, which is not as significant compared to other sources during storm events, but could be significant since the majority of this flux would occur during summer low flow. However, due to the preliminary nature of this estimate, a more detailed study on sediment fluxes is needed to characterize loading from this potential source. Notably, the rate of phosphorus evolution from the sediment depends on dissolved oxygen conditions at the sediment-water interface, and may thus respond to management efforts that improve DO in the Laguna.

Nutrient loadings under flood conditions

One unique characteristic of the Laguna is that it is subjected to flood inundation due to backwater from the Russian River. When flooding occurs, lands that were originally agricultural or had other uses are submerged. Soils, sediments, nutrients and BOD originally accumulated on lands can be washed off by water. Sediments carried by flood water can also be deposited on lands when flood receded. During the flood of April 1999, aerial photos showed 3 areas of inundation in addition to wetlands including: 1) the Laguna at the Mark West confluence to 0.5 mi south (0.125 square miles); 2) 0.5 mile north of Guerneville Road (0.25 square miles); and 3) between Santa Rosa Creek and Occidental Road (0.5 square miles; PWA, 2004). These areas are scattered with agricultural areas of vineyards and dairies. The deposition of sediment and its associated water quality effecting constituents (N, P, and OM) is deposited on the floodplain above the low flow channel. This process would sequester at least some portion of the transported load away from the low flow sediment interface. More information is needed on frequency and duration of floods and the inundation areas.

Decker (2007) specifically describes a conceptual model of nitrogen and phosphorus immobilization and mobilization on the Laguna de Santa Rosa floodplain, particularly due to flood inundation. The Laguna de Santa Rosa floodplain contains agricultural land uses such as pasture and vineyards, which receive heavy fertilization. When manure or fertilizers are applied to these lands, excess application or asynchrony with crop demands can result in nutrient leaching, particularly for the more mobilized form NO_3^-. Phosphorus on the other hand can be adsorbed and accumulated in soils. When these soils with high nutrient levels are inundated with floodwater for a prolonged time, it potentially presents a way of immobilizing these nutrients to water. Decker (2007) estimated, for a flood event of winter 2006, the inundation area contains 42% pasture, 24% vineyards, and 26% natural woodlands. Nonetheless, the inundation of floodplains particularly on the agricultural lands can be an important and not yet quantified pathway of mobilizing nutrients to the Laguna.

Ranking of watershed loadings

Within the Laguna watershed urban stormwater is the largest source for ammonia, total nitrogen, total phosphorus and BOD (Table 5-9). Although concentrations in urban stormwater runoff are much lower than municipal wastewater, stormwater runoff is of much larger volume and therefore contributes to larger loadings of TN, TP and BOD. Note that nitrogen in municipal wastewater discharges to the Laguna is mostly in the nitrate form. As a result, municipal wastewater discharge is the largest source of nitrate loading. Nitrogen from dairies is mostly in ammonia form and therefore dairies are the second largest source of ammonia following urban stormwater runoff. For nitrate and phosphate, municipal wastewater discharge and urban stormwater runoff are generally equivalent sources. Here urban stormwater runoff includes loadings from the cities of Santa Rosa, Rohnert Park and Cotati (total area of 49 square miles).

The estimated loads for ammonia and total nitrogen from municipal wastewater and dairies are less than the previous estimates by CH2M Hill and Merritt Smith (1994; Table 5-10). Calculated ammonia loads from urban water are greater than the previous estimates. The estimated loads for nitrate and total nitrogen from urban areas were also greater, compared to other previous estimates reported (Table 5-10). The estimated phosphorus loading from urban areas compared favorably to the previous estimate (Table 5-11). Figures 5-6 through Figure 5-8 illustrate the relative magnitude of loadings by category for nitrogen, phosphorus, and BOD for the Laguna watershed.

Table 5-9
Summary of estimated pollutant loadings during winter by land uses

	Ammonia (lbs/yr)	Nitrate (lbs/yr)	Total Nitrogen (lbs/yr)	Phosphate (lbs/yr)	Total Phosphorus (lbs/yr)	BOD (lbs/yr)
Municipal wastewater	5,563	104,758	121,290	21,839	21,839	32,338
Dairies	37,273	782	66,857	1,434	--	187,201
Pasture on dairies	732	916	8,606	549	--	24,097
Urban stormwater*	80,437	69,380	562,591	12,915	31,053	657,994
Atmospheric deposition to urban areas	12,564	55,836	68,400			

* *calculated based on total urban area of 49 square miles (including the cities of Santa Rosa, Rohnert Park and Cotati).*

Table 5-10
Loads to the Laguna during winter storm and non-storm periods

Estimated by CH2M Hill and Merritt Smith (1994)

	Ammonia (lbs/yr)	Total Nitrogen (lbs/yr)
Municipal wastewater	56,610	424,400
Dairies	179,000	179,000
Urban	21,400	246,000

Table 5-11
Loads from urban stormwater

(NPDES permit, 1996)

	Nitrate (lbs/yr)	Total Nitrogen (lbs/yr)	Phosphorus (lbs/yr)
Urban	72,000	242,000	62,000

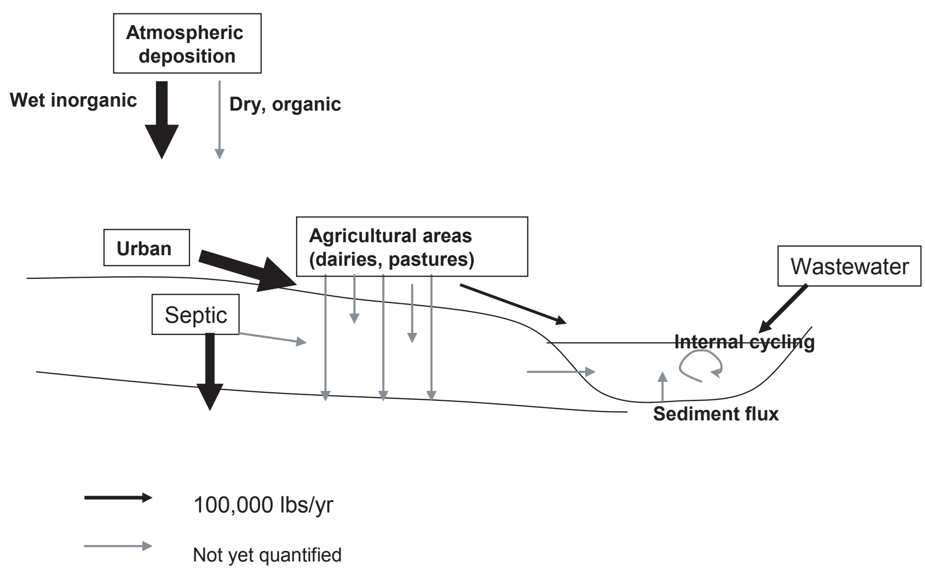


Figure 5-6 Preliminary TN loading conceptual model

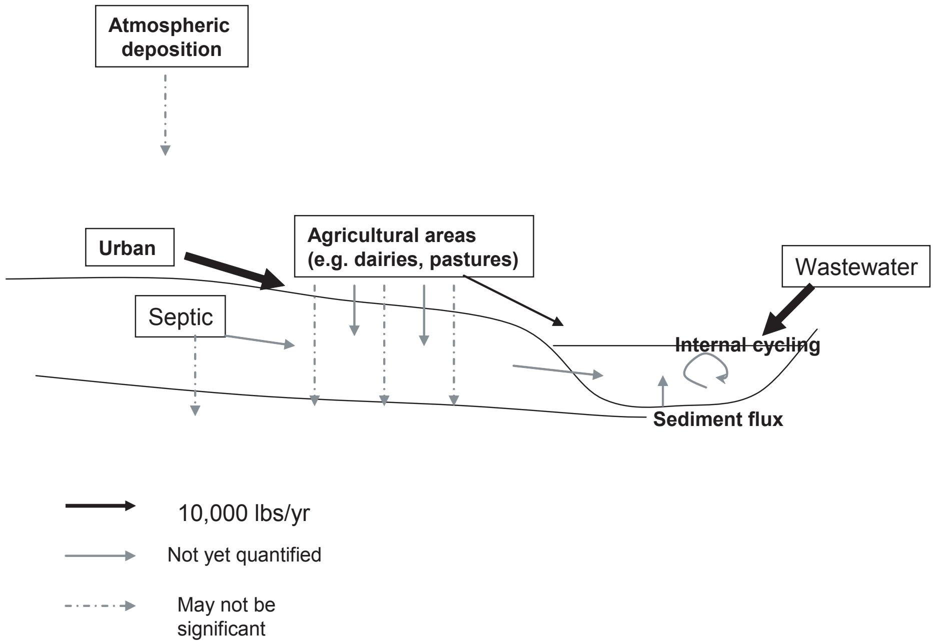


Figure 5-7 Preliminary dissolved phosphate loading conceptual model

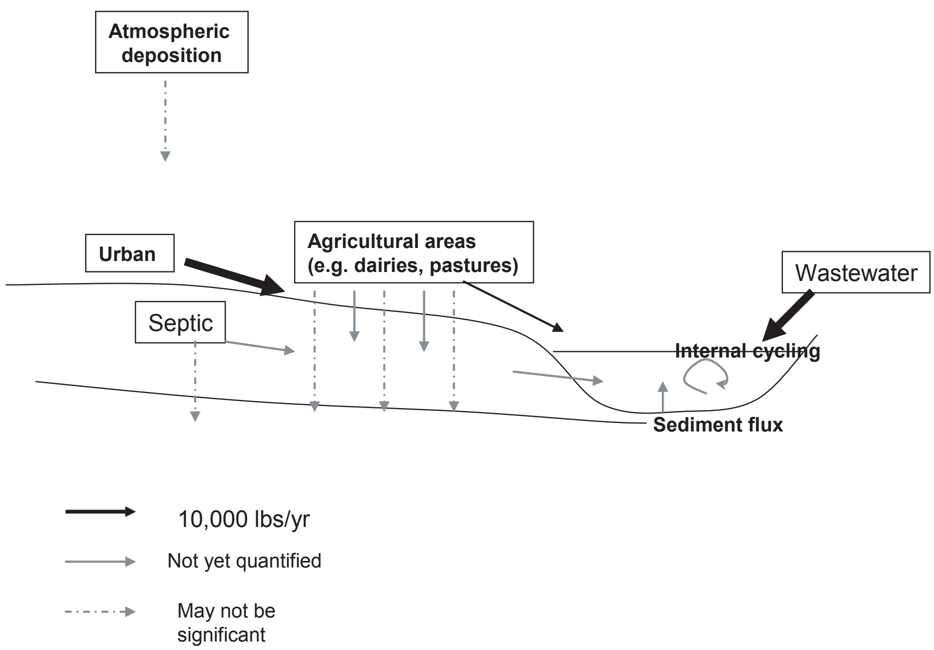


Figure 5-8 Preliminary BOD loading conceptual model

Loadings by tributaries

Loadings by tributaries were calculated based on available USGS flow data and monthly average nutrient concentrations observed in the same reach for the years 2004 through 2006. Figures 5-9 through 5-11 show the relative magnitude of loadings by tributaries. BOD concentrations are not available therefore loadings by tributaries could not be calculated. Spatially there are increases in loadings of ammonia, nitrate, and total phosphorus from upstream (LSP) to downstream (LOR). Loadings from Santa Rosa Creek are generally less than LOR (upstream of Santa Rosa creek confluence). USGS flow data suggested the flow at Santa Rosa Creek is generally equivalent to the flow at Laguna Sebastopol. However, higher loadings at the Laguna near Sebastopol suggested various other potential sources or reasons (*e.g.*, point source, dairies, or clay based soils) exist in the upper Laguna and other tributaries that contribute to higher loadings and that these sources are absent or less evident in the Santa Rosa Creek sub-watershed.

For ammonia, loading at LSP is greater than loading from Meadow Lane Ponds, suggesting the contribution of non point sources (*e.g.*, urban runoff, pasture, and dairies). Nitrate loading at LSP is roughly equivalent to Meadow Lane Ponds, suggesting both point and non-point source loadings of nitrate to the Laguna main channel. For total phosphorus, loading from the wastewater discharge is generally equivalent to the loading from Colgan Creek and less than LSP, again suggesting the contribution of both non-point and point sources to TP loading.

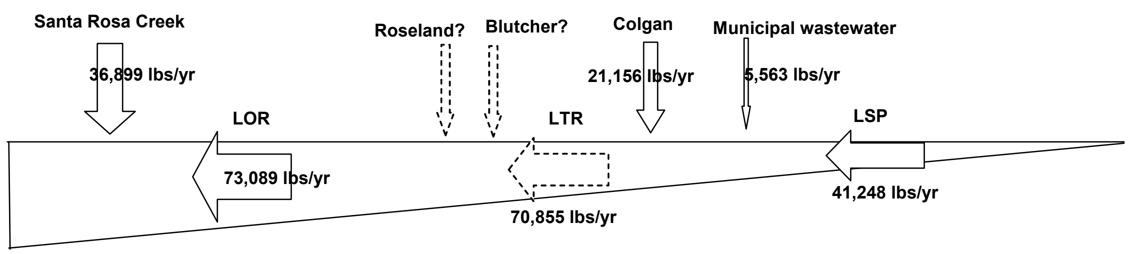


Figure 5-9 Total ammonia loadings by reaches
(note location of municipal wastewater discharge varies with year, with most recent discharge point located below LOR)

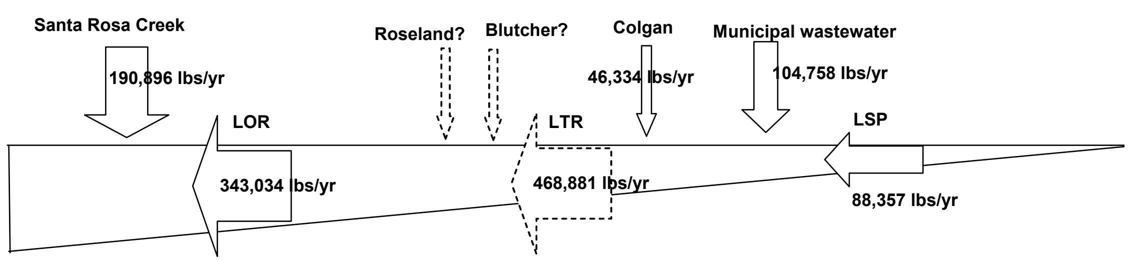


Figure 5-10 Nitrate loadings by reaches
(note location of municipal wastewater discharge varies with year, with most recent discharge point located below LOR)

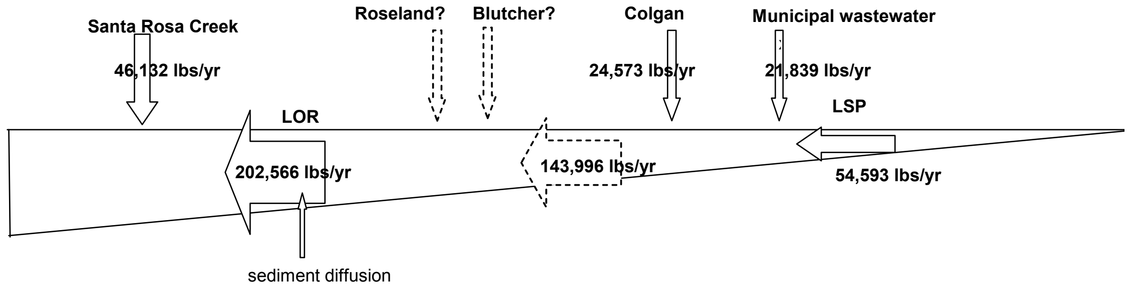


Figure 5-11 Total phosphorus loadings by reaches
(note location of municipal wastewater discharge varies with year, with most recent discharge point located below LOR)

5.2.2 Historical and current status of nutrient concentrations

A summary of the current nutrient concentrations that reflects the current status in the Laguna (2000-2005), compared to historical levels (1989-1994, 2000-2005) is provided below. Spatial and temporal patterns of nutrient concentrations were also explored. Some key observations from the analysis are:

- Historically 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.
- Nutrient concentrations have shown large decreases since 1989. The largest decreases are in total NH_3 and TKN concentrations.
- Current median nutrient concentrations for the Laguna main channel are mainly 0.3-0.5 mg N/l for total NH_3, 1-3 mg N/l for NO_3 and 1-2 mg N/l for organic nitrogen. Median TP concentrations are generally between 0.5- 1 mg P/l with a few locations above 1 mg P/l.
- For the main channel of the Laguna, nutrient concentrations generally increase from upstream station (LSP) to LTR and LOR, and then decrease downstream of LOR. The section between LOR and upstream of the Santa Rosa Creek confluence can potentially function as a nutrient sink. 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.

Available data for analysis

The available data for analysis includes: 1) City of Santa Rosa Self Monitoring Program (SMP) nutrient data for 2000 to 2005; 2) TMDL monitoring data collected by NCRWQCB during 1995 to 2000; and 3) collated data from the City of Santa Rosa and NCRWQCB for the period of 1989 to 1994. Using these data requires knowledge recycled water discharge (ie where, when and amount). Discharge location, timing and amount in the future may not be the same as that in the past.

- *City of Santa Rosa SMP data for 2000 to 2005.* These are weekly grab samples collected upstream and downstream of the city's wastewater discharging locations during discharging periods. Constituents monitored include total NH_3-N, NO_3, organic nitrogen, and TP. This set of data provides us the current status of nutrient concentrations in the watershed.
- *TMDL monitoring data collected by NCRWQCB during 1995 to 2000.* These are TMDL monitoring data collected by NCRWQCB at five stations (LSP - Laguna at Stony Point, LOR - Laguna at Occidental Road, LGR - Laguna at Guerneville Road, LTH - Laguna at Trenton-Healdsburg Road, and SRCWS - Santa Rosa Creek at Willowside Road) for the period of 1995 to 2000. The data are bi-weekly grab samples. During this period, the Waste Reduction Strategy (WRS) was implemented, and therefore this set of data provides us with the effect of WRS.
- *Combined data from the City of Santa Rosa and the NCRWQCB for the period of 1989 to 1994.* These are weekly or biweekly samples collected at a few key locations of the Laguna during 1989 to 1994 by both the City of Santa Rosa and NCRWQCB. Data in this period generally reflect status before the implementation of WRS.

Data for 2000 to 2005 were collected for the discharging months only. For consistency, for 1989 to 1994 and 1995 to 2000 only data for the discharging months were used in the analysis. Locations and total number of data points for different periods are shown in Figure 5-12.

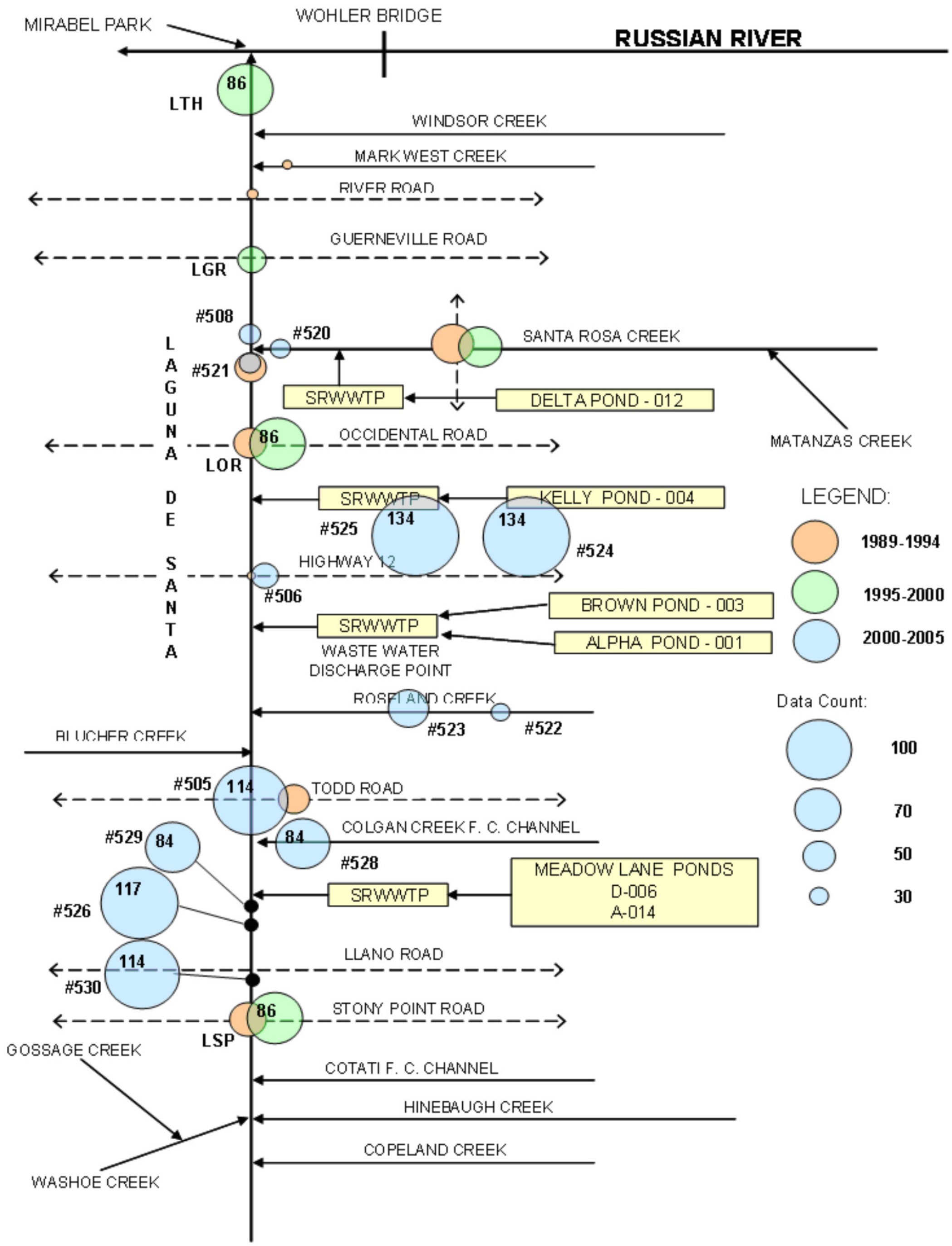


Figure 5-12 Total number of data points for the samples during 1989-1994, 1995-2000, and 2000-2005.

Spatial and temporal trends in nutrient concentrations

Spatial pattern and temporal changes in NO_3 concentrations

For 1989-1994, mean NO_3 concentrations increase from upstream (LSP) to LTR (3.8 mg N/l) and LOR (4.0 mg N/l; Figure 5-13). NO_3 concentrations decreased between the section of LOR and upstream of the confluence of Santa Rosa Creek, suggesting possible nutrient sinks in this section. Mean NO_3 concentrations continued to decrease downstream below the confluence of Santa Rosa Creek due to dilution of Santa Rosa Creek. For the period of 1995 - 2000, observed mean NO_3 concentrations are much lower (Figure 5-14). The highest mean NO_3 concentrations were again observed at LOR (1.8 mg N/l), below wastewater discharge points. The rest of the Laguna main channel and Santa Rosa Creek all showed mean NO_3 below 1 mg N/l.

For the period of 2000 - 2005, observed mean NO_3 concentrations range from 0.9 – 3.5 mg/l at the main channel (Figure 5-15). NO_3 concentrations again increase downstream below A pond discharge (Station #526; 2.3 mg N/l), and further downstream at LTR (3.5 mg N/l). Monitoring stations at several tributaries upstream and downstream of discharge points indicate relatively high NO_3 concentrations below discharge point.

Overall for the three sampling periods, 1995 - 2000 has a large decrease in NO_3 compared to concentrations from 1989- 1994. For 2000 -2005, the Laguna above the confluence of Santa Rosa Creek also has a decrease in NO_3 from 1989 - 1994. However, NO_3 concentrations at LTR, the Laguna at Highway 12, and the Laguna below Llano Road continue to have high concentrations. Monitoring data for 2000 -2005 also show some relatively large NO_3 concentrations in the tributaries.

For NO_3, generally higher concentrations are observed for winter and spring months in December to April for LSP, LOR and LTH. Summer generally has lower NO_3 concentrations. Lower total NH_3/NO_3 concentrations during summer months indicated nitrogen is rapidly taken up by algae or plants.

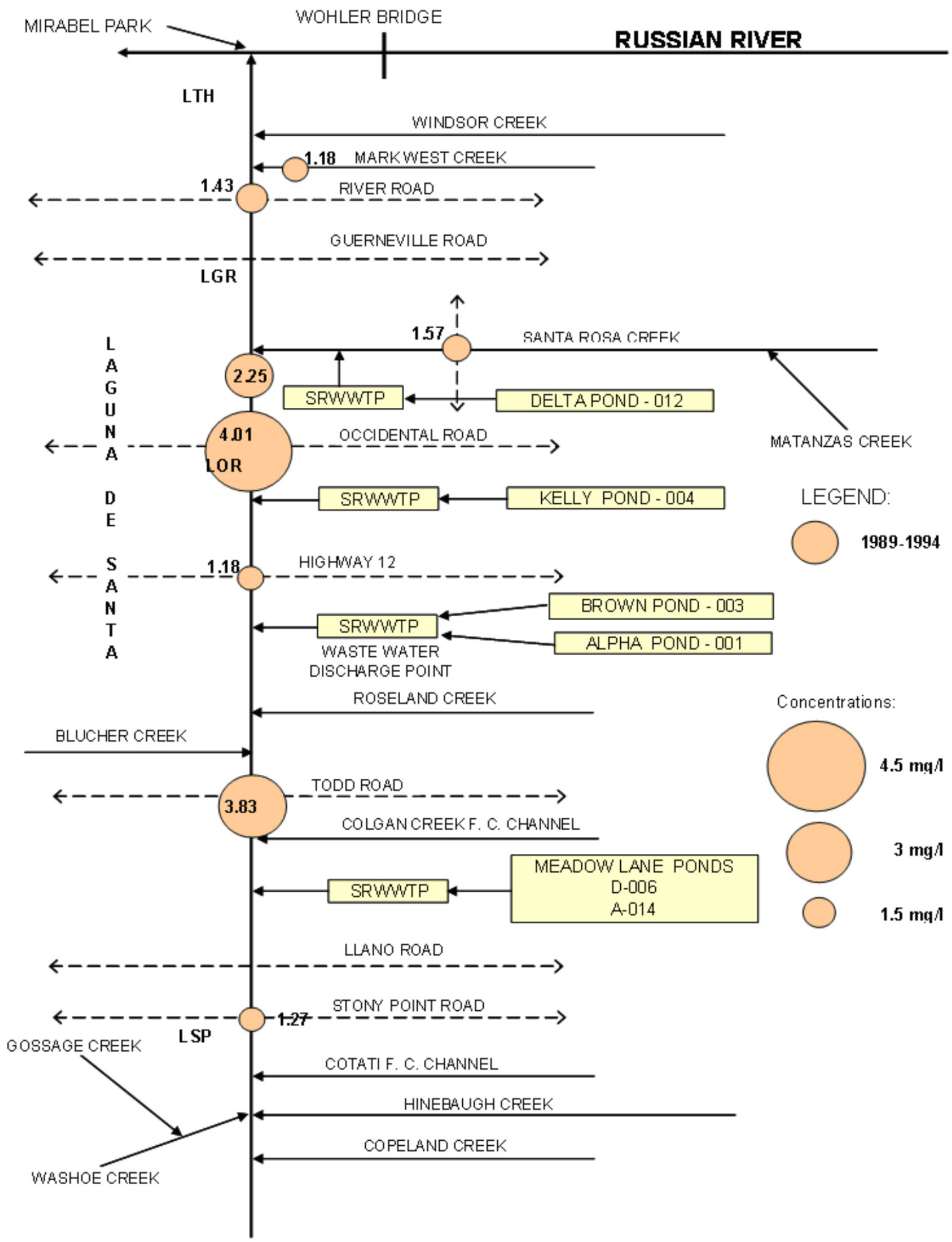


Figure 5-13 Mean NO_3 concentrations for 1989-1994

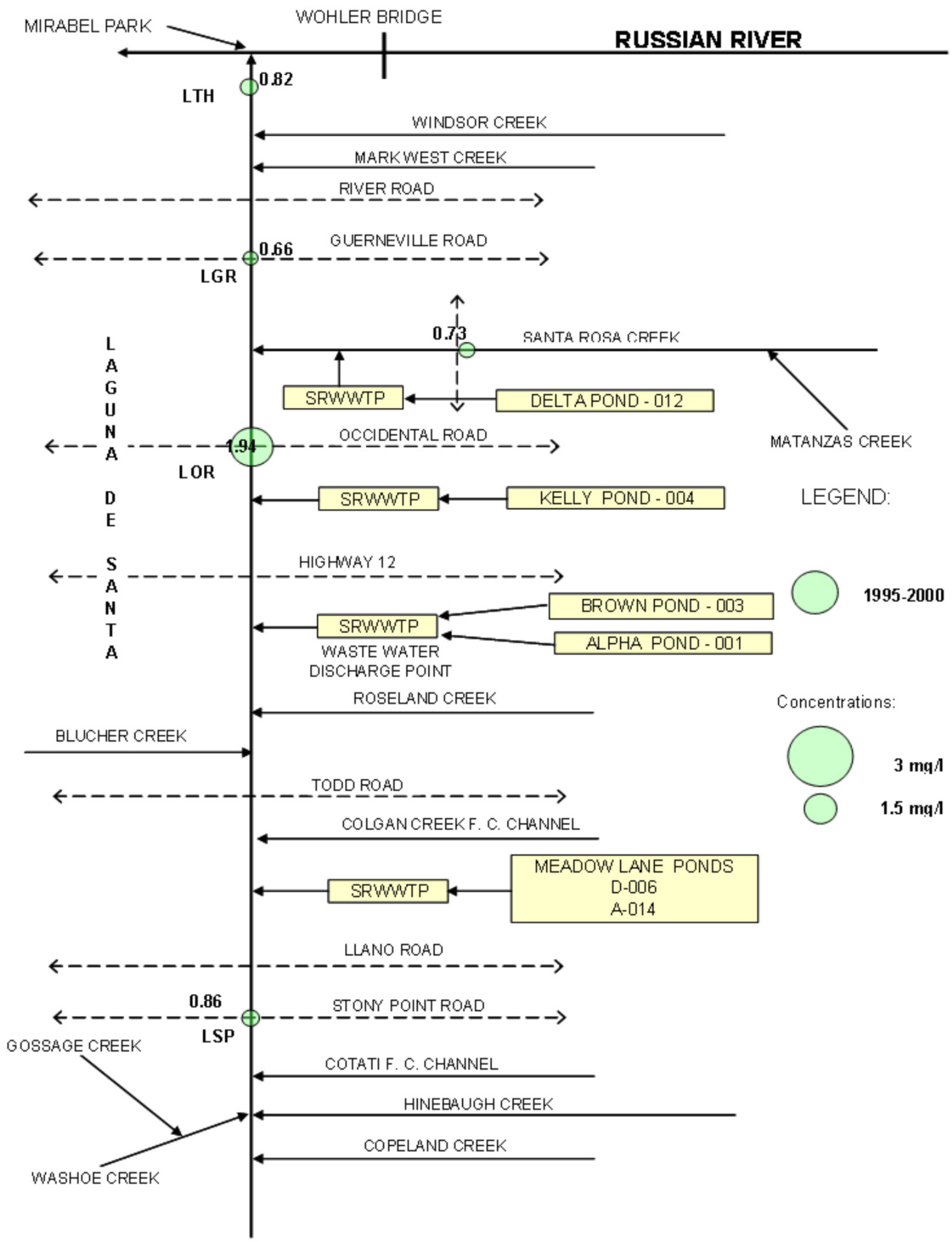


Figure 5-14 Mean NO_3 concentrations for 1995-2000

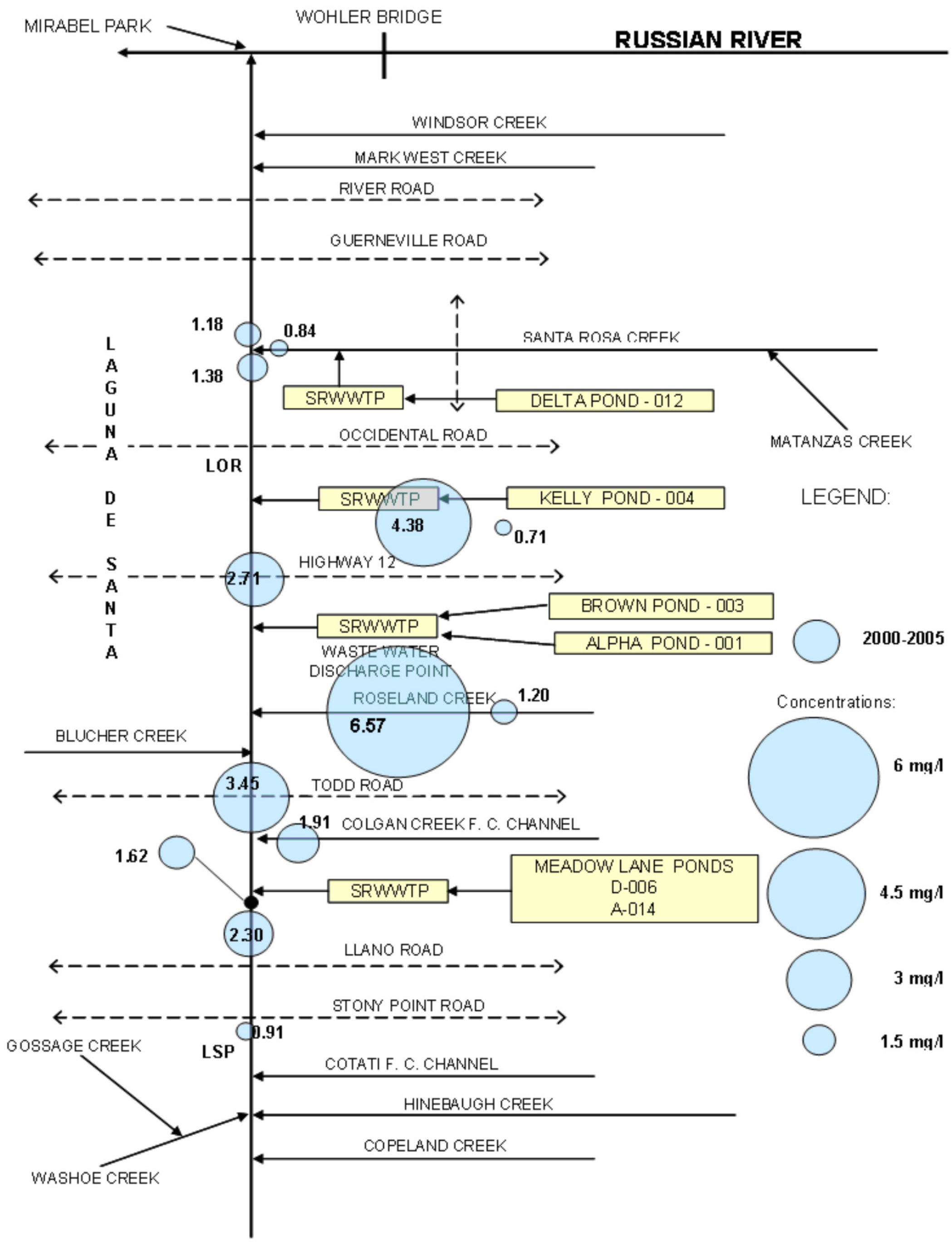


Figure 5-15 Mean NO_3 concentrations for 2000-2005

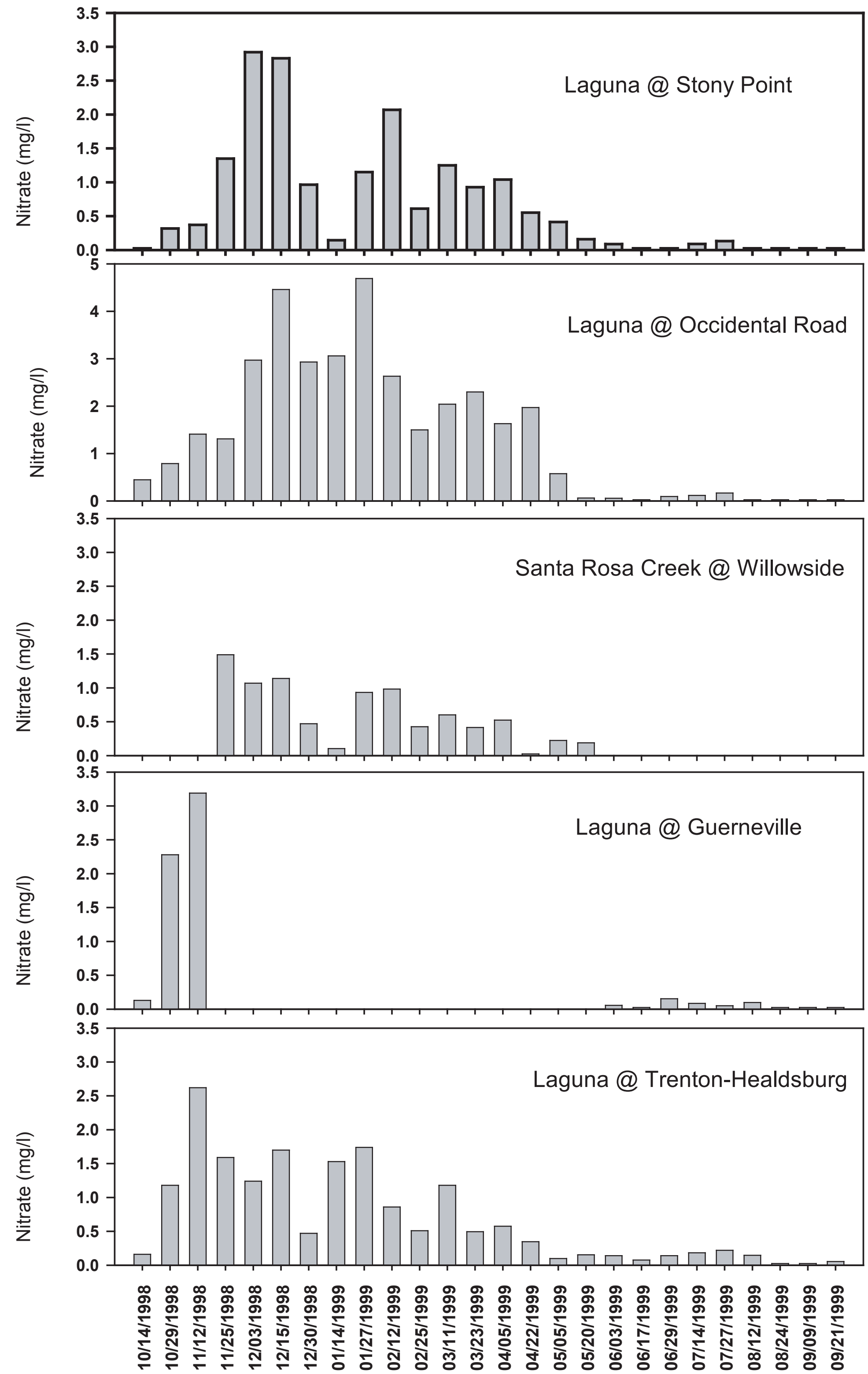


Figure 5-16 Seasonal pattern of NO_3 concentrations

Spatial pattern and temporal changes in TKN concentrations

For the period of 1989-1994, very high TKN concentrations have been observed at LTR (mean of 6.8 mg N/l) and the Laguna at Highway 12 (mean of 7.6 mg N/l; Figure 5-17). TKN measures the sum of ammonia and organic nitrogen forms. High TKN, if predominantly due to elevated NH_3, is usually an indicator of recent contamination of animal wastes, possibly from dairies. The most upstream station LSP showed lower TKN of 1.1 mg/l. Average TKN values increased downstream from the Laguna at Highway 12 to 3.0 mg/l at LOR and 2.4 mg/l upstream of Santa Rosa Creek (Figure 5-18). Observed TKN values during 1995 to 2000 were lower and were relatively uniform across the main channel of the Laguna ranging from 0.9-1.2 mg/l. Observed TKN values for the period of 2000 to 2005 are also relatively uniform across the Laguna ranging from 1.1-1.5 mg/l (Figure 5-19). Slight increases in TKN have been observed upstream and downstream of the discharge point at Roseland Creek.

Overall, large decreases in TKN have been observed in the main channel of the Laguna during 1995 to 2005, compared to the high concentrations in 1989 to 1994. This may possibly be due to the effect of the waste reduction strategy.

Generally higher total NH_3 concentrations are observed for winter months particularly in November/December for LSP, LOR, and LTH. Summer and fall generally show lower total NH_3 concentrations. Due to the lack of data, the seasonal pattern at LGR and Santa Rosa Creek is unclear. TKN concentrations show a less clear seasonal pattern as total NH_3 or NO_3. Relatively uniform TKN concentrations were observed throughout the year.

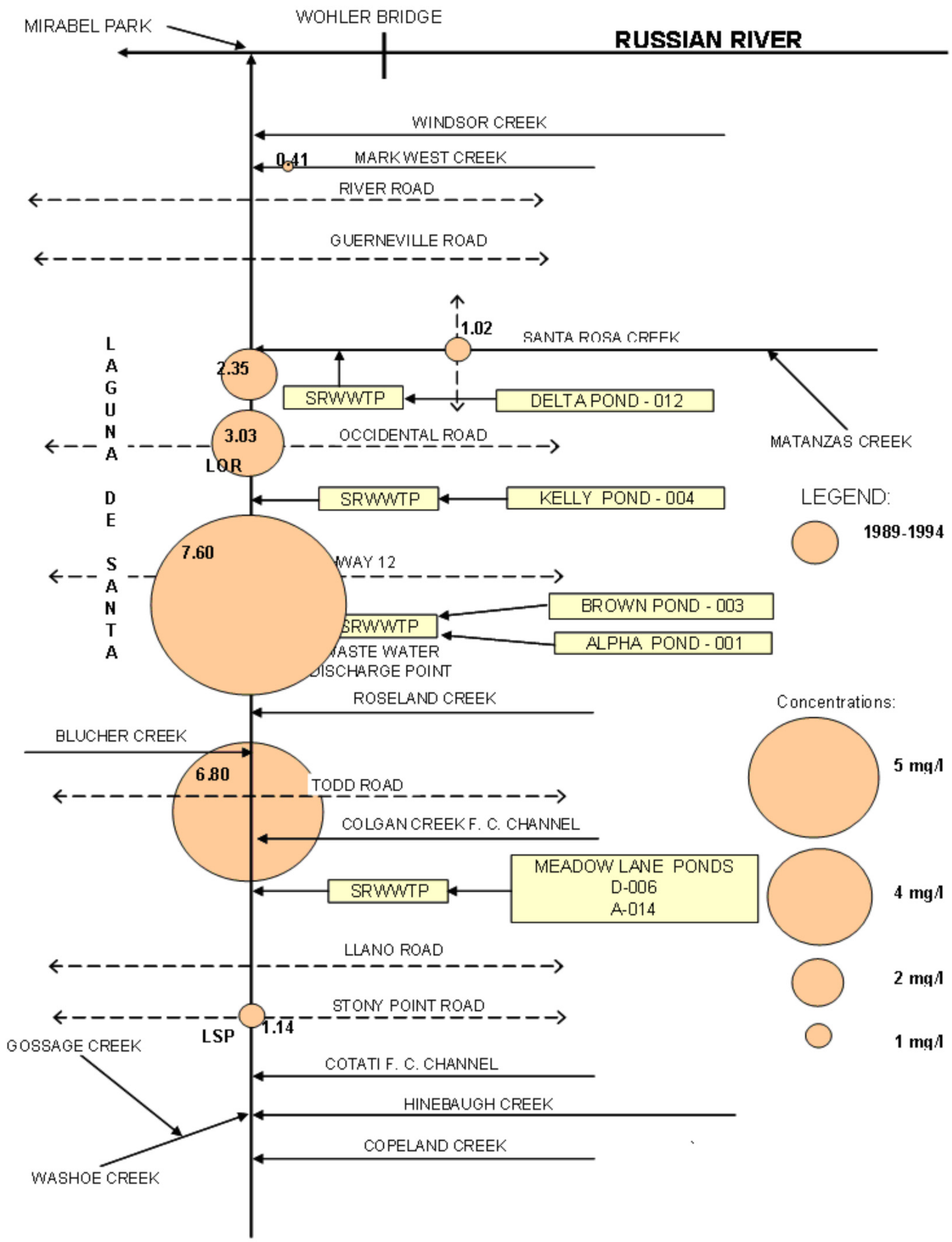


Figure 5-17 Mean TKN concentrations for 1989-1994

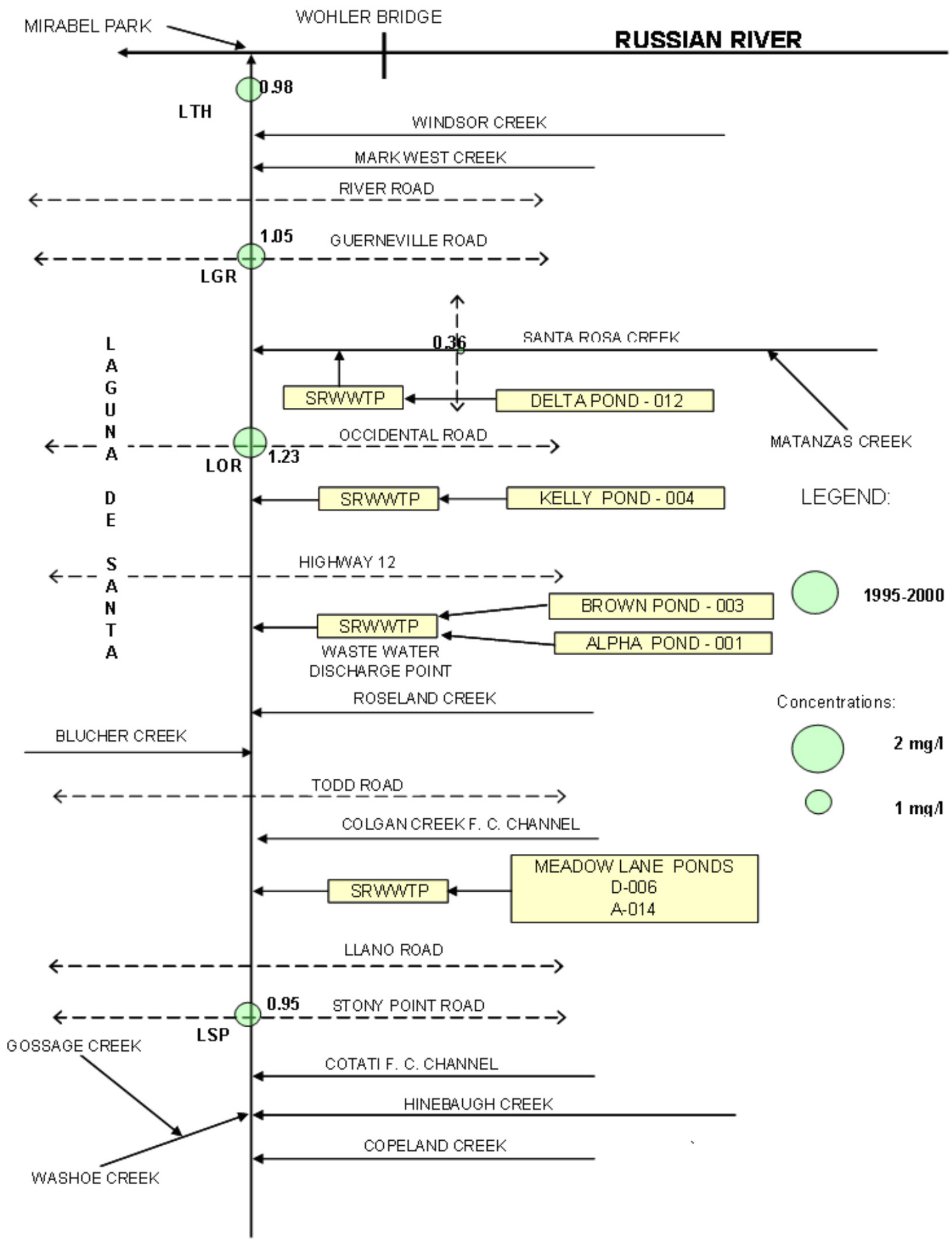


Figure 5-18 Mean TKN concentrations 1995-2000

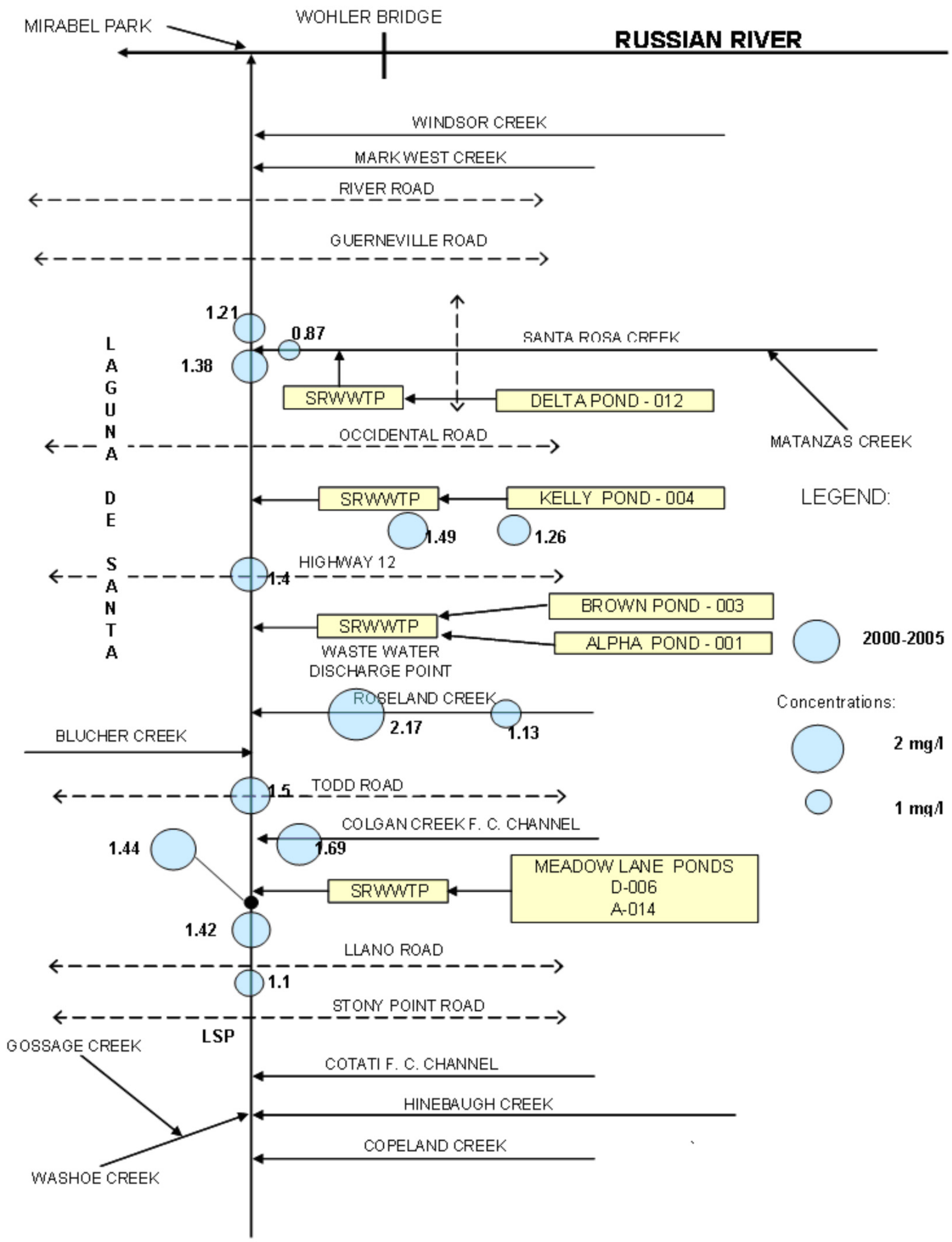


Figure 5-19 Mean TKN concentrations for 2000-2005

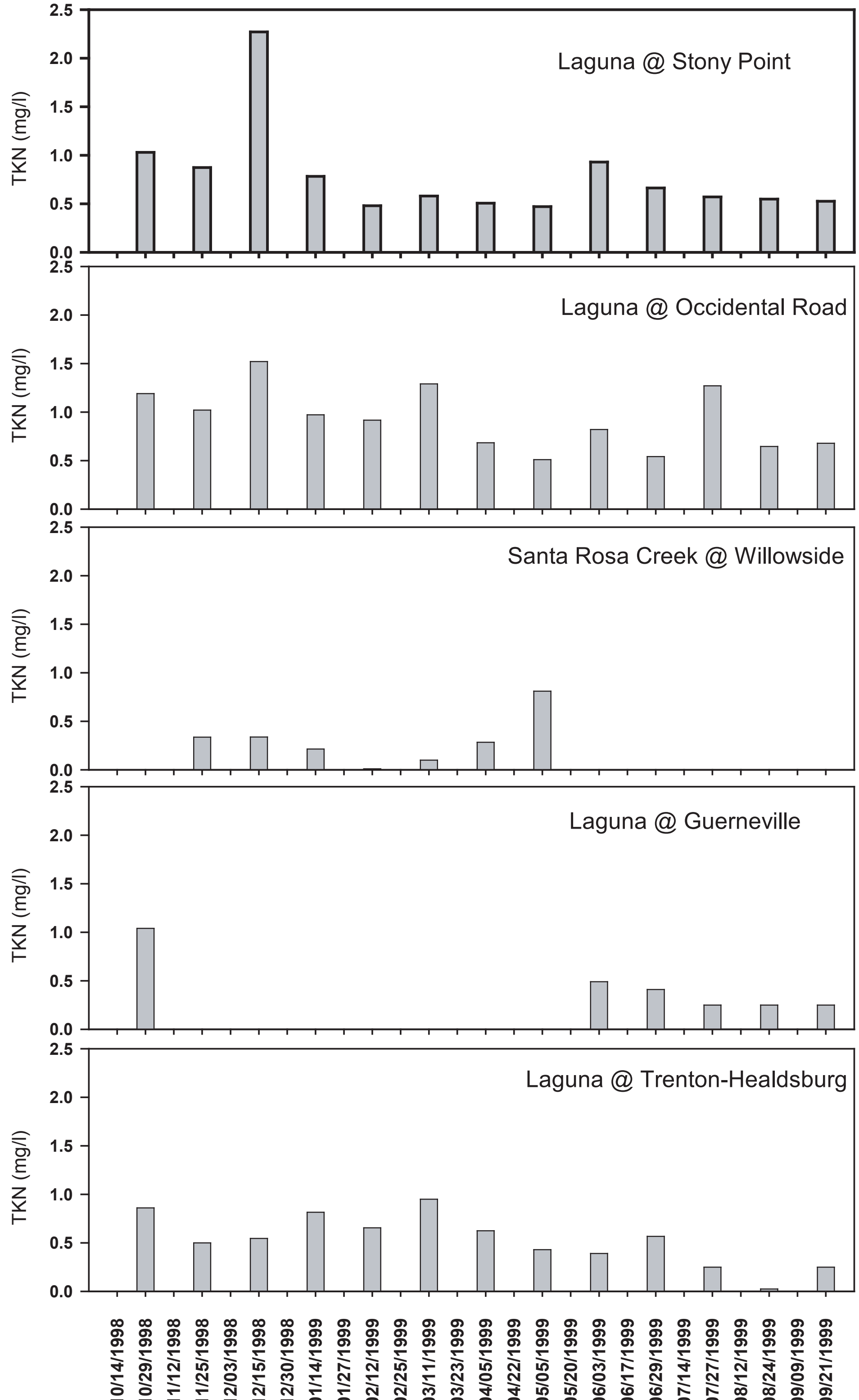


Figure 5-20 Seasonal Pattern of TKN

Spatial pattern and changes in TP concentrations

For the period of 1989 to 1994, observed mean TP concentrations ranged from 0.6 -1.8 mg P/l at the Laguna main channel (Figure 5-21). TP concentrations also show a trend of increasing from upstream (LSP) to mid-section stations (LTR and LOR) and decrease downstream. Mean TP concentrations decreased between the section of LOR and upstream of the Santa Rosa Creek confluence are likely due to a combination of factors such as precipitation due to binding to sediments (Wickham, 2000) and dilution from surrounding watershed. TP concentrations continued to decrease downstream of the Santa Rosa Creek confluence due to dilution from Santa Rosa Creek. The observed TP concentrations at Santa Rosa Creek were relatively low at 0.24 mg P/l. Large decreases in TP concentrations were observed for the period of 1995 -2000 relative to 1989 to 1994 (Figure 5-22). The monitoring period of 2000 - 2005 also shows lower TP concentrations compared to 1989 - 2004 (Figure 5-23).

TP also has relatively higher concentrations during late fall and winter months, particularly at LOR and LTH. However, relatively high TP concentrations are also observed in summer months across the Laguna including LSP (over 0.5 mg/l), LOR (around 0.4 mg/l), LGR (0.3 mg/l) and LTH (around 0.3 mg/l). The observed TP concentrations during summer indicate sources other than wastewater discharge are contributing to TP loading, possibly from internal cycling of phosphorus in the Laguna. The pattern is also affected by P uptake by algae and plants. Inorganic nitrogen is depleted in summer, but P remains at relatively high levels.

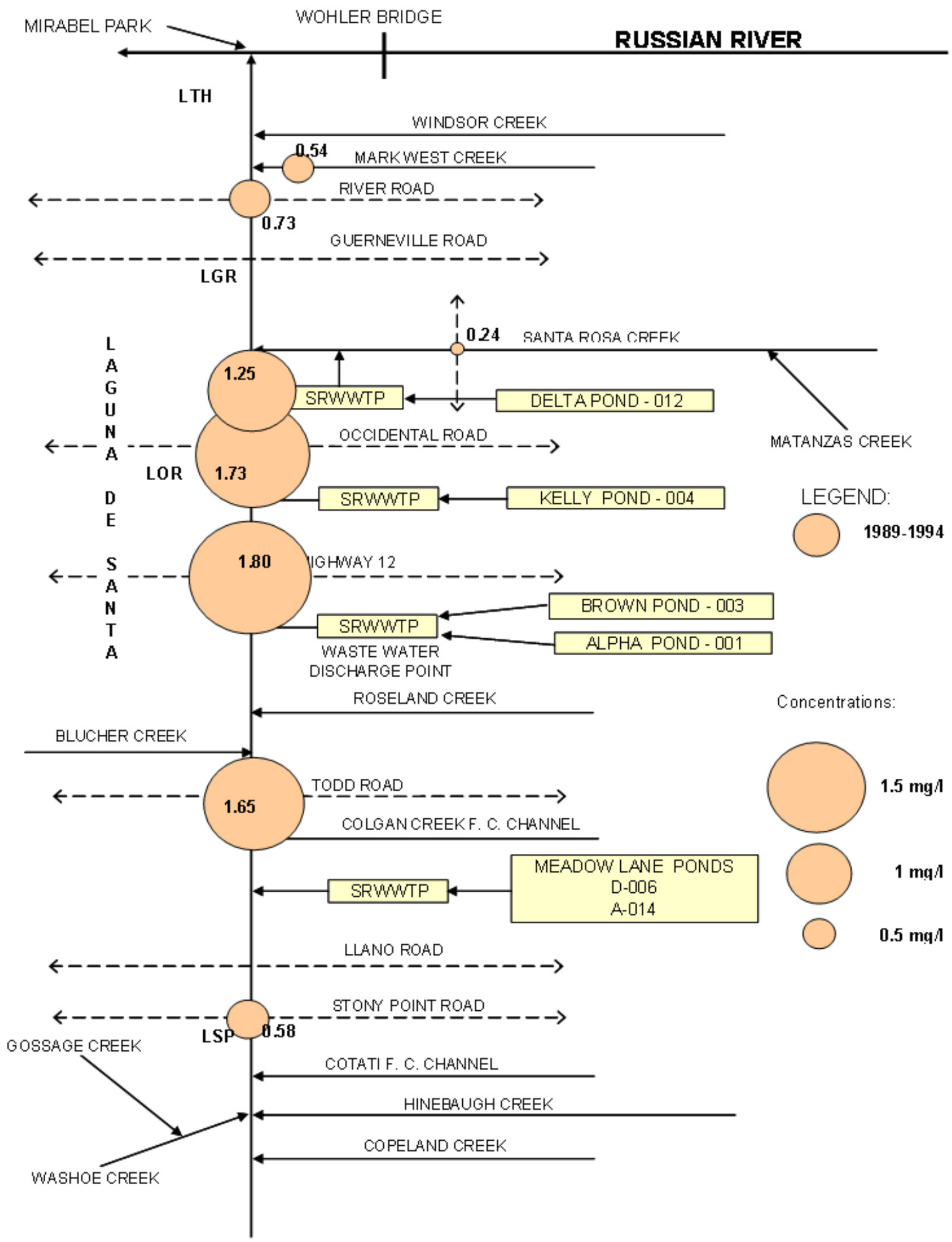


Figure 5-21 Mean TP concentrations for 1989-1994

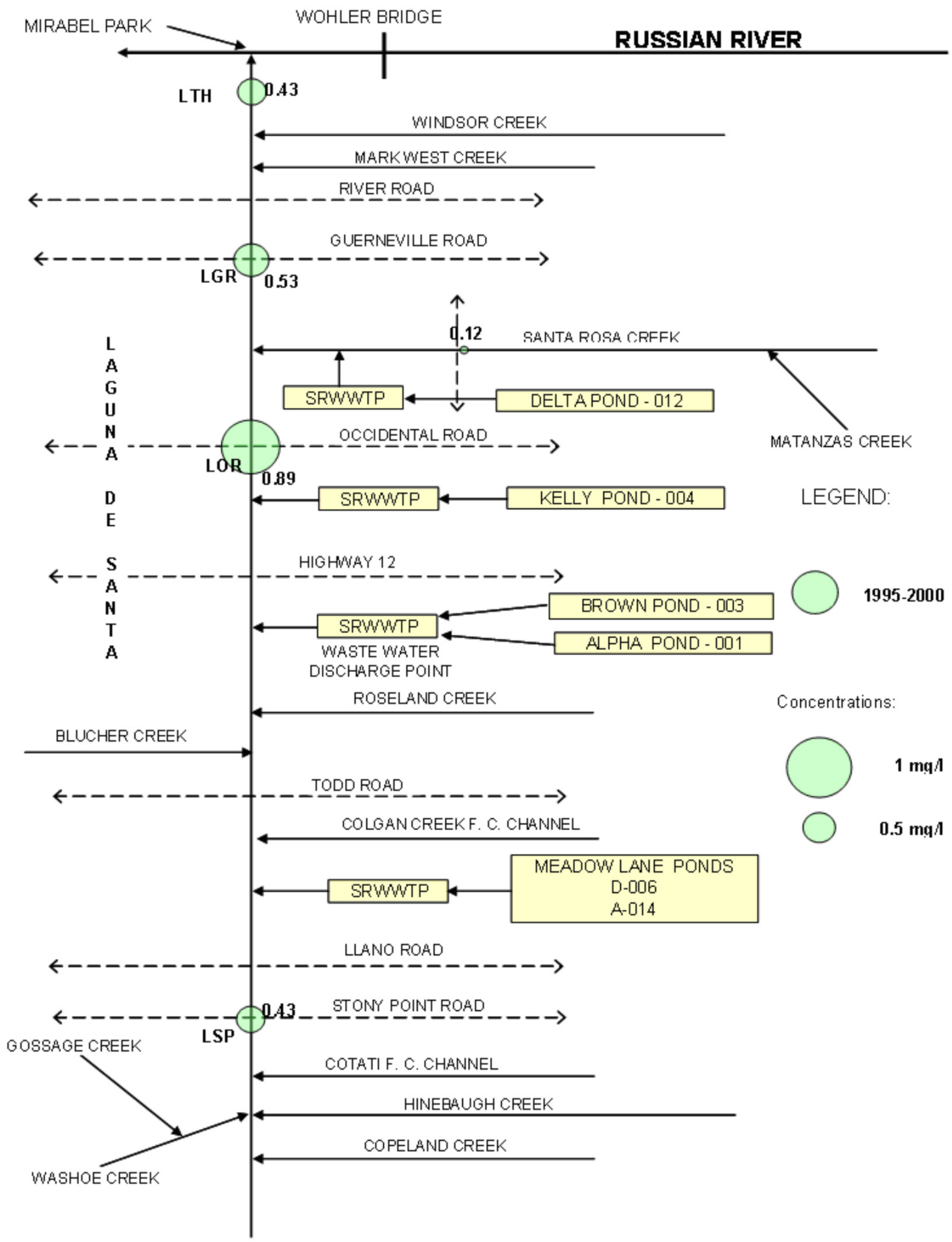


Figure 5-22 Mean TP concentrations for 1995-2000

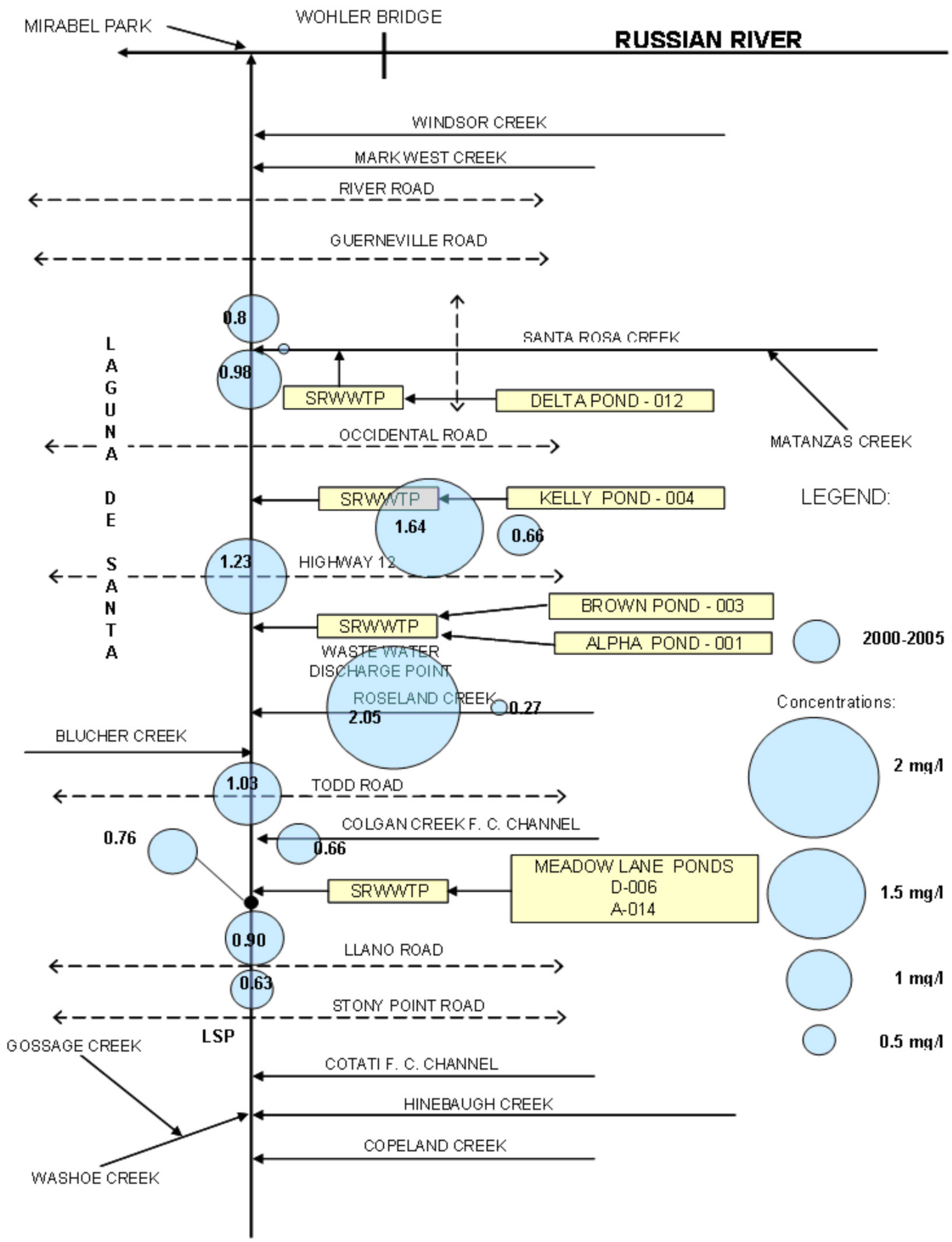


Figure 5-23 Mean TP concentrations for 2000-2005

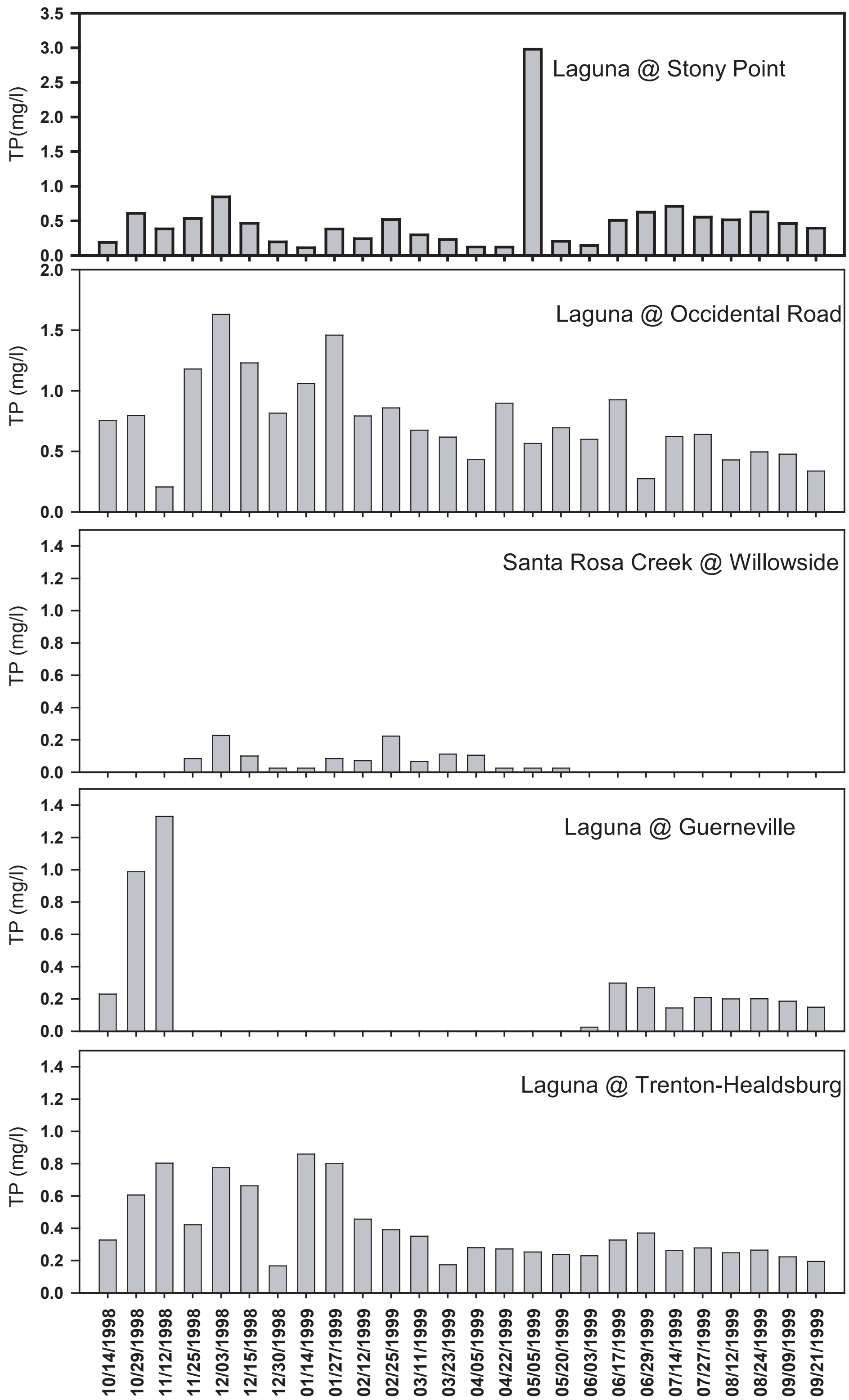


Figure 5-24 Seasonal pattern of TP

Figure 5-25 through Figure 5-36 present the range of concentrations of total NH_3, NO_3, organic N, and TP by sampling station for 1989–1994, 1995–2000, and 2000–2005.

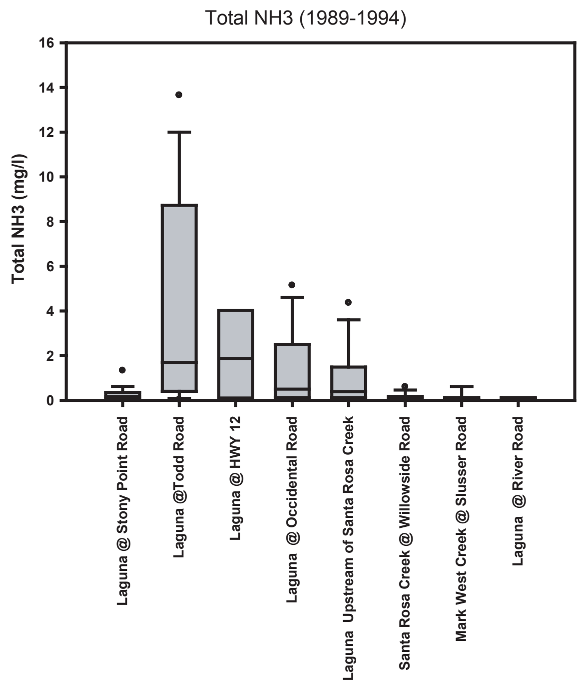


Figure 5-25 Total NH_3 concentrations for 1989-1994 by sampling locations

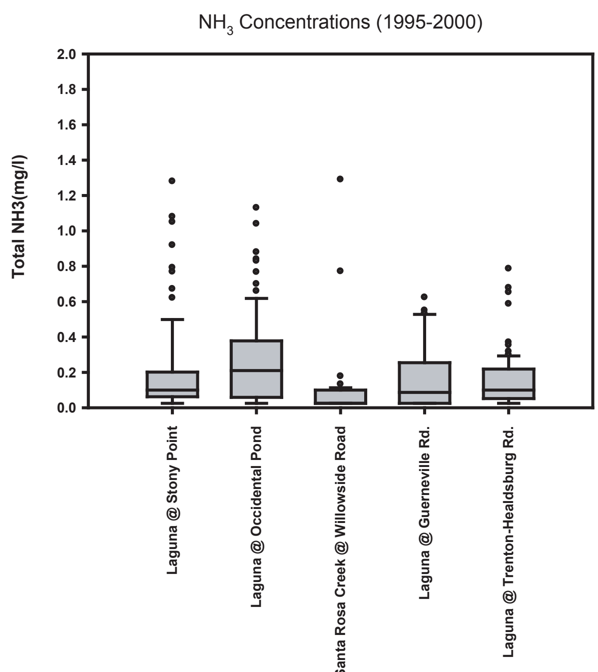


Figure 5-26 Total NH_3 concentrations for 1995-2000 by sampling locations

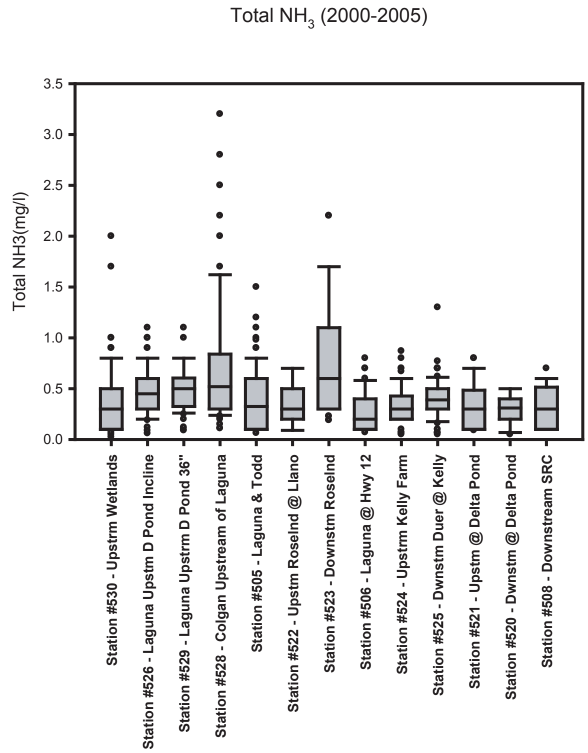


Figure 5-27 Total NH_3 concentrations for 2000-2005 by sampling locations

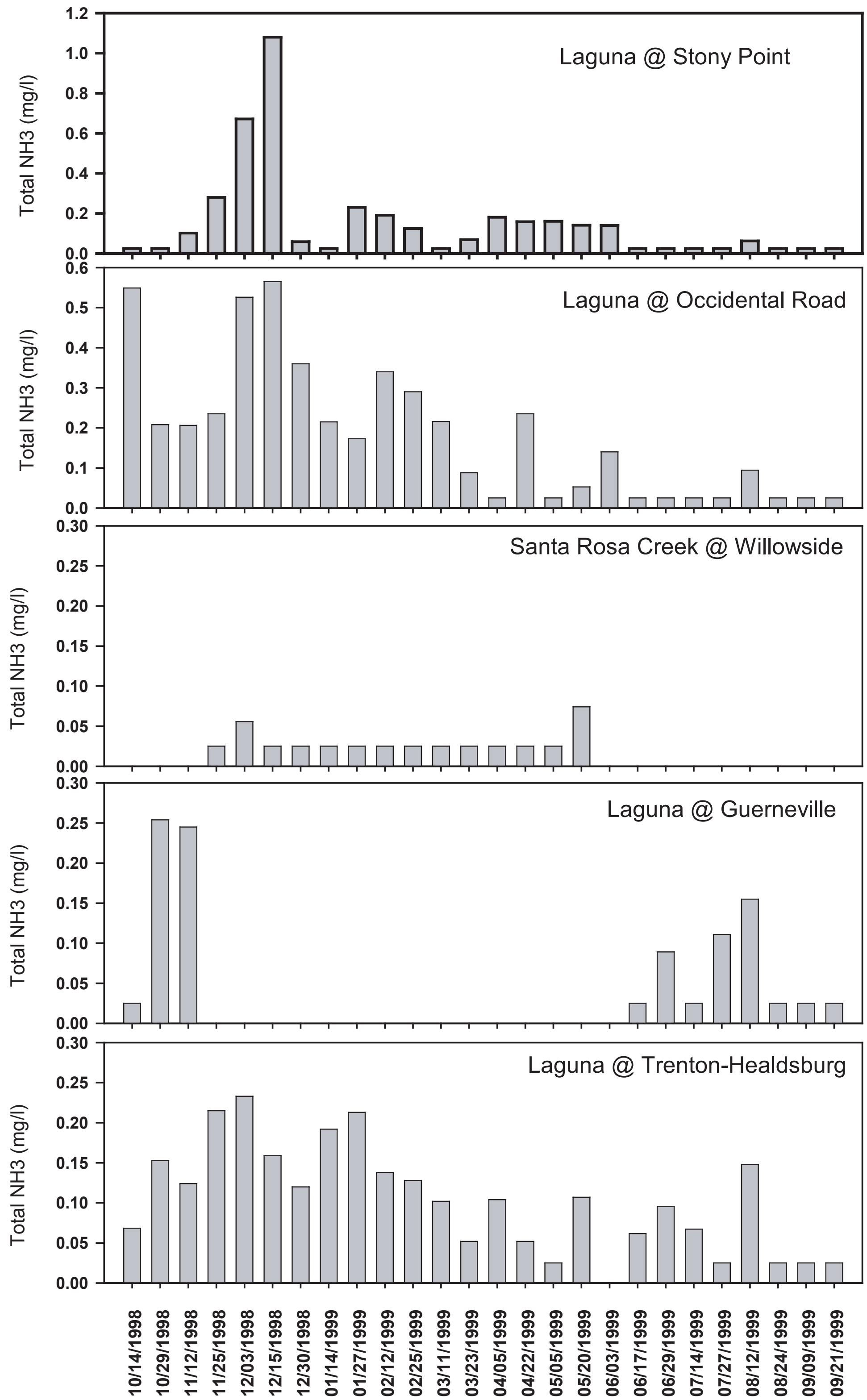


Figure 5-28 Seasonal pattern of total NH_3 concentrations

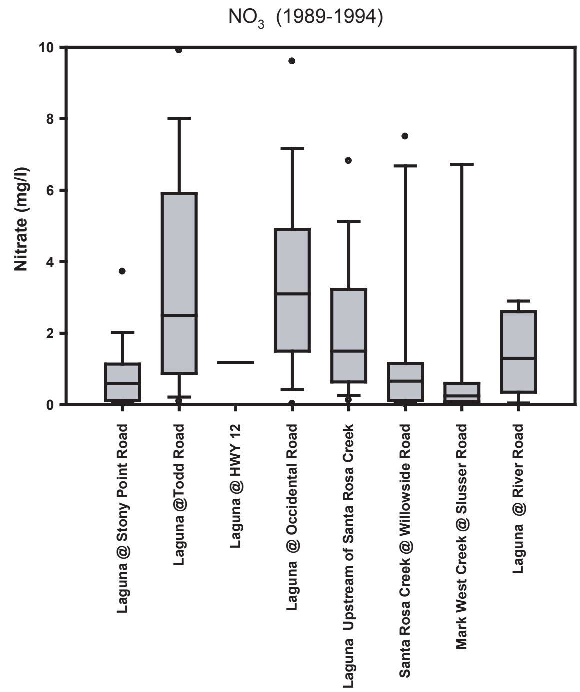


Figure 5-29 Total NO_3 concentrations for 1989-1994 by sampling locations

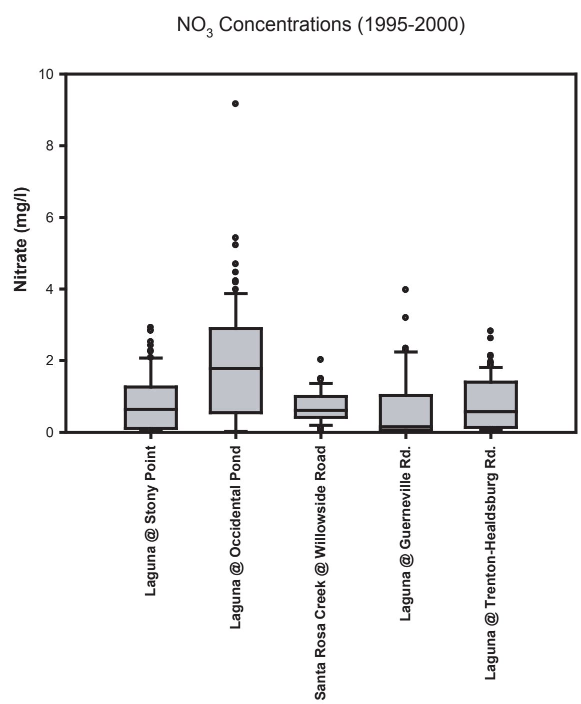


Figure 5-30 Total NO_3 concentrations for 1995-2000 by sampling locations

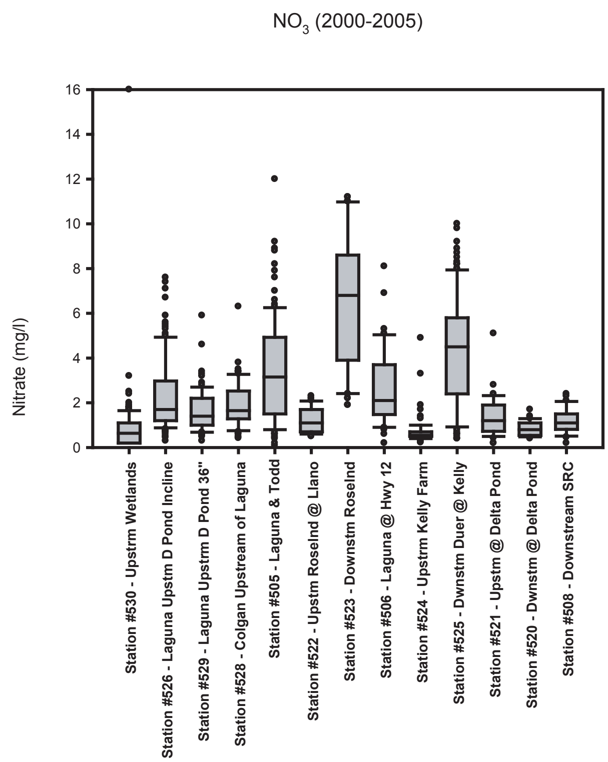


Figure 5-31 Total NO_3 concentrations for 2000-2005 by sampling locations

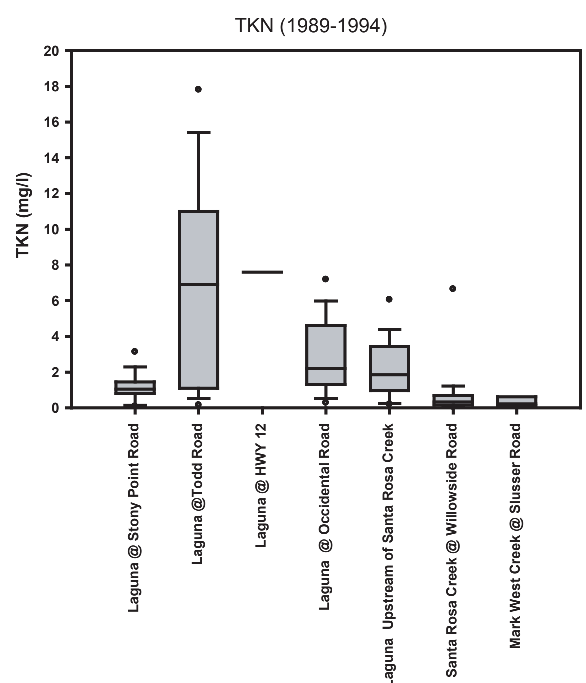


Figure 5-32 TKN concentrations for 1989-1994 by sampling locations

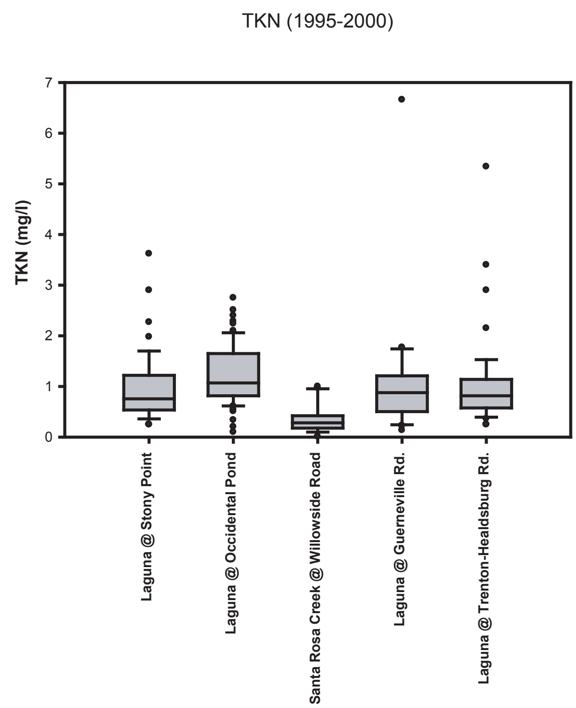


Figure 5-33 TKN concentrations for 1995-2000 by sampling locations

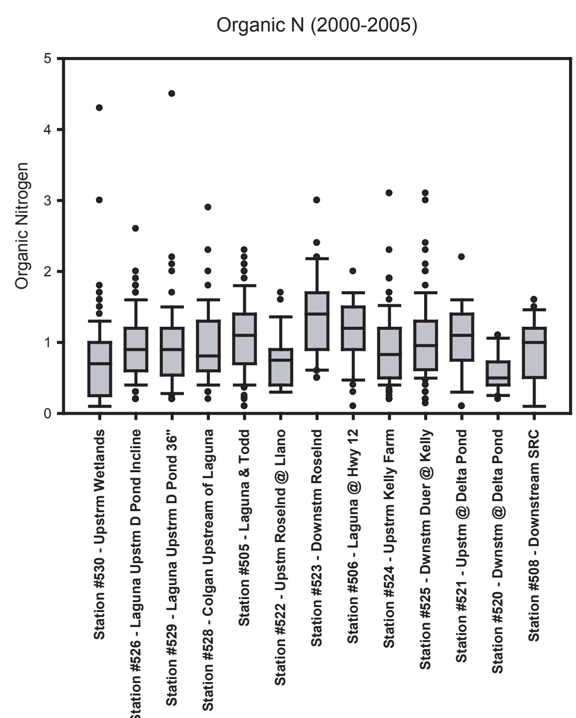


Figure 5-34 Organic nitrogen concentrations for 2000-2005 by sampling locations

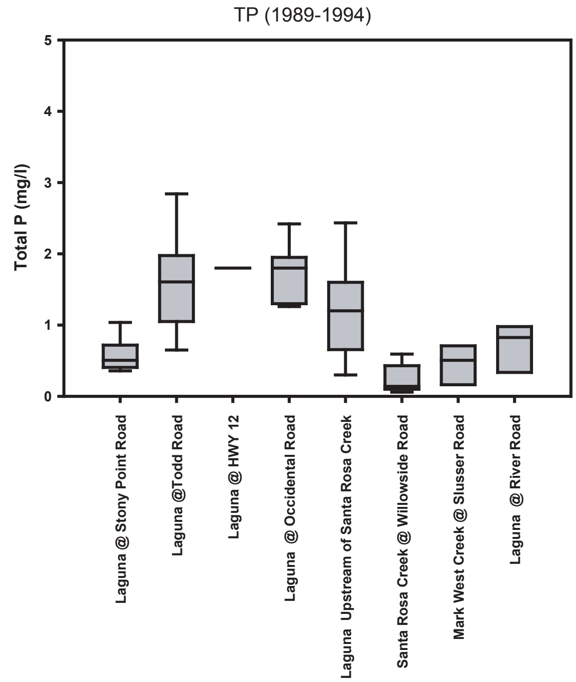


Figure 5-35 TP concentrations for 1989-1994 by sampling locations

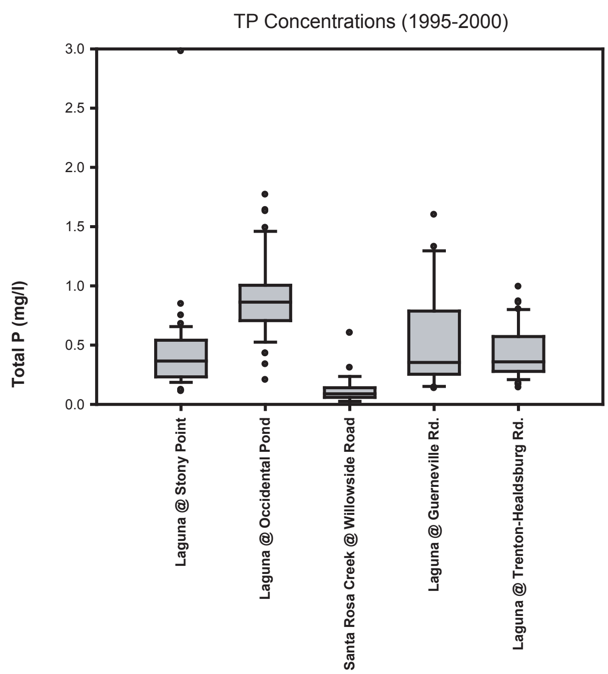


Figure 5-36 TP concentrations for 1995-2000 by sampling locations

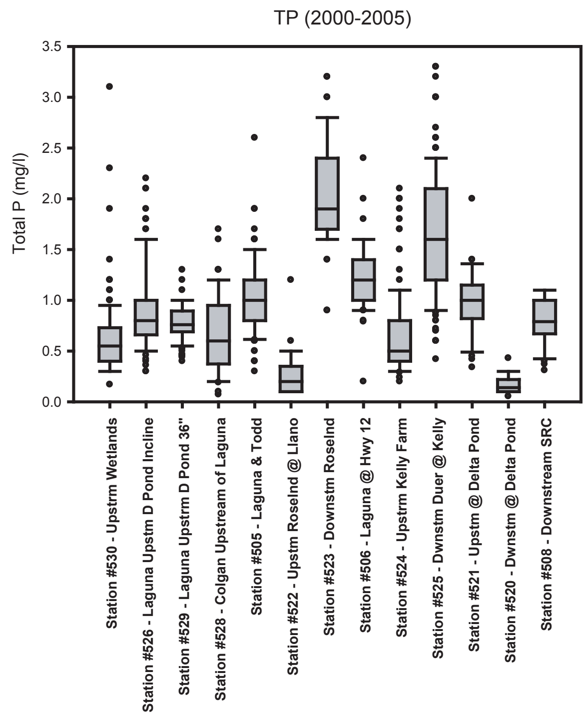


Figure 5-37 TP concentrations for 2000-2005 by sampling locations

Ranges of current nutrient concentrations

The following tables (Table 5-12 to Table 5-15) list the range of concentrations observed at different locations of the Laguna from 2004 to 2006 (after the Geyser Disposal Project).

Table 5-12 Range of concentrations for total ammonia (mg/l)

Total ammonia	Median	Mean	Min	Max	Count
Station #530 Laguna Upstream Wetlands	0.6	0.55	0.1	1	11
Station #504 Laguna & Llano	0.75	0.75	0.7	0.8	2
Station #529 Laguna Upstream D Pond	0.59	0.53	0.26	0.8	23
Station #526 Laguna Upstream D Pond	0.6	0.60	0.25	1	15
Station #527 Laguna Downstream D Pond	0.55	0.55	0.5	0.6	3
Station #528 Colgan Upstream	0.48	0.59	0.22	2.8	23
Station #505 Laguna & Todd	0.5	0.49	0.1	1.5	24

Station #506 Laguna @ Hwy 12	0.38	0.38	0.38	0.38	1
Station #524 Upstream Kelly	0.37	0.37	0.2	0.6	26
Station #525 Downstream Duer	0.4	0.42	0.3	0.6	26
Station #521 Laguna Upstream @ Delta	0.25	0.28	0.1	0.5	13
Station #508 Laguna Downstream SR Ck.	0.3	0.28	0.1	0.6	13
Station #520 SR Ck. Downstream @Delta	0.32	0.31	0.2	0.4	12
Station #515 SR CK. Upstream	0	0.00	0	0	1

Table 5-13 Range of concentrations for nitrate (mg/l)

Nitrate	Median	Mean	Min	Max	Count
Station #530 Laguna Upstream Wetlands	1.10	1.13	0.41	1.80	11
Station #504 Laguna & Llano	1.65	1.65	1.60	1.70	2
Station #529 Laguna Upstream D Pond	1.30	1.55	0.50	4.60	23
Station #526 Laguna Upstream D Pond	1.50	1.66	0.45	3.80	15
Station #527 Laguna Downstream D Pond	3.20	2.67	1.50	3.30	3
Station #528 Colgan Upstream	2.20	2.10	0.42	3.40	23
Station #505 Laguna & Todd	2.85	2.96	0.40	5.70	24
Station #506 Laguna @ Hwy 12	0.89	0.89	0.89	0.89	1
Station #524 Upstream Kelly	0.50	0.52	0.22	0.90	26
Station #525 Downstream Duer	2.50	3.38	0.59	6.70	26
Station #521 Laguna Upstream @ Delta	0.69	0.87	0.20	2.80	13
Station #508 Laguna Downstream SR Ck.	0.71	0.75	0.20	1.20	13
Station #520 SR Ck. Downstream @Delta	0.58	0.64	0.46	1.10	12
Station #515 SR CK. Upstream	1.00	1.00	1.00	1.00	1

Table 5-14
Range of concentrations for organic nitrogen (mg/l)

Organic N	Median	Mean	Min	Max	Count
Station #530 Laguna Upstream Wetlands	0.70	0.69	0.10	1.80	11
Station #504 Laguna & Llano	2.00	2.00	0.10	3.90	2
Station #529 Laguna Upstream D Pond	0.69	0.81	0.20	2.20	23
Station #526 Laguna Upstream D Pond	1.00	1.04	0.20	1.80	15
Station #527 Laguna Downstream D Pond	0.60	0.60	0.40	0.80	3
Station #528 Colgan Upstream	0.80	0.90	0.40	1.60	23
Station #505 Laguna & Todd	1.00	0.96	0.10	2.10	24
Station #506 Laguna @ Hwy 12	1.00	1.00	1.00	1.00	1
Station #524 Upstream Kelly	0.53	0.73	0.30	1.90	26
Station #525 Downstream Duer	0.84	0.86	0.20	1.70	26
Station #521 Laguna Upstream @ Delta	0.90	0.84	0.10	1.60	13
Station #508 Laguna Downstream SR Ck.	0.51	0.65	0.10	1.50	13
Station #520 SR Ck. Downstream @Delta	0.50	0.55	0.24	1.10	12
Station #515 SR CK. Upstream	0.60	0.60	0.60	0.60	1

Table 5-15 Range of concentrations for total phosphorus (mg/l)

Total P	Median	Mean	Min	Max	Count
Station #530 Laguna Upstream Wetlands	0.60	0.59	0.39	0.80	11
Station #504 Laguna & Llano	0.69	0.69	0.62	0.75	2
Station #529 Laguna Upstream D Pond	0.60	0.63	0.44	0.90	23
Station #526 Laguna Upstream D Pond	0.65	0.65	0.36	0.85	15
Station #527 Laguna Downstream D Pond	0.70	0.70	0.54	0.85	3
Station #528 Colgan Upstream	0.57	0.60	0.20	1.10	23
Station #505 Laguna & Todd	0.98	0.96	0.61	1.40	24

Station #506 Laguna @ Hwy 12	0.79	0.79	0.79	0.79	1
Station #524 Upstream Kelly	0.55	0.61	0.36	1.30	26
Station #525 Downstream Duer	1.15	1.22	0.42	1.90	26
Station #521 Laguna Upstream @ Delta	0.81	0.80	0.34	2.00	13
Station #508 Laguna Downstream SR Ck.	0.68	0.65	0.31	0.94	13
Station #520 SR Ck. Downstream @Delta	0.12	0.17	0.05	0.43	12
Station #515 SR CK. Upstream	0.11	0.11	0.11	0.11	1

5.2.3 Current status and factors influencing the DO dynamics

The following section describes the data analysis of existing DO data for the Laguna de Santa Rosa. The analysis explores the spatial and temporal patterns of DO impairment at different scales (inter-annual, seasonal and diurnal, temporally, and by reach and water column scale, spatially). One of the main objectives of the analysis is to better understand when and where DO impairment occurs and to form the basis for inferring and identifying processes and factors that contribute to the DO impairment. The analysis also provides an update of current status with respect to DO in the Laguna. In the analysis we review previous studies of nutrient and dissolved oxygen dynamics in the Laguna by Otis (2006) to provide a synthesis of the current understanding of the DO dynamics in the Laguna.

Available data for analysis

The available data for analysis includes: 1) short-interval DO data collected by the City of Santa Rosa for the period of 1998 to 2006; 2) short-interval DO data collected by *Ludwigia* Abatement Project team during the summers of 2005 and 2006; 3) grab samples collected by NCRWQCB for the period of 1995 to 2000; and 4) DO profile collected by NCRWQCB during the summers of 1997, 1998 and 1999.

- *Short-interval DO data collected by the City of Santa Rosa:* These are continuous DO data collected by the City of Santa Rosa using data sondes at 15 minute intervals, upstream and downstream of the city's wastewater discharging locations for the period of 1998 to the present. Generally there are two weeks of data each month during the discharging period (October 1 to May 14). Main sampling locations are upstream and downstream of the discharging points of 06A (Meadow Lane Pond D incline pump), 06B (Meadow Lane Pond D 36'' discharge), 12A (Delta Pond 24'' pipeline) and 12B (Delta Pond 48'' pipeline). Figure 5-38 schematically illustrates the approximate sampling locations with the number of data points for the years 2005 and 2006.
- *Short-interval DO data collected by Ludwigia Abatement Project team:* In the summer of 2005 and 2006, continuous DO data at 30 and 15 minute intervals were collected

using data sondes at three locations (SCWA WQ4/5, CDFG WQ1, CDFG WQ3) within two *Ludwigia* control areas of the Laguna (Sonoma County Water Agency Site and Department of Fish and Game Site) by *Ludwigia* Abatement Project team. The measurements were taken generally five to tweleve inches below water surface. It was noted during sampling that DO probes are subject to hydrogen sulfide fouls and resulted in some erratic readings, particularly at CDFG WQ3. CDFG WQ3 is located in an area with 80 percent *Ludwigia* cover and a shallow water depth of 2.5 feet, where sediment probably poses a big effect on water quality in the water column (Sonoma County Water Agency and Laguna de Santa Rosa Foundation, 2006). The anaerobic sediment frequently fouled the probes. The false readings due to DO probe fouling were therefore excluded from the analysis. Approximate sampling locations are shown in Figure 5-38 with total number of valid samples collected for the summers of 2005 and 2006.

- *Grab samples collected by NCRWQCB:* These are TMDL monitoring data collected by NCRWQCB at five stations (LSP-Laguna at Stony Point, LOR-Laguna at Occidental Road, LGR-Laguna at Guerneville Road, LTH-Laguna at Trenton-Healdsburg Road, and SRCWS-Santa Rosa Creek at Willowside Road) for the period of 1995 to 2000. The data are bi-weekly grab samples, with most of the samples taken before noon. The Waste Reduction Strategy (WRS) was implemented during this period to reduce nitrogen loads in the watershed and to meet EPA's criterion for unionized ammonia by phases (60% by July 1996, 70% by July 1998, and 80% by July 2000). Therefore the data from the most recent years will be closer to current conditions. For this reason we used the data from the most recent years of 1998 to 2000.
- *DO profile collected by NCRWQCB:* These are data from the water column study at several locations in the Laguna (LOR1, LOR2, LOR3, SEB1, SEB2, SEB3 (SEB-Laguna @ Sebastopol), including profiles of DO, temperature, specific conductivity and pH, conducted by Peter Otis of RWQCB for the summers of 1997, 1998, and 1999.

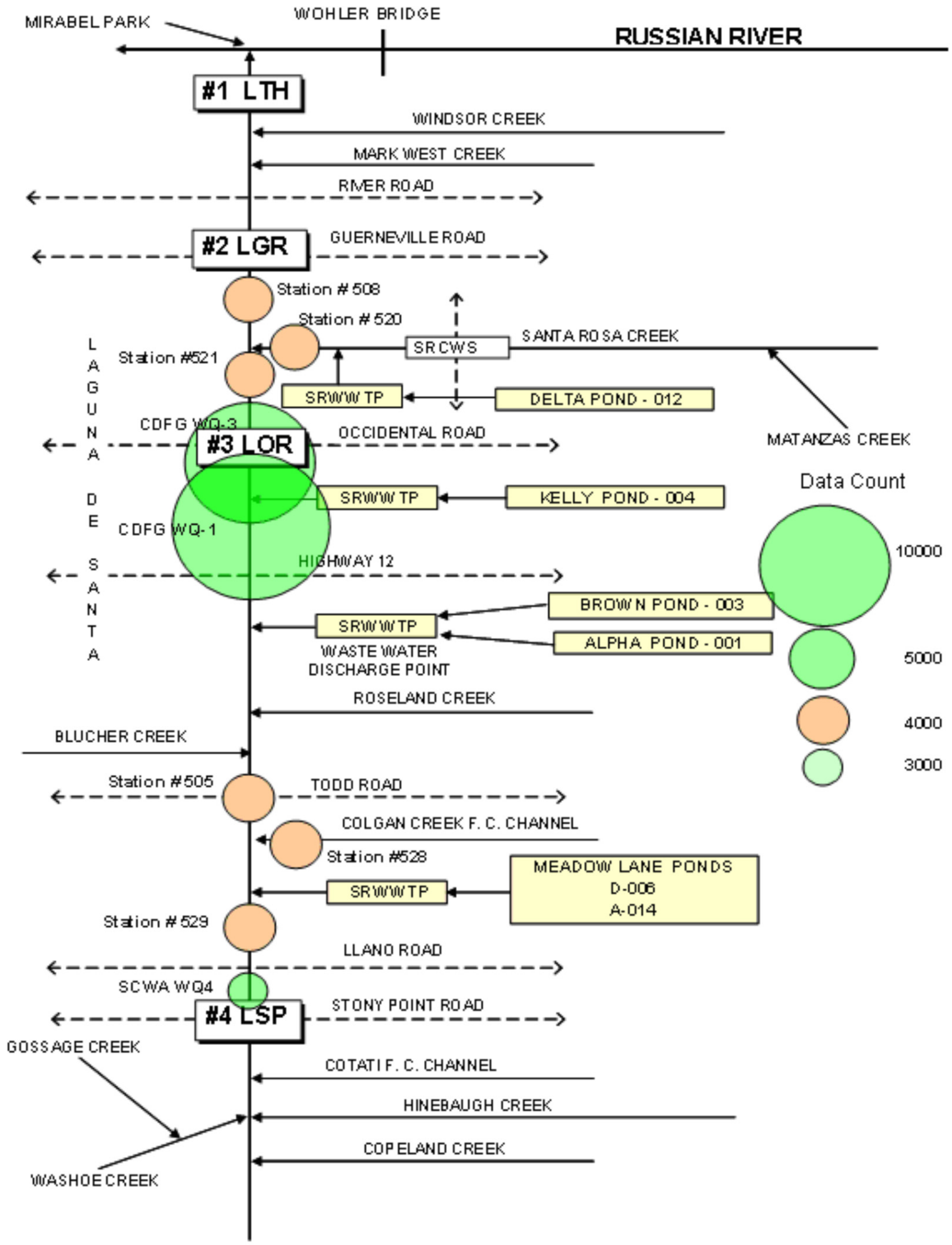


Figure 5-38 Locations and total number of data collected for dissolved oxygen.
Short-interval (15 or 30 minutes) DO monitoring
Orange: City of Santa Rosa (spring/winter 2005 and 2006)
Green: *Ludwigia* Control Project team (summer 2005 and 2006)

Spatial and temporal patterns of dissolved oxygen

Temporal pattern–inter-annual

Figure 5-39 through Figure 5-44 show the range of DO concentrations at different monitoring locations collected by City of Santa Rosa during discharging months (winter/spring) for 1998-2006, compared to the Basin Plan objective (minimum 7 mg/l at all times). The general observations for these data are for the monitoring period, there is no clear trend of increase in DO concentrations, even the nutrient concentrations have shown large decreases. Some stations (e.g., Station #529 upstream of discharge point and Station #505 Laguna Todd Road) even show a trend of decreasing DO below basin plan objectives. It is not clear what is causing this downward trend. A likely cause may be due to the infestation of *Ludwigia* which can consume oxygen when decaying. Further analysis is needed to identify factors that are driving the observed trend. The collected data also indicated large month-to-month variation.

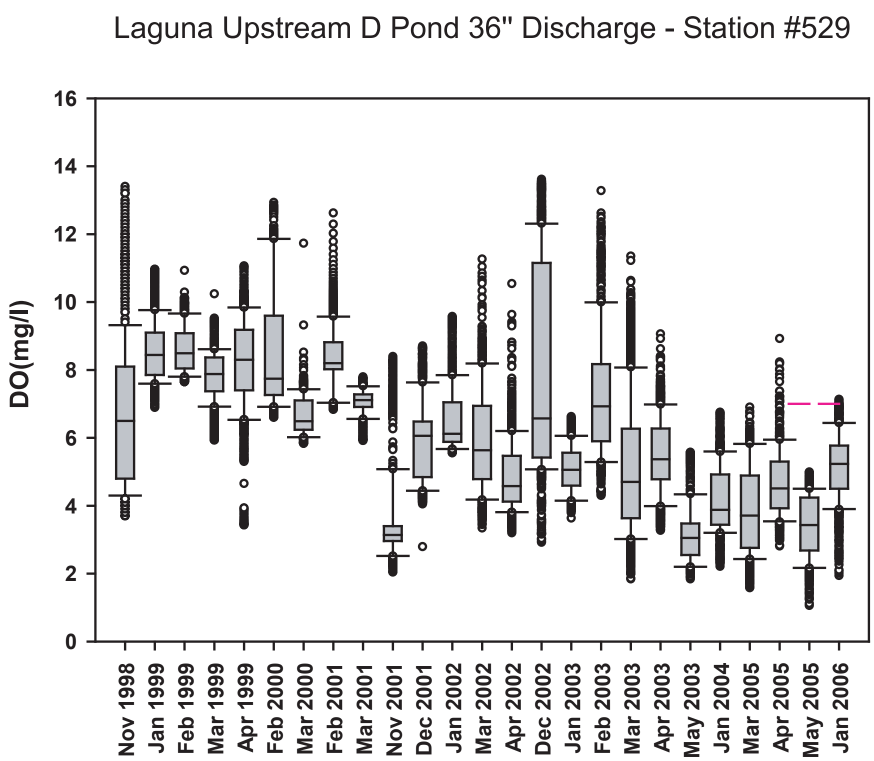


Figure 5-39 Range of DO concentrations by sampling months at Laguna upstream of D Pond 36" discharge

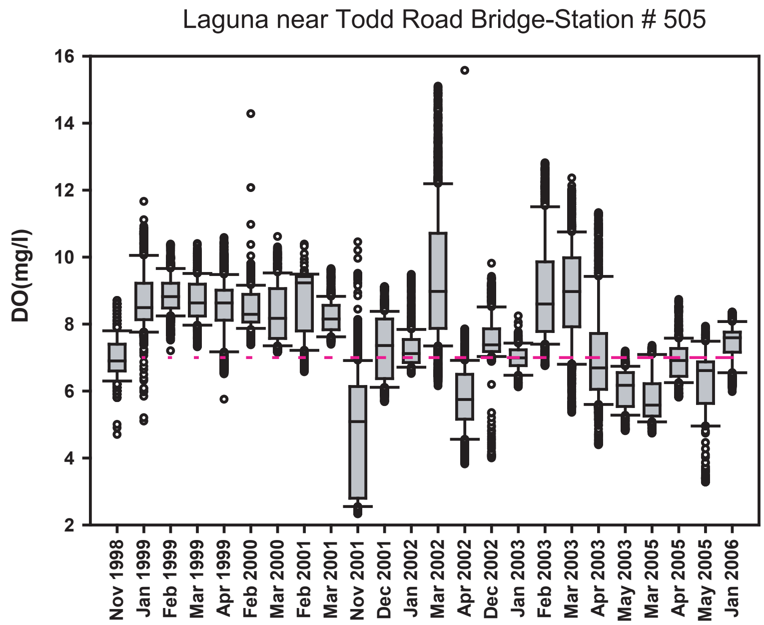


Figure 5-40 Range of DO concentrations at Laguna near Todd Road bridge

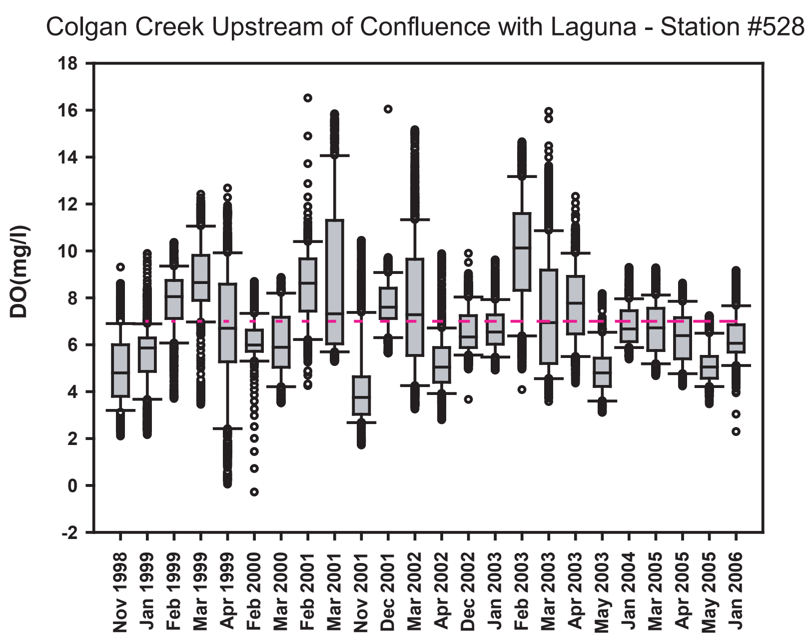


Figure 5-41 DO at Colgan Creek upstream of confluence with Laguna

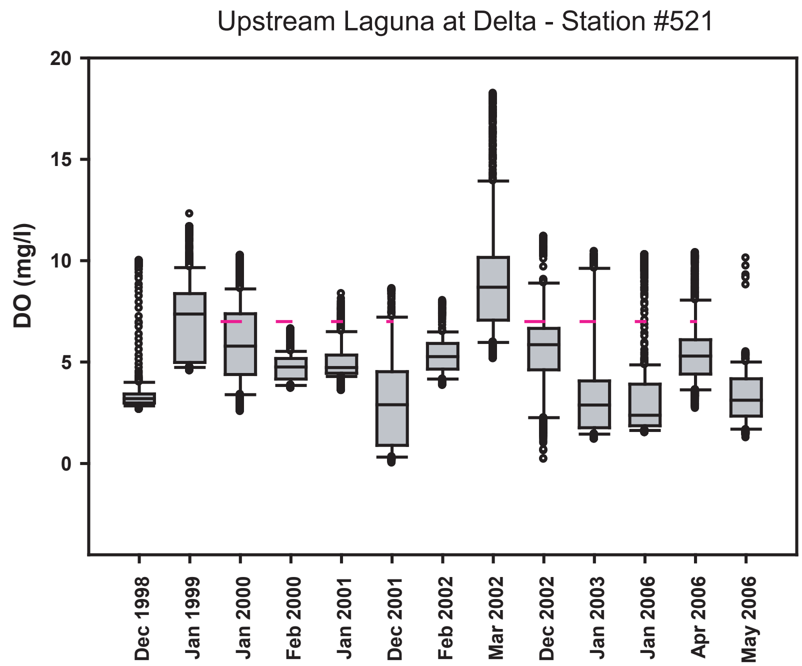


Figure 5-42 DO at Laguna upstream of Delta Pond

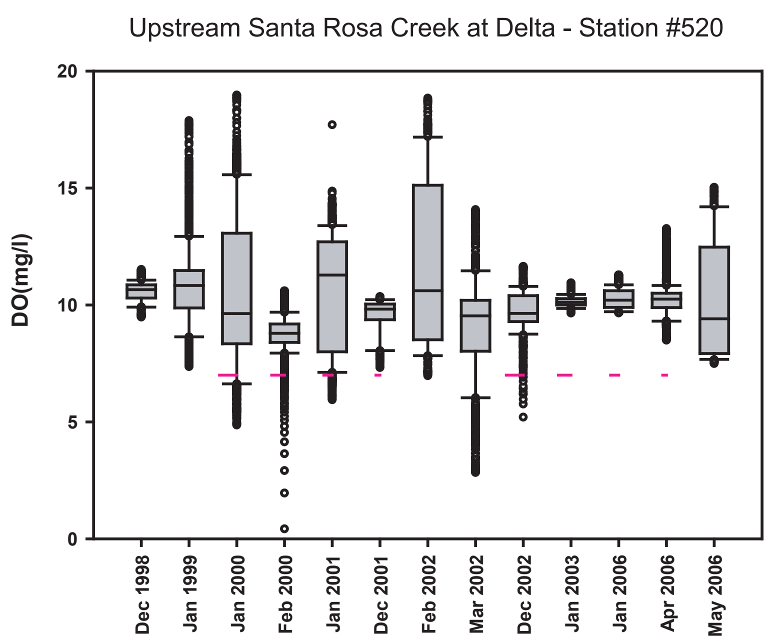


Figure 5-43 DO at Laguna near Santa Rosa Creek

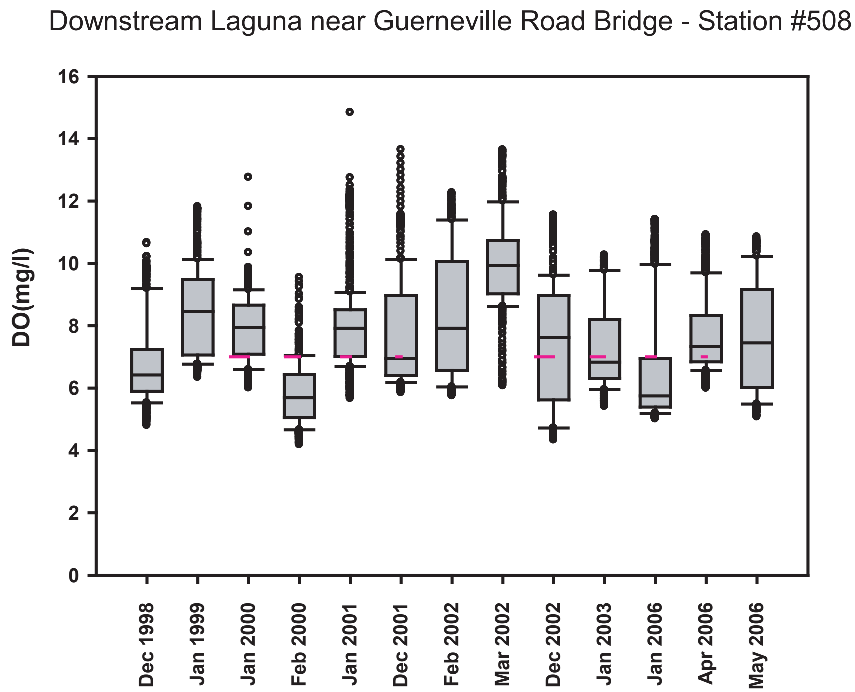


Figure 5-44 DO at Laguna near Guerneville Road

While the data presented above were based on monitoring during winter/spring months, Figure 5-45 through 5-47 show the range of DO concentrations at the three sampling locations in the *Ludwigia* control areas for the summers of 2005 and 2006. CDFG WQ-1, which is upstream of the *Ludwigia* control area, generally has moderate DO. For summer 2005, 75th percentiles of DO in both July and August were below 7 mg/l. Median DO concentrations appear to be higher in 2006. The minimum DO in summer 2006 also seem slightly higher than 2005, although two years of data are probably not sufficient for inferring any inter-annual temporal trend.

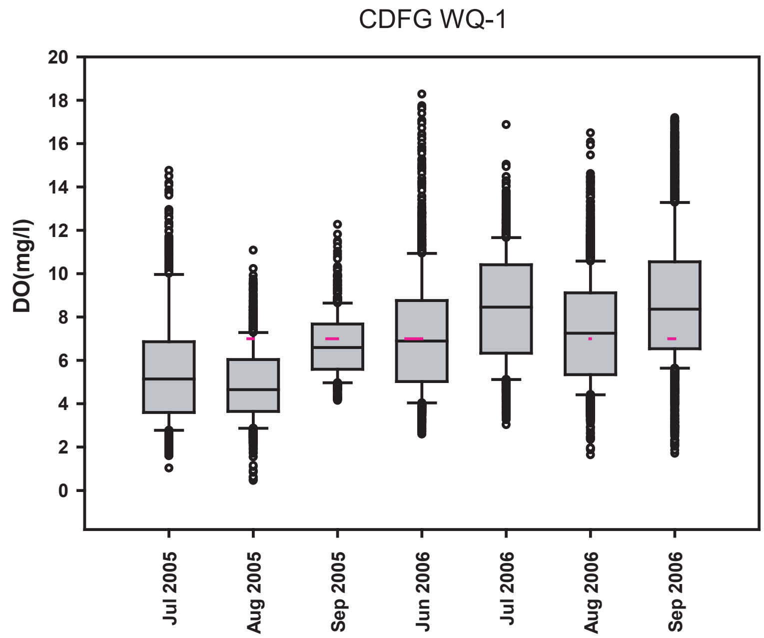


Figure 5-45 DO at CDFG WQ-1 during summer 2005 and 2006

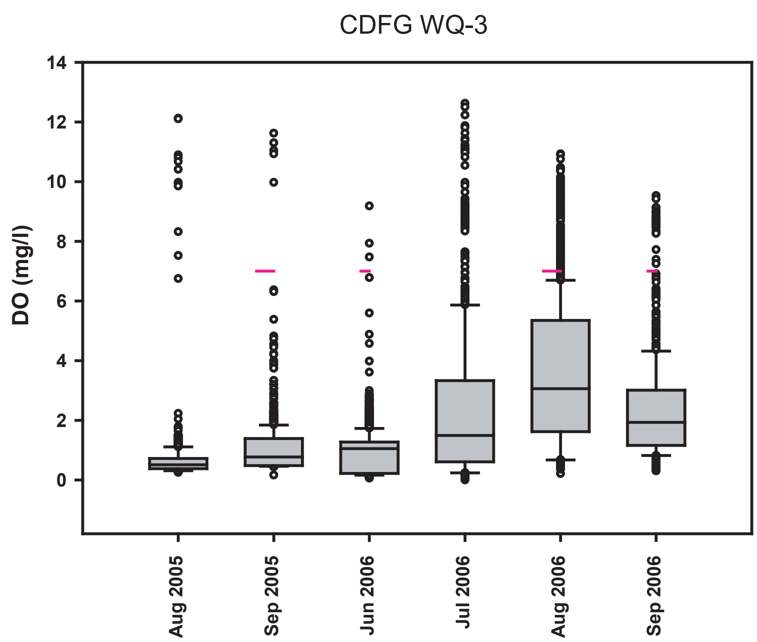


Figure 5-46 DO at CDFG WQ-3 during summer 2005 and 2006

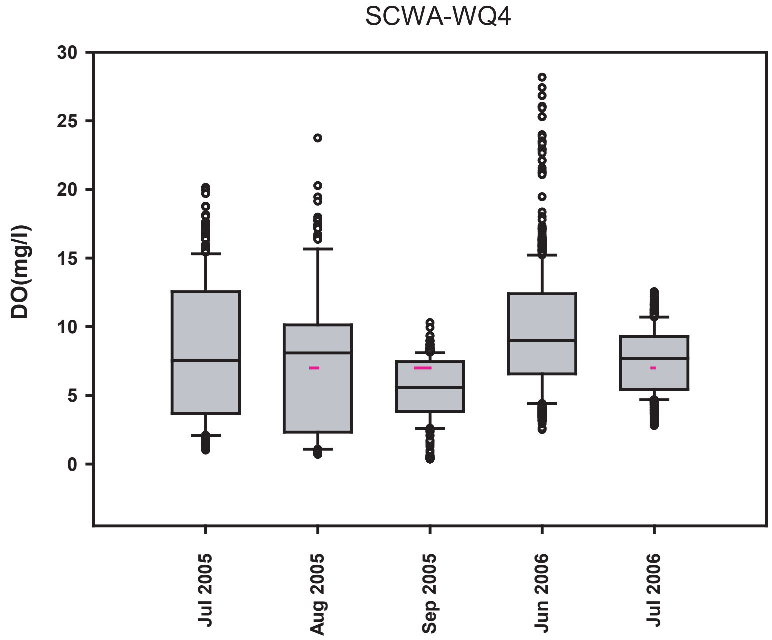


Figure 5-47 DO at SCWA-WQ4 during summer 2005 and 2006

DO concentrations at CDFG WQ-3 were severely depressed due to shallow water susceptible to a large influence from the sediment. DO concentrations at CDFG WQ-3 in summer 2005 were below 2 mg/l for over 90 percent of the time (Figure 5-46). DO concentrations during the summer of 2006 appear to be higher, but still remain at very low levels. Data for summer 2006 also indicated an increase in the diurnal fluctuations in DO. CDFG WQ-3 is located within the *Ludwigia* control area. It is possible that *Ludwigia* removal has opened up the water column promoting algal growth that contributes to the more evident diurnal pattern and higher median DO concentrations. However, minimum DO at CDFG WQ-3 during summer months remains near zero.

DO concentrations at SCWA-WQ4, downstream of *Ludwigia* control area in the Sonoma County Water Agency site, did not show marked difference between the two years; however, it seems that the minimum DO for 2006 are slightly higher than 2005.

Temporal pattern – seasonal

Because continuous DO measurements were not available at the same locations for different seasons, biweekly grab sample DO measurements taken by the NCRWQCB for the period of 1999 to 2000, which cover 12 months of the year at five locations were used to explore the seasonal pattern. During the period of October 1999 to August 2000, LSP has 13 samples out of 23 samples below the Basin Plan objective (56%). Seasonally there appear to be low DO in both winter and summer months. Low DO was observed in the months of November through early February, April to early June, and August (Figure 5-48). Low DO in winter months indicates that processes other than algal activity (e.g. BOD/SOD due to organic carbon or TKN) are contributing to the oxygen consumption, as algae activity would be low during this time of the year. During the high flow period of late February and March, DO concentrations are generally higher.

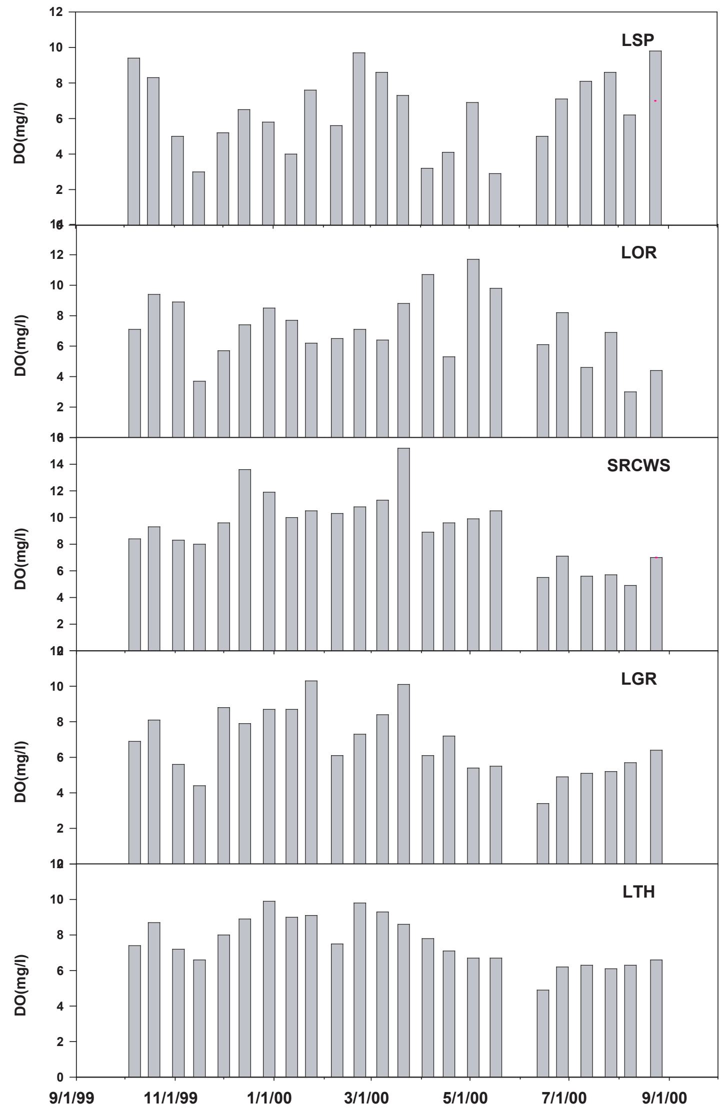


Figure 5-48 Seasonal Pattern of DO

Low DO was also observed at LOR in November 1999, April 2000 and June 2000. For SRCWS, DO concentrations are generally above the Basin Plan objective for most months of the year, with low DO occurring during the summer. LGR has low DO for the months of April to August, as well as in November. DO concentrations at the last attainment point (LTH) are generally above Basin Plan objective for most months of the year, except summer months.

Therefore, overall low DO was observed both in the winter months of November to January and the late spring/summer months of April to August at different locations in the Laguna. High flow months of February and March generally show higher DO. The observed seasonal pattern is consistent with the pattern shown in the continuous monitoring data (Figure 5-40 through Figure 5-47). As noted previously, very low DO was observed in the winter months of November to January as well as the spring/summer months.

Temporal pattern – diurnal

Continuous monitoring by the city at different locations during the WWTP winter/spring discharging period indicated that large DO swings (probably due to algal growth) are most common in March, April, and May and occasionally in January and February. In months without large DO variation (*e.g.*, January), DO is generally continuously depressed at multiple locations with less variation, and in some cases the variation may be related to flow.

Continuous monitoring data in the summer months indicated a large DO swing at SCWA WQ4/5 and CDFG WQ-1, indicating a large influence of photosynthesis activity and respiration. The magnitude of DO swing can be as high as 8 mg/L. There are large increases in DO during a certain time of the day, the respiration phase of the cycle results in lower DO that would be harmful to fish and other aquatic life. As important to the magnitude of the DO swing, baseline DO can also affect minimum DO observed. In summer 2005, CDFG WQ-3 shows continuously depressed DO below 2 mg/l without any variation. In summer 2006, some DO swing was observed as well as higher baseline DO. Figure 5-49 presents a snapshot of the diurnal pattern observed in January 2006 and summer 2006 in the Laguna. Chl-a concentrations observed in previous monitoring conducted by the Water Board from 1989 to 1994 (Table 5-16) confirmed that algal growth is evident at several locations within the Laguna. The California Nutrient Numeric Endpoint framework (Tetra Tech 2006) suggests a concentration boundary condition of 25 μg/L for impairment to WARM Beneficial Use.

Table 5-16
Average Chl-a concentrations for 1989-1994

	Chl-a (μg/l)	Count
Laguna @ Stony Point Road	25.2	25
Laguna @ Todd Road	57.0	25
Laguna @ HWY 12	43.0	19
Laguna @ Occidental Road	78.7	23
Laguna Upstream of Santa Rosa Creek	53.0	25
Santa Rosa Creek @ Willowside Road	5.7	24
Laguna @ River Road	28.8	25
Mark West Creek @ Slusser Road	24.5	10
Laguna @ Trenton-Healdsburg Road	14.0	15

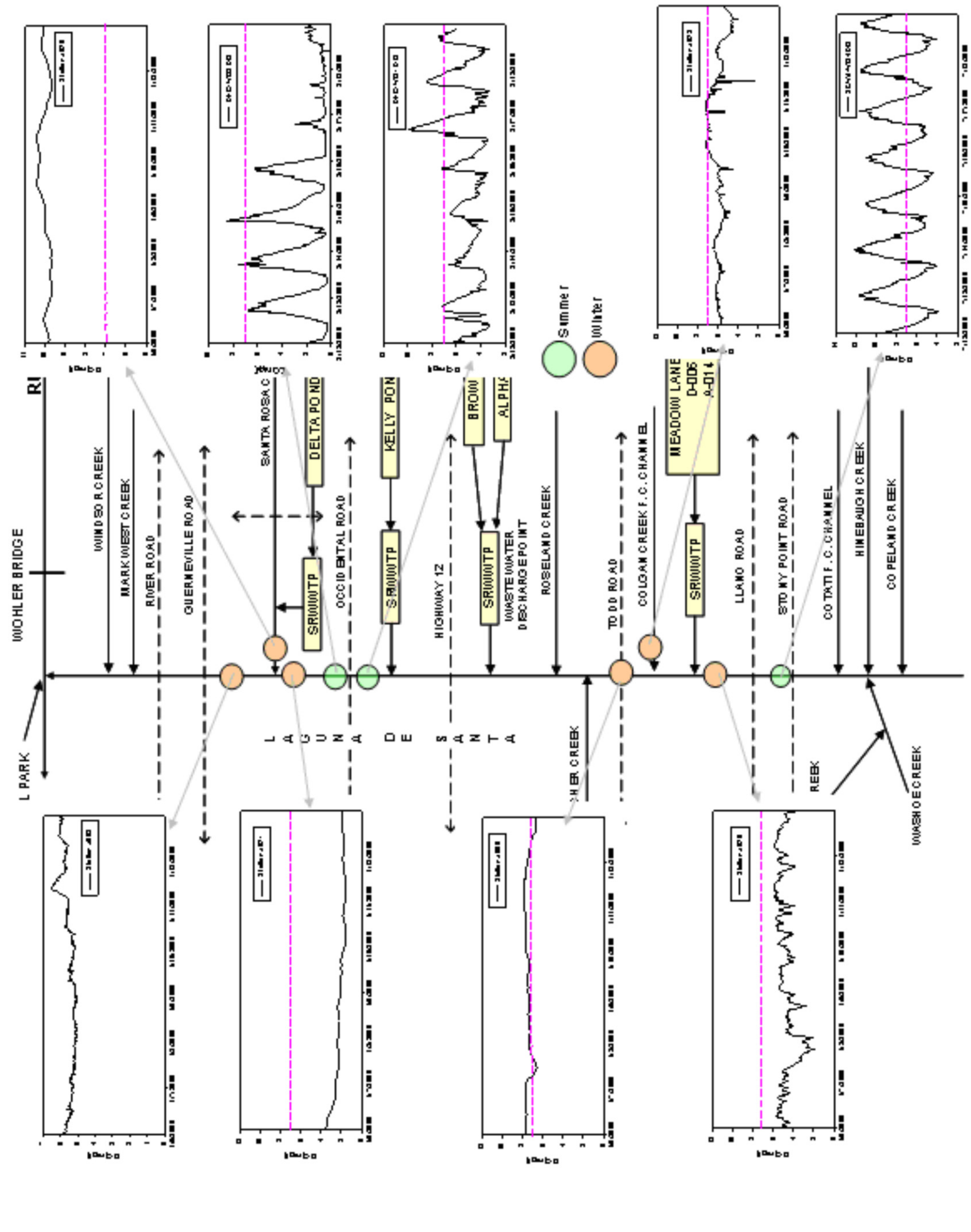


Figure 5-49 Examples of DO diurnal cycle at various locations of Laguna during winter and summer season respectively.

Spatial pattern – reach scale

For all the sampling periods in the winter/spring of 2005 and 2006, various stations (*e.g.*, Station #529, Station #521, Colgan Creek, Station #505 and Station #508) have shown over 50 percent of samples below objective (Figure 5-50). For all the summer monitoring periods of 2005 and 2006, station CDFG WQ-3 show near 100 percent of the time below the objective. The Laguna between Occidental Road and upstream of the Santa Rosa Creek confluence seems to be a critical section with prolonged DO depression, both in the winter and summer. The reach above D Pond discharge also shows depressed DO in winter months. Colgan Creek is also a critical reach with low DO. During the sampling period of winter 2005 and 2006, Santa Rosa Creek is the only stream that has DO above 7 mg/l at all times. However, as indicated in the previous analysis based on data of 1999 to 2000, low DO has also been observed in Santa Rosa Creek during the summer months.

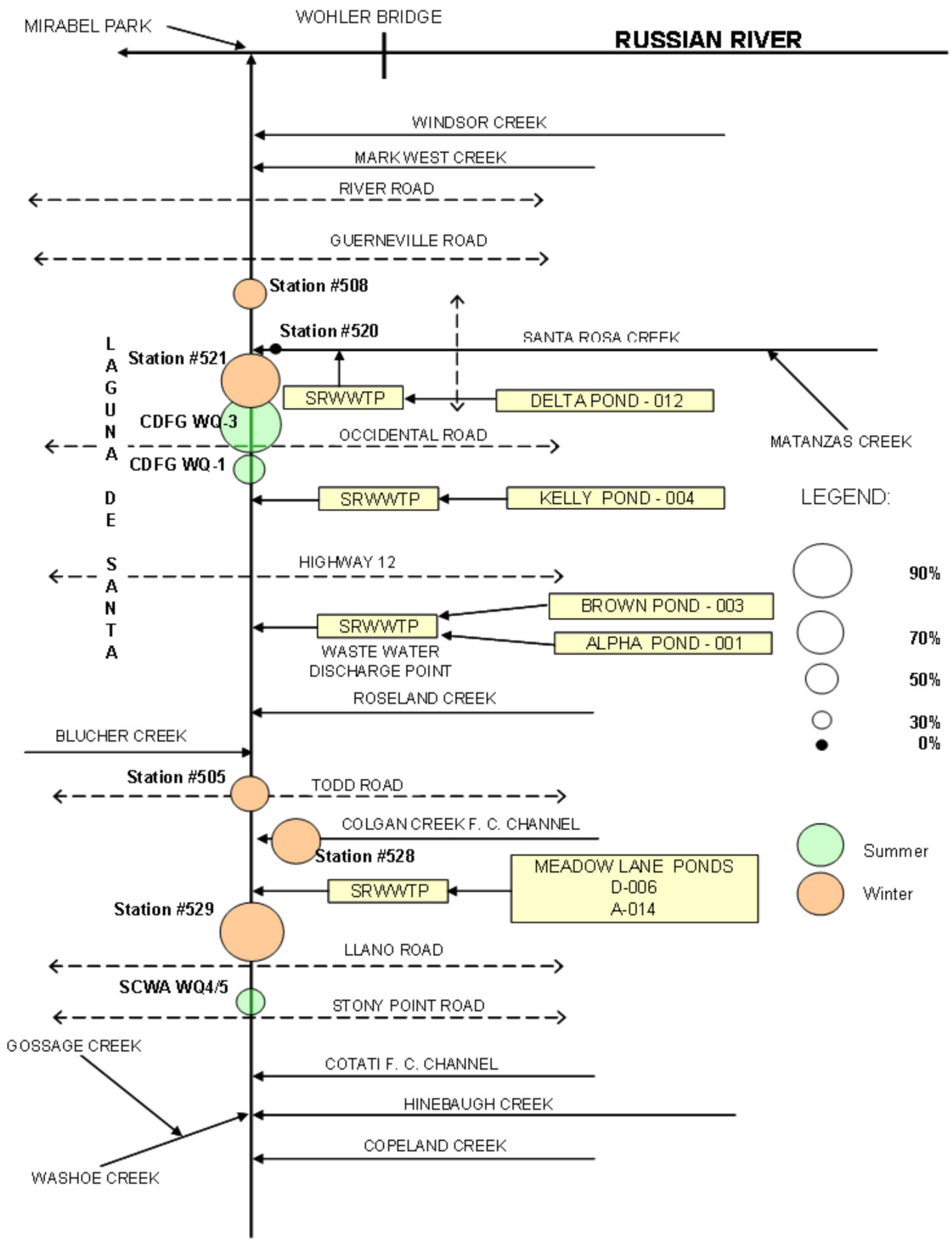


Figure 5-50 Percent of time below Basin Plan Objective (7 mg/l)
for all the samples collected in 2005 and 2006

Figure 5-51 shows the 50th percentile of the DO concentrations observed for the entire sampling period of 2005 and 2006. The 50th percentile concentrations indicated for the sampling period, for 50 percent of the time DO concentrations are at or below the concentrations shown. Similarly the reach between Occidental Road and Santa Rosa Creek has the lowest 50th percentile. The Laguna above D Pond shows very low 50th percentile of around 4.3 mg/l. Santa Rosa Creek has the highest 50th percentile. As shown in the box plot (Figure 5-53), the Laguna below Stony Point (SCWA-WQ4), the Laguna at Todd Road (Station #505), the Laguna above Occidental Road (CDFG WQ-1), and the Laguna downstream of Santa Rosa Creek (Station #508) generally show moderate DO concentrations.

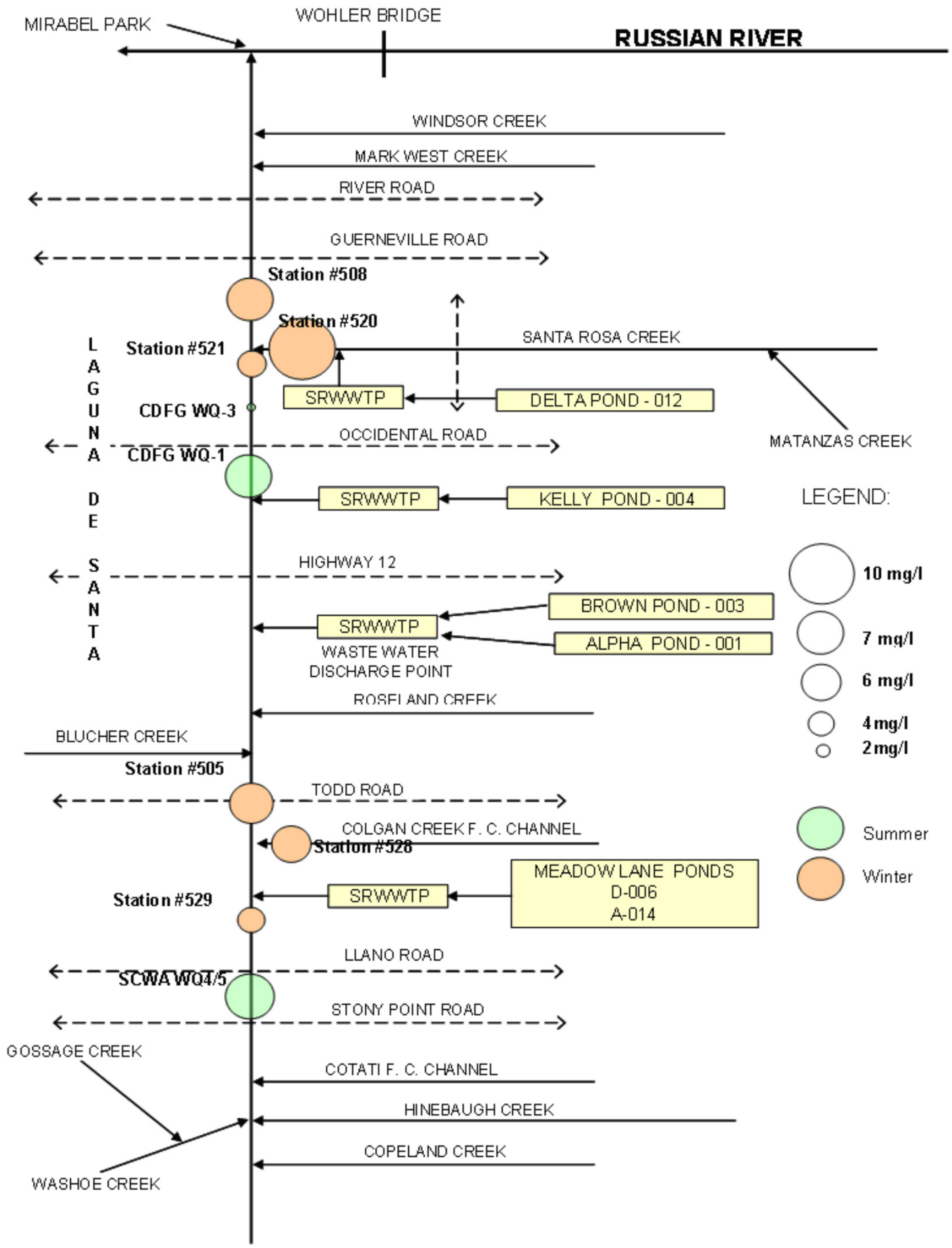


Figure 5-51 Median (50th percentile) DO concentrations
for all the short-interval samples collected in 2005 and 2006.

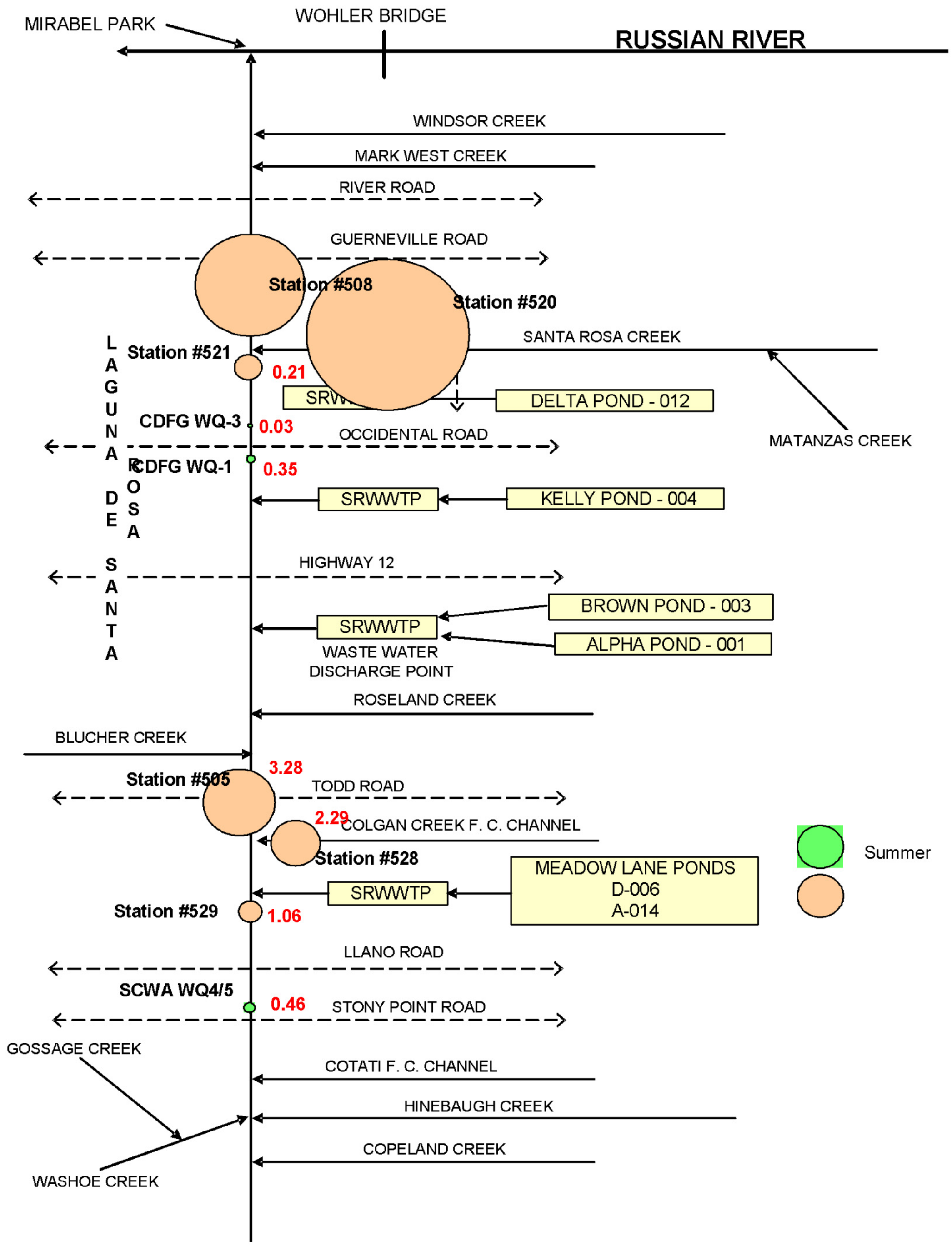


Figure 5-52 Minimum DO observed in 2005 and 2006

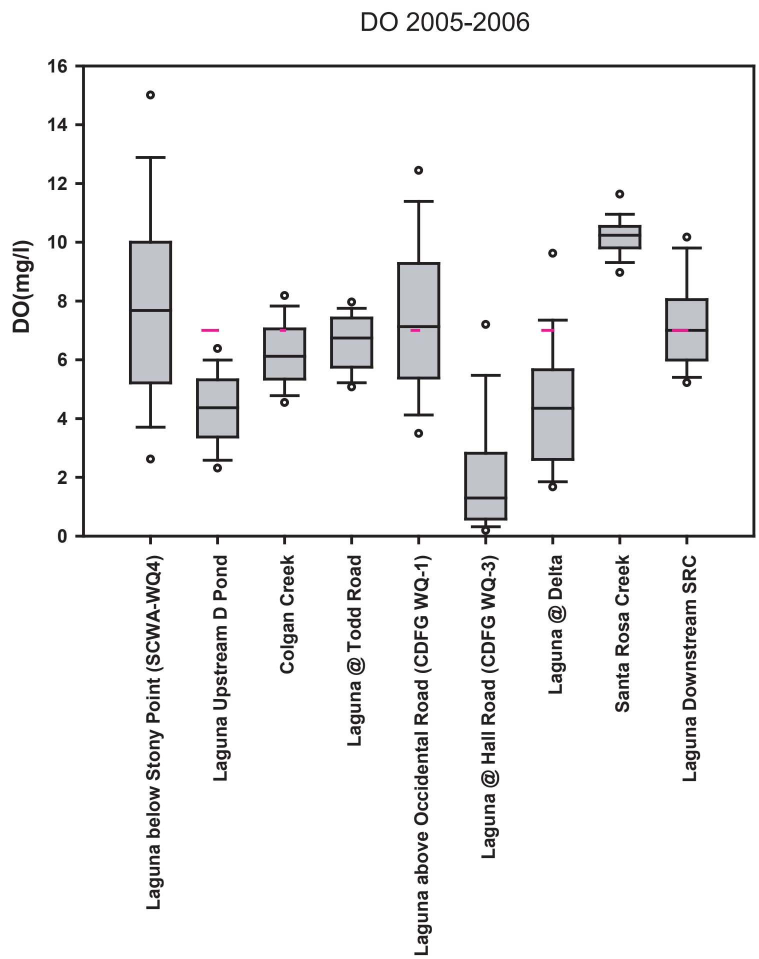


Figure 5-53 Ranges of DO observed in 2005 and 2006 at the continuously monitored locations (number of samples were shown in Figure 5-38)

Spatial pattern – water column scale

The data and results presented below are directly obtained from a nutrient/DO study conducted by RWQCB. In the summers of 1997, 1998, and 1999, profile data of DO, pH, specific conductivity and temperature were sampled at the Laguna at Occidental Road (site LOR1, LOR2, LOR3) and Sebastopol pond (SEB1, SEB2 and SEB3) in a nutrient and dissolved oxygen dynamic study conducted by RWQCB (Otis, 2006).

Figure 5-54 through Figure 5-61 illustrate the profiles for DO, pH, and specific conductivity at two sampling locations of LOR1 and SEB2 obtained through the study. The profiles shown here are typical for the sites studied. As expected, DO and temperature usually decrease with depth. Generally very low DO was observed near the bottom of the water column (as low as 1.75 mg/L at LOR1, 9/23/1998 and near zero in frequent measurements at SEB2). Low DO in the lower water column was partly attributed to stratification, which prevents transfer of oxygen to the lower water column (Otis, 2006). As shown in the temperature profile, well-established stratification is evident at LOR1 and SEB2 (Figure 5-54).. In the case when water is well mixed (10/22/1997), DO is uniformly low across the water column with slight decrease with depth. Low DO in the water column (4-5mg/l) during well- mixed conditions indicates high oxygen demand in both the water and from sediments. Specific conductivity slightly increases with depth, indicating possible releasing of constituents from the sediment. The pH profile resembles the DO profile, with higher pH in the surface of water, suggesting photosynthesis activity.

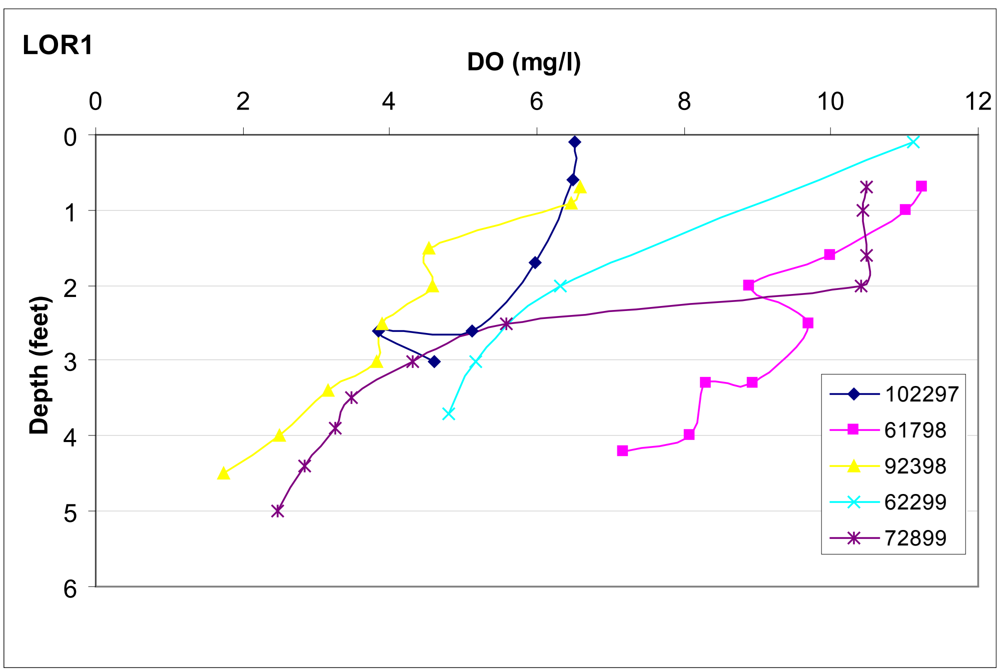


Figure 5-54 DO profile at LOR1 for summer 97, 98 and 99
(Otis, 2006)

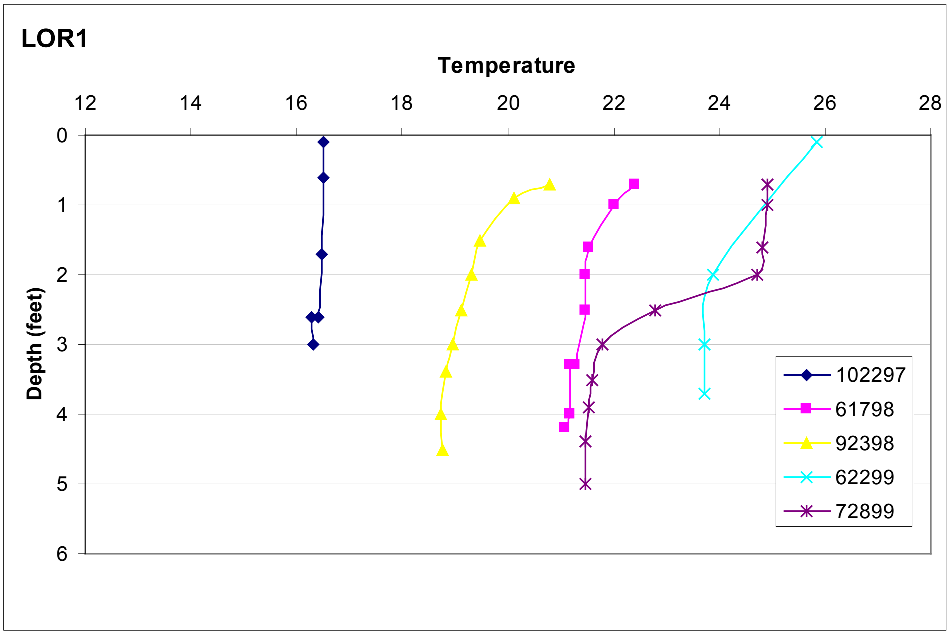


Figure 5-55 Temperature profile at LOR1 for summer 97, 98 and 99 (Otis, 2006)

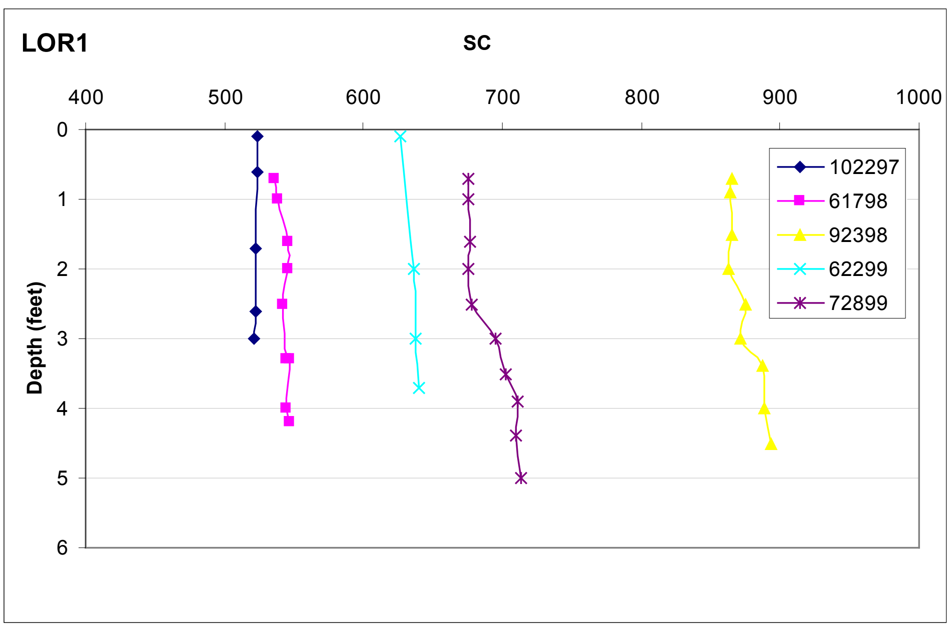


Figure 5-56 Specific conductivity profile at LOR1 for summer 97, 98 and 99 (Otis, 2006)

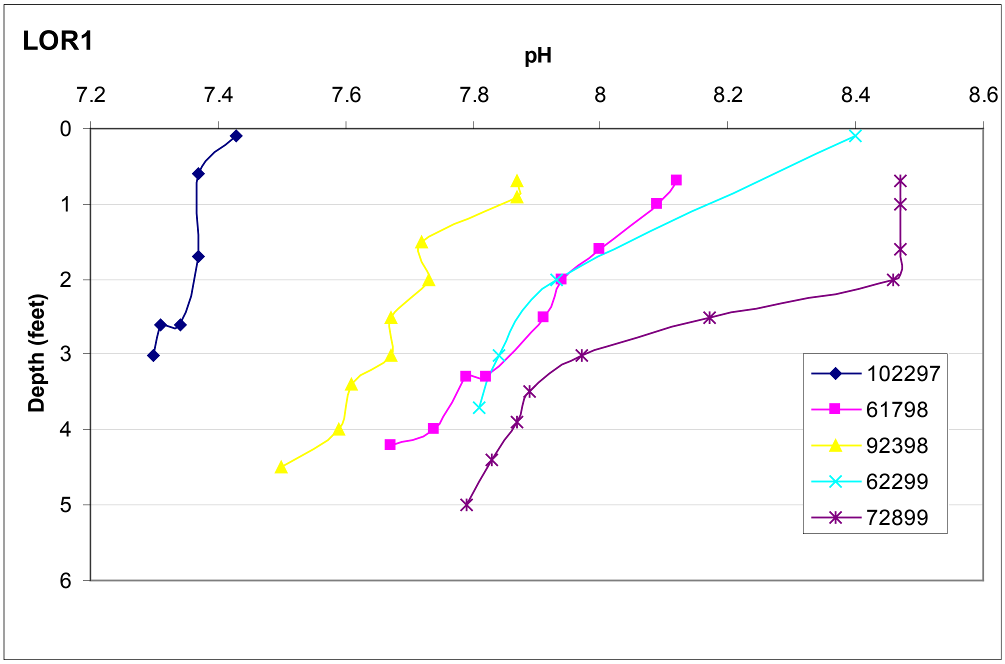


Figure 5-57 pH profile at LOR1 for summer 97, 98 and 99
(Otis, 2006)

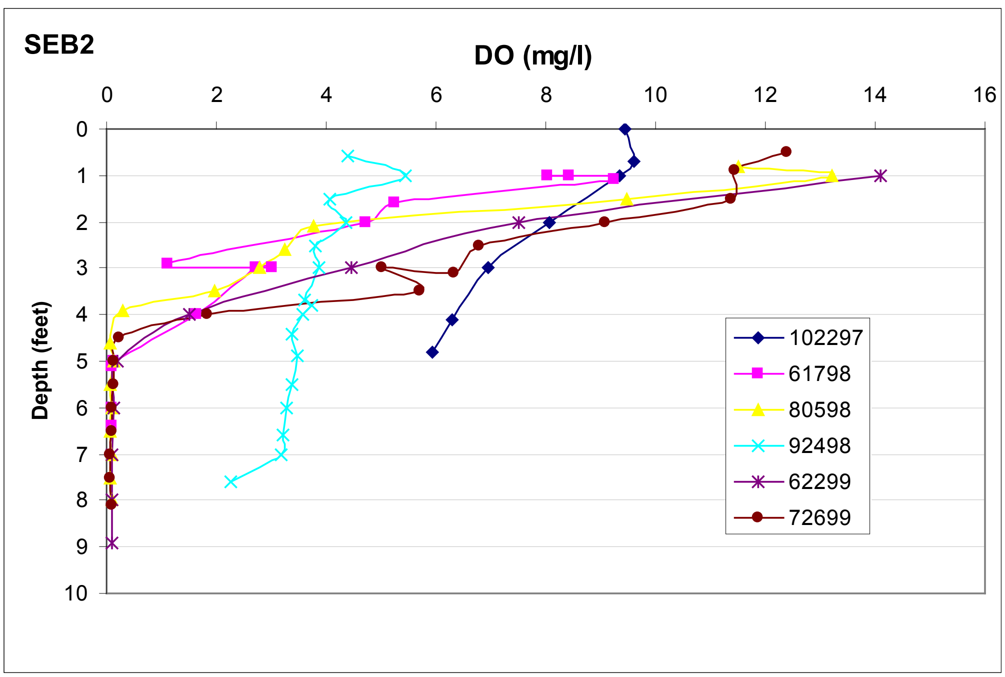


Figure 5-58 DO profile at SEB2 for summer 97, 98 and 99
(Otis, 2006)

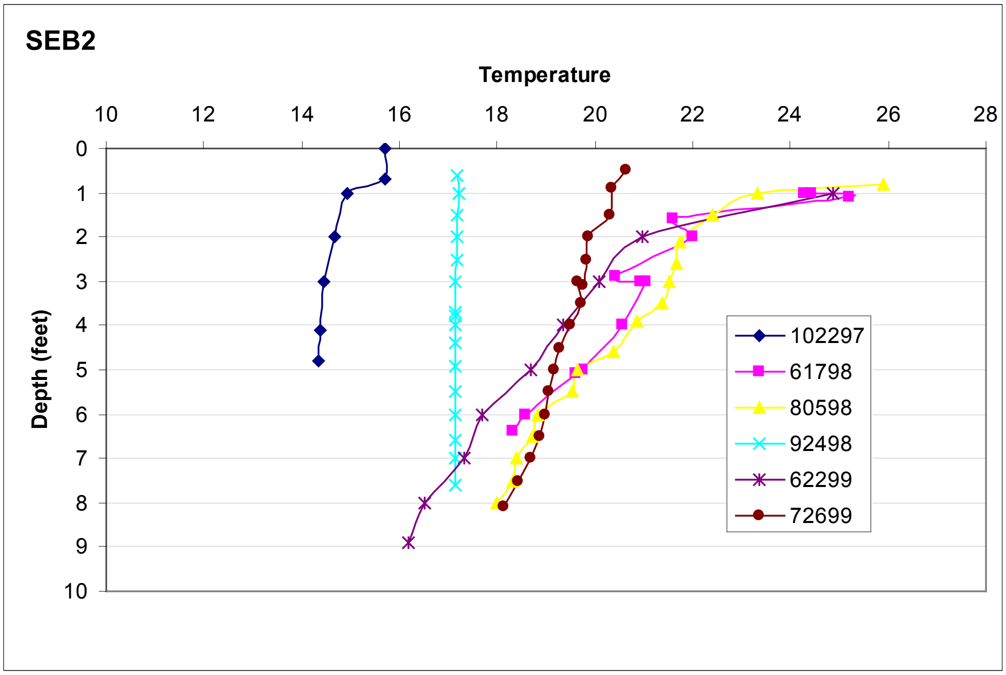


Figure 5-59 Temperature profile at SEB2 for summer 97, 98 and 99
(Otis, 2006)

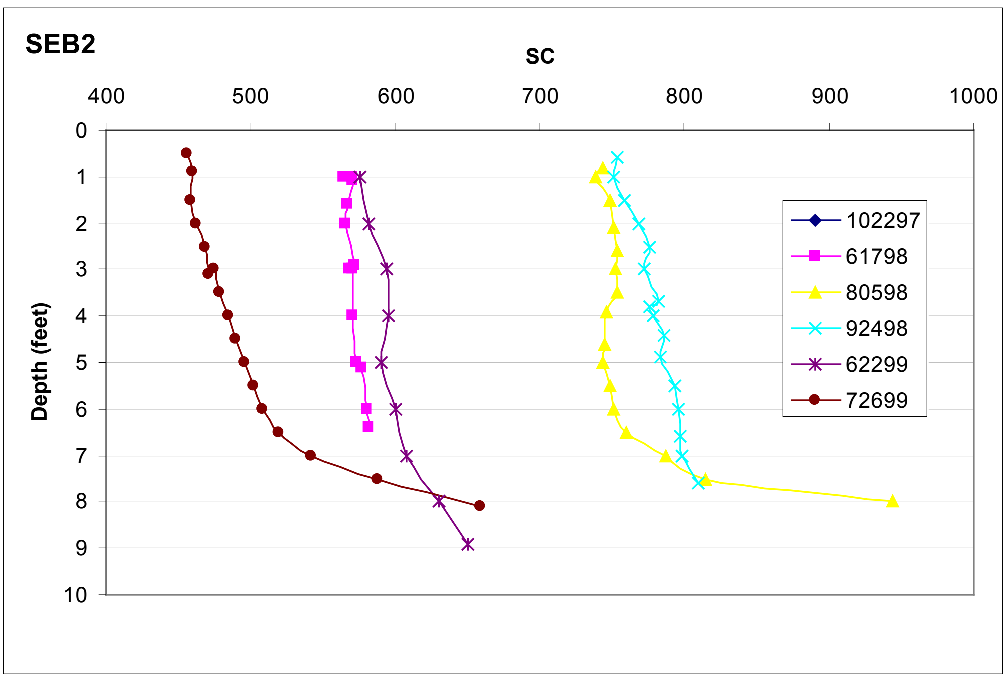


Figure 5-60 Specific conductivity profile at SEB2 for summer 97, 98 and 99
(Otis, 2006)

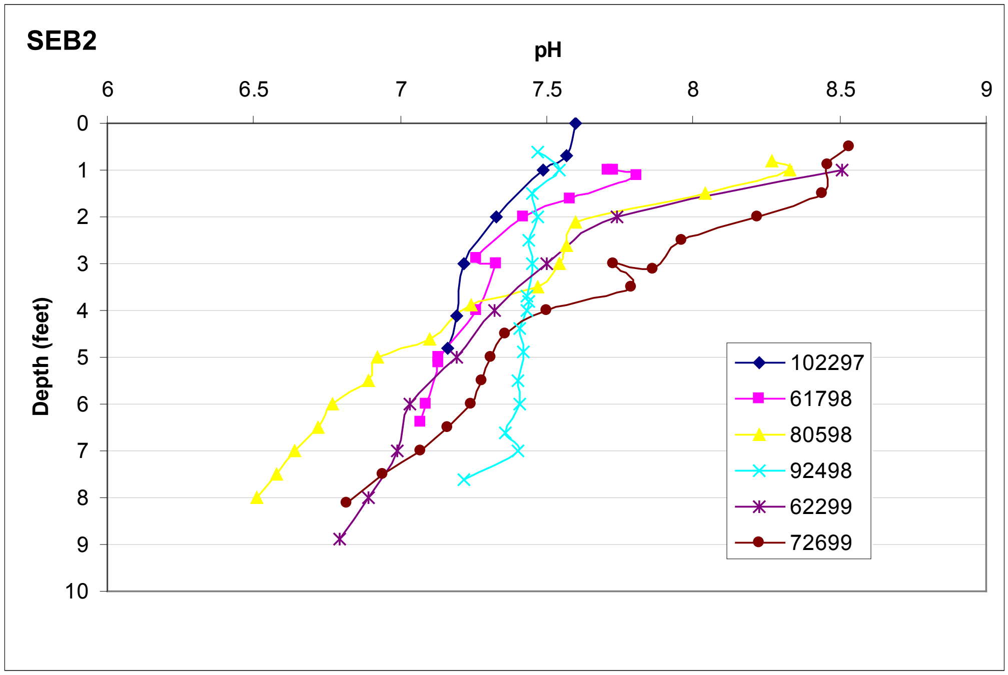


Figure 5-61 pH profile at SEB2 for summer 97, 98 and 99
(Otis, 2006)

Similar to LOR1, the DO profile at SEB2 suggested significant anoxia has developed in the lower water column. As documented in Otis (2006), the anoxic zone at SEB2 can reach 4 feet above the sediment. DO concentrations at the surface show large variations and can be as high as 14 mg/l suggesting supersaturation due to high photosynthetic activity. Stratification is also evident at SEB2. In the case when water is well mixed (9/24/1998), DO concentrations are uniformly low across the water column; however, DO remains above 0 without the development of an anoxic zone, showing that thermal stratification is an important causal factor for low DO. In the well mixed case, DO in the lower water column was above 2 mg/l. Specific conductivity at SEB2 showed very significant increases near the bottom of the water, indicating possible sources of nutrients/constituents from the sediment.

As concluded from the study, lowest DO is generally observed in deeper water with occasional anoxia near the sediment/water interface. Low DO in the lower water column is due to a combination of multiple factors including algal activity, thermal stratification, and high sediment oxygen demand.

5.2.4 Factors contributing to DO impairment

Various physical, chemical, and biological factors contribute to the DO dynamics in the Laguna. For example, physical factors such as wind and temperature that influence the mixing of water can influence the reaeration of dissolved oxygen. Chemical factors such as high TKN in the water column can consume oxygen. And noticeably, biological activity of algae and macrophytes has been attributed to causing large variation of DO in the water column. Other factors such as low flow, and high organic carbon loadings can also contribute to sustained low DO in the Laguna. The following synthesized diagram (Figure 5-62) was based on current general understanding of DO dynamics and factors identified as particularly important in the Laguna in previous studies of Otis (2006) and the data analysis presented above.

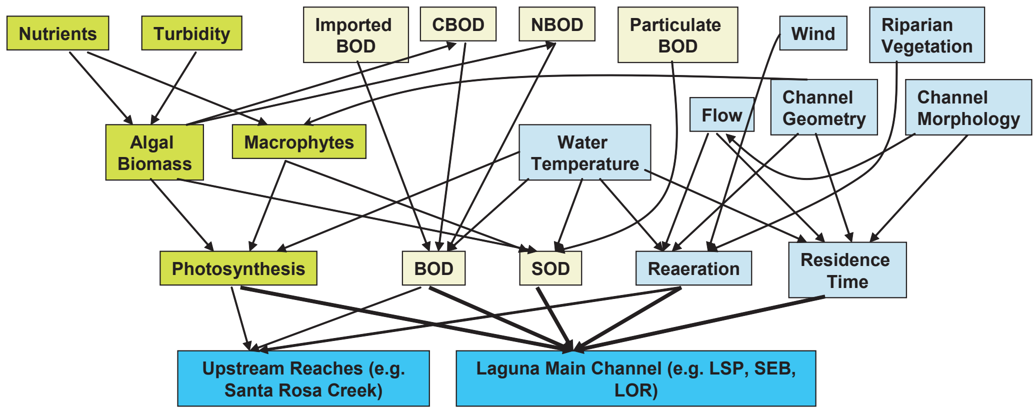


Figure 5-62 Physical, biological and chemical factors impacting DO dynamics

Physical

Flow: Flow is an important factor influencing the residence time of water and the reaeration rate, particularly in streams. Low flow and low velocity can contribute to low DO, as it will limit reaeration and promote the development of thermal stratification. Low flow also promotes settling of organic sediments, which may increase sediment oxygen demand. As indicated in the previous analysis, the high flow months of February and March generally have higher DO. There are sections in the Laguna such as LSP where low DO was observed during low flow months.

Temperature: Low flows, poor riparian cover, and degraded channel conditions can contribute to warmer column temperatures. Warmer temperatures decrease oxygen solubility while increasing rates of biological respiration, both of which increase the risk of unacceptably low DO in the water. A more detailed analysis of temperature monitoring data is not available at this time.

Channel Geometry: Channel geometry (channel width and depth) plays an important role in DO dynamics in some sections of the Laguna. There are sections in the Laguna where the channel widens, slowing down flows and leading to the formation of a ponding area. In ponding areas, flow conditions often become stagnant and wind mixing becomes an important way to reaerate the water column. As observed at LOR, in sections where the ponding area is shallow with long fetch, wind mixing is easier to result in complete mixing of water. In sections where water depth is deep, thermal stratification may establish and prevent mixing of oxygen in the lower layer. The Laguna at Sebastopol pond is a section where thermal stratification is common in summer time (SEB2, Otis, 2006). Increased depth and width and thermal stratification increases residence time of water, therefore allowing more time for biological and chemical reactions that consume oxygen to occur.

In sections with shallow water depth, DO in the water column can be more rapidly depleted by oxygen demand from bottom sediments if reaeration is limited. Shallow water depth also allows sunlight to penetrate to the bottom of the water and promotes benthic algal growth, which adds oxygen during the day from photosynthesis but depletes oxygen at night from respiration. The shallow water depth also allows rooted macrophytes to grow, and dense coverage by macrophytes can further reduce reaeration rates. LSP is a section with shallow water depth. In this section, growth of *Ludwigia* is abundant and low DO was observed. Also as observed in CDFG WQ-3 shown in previous analysis, shallow water depth and abundance of *Ludwigia* resulted in prolonged depression of DO during the summer time.

Channel Morphology: Channel morphology such as gradient, bottom roughness, and sediment can influence flow and residence time of water. Sediments have been deposited in the Laguna. It was hypothesized that the deposited sediments in some cases can form sediment plugs serving as in-stream dams that prevent water from flowing downstream. The water behind these "sediment plugs" can become stagnant without mixing, promoting algae and macrophytes growth, resulting in low DO. The infestation of *Ludwigia* also increases channel bottom roughness and decreases flow velocity, which can influence DO reaeration.

Riparian Vegetation and Wind: The lack of riparian vegetation can result in an increase in water temperature, which can contribute to low DO conditions. In some areas, lack of riparian vegetation cover may result in higher surface temperature and promote thermal stratification as observed in SEB2. In some cases, dense riparian vegetation, however, can reduce the effect of wind mixing.

Chemical

Decomposition of organic carbon in water column and particulate organic matter in sediments consumes oxygen. Organic carbon can be from aquatic sources, fom benthic and planktonic algae and plants, as well as from terrestrial sources of urban/agricultural/forest runoff and point source. The oxygen demand can also be originated from nitrification of nitrite and ammonia to nitrate. Organic nitrogen can be decomposed into ammonia, which also contributes to oxygen demand in nitrification.

Therefore the chemical factors of high nutrient (ammonia and organic nitrogen, TKN) and organic carbon loadings can directly contribute to the oxygen demand in water. High nutrient loadings (phosphate, nitrate, ammonia) can also promote primary production of algae and macrophytes in the water column, which when settled to sediment result in sediment oxygen demand. High concentrations of various forms of nutrients (phosphate, nitrate, ammonia, organic nitrogen) and BOD loadings have been observed in various sections of the Laguna. As indicated in the previous sections, sediment oxygen demand contributes significantly to low DO.

Biological

The biological factors of algae and *Ludwigia* growth undoubtly can contribute to DO dynamics. The photosynthesis and respiration activity of algae and macrophytes can result in large DO swings, as demonstrated in previous sections. Limited algal concentration monitoring results presented in Section 5.2.3 suggests that high algae concentrations are occurring within the Laguna. The aerobic bacterial decomposition of detrital material derived from algae and plants consumes oxygen and is the primary contributor to measured BOD and SOD.

Based on the description in Otis (2006), the following discussion presents several scenarios of the combination of different factors that contribute to low DO (Figure 5-63 through Figure 5-65).

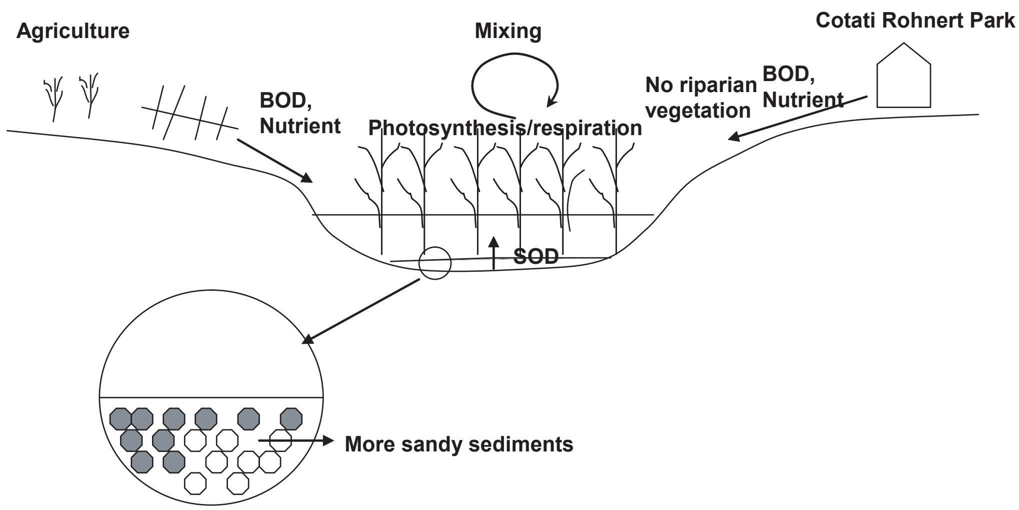


Figure 5-63 Preliminary DO conceptual model at the Laguna at Stony Point (LSP)

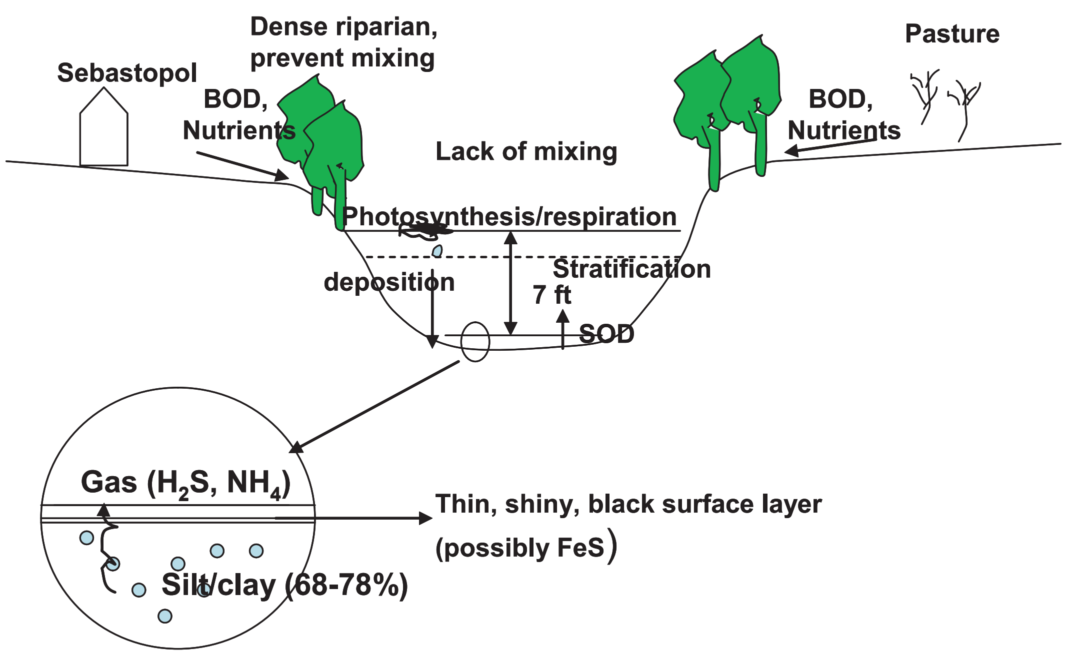


Figure 5-64 Preliminary DO conceptual model for the Laguna at Sebastopol Pond (SEB)

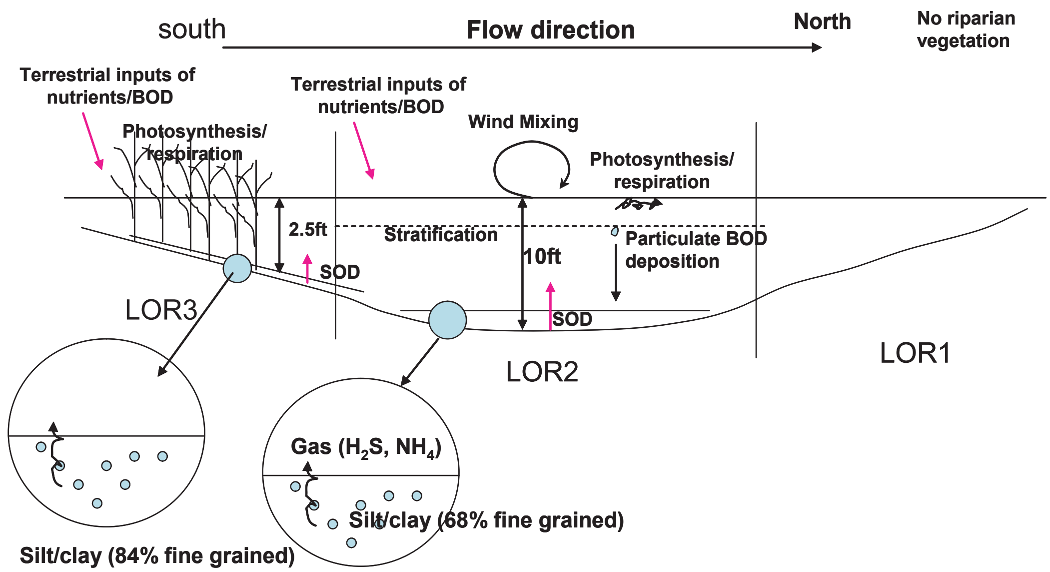


Figure 5-65 Preliminary conceptual model for the Laguna at Occidental Road (LOR)

Laguna at Stony Point (LSP) is a shallow stream section that receives nutrients and BOD inputs from agriculture and urban runoff (Figure 5-63). This section is infested with *Ludwigia*. Shallow water depth and low flow may result in large influence of SOD from bottom sediments on the water column.

The Laguna at Sebastopol Pond (Figure 5-64) is a section with a narrower and deeper channel. This section also receives nutrients and BOD inputs from a mix of urban and agricultural runoff. The bottom sediments accumulate a high level of organic matter and nutrients, which can pose high SOD. In this section dense vegetation prevents wind mixing and deeper water promotes thermal stratification. Stratification prevents water mixing and replenishing of oxygen and results in anoxia in hypolimnion. High residence time allows more time for biological and chemical reactions to occur that consume oxygen. In open water, algal photosynthesis and respiration influence DO dynamics, lowering DO in certain time of the day. Settling of algae also contributes to particulate BOD.

The Laguna at Occidental Road (Figure 5-65) is also a ponding area that receives terrestrial inputs of nutrients and BOD. The sediments also accumulate high levels of organic matter and nutrients, which may pose a high SOD. High nutrients in the water column and sediments can promote the growth of algae and macrophytes. The south section (LOR1) is shallower and is infested with *Ludwigia*. In open deeper water (LOR2) algal photosynthesis/respiration is present. Deeper water also allows thermal stratification to develop and results in low DO in the hypolimnion.

Ecosystem 6

6.1 Overview

6.1.1 Geologic basis for biological diversity

The Laguna de Santa Rosa watershed is host to a wide variety of plant communities. The watershed's underlying geological formations provide the historical basis for this diversity, while its climate provides the mechanism for sustaining it. Understanding the interplay between functional ecosystems and clean water, requires a brief review of the patterns of physical and biological forces at work in the watershed.

An in-depth study of this is provided in Enhancing and Caring for the Laguna (Honton & Sears 2006). In brief summary: two great tectonic plates—the North Atlantic Plate and the Pacific Plate—are slipping past each other along the San Andreas Fault: in the past this movement triggered the Sonoma Volcanics that historically spread lava and ash over the Mayacama Range and Sonoma Mountain. This simple geologic activity was complicated when in former times a third plate—the Farallon Plate—subducted, forming the Coast Range. The highly diversified soils of the watershed are a direct result of these geological activities. In turn, this diversified substrate has given rise to a complex pattern of soils that have in turn supported a wide range of plant communities, supported by a climate characterized by an average annual rainfall ranging from 30 inches in the southern plain to 60 inches in the upper mountains. The watershed's diverse geology and wide climate range have together contributed toward the creation of an environment that supports many different types of plants, and an abundance of wildlife.

Today's expression of this geologic activity can be seen in the four distinct topographic zones that remain: mountains in the eastern half of the watershed, a level plain in the central watershed, the Laguna floodplain along the western edge of the plain, and a short line of hills along the far western edge of the watershed. This simplified view of the watershed's topography is useful when thinking in conceptual terms about ecosystem processes as they relate to water quality. In this part of the document we've chosen to model the watershed using this simplified view, and have developed two broad conceptual models of the relationship between water and biology: one for the upper watershed (which is a surrogate for the mountains in the east and the hills in the west) and one for the lower watershed (which is a surrogate for the central plain and floodplain.)

6.1.2 Biological diversity timeline

A conceptual model of biological diversity over time has been sketched out as a means to understand loss and gain of ecologic potential. (Figure 6-1). In this model the x-axis represents the two and one half century time period from 1800 to 2050, while the y-axis represents biodiversity gain or loss—as expressed through the impacts on upper trophic level species (e.g. slaughter of top predators) or direct habitat alterations (e.g., nutrient and sediment excesses). The estimate of biodiversity sketched out on this chart is conceptual rather than quantitative, and thus has no unit markers along the y-axis. The bases for the chart are the historical narrative accounts cataloged by the Laguna Foundation during the development of the restoration and management plan, *Enhancing and Caring for the Laguna*. References to these first hand accounts appear in Volume I of the plan on pages 338-343.

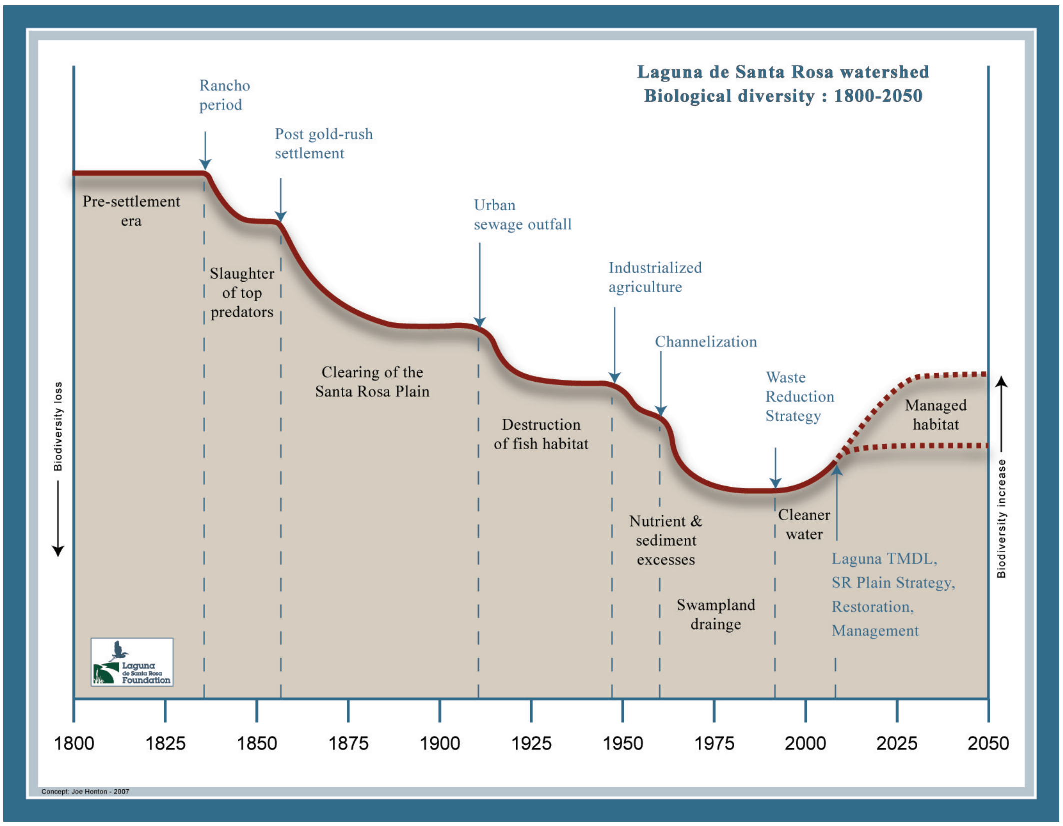


Figure 6-1
Biological diversity 1800-2050

As shown on the chart, biodiversity loss has occurred in stages, with rapid declines occurring in five stages, each stage followed by a period of new stability at a lower level. At the very end of the 20th century, a reversal of the downward trend is shown, with a hopeful upward trend beginning. Two projected trend-lines are plotted for the future, one at the existing plateau, the other at a slightly higher level. The lower trend line predicts a future based on the status quo; the upper trend line predicts a future based on the promulgation of a Laguna TMDL, implementation of the Santa Rosa Plain Strategy, and progress made towards the goals set forth in the Restoration and Management Plan.

Historical interpretation of events in the watershed as they relate to water quality are provided here to aid in reading the chart.

Pre-settlement

Very little documentation is available regarding the intentional tending of the landscape by the inhabitants of the eight Miwok- and Pomo-speaking villages known to have been situated along the Livantuyolomí (Tcétcewani, Butswáli, Kápten, Cakákmo, TciLeton, Kacíntui, Masikawáni, and Batíkletcawi) during the early decades of the 19th century. Human habitation in the watershed is commonly thought to have had some role in its active stewardship even prior to recorded history. Whether this pre-historic tending created an impaired system or an enhanced system is not known. For the purpose of this conceptual model, the pre-settlement era is regarded as a time of high biodiversity, where severe impairments and biological extinction were more likely due to natural phenomenon (fires, floods, earthquakes, landslides, etc.) than to human use.

Rancho period

Exploration by the Russians (1808-1841), the Spanish (1813-1820), the Mexicans (1820-1848), and later the Americans (1848-onward) revealed a landscape that supported grizzly bears, wolves, elk, pronghorn, beavers and condors, as well as other large predators and scavengers. Trapping by the Hudson's Bay Company and the Russian-American Company just prior to the Rancho period eliminated the beaver: it is curious—but speculative—to imagine what the absence of these ecosystem engineers has meant to the water bodies of the watershed.

The first Rancho period inhabitants, beginning in the early 1840s, brought with them cattle, sheep and horses which were free-ranged over the plains and foothills. In order to protect these domesticated livestock from predation, a concerted effort to eliminate the area's top carnivores was carried out. Simultaneous with the effort to eliminate the large carnivores, the hide and tallow trade capitalized on the rich fat obtainable from the Tule Elk, and through over-hunting, eliminated them from the watershed by 1851. Soon after, hunters supplying the dinner tables of the then-booming San Francisco market, wiped out the pronghorn. In terms of water quality, the presence of tens of thousands of free-range cattle, is thought to have resulted in localized patches of riparian vegetation thinning, possibly triggering the first artificially induced stream bank erosion.

Post Gold Rush

Soon after the Gold Rush, a wave of settlement occurred in the watershed, with the newcomers seeking a new type of gold—wheat. The Santa Rosa Plain was cleared of its many valley oaks to make way for large fields of wheat. Oak wood from the cleared plain was turned into charcoal and sent by barge from Petaluma to San Francisco. In terms of water quality, this conversion of the plain to agriculture, meant that fields were seasonally plowed, sown, and reaped—a disturbance regime that almost certainly induced large sheet and rill erosion. This extended period—from the early 1850s through the late 1930s—was characterized by family farmers with 40-, 80-, or 160-acre farms. Agriculture in this period was diversified, with grapes, prunes, apples, wheat, potatoes, hops and livestock growing side-by-side. Fertilizers were home-grown mixtures of composted material and manure and would have been too highly-prized to waste: fertilizer run-off into nearby streams probably was not a problem.

Irrigation though was a limiting factor, and profitable farms had to be situated alongside nearby streams that flowed year-round. In the Laguna, this meant placing farms in the floodplains of Gravenstein Creek, lower Irwin Creek, Santa Rosa/Matanzas Creeks, Mark West Creek, and lower Windsor Creek. Pumping and diversion of water from these creeks would have reduced the quantity of summertime flow towards the Laguna and the Russian River somewhat, but no anecdotal stories have been uncovered to suggest that downstream water shortages were a problem in the watershed. In terms of water quality, farming in the floodplain certainly contributed to wintertime erosion from fields that had been cultivated the prior season, although no evidentiary record exists to suggest its magnitude.

Turn of the century

During this time the city of Santa Rosa had grown as new markets opened with the installation of the railroad. By the first decade of the 20th century, this new populace was complaining about the stench from too many poorly designed effluent ditches, which prompted the public works department to construct pipes whose outfall was Santa Rosa Creek downstream of the city (and upstream from the Laguna.) A similar, but smaller effort was conducted by Sebastopol. This direct discharge of wastewater into these waterways led to the watershed's third marked decrease in biodiversity (see chart) as fish were killed and their habitat was polluted. The impact to the waterway is believed to have also extended to the aquatic invertebrate, bird and mammal populations—a ripple effect in the food web.

Industrialized agriculture

Industrialized agriculture arrived immediately after the conclusion of World War II as munitions factories nationwide were converted to fertilizer factories and as diesel powered tractors became increasingly affordable. This new style of farming allowed the early adopters to effectively dominate the market, producing bumper-sized crops year after year. This new way to farm resulted in winners and losers and the eventual consolidation of some of the smaller farms. In terms of water quality, the affordability of fertilizer—and the predictability of increased yields—may have been inducement enough to apply excessive amounts of fertilizer to fields. The later 1940s probably marked the beginning of excess nutrients to the Laguna.

Channelization

The growing population within the county—coupled with the beginnings of the trend to seek alternatives to life in Santa Rosa—reached the point where it became politically desirable to convert the poorly drained areas north and west of Cotati. The areas just east and west of Stony Point Road were the subject of a roads project which was simultaneously designed for passage and drainage—even today the ditches that flank either side of each road act as a dendritic network for surface drainage.

By 1960 the conversion of the formerly marshy areas north of Cotati—which had been used for decades as a seed farm—was in full swing as the City of Rohnert Park sprang up. The growth of Rohnert Park west of Highway 101 was checked by the temporary enactment of urban growth boundaries, forestalling the complete conversion and development of the area. In terms of water quality, the loss of these former marshes represents a significant spatial shift in water and sediment transport. The large alluvial plain that fans out at the base of Sonoma Mountain was created over millennia as the waters of Copeland, Hinebaugh, Hunter, and Five Creeks hit the level plain, lost energy, and dropped their sediment loads. Periodic avulsions allowed these creeks to reposition themselves to low spots on the plain, thus creating a shifting zone of deposition.

Today's urban use of the area (east of Highway 101) makes it imperative to keep water in well defined channels: regular maintenance of these artificial channels are needed to keep them free of cobbles, gravel, sand, and silt. In terms of water quality this is a big issue: how can maintenance designed with an eye towards public safety and property protection be carried out in a way that safeguards fish habitat and protects riparian resources? This part of history is yet to be played out.

The historic trend in channel confining activities, both east and west of Cotati/Rohnert Park, using former design criteria, will continue to lead towards more water and more sediment reaching the Laguna west of Stony Point Road. Because of our need for public safety and property protection, the ultimate fate of sediment originating in the Sonoma Mountain foothills will either have to be east or west of the cities. Again, history will await the decisions made over the next decade, regarding management of this issue, to see if this becomes a water quality problem or a water quality solution.

Waste Reduction Strategy

In 1995 the North Coast Regional Water Quality Control Board promulgated the Waste Reduction Strategy for the Laguna de Santa Rosa in response to the seasonally high levels of ammonia and low amounts of dissolved oxygen levels caused by excessive nutrient loadings. By 1998, this phased TMDL had made enough of an impact that the Laguna was removed from the 303(d) list of impaired water bodies, but by 2002, the Laguna was again placed on the 303(d) list, this time for sediment, nitrogen, phosphorus, low dissolved oxygen, and temperature. In 2006 the listing for mercury was added. A new TMDL to address these impairments is expected in the 2008–2011 timeframe.

6.1.3 Endangered species

A chart of the rare (threatened or endangered) species found in the watershed is shown in Figure 6-2. The chart is laid out as a cross-sectional diagram slicing the watershed at approximately its midpoint, from east to west. Along the bottom of the chart, seven of the watershed's eighteen regions are listed (as the cross-section does not bisect all regions) together with key features seen in the landscape, such as named mountains, plains and hills. Above the elevation profile-line ten distinct habitat communities are listed and ten columns of species names are shown. For each habitat community, the rare species that are found in that community are listed under one of three headings: 1) federally listed species are at the top; 2) California species of concern are in the middle; and 3) species of local concern are at the bottom. Each of these are described in detail in the paragraphs below, with particular emphasis placed on species that are affected by water quality concerns.

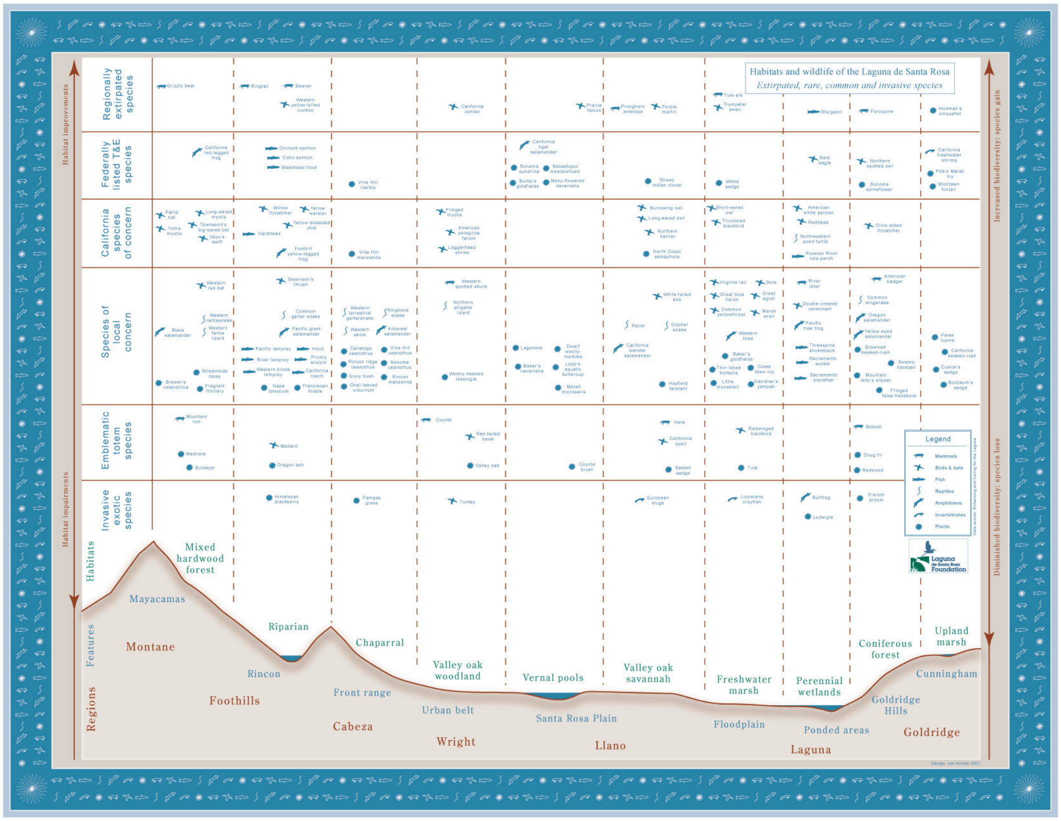


Figure 6-2
Habitats and wildlife
(see full-sized inset)

Figure 6-2 also lists species that have been extirpated from the watershed since 1850, although no further documentation of these are provided in this report. Emblematic species, which are common and occur ubiquitously, are listed on the chart for reference—these are subjective and are included to give flavor to the chart and to emphasize one of the RMP's goals which was to "keep common species common." Finally, invasive exotic species are shown on the chart because these are the targets of many of our management efforts.

Federally listed species

At a different scale, we also looked at species and communities as they relate to water quality. The Federal Endangered Species Act of 1973 (FESA) provides special protection to species when they become officially listed as threatened or endangered, with greater emphasis being placed on animals than plants. Many species that are listed as threatened or endangered (T&E) are known to inhabit the watershed. While developing the watershed-scale conceptual models, it became apparent that special models needed to be considered to provide an understanding of how water quality issues relate to the survival and revival of these T&E species (Table 6-1). Official consultations regarding the disturbance of species or their habitats are under the jurisdiction of the US Fish and Wildlife Service, with the exception that migratory fish that spend part of their life cycle in marine water are under the jurisdiction of NOAA's National Marine Fisheries Service.

Not all of the species listed in Table 6-1 have an easily discernable connection to water quality. In the notes below, the T&E species that have a strong connection to water pollution are discussed.

Of particular note are Coho *(Oncorhynchus kisutch),* Chinook *(Oncorhynchus tshawytscha),* and Steelhead *(Oncorhynchus mykiss)* and their need for passage, spawning habitat, and rearing habitat. These anadromous fish need unobstructed passageways from the Pacific Ocean to spawning areas in the upper Mark West Creek and Santa Rosa Creek tributaries. The peak of this migration occurs between January and March for Steelhead and between November through January for Coho. Chinook, which have not been found in recent years in the Laguna watershed, have an upstream migration season—in the main stem of the Russian River—between September and November, and a downstream emigration between February to June. Downstream emigration for Coho occurs between February and mid-May. In contrast to Coho and Chinook, Steelhead juveniles remain year round in fresh water and are more impacted by the warmer temperatures of the Laguna than by fish passage concerns (USACE 2004). For successful breeding these anadramous species require:

- upstream gravel beds with properly-sized cobles,
- adequate water depth,
- appropriate water temperatures (e.g., 13-17°C),
- a tolerable stream velocity, and
- a lack of excessive siltation, which smothers eggs and hampers gill function.

California freshwater shrimp *(Syncaris pacifica),* which occur within the Laguna watershed only in Blucher Creek, deserve special consideration in terms of water quality. Pollution in the form of high algal production and high ammonia from nearby dairies is implicated in their recovery plan as being of key concern. Loss of riparian cover and encroachment from rural residential neighbors is also of concern (USFWS 1998). The possibility of a link between poorly designed or failing septic systems—suspected to occur in the area—and shrimp decline, is a question which deserves further research.

California red-legged frogs *(Rana aurora draytonii),* known to occur on Taylor and Sonoma Mountains, require dense, shrubby or emergent riparian vegetation located near still or slow moving water. Pools that are deep, fringed by cattails and surrounded by overhanging willows are ideal. A nearby well-vegetated riparian corridor provides the best habitat for wintertime aestivation (USFWS 1996).

Among the plants listed in Table 6-1, White sedge *(Carex albida)* is one of the rarest and has a direct connection to waterway impairment: the marsh which was the type locality for the plant—at the confluence of Santa Rosa Creek and the Laguna—was destroyed in the 1960s by channelization. A second marsh where it was known to occur, on the City of Sebastopol's Meadowlark Field, was destroyed through the repeated application of cannery waste from 1971 to 2001, causing the loss of the population (USFWS 1997). Other threats to this plant include the possibility of habitat loss from hydrological alterations.

The remaining species in Table 6-1 are not directly impacted by poor in-stream water quality. Nevertheless, summer irrigation using reclaimed wastewater, and increased atmospheric nitrogen deposition near major roads (Gluesenkamp and Wirka 2006, Fenn et al 2003) may impact several listed T&E plants (e.g., Sonoma sunshine, Burke's goldfields, Sebastopol meadowfoam); these are plants that are adapted to low nitrogen conditions in vernal pool systems on the Santa Rosa Plain. This deserves further research.

Table 6-1
FESA-protected species occurring in the watershed

Species	Common name	Taxonomy	Federal status
*Rana aurora draytonii**	California red-legged frog	Amphibian	Threatened
*Oncorhynchus mykiss**	Steelhead trout	Fish	Threatened
*Oncorhynchus kisutch**	Coho salmon	Fish	Endangered
*Oncorhynchu tshawytscha**	Chinook salmon	Fish	Threatened
*Syncaris pacifica**	California freshwater shrimp	Invertebrate	Endangered
*Carex albida**	White sedge	Plant	Endangered
Ambystoma californiense	California tiger salamander	Amphibian	Threatened
Lilium pardalinum	Pitkin Marsh lily	Plant	Endangered
Alopecurus aequalis	Sonoma alopecurus	Plant	Endangered
Strix occidentalis caurina	Northern Spotted Owl	Bird	Threatened
Chorizanthe valida	Sonoma spineflower	Plant	Endangered
Clarkia imbricata	Vine Hill clarkia	Plant	Endangered
*Lasthenia burkei***	Burke's goldfields	Plant	Endangered
*Blennosperma bakeri***	Sonoma sunshine	Plant	Endangered
*Limnanthes vinculans***	Sebastopol meadowfoam	Plant	Endangered
Navarretia leucocephala	Many-flowered navarretia	Plant	Endangered
Potentilla hickmanii	Hickman's cinquefoil	Plant	Endangered
Trifolium amoenum	Showy Indian clover	Plant	Endangered

* *Species significantly impacted by poor water quality.*
***Species potentially impacted by summer irrigation with reclaimed waste water or atmospheric N deposition from major roads on the Santa Rosa Plain.*

California listed species

The California Endangered Species Act of 1984 (CESA) provides additional protection to rare species that are not listed under FESA. In some cases species listed under the federal law have received less protection than needed—in the opinion of California state experts—and have accordingly been given a higher status under California law. Bald eagles, for example, are listed by the California Department of Fish and Game as endangered, a higher level of protection than afforded by the federal threatened classification. The species known to occur within the watershed that are listed as threatened or endangered under California law, but not under federal law (or to a lesser status under federal law), are listed in Table 4-2. Official consultations regarding the disturbance of these species or their habitats are under the jurisdiction of the California Department of Fish and Game.

Bald eagles *(Haliaeetus leucocephalus)*, which beginning in 2005 were observed regularly in the CDFG Laguna Wildlife Area along the Laguna (J. Honton, pers. obs.), have a strong connection to open water habitat and fish abundance. As generalist raptors Bald eagles, eat fish, small mammals, and waterfowl. Cloudy water has been implicated by researchers in the Everglades as an impediment to successful hunting by osprey and other raptors (Regan 1996). Nearby perching and nesting sites on strong limbed mature trees, such as pines or Douglas firs, are also needed for a viable habitat.

The American Peregrine Falcon *(Falco peregrinus anatum),* which was listed federally as endangered until delisting in 1999, is still listed as endangered under CESA. Peregrine Falcons likely target blackbirds, ducks, and pigeons in the Laguna. It is well known that falcons can adapt urban environments into suitable nesting and feeding habitat; nevertheless, the more traditional open-water and emergent marsh habitats—which have diminished in size in the watershed—are thought to support falcons better. A reversal of the declining trend in perennial ponds and emergent marshes should favor the revival of falcons as well as other more common raptors.

Table 6-2
CESA-protected species occurring in the watershed

Species	Common name	Taxonomy	California status
Haliaeetus leucocephalus	Bald Eagle	Bird	Endangered*
Falco peregrinus anatum	American peregrine falcon	Bird	Endangered
Coccyzus americanus occidentalis	Western yellow-billed cuckoo	Bird	Endangered
Empidonax traillii	Willow Flycatcher	Bird	Endangered
Arctostaphylos densiflora	Vine Hill manzanita	Plant	Endangered
Pleuropogon hooverianus	North Coast semaphore	Plant	Rare

** The Federal Eagle Protection Act of 1940 provides special protections to Bald Eagles and Golden Eagles (both of which are known to occur in the watershed) preventing the taking of eagles. Significantly in this context, disturbance of their nests and their immediate habitat during nesting season is subject to regulatory permits.*

The Western yellow-billed cuckoo *(Coccyzus americanus occidentalis),* which has not been observed in the Laguna in the past decade, is associated with large contiguous stands of riparian habitat comprised of cottonwoods and willows—a dense understory also appears to be an important factor in their habitat selection. In general, declines throughout their range have been attributed to degradation and fragmentation of riparian habitat, overgrazing, and a shift in native riparian woodland species to non-natives species. Also implicated in their decline are altered stream flow and sediment regimes, channelization, bank protection measures and similar flood control management practices (USFWS 2001).

The Willow flycatcher *(Empidonax traillii*), is an insectivorous bird inhabiting dense riparian stands of willows. In the spring it migrates north from Mexico searching for suitable breeding and nesting sites; in the autumn it returns south. Suitable summertime foraging habitat includes moist brushy thickets, open second-growth, and riparian willow and buttonbush, with even linear narrow riparian strips providing suitable food supply. Breeding habitat is typically moist meadows with perennial streams; tree-formed willows, cottonwoods, alders, and small spring-fed areas. (Craig 1998) Areas in the watershed that approach this description are found in the Occidental Rd. to River Rd. reach of the Laguna: this is the area most heavily impacted by sediment deposition which in turn has caused the demise of the mature willow forest.

The two plants species in Table 6-2 are not directly impacted by poor water quality.

The California Department of Fish and Game also provides another type of protection to species which do not fit the criteria for being listed as threatened or endangered; this protection is to list a species as being of special concern. A species of special concern is so listed due to declining population levels, limited ranges, or continuing threats that have made the species vulnerable to extinction. These are listed in Table 6-3.

Foothill yellow-legged frogs *(Rana boylii)* inhabit partially shaded riffle patches of shallow perennial streams containing cobble-sized rocks occurring in chaparral, open woodland and forested areas. They attach their eggs to cobbles and boulders in low-velocity streams and wide shallow reaches near tributary confluences. This species responds well to stream channels that have been restored through "bank feathering" (NatureServe 2006). Suitable habits are in the upper watershed where localized sediment deposits may impact its persistence.

Northwestern pond turtles *(Emys marmorata)* inhabit perennial ponds that have islands of vegetation where they can bask. In the Laguna they are frequently observed near Sebastopol. Additional suitable habitat include the creeks and man-made channels in the watershed that have in-stream logs or other anthropogenic refuge areas where predators cannot reach adults or their eggs. Straight, heavily maintained channels, such as found throughout the Santa Rosa Plain, are poor habitats.

Redheads *(Aythya americana)* inhabit seasonally flooded wetlands with persistent emergent vegetation. They forage on the rhizomes and tubers of aquatic vegetation, as well as on aquatic invertebrates including crustaceans, mollusks and insects. (Mitchell 1993) In the Laguna, cattails and tules are a likely habitat for Redheads, with mature tule seeds providing food. The intentional removal of cattails and tules for mosquito and flood control may be a limiting factor in their local abundance.

American white pelican *(Pelecanus erythrorhynchos)* are fish feeders and need large open water bodies for feeding habitat. A recent restoration project in the Laguna—the Hummock and Swale project in the CDFG Laguna Wildlife Area—was very successful at attracting a squadron of these birds immediately after its completion in 2003. The area's large population of introduced Louisiana crayfish *(Procambarus clarkii)* is also thought to be an important part of their local diet. The Laguna is at the far northern edge of their winter range.

Olive-sided flycatchers *(Contopus cooperi)* are nearctic-neotropical migrants, with the Laguna at the southern edge of their summertime range: they typically arrive in May. Their preferred habitat consists of montane and coniferous forests, often associated with forest openings and edges, especially those with snags or live trees that provide foraging and singing perches. They are frequently found along streams, lakes and wetlands where natural edge habitat and standing dead trees occur. Their prey is almost exclusively flying insects, including bees, wasps, beetles, flies, moths and dragonflies (Kotliar 2007). The most likely habitats for Olive-sided flycatchers in the Laguna watershed are the eastern edge of the

Goldridge hills adjacent to the standing water of the Laguna. Lack of natural fire-created openings in the forest has been cited in other areas as being a limiting factor, but the lack of regular insect foraging habitat may be more limiting in the Laguna, especially in otherwise suitable habitats that are adjacent to orchards and vineyards which employ insecticides.

Table 6-3
California species of special concern occurring in the watershed

Species	Common name	Taxonomy	California status
*Rana boylii**	Foothill yellow-legged frog	Amphibian	Special concern
Emys marmorata *	Northwestern pond turtle	Reptile	Special concern
*Aythya Americana**	Redhead	Bird	2nd level concern
*Pelecanus erythrorhynchos**	American white pelican	Bird	1st level concern
Circus cyaneus	Northern harrier	Bird	2nd level concern
Athene cunicularia hypugea	Burrowing owl	Bird	1st level concern
Asio otus	Long-eared owl	Bird	2nd level concern
Asio flammeus	Short-eared owl	Bird	2nd level concern
Chaetura vauxi	Vaux's swift	Bird	3rd level concern
Contopus cooperi	Olive-sided flycatcher	Bird	2nd level concern
Progne subis	Purple martin	Bird	1st level concern
Lanius ludovicianus	Loggerheaded shrike	Bird	2nd level concern
Dendroica petechia	Yellow warbler	Bird	2nd level concern
Icteria virens	Yellow-breasted chat	Bird	3rd level concern
*Agelaius tricolor**	Tricolored blackbird	Bird	1st level concern
Myotis evotis	Long-eared myotis	Mammal	Special concern
Myotis thysanodes	Fringed myotis	Mammal	Special concern
Myotis yumanensis	Yuma myotis	Mammal	Special concern
Corynorhinus townsendii	Townsend's big-eared bat	Mammal	Special concern
Antrozous pallidus	Pallid bat	Mammal	Special concern
Bassaricus astutus	Ringtail	Mammal	Special concern
*Mylopharodon conocephalus**	Hardhead	Fish	Special concern
Hysterocarpus traskii spp. *pomo**	Russian River tule perch	Fish	Special concern

* *Species significantly impacted by poor water quality.*

Tricolored blackbirds *(Contopus cooperi)* nest in cattails, tules, and a variety of other species found in flooded areas that are defensible against mammalian predators. Tricolors will not roost/nest without access to open water, and will avoid narrow strips of emergent vegetation along channels. Tricolors favor agriculturally productive habitats such as irrigated pasture, maturing grain crops and dairies. Foraging tricolors are particularly attracted to ephemeral pools. As an endemic North American bird species with a narrow habitat range, Tricolored Blackbirds are at a far greater risk than other widely distributed endangered species such as Swainson's Hawks and Burrowing Owls, but because they are a flocking species, and are in some places abundant, they often fail to command much conservation attention. (Hamilton 2004) In the Laguna the encroachment of hayfields in the floodplain and the loss of cattail and tule stands are likely limiting factors.

Hardhead *(Mylopharodon conocephalus)* are bottom feeders that forage for benthic invertebrates and aquatic plant material in quiet water. Hardhead require large to medium-sized, cool to warm-water streams with natural flow regimes for their long-term survival. Younger fish feed primarily on mayfly larvae, caddisfly larvae, and small snails; while adults feed more on aquatic plants, crayfish, and other large invertebrates. Hardhead prefer clear, deep pools with sand-gravel-boulder substrates and slow water velocities. Low oxygen levels are implicated as an impairment to their natural habitat. The specialized habitat requirements of Hardhead, combined with alteration of downstream habitats makes them vulnerable to local extirpation (CDFG 1995a). The most likely habitat for Hardhead in the Laguna watershed are the local stream pools of the upper Mark West and Santa Rosa Creek.

Russian River tule perch *(Hysterocarpus traskii spp. pomo)* are specially adapted to the unpredictable flow conditions of the Russian River system. These Tule perch require clear, flowing water and deep pools together with abundant cover, such as beds of aquatic macrophytes, submerged tree branches, and overhanging plants which are used by the young as a refuge from predators. Tule perch feed on benthic and plant-dwelling aquatic invertebrates. In the Laguna, a population of Tule perch survived for a number of years in a deep water pond near Cotati / Rohnert Park, but this population is now gone. They are usually absent from polluted water with reduced flows, high turbidity and lack of cover; alterations to these habitat conditions are the most significant threats to their survival (CDFG 1995b).

Townsend's Big-eared bats *(Plecotus townsendii)* live in a variety of communities, including coastal conifer and broadleaf forests, oak and conifer woodlands, arid grasslands and deserts, and high-elevation forests and meadows. Throughout most of its geographic range, it is most common in mesic sites (Kunz and Martin, 1982).

6.2 Available data for analysis

Efforts at compiling existing data focused on the recently published reference sources within *Enhancing and Caring for the Laguna* (Honton and Sears 2006) and available GIS layers in the Laguna Foundation geo-database. Additional information was obtained via the Russian River Interactive Information System (RRIIS), from the Sonoma County Water Agency Website, and was made available to us by City of Santa Rosa staff and USDA/ARS researchers.

6.2.1 Laguna de Santa Rosa watershed fish and aquatic habitat surveys

Sonoma County Water Agency

As part of a Fisheries Enhancement Program, the Sonoma County Water Agency (SCWA) conducts wildlife and habitat studies aimed at endangered Salmonid species within the Russian River watershed. The fish and habitat monitoring program contains several Russian River tributaries, including Mark West Creek, Santa Rosa Creek and Millington Creek within the Laguna de Santa Rosa watershed.

The aim of the salmonid monitoring program was to detect trends in salmonid populations and identify possible fisheries management and enhancement opportunities (Cook & Manning 2002). The program began in fall 1999 with a pilot study to collect detailed distribution, habitat use and juvenile abundance data in streams of the Russian River basin, sampling five of its tributaries via electrofishing and snorkel surveys for three years (Cook & Manning 2002).

Table 6-4 (a)
Fish species composition and relative abundance by channel type in Mark West Creek in 2000

Species	F4 Channel	Lower B2 channel	C4 Channel	Upper B2 channel
CA Roach	70%	61%	33%	0%
Green sunfish	<1%	0%	0%	0%
Lamprey Amnoceoete	7%	14%	3%	0%
Three-spined Stickleback	1%	0%	0%	0%
Sculpin	14%	3%	52%	0%
Steelhead	<1%	19%	52%	100%
Tule Perch	1%	0%	0%	0%
Sacramento Sucker	7%	3%	0%	0%

Table 6-4 (b)
Fish species composition and relative abundance by channel type in Santa Rosa Creek in 1999-2001

Species	F4 Channel*			C4 Channel			B2 channel		
	1999	2000	2001	1999	2000	2001	1999	2000	2001
CA Roach	50%	25%	-	35%	26%	33%	<1%	0%	0%
Pikeminnow	<1%	0%	-	<1%	0%	0%	0%	0%	0%
Hardhead	<1%	0%	-	0%	0%	0%	0%	0%	0%
Bluegill	1%	<1%	-	1%	<1%	<1%	0%	0%	0%
Lamprey Amnocoete	5%	8%	-	5%	5%	11%	1%	<1%	0%
Three-spined Stickleback	1%	2%	-	5%	3%	<1%	0%	0%	0%
Sculpin	9%	54%	-	29%	52%	47%	26%	32%	33%
Steelhead	2%	10%	-	14%	11%	8%	73%	68%	67%
Sacramento Sucker	32%	1%	-	6%	3%	1%	0%	0%	0%
Green sunfish	0%	<1%	-	5%	<1%	<1%	0%	0%	0%
Redear Sunfish	0%	<1%	-	0%	0%	0%	0%	0%	0%
Mosquitofish	0%	0%	-	0%	<1%	0%	0%	0%	0%
Brown bullhead	0%	0%		0%	<1%	0%	0%	0%	0%

** Channel type F4 is closest to the Laguna de Santa Rosa confluence, and channel type B2 represents the extreme upper reach of the creek.*
** F4b channel in 2000. (adapted from Cook & Manning 2002).*

The three year study assessed both salmonid demographic data, and fish community species composition and abundance along a longitudinal creek profile from e.g. the confluence of Mark West creek with the Laguna de Santa Rosa to the creek headwaters in the mountains. Table 6-4 (a) shows fish species composition and relative abundance by channel type in Mark West Creek in 2000.

At present, the SCWA is no longer surveying Mark West, Santa Rosa, and Millington creeks (D. Cook pers. comm.). Extensive long-term datasets that incorporate fish demography, species composition and abundance along the creek profile are crucial in elucidating the natural variations in fish population abundance and community composition, and so are well suited to serve as reliable indicators for environmental changes affecting water quality. For example, Table 6-4 (b) shows a slight shift in species composition in Santa Rosa Creek from 1999 to 2001, showing an increased relative abundance of Sculpin, accompanied by a decrease in the relative abundance of Steelhead. It becomes apparent that three years are not long enough to get a comprehensive picture of the dynamics of the system. Long-term fish-survey programs are critically needed in order to determine whether observed fluctuations in Salmonid or other fish indicator species populations are due to natural or anthropogenic causes.

In addition, SCWA has prepared the Copeland Creek Restoration Project Monitoring Plan (Cook & Lamb 2001) to restore fish and wildlife habitat along this upper Laguna de Santa Rosa tributary. The plan outlines extensive surveys of stream profile, vegetation, stream habitat, fish, reptiles, amphibians, birds, and small mammals. As part of these annual surveys this effort will identify habitat used by steelhead, quantify aquatic habitats, and characterize streambed composition to evaluate salmonid spawning and habitat value. Data from this program will be very valuable to assess the habitat and water quality along this tributary creek. Data collections have been ongoing, and a monitoring report is forthcoming (D. Cook pers. comm.)

California Department of Fish and Game

Stream inventory reports from California Department of Fish and Game (CDFG) are available for several tributaries of the Laguna de Santa Rosa: Santa Rosa Creek, North Fork Santa Rosa creek, Blucher creek, and Copeland creek The latest inventories were conducted during the summer of 1998 for Santa Rosa Creek and North Fork Santa Rosa Creek, and in July & August of 2001 for Copeland and Blucher creeks. All inventories followed the methodology presented in the California Salmonid Stream Habitat Restoration Manual (Flosi et al. 1998), sampling approximately 10% of habitat units within the survey reach. Due to inadequate staffing levels, no biological surveys were conducted for Copeland, Blutcher and North Fork Santa Rosa creeks as part of these most recent inventories. In the North Fork Santa Rosa Creek, Steelhead trout and Sculpin were observed and noted during the habitat inventory (CDFG 2000a). A biological inventory of Santa Rosa Creek is available, and Table 6-5 shows aquatic fauna observed in historical and recent CDFG/SCWA surveys.

Table 6-5
Aquatic fauna observed in historical and recent CDFG/SCWA surveys

Years	Species	Source	Native/ Introduced
1954, 1957, 1958, 1973, 1975, 1991, 1998, 1999	Steelhead	CDFG/SCWA	N
1998	Brown Bullhead	SCWA	I
1973, 1975, 1977, 1991, 1999	Sculpin	CDFG/SCWA	N
1954, 1957, 1973, 1975, 1977, 1991, 1999	Roach	CDFG/SCWA	N
1954, 1957, 1991, 1999	Sacramento Sucker	CDFG/SCWA	N
1977, 1991, 1999	Stickleback	CDFG/SCWA	N
1999	Blue Gill	SCWA	I
1954, 1957, 1991, 1999	Green Sunfish	CDFG/SCWA	I
1999	Hardhead	SCWA	N
1954, 1999	Pike Minnow	CDFG/SCWA	N
1973, 1991, 1999	Lamprey Amnocoetes	CDFG/SCWA	N
1977	Crayfish	CDFG	N/I
1954	Carp	CDFG	I
1957	Largemouth Bass	CDFG	I
1957	Catfish	CDFG	I
1998	Tree Frog	SCWA	N
1998	Bull Frog	SCWA	I

** Historical records reflect fish transfer operations in 1974 (CDFG 2000b).*

City of Santa Rosa

Macroinvertebrate Surveys

The City of Santa Rosa stormwater monitoring program includes a professional benthic community survey for six creeks within the Santa Rosa urban boundary. Benthic macroinvertebrate (BMI) sampling has been conducted at set monitoring sites along Brush, Colgan, Matanzas, Paulin, Piner, and Peterson creeks by City of Santa Rosa staff from 1998-2005. BMI samples are sent to a certified laboratory (SLSI in Chico, CA) each year and processed and evaluated according to the appropriate regional Index of Biotic Integrity (norCal IBI, Rehn and Ode, in press).

Results indicate that each of the six monitoring reaches are in very poor biological condition and that conditions are similarly poor for most years (Sustainable Land Stewardship Institute 2005). In 2005, the total number of benthic taxa at all sites only ranged from 8 to 15, very low when compared to the average 37 for reference conditions in Northern California. Most of the invertebrates collected in 2005 (chironomids, oligochaeta, and beatids) tolerate sedimented streams and have no need for complex habitats (Sustainable Land Stewardship Institute 2005). Further, a high percentage of collector and filterers and the presence of Oligocheata worms indicated organic enrichment at all six sites in 2005.

Overall, none of the sites was in better condition compared to the other sites (Sustainable Land Stewardship Institute 2005). Physical habitat condition at all six sampling reaches has been rated good to fair throughout the four years of determining scores, suggesting that improved biological condition would be expected with improved water quality (Sustainable Land Stewardship Institute 2005).

Creek bioassays

The City of Santa Rosa conducts bioassay tests to determine whether storm water runoff is impacting the water quality in creeks that support fish populations (City of Santa Rosa 2005). Toxicity is measured by exposing twenty rainbow trout fry (15-30 days of age) under controlled conditions to 100% sample water for 96 hours, noting percent survival. Bioassay samples were collected from eight sampling sites within the Santa Rosa urban boundary during the 2004-2005 rainy season (City of Santa Rosa 2005). Table 6-6 shows the results for two samples per site, overall showing no significant effects on trout survival at most sites.

Table 6-6
Bioassay results 2004-2005 - City of Santa Rosa 2005

Sampling Location	First Flush October 19, 2004	Representative Storm May 4, 2005
Peterson Creek @ Fulton Road	100%	100%
Matanzas Creek @ Hoen Frontage Rd	100%	95%
Paulin Creek @ Mendocino Avenue	100%	100%
Brush Creek @ Hwy 12	100%	90%
Colgan Creek @ Bellevue Road	100%	80% (65%)
Piner Creek @ Marlow Road	100%	100%
Santa Rosa Creek @ Melita Road	100%	100%
Santa Rosa Creek @ Piner Creek	100% (100%)	100%
Controls	90% (100%)	100% (100%)

* *Duplicates shown in parentheses.*

Environmental field data accompanied results from each sampling location, indicating conditions that meet basin plan objectives for pH, and odors for all sites. Elevated turbidity levels were observed in Santa Rosa and Peterson creeks. The representative storm at Santa Rosa creek exceeded basin plan objectives for temperature with a difference of 5.4 degrees F (City of Santa Rosa 2005).

Invasive *Ludwigia* sp. research

Exotic Uruguayan primrose-willow (*Ludwigia* sp.) has aggressively spread in recent years and has impacted sensitive wetlands of the Laguna de Santa Rosa and greater Russian River watershed. While non-invasive members of the same genus (*Ludwigia peploides* spp. *peploides* and *L. palustris*) are extant in the watershed aquatic plant community, the invasive *Ludwigia* sp. is a fast-spreading, perennial, creeping emergent weed. The invasive *Ludwigia* sp can rapidly form extensive dense floating mats that displace native vegetation and open water habitat, degrade water quality, increase flood risk, and inhibit effective mosquito control. Definitive species identification and management recommendations throughout California have been complicated by variable growth responses of this invasive to environmental conditions.

Dr. Brenda Grewell, a research ecologist with the USDA-Agricultural Research Service has initiated ecological, cytological and genetic studies in 2005 to confirm species identity in California and to assess factors influencing invasion success and so address a number of key uncertainties with regard to the *Ludwigia* sp. invasion. The overall goal of her research program is to understand the mechanisms that control the dynamics of aquatic and riparian plant communities and promote the invasion of exotic species, and to identify key factors that must be overcome for successful integrated weed management and wetland restoration.

The development of effective management strategies for invasive *Ludwigia* sp. control requires information regarding weed tolerance and response to a range of environmental conditions.

The current experimental invasive *Ludwigia* sp. research program includes:

- Identification of invasive *Ludwigia* sp. growth responses to biotic and abiotic factors
- Investigating life cycle vulnerability
- Study of the effects of invasive *Ludwigia* sp. growth and control strategies on native plant community restoration
- Invasive *Ludwigia* sp. establishment, growth, nutrient allocation, and decomposition dynamics across environmental gradients in field and mesocosm experiments
- Assessing sediment seed bank dynamics, plant and animal species interactions with invasive *Ludwigia* sp., ecological attributes and biogeochemical functions of reference and invaded wetlands
- Assessing the potential for directed succession of plant communities to inhibit invasive *Ludwigia* sp. establishment
- Investigation of the ecology and population controls of *Ludwigia* in its native range in South America (Uruguay and Argentina).

Ludwigia control project

The Laguna de Santa Rosa Foundation (LdSRF) is currently engaged in a three-year active invasive *Ludwigia* sp. control and removal program at two large invaded areas in the Laguna de Santa Rosa watershed: the Bellevue-Wilfred Channel, a Sonoma County Water Agency (SCWA) site near Rohnert Park, and the Laguna Wildlife Area, a California Department of Fish and Game (CDFG) site near Sebastopol. Vegetation monitoring completed prior to year two (2006) herbicide application and mechanical removal showed variable responses of *Ludwigia* depending on site conditions. Deeper and wider channels, present at the CDFG site and the SCWA site near Rohnert Park, showed very little re-growth after the prior year's removal. Invasive *Ludwigia* sp. must root in sediment and is therefore forced to begin at the bank and "creep" across the channel. In shallower channels where rooting is possible across the entire channel base, invasive *Ludwigia* sp re-growth was estimated at 54%. In the flooded wetlands of the CDFG site where vegetation could not be removed in year one, re-growth was widespread. However, the density of *Ludwigia* within this area was significantly reduced. Where 80% of the monitored plots had greater than 95% cover prior to year one, only 6% had the same cover in year 2. Greater species richness and open water were also observed following year one control activities (LSRF 2007).

Year two control acreages were expanded at both sites. Control methods employed in year two again included application of herbicide followed by mechanical removal where necessary and where feasible. The herbicide triclopyr (Renovate®) appeared to have greater efficacy than glyphosate in controlling *Ludwigia* and was applied at one-third the rate of glyphosate. Mechanical removal was limited to expanded control areas and to the Bellevue Wilfred Channel near Rohnert Park. Post-season monitoring at the CDFG flooded wetland site indicated that re-growth did occur after the herbicide application but that in the drier areas there was a marked increase in species richness. Dense patches of non-*Ludwigia* species occupied significant areas. True evaluation of the effect of year two will only be possible after monitoring in late spring 2007 (LSRF 2007).

The LSRF has initiated a yearly invasive *Ludwigia* sp. mapping and monitoring program in 2006, covering a subset of creeks in the Laguna de Santa Rosa watershed. This effort has yet to incorporate the distinction between the native *Ludwigia peploides* ssp. *peploides* and the invasive *Ludwigia* sp., the taxonomy of which is still unclear. Planned field training sessions with Dr. Brenda Grewell will allow Laguna de Santa Rosa Foundation staff to indicate these two species in future monitoring.

6.3 Ecosystem conceptual models

6.3.1 Model extent

In *Enhancing and Caring for the Laguna* (Honton & Sears 2006, Volume II, Appendix E), the Laguna was divided into eighteen distinct geophysical regions through a detailed analysis of surficial geology, topography and precipitation. For the purposes of this study, the boundaries to these eighteen regions are used, in aggregate form, to define the boundaries to the two conceptual models: six regions correspond to the lower watershed model; twelve regions correspond to the upper watershed model.

Table 6-7
Watershed regions as they correspond to the two conceptual models

Geophysical Region	Topographic zone	Conceptual Model
Taylor	Mountains	Upper watershed
Bennett	Mountains	Upper watershed
Matanzas	Mountains	Upper watershed
Los Guilicos	Mountains	Upper watershed
Cabeza	Mountains	Upper watershed
Montane	Mountains	Upper watershed

Foothills	Mountains	Upper watershed
Gossage	Goldridge Hills	Upper watershed
Blucher	Goldridge Hills	Upper watershed
Goldridge	Goldridge Hills	Upper watershed
Forestville	Goldridge Hills	Upper watershed
River	Goldridge Hills	Upper watershed
Cotate	Santa Rosa Plain	Lower watershed
Llano	Santa Rosa Plain	Lower watershed
Wright	Santa Rosa Plain	Lower watershed
Piner	Santa Rosa Plain	Lower watershed
San Miguel	Santa Rosa Plain	Lower watershed
Laguna	Floodplain	Lower watershed

6.3.2 Upland, riparian and stream knowledge bases

The draft Russian River Watershed Management Plan Synthesis Report for Baseline Watershed Assessment (Smith 2006) outlines logic networks for the Russian River watershed upland, riparian, and stream knowledge bases. These logic networks represent the key conceptual elements used to evaluate the upland, riparian and stream systems in the Russian River watershed, of which the Laguna de Santa Rosa is a small part. These networks contain the conceptual relationships that exist in the Laguna de Santa Rosa watershed at certain scales with respect to upland, riparian and stream conditions, as well as to the potential anthropogenic influences on these systems, and anadromous fish dynamics. Smith also incorporates networks of indicators of hydrologic alterations, upland, riparian and stream vulnerability.

We feel that these networks are directly applicable to the Laguna de Santa Rosa system and we therefore saw no need to repeat this portion of conceptual work. In addition, we will present specific models for the Laguna de Santa Rosa in the next section that show the more detailed dynamics of the upper and lower watershed, and the invasion of an exotic aquatic Primrose species (invasive *Ludwigia* sp.) into parts of the lower watershed. The next sections describe in more detail the Russian River knowledge bases and logic networks presented by Smith.

Upland knowledge base

The upland knowledge base reflects the proposition that upland areas of an assessment unit exhibit conditions within the range of natural variability regarding vegetation, fauna landscape patches, human disturbance, and fire regime. The upland knowledge base consists of three primary logic networks related to condition of habitat, human disturbance, and fire regime (Figure 6-3).

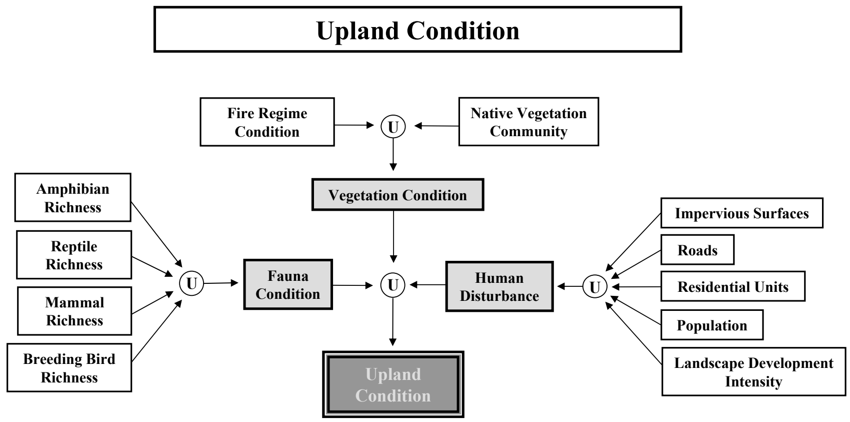


Figure 6-3 Upland condition knowledge base schematic (Smith 2006)

Riparian condition knowledge base

The Riparian condition knowledge base reflects the proposition that riparian areas along the main stem of each assessment unit show conditions within the range of natural variability with respect to vegetation, fauna, corridor structure, and hydrologic regime (Smith 2006). The knowledge base consists of four primary logic networks related to vegetation condition, fauna condition, corridor condition, and hydrologic condition (Figure 6-4).

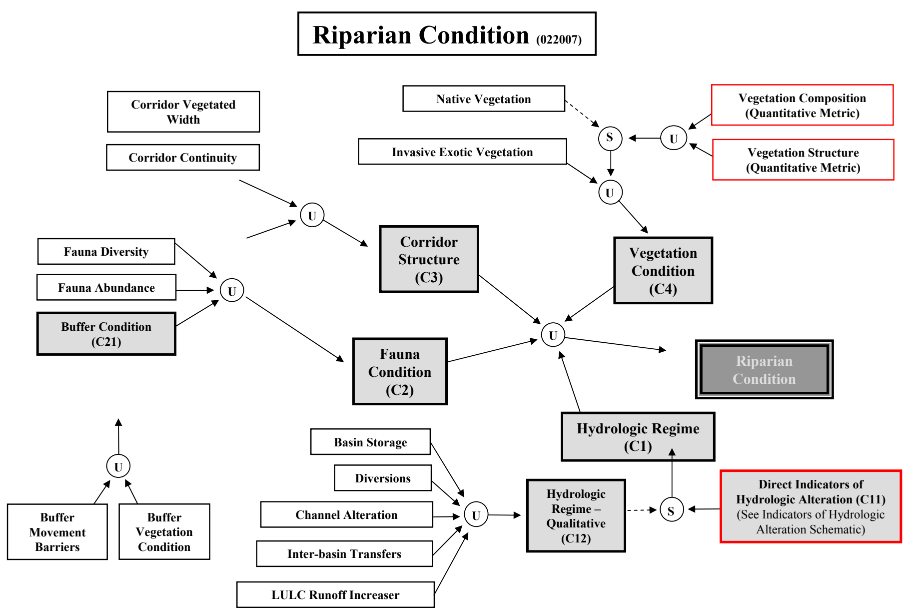


Figure 6-4 Riparian condition knowledge base schematic (Smith 2006)

Physical and chemical stream condition knowledge base

The physical and chemical conditions in the main stem stream channel of an assessment unit are, (1) within the range of natural variability, or (2) not subject to anthropogenic disturbances with the potential to alter physiochemical stream conditions, or (3) within the range of current water quality, flow, or other standards, objectives, or recommendations (Smith 2006).

The Physical and Chemical Stream Condition knowledge base includes logic networks for four key factors that influence physical and chemical conditions of a stream including: hydrologic regime, sediment regime, geomorphic condition, and water quality Figure 6-5. The Anthropogenic Sediment Erosion Potential knowledge base schematic is shown in Figure 6-6. Each logic network incorporates direct indicators that quantitatively represent important characteristics or processes related to physicochemical stream condition and indirect indicators that quantitatively, or qualitatively, represent anthropogenic disturbances with the potential to alter physicochemical stream conditions (Smith 2006). Switch nodes dictate that direct indicator data is used when available and indirect data when direct data is not available (Smith 2006). The Physical and Chemical Stream Condition truth value is the union of the truth values resulting from the hydrologic regime, water quality, geomorphic condition, and sediment regime logic networks.

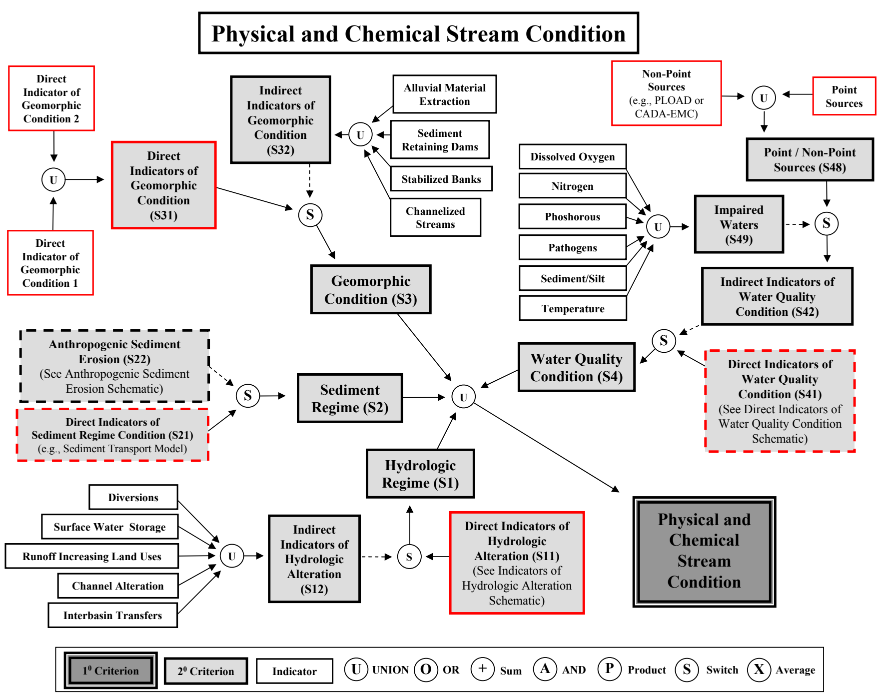


Figure 6-5 Physical and chemical stream condition knowledge base schematic (Smith 2006)

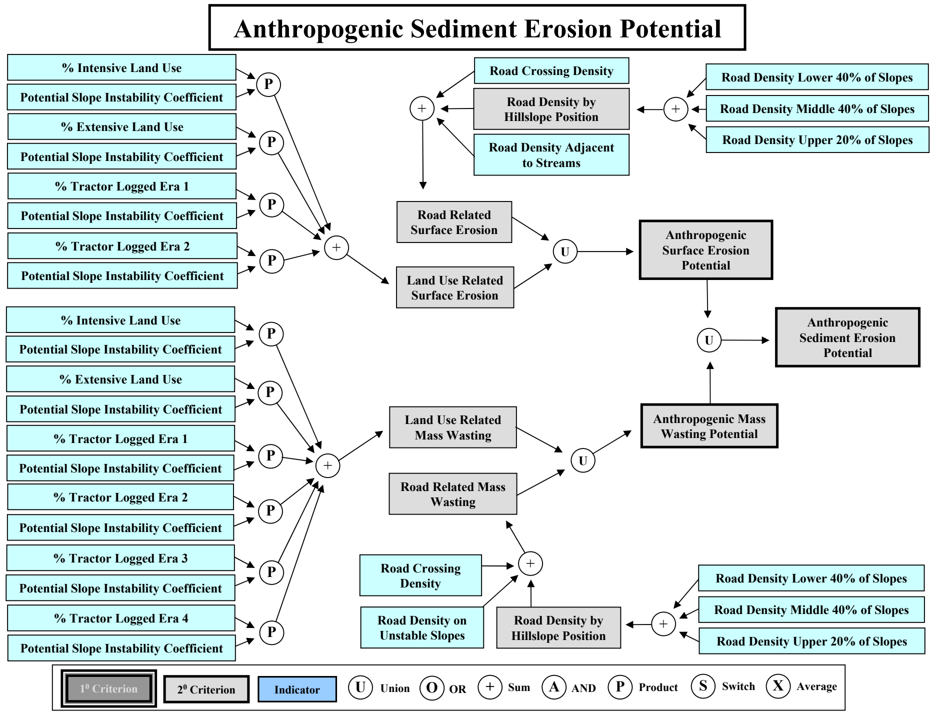


Figure 6-6 Anthropogenic sediment erosion potential schematic (Smith 2006)

Anadromous fish suitability

The main stem stream channel of an assessment area exhibits physical conditions that are either: (1) within the range of natural variability, or (2) within the range of existing regulatory standards (e.g., TMDL or other water quality standards) (Smith 2006). Also, the main stem stream channel of an assessment area, (1) meets the target habitat objectives for embeddedness, riparian canopy, primary pools, and upper water temperature established for North Coast salmonid bearing streams (tributary level) in the CDFG Russian River Basin Fisheries Restoration Plan (Coey et al. 2002), (2) meets the desired salmonid freshwater habitat condition established for sediments by the North Coast Regional Water Quality Board (NCRWQB), and (3) is not affected by downstream anadromous fish migration barriers (Figure 6-7). Coey developed four reach level variables to explain the state of salmonid habitat condition. These variables included riparian canopy, primary pools, upper water temperature, and embeddedness. The Anadromous Fish Suitability truth value is the union of Anadromous Fish Habitat Condition, the Physical Stream Condition, and the access barriers indicator truth values. Habitat Condition, the Physical Stream Condition, and the access barriers indicator truth values.

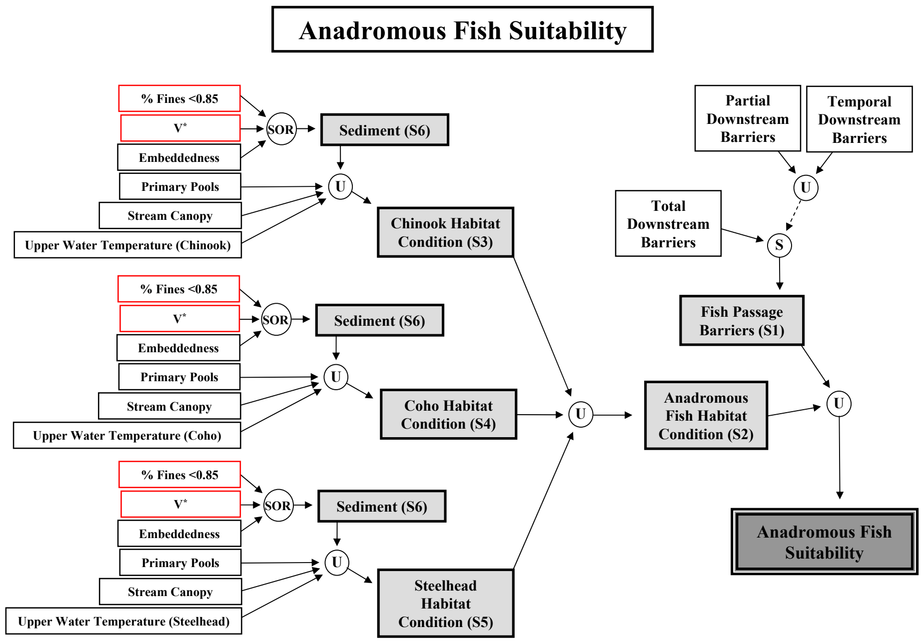


Figure 6-7 Schematic of the anadromous fish suitability knowledge base (Smith 2006)

Riparian vulnerability

Riparian areas along the main stem of an assessment area exhibit current conditions, or predicted future conditions, with the potential to reduce the truth value of the Riparian Condition criterion. The Riparian Vulnerability criterion schematic is shown in Figure 6-8 and the Indicators of Hydrologic Alteration is shown in Figure 6-9.

Riparian Vulnerability criterion is the union of the Hydrologic Regime, Proximity of Invasive Species, Human Stressors, and Development Potential criteria truth values, and the Land Ownership and Riparian Buffer Land Use / Land Cover indicator truth values (Smith 2006).

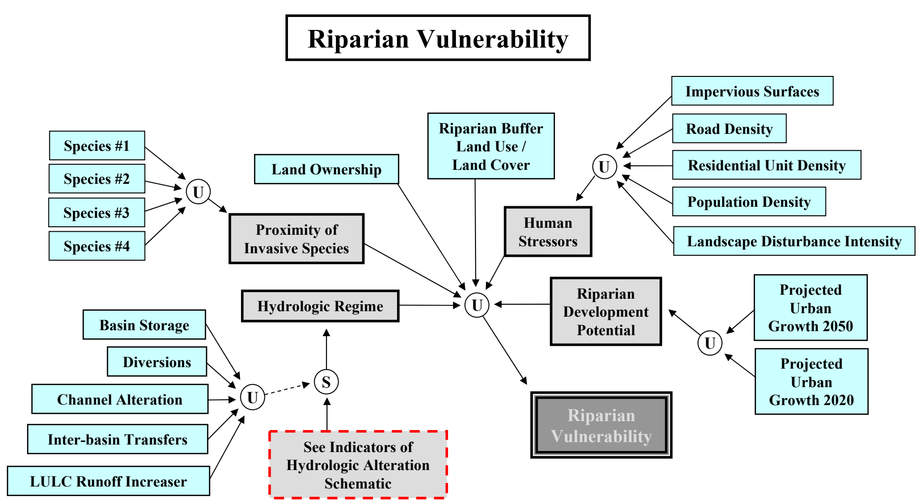


Figure 6-8 Riparian vulnerability knowledge base schematic (Smith 2006)

Indicators of hydrologic alteration

The main stem stream channel in an assessment area exhibits a hydrologic regime within the range of natural variability with respect to flow duration, frequency, and timing. Inter-annual and intra-annual variation such as seasonal flow patterns; frequency, duration, and predictability of floods, droughts, and intermittent flows, timing of extreme flows; daily, seasonal, and annual flow variability; and rates of change play a critical role in maintaining biodiversity and the evolutionary potential of aquatic, riparian, and wetland ecosystems (Poff and Ward 1989, Richter et. al. 1996, Olden and Poff 2003, and Nature Conservancy 2005). The indicators of hydrologic alteration truth values is the union of the magnitude of monthly conditions, magnitude and duration of annual extremes, timing of annual extremes, frequency and duration of high and low pulses, and rate and frequency of change truth values (Smith 2006).

Smith proposes further networks addressing restoration and conservation potential with respect to all three knowledge bases, and non-point sources, organic and inorganic chemicals, nutrients, dissolved oxygen, specific conductance with regard to the stream knowledge base (Smith 2006). With regard to integrating data nd information, Smith suggests Ecosystem Management Decision Support 3.1 (EMDS) as the most fitting data and information integration framework (Reynolds et al 1996, Reynolds et al 2000, Reynolds 2002, Reynolds and Hessburg 2005). As a mature ArcGIS extension, EMDS incorporates knowledge based model development with GIS, allowing the display of results, evaluation of the influence of missing data, scenario simulation, and priority analysis (Smith 2006). This type of modeling may prove fruitful with specific focus on the Laguna de Santa Rosa watershed.

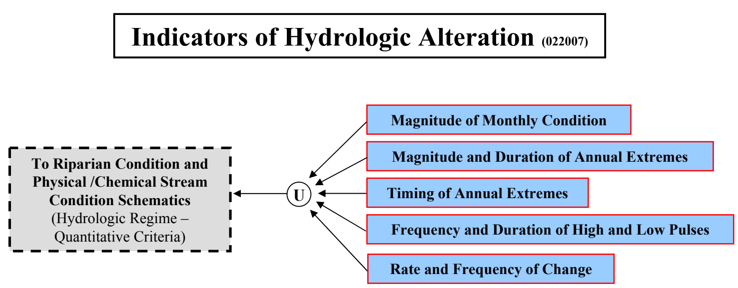


Figure 6-9 Indicators of hydrologic alteration knowledge base schematic (Smith 2006)

6.3.3 Upper watershed model

In specifically addressing the upper and lower Laguna de Santa Rosa watershed models, and a species-specific model regarding invasive *Ludwigia* sp. dynamics in sections of the lower watershed, we followed the framework for conceptual models outlined in Duever (2005) and in the Delta Regional Ecosystem Restoration Implementation Plan (DRERIP) Draft Framework for the Development of DRERIP Ecosystem Conceptual Models (May 2005). These approaches outline the conceptual relationships between drivers, stressors, effects, and attributes, showing the linkages between components, and can be applied to

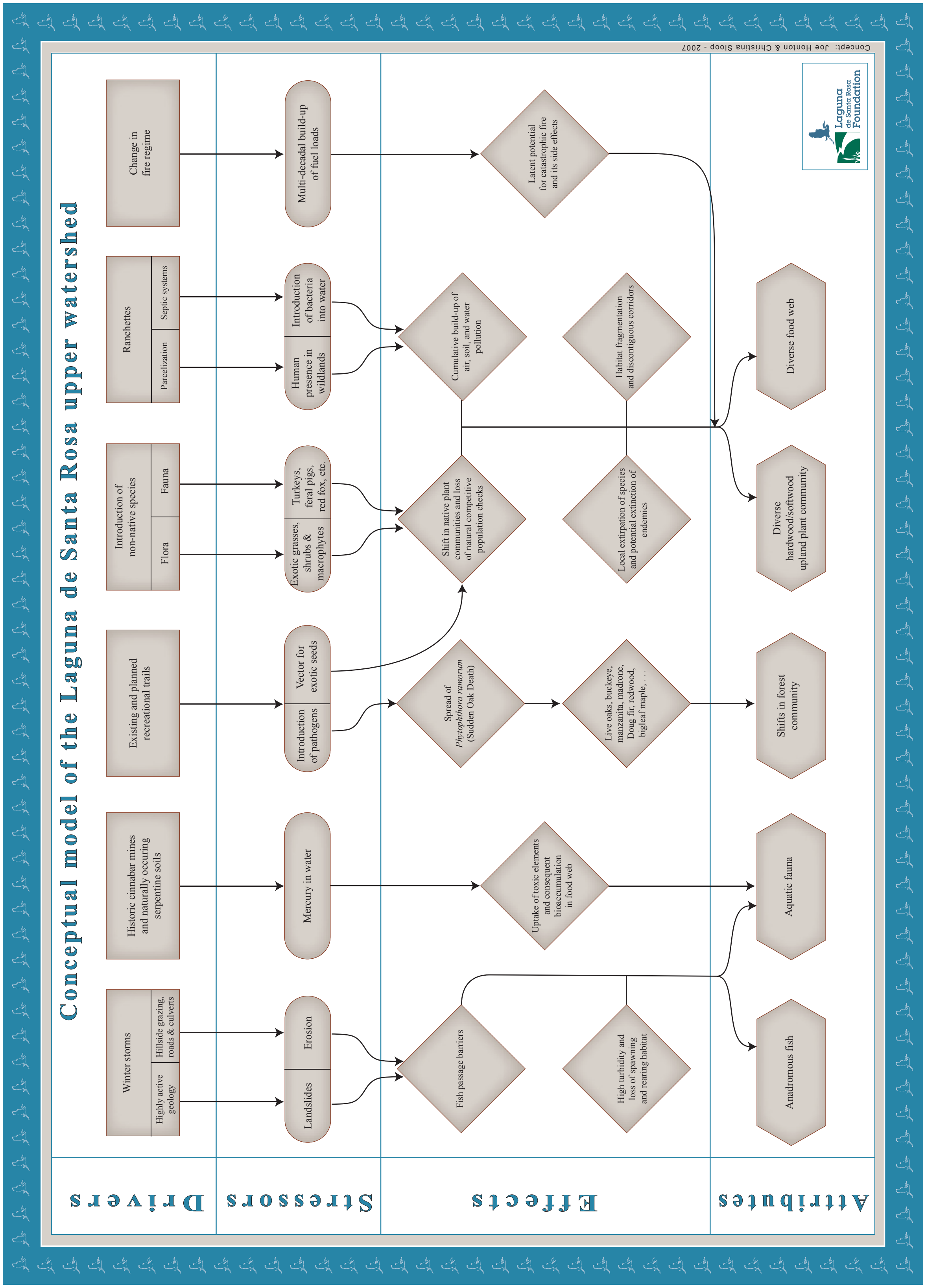


Figure 6-10
Conceptual model of upper watershed

several scales of investigation. This level of conceptual modeling may or may not incorporate directional relationship and various levels of predictability, depending on the status of available data.

The upper watershed conceptual model is laid out in four rows with one row each showing drivers, stressors, effects, and attributes, and with arrows representing the major connections between the model's components. Drivers are the large events, either natural or anthropogenic, that trigger responses in the environment. Some of these drivers occur synchronously, some periodically and some stochastically: only a few of them can be modulated with human endeavor. Stressors are the expression of these drivers in the environment: many of these stressors are the logical target of management decisions—with time and effort some of these stressors can be reduced. Effects are the observable changes in the environment: measurement of the magnitude of these effects gives us indirect feedback on the severity of the stressor. Finally, attributes are the tangible things in the environment (flora, fauna, water, soil, etc.) that are impacted by the effects.

The upper watershed model, as diagrammed in Figure 6-10, shows six key drivers:

- Winter storms in concert with a highly active geology that trigger landslides, especially on the Taylor Ridge; and winter storms in connection with hillside grazing, unpaved roads and driveways, and inadequately sized culverts that trigger sheet and rill erosion and cause fish passage barriers.
- Historic cinnabar mines and naturally occurring serpentine soils that leach mercury into the waterways.
- Existing and planned recreational trails that can act as a repeated source for the introduction of new pathogens (from footwear and tire treads), and these same trails acting as a vector for exotic invasive plants to enter upland habitats.
- The introduction of non-native flora including exotic grasses, forbs, shrubs, and macrophytes that cause a shift in native plant communities, the loss of natural competitive population checks, the potential for local extirpation of species, and the potential for extinction of endemics; and the introduction of non-native fauna such as turkeys, red fox, feral pigs and feral cats causing similar effects in habitat shift and local population loss.
- The presence of ranchettes in the watershed is a dual driver: Parcelization in its own right leads to increased human presence in the watershed, disruption of corridors, and additional pollutants to the soil, air, and water; while septic systems in particular—as they were often constructed on soils that didn't meet today's percolation standards—have added bacteria into the waterways, with unknown effects to the wildlife.
- Fire suppression and indeed an entire change in the fire regime have dramatically built up fuel loads in the mixed conifer/hardwood forests, leading to the latent potential for large-scale catastrophic fire and its side effects, including the potential for massive erosion, and the certain shift in the diversity of upland communities. This driver, if unleashed will have both beneficial and non-beneficial consequences: benefits will accrue from the release of closed-cone seeds as well as dormant subsoil ruderals that take advantage of disturbance.

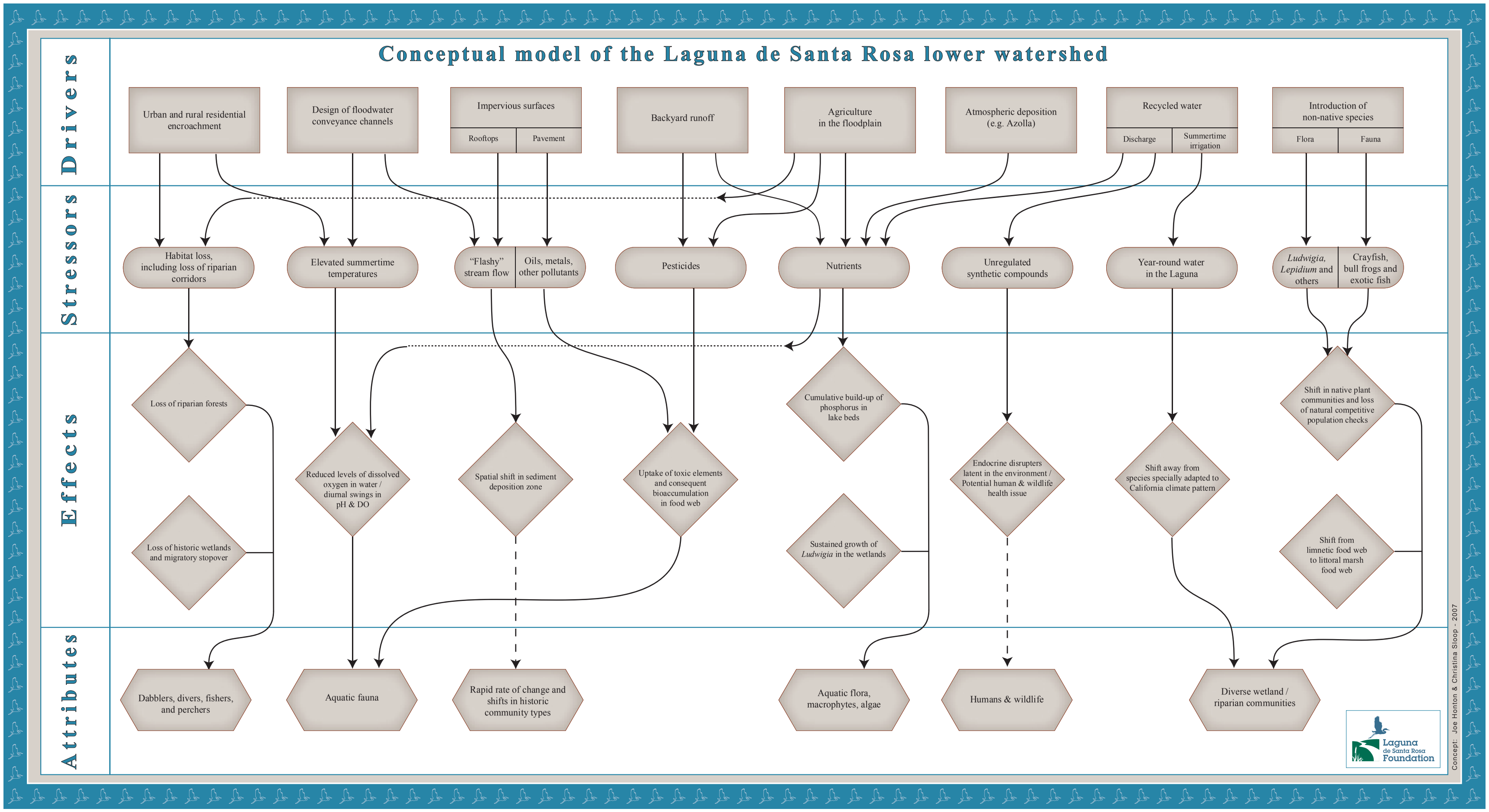


Figure 6-11
Conceptual model of lower watershed

6.3.4 Lower watershed model

The lower watershed conceptual model is laid out similarly to the upper watershed model with the same four rows of components: drivers, stressors, effects, and attributes. The model is composed of seven key drivers, which connect in a slightly more interconnected way than the simpler top-to-bottom connections diagramed for the upper watershed. The lower watershed model, as diagrammed in Figure 6-11, shows these seven key drivers:

- Urban and rural residential encroachment has led to the loss of riparian buffers and the constricting of channels such that the former wiggle room of creeks is eliminated and the need for public safety and property protection trumps the needs for water, sediment transport and deposition, and habitat succession. The result is an artificial need for regular maintenance to keep these stream systems operating in a more-or-less static way. In the flood plain near the Laguna's ponded areas, the loss of wetlands from this encroachment is a problem most apparent in the Sebastopol area.
- The design of floodwater conveyance channels leads to dual effects: channel banks kept clear of woody over-story have elevated temperatures with the consequence that macroinvertebrates are unable to survive and fish and birds are displaced upstream or downstream to cooler habitats that support higher levels of oxygen in the water. The design of floodwater conveyance channels also cause an accumulated effect downstream as more water arrives in the Laguna's ponded and low lying areas in much less time, causing a greater than normal reliance on the floodplain to buffer this flow as it makes its way towards the Forestville Narrows.
- Impervious surfaces, in the form of rooftops, led to the same stressors and effects as floodwater conveyance channels: flashy stream flow. Impervious surfaces, such as roads and parking lots, have the added stressor of acting as sources of oils, metals, and other pollutants from cars. An often unnoticed pollutant is Styrofoam, rubber, plastic bottles, and other trash that floats downstream and becomes entangled in localized collection spots along the Laguna's lowland.
- Backyard runoff is the source of both pesticides and nutrients running off into the waterways. A significant amount of this comes from rural residential units, where the bare soil is seen by some as a sign of tidiness and weedy patches are seen as a sign of an unkempt property. A significant source of pesticides also comes from road maintenance activities which in recent years has begun to rely less on mechanical mowers, and more on herbicides, to remove vegetation from the areas directly adjacent to highways.
- Agriculture in the floodplain leads to the same loss of riparian corridors through encroachment as that described for urban and rural residences. Agriculture in the floodplain also adds nutrients to the system, especially when dairy and cattle pastures are directly in the zone of annual inundation.
- Recycled water discharged into the Laguna leads to elevated nutrient levels in the water column and over time has probably lead to the accumulation of phosphorus in the soil of these water bodies. The sustained growth of invasive *Ludwigia* sp. and other macrophytes in the water column are likely an effect

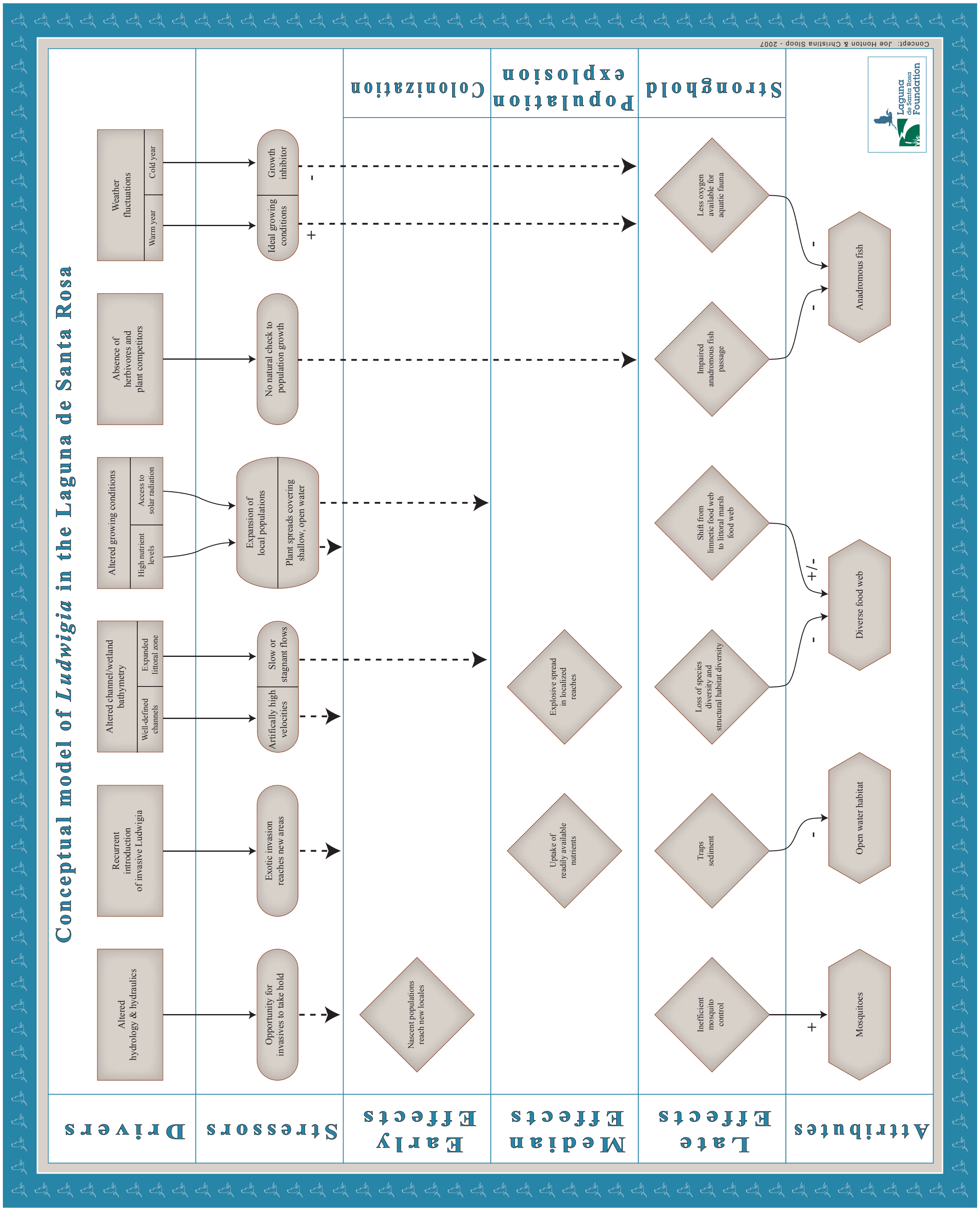


Figure 6-12
Conceptual model of invasive *Ludwigia* sp.

of this multi-decadal input and binding to the soil substrate. Recycled water also contains unregulated synthetic compounds such as estrogenic compounds (birth control pills), other pharmaceuticals and cosmetics, whose affects have not been quantified in the Laguna but which may be causing the disruption of the endocrine systems of wildlife, especially the amphibian populations. These unregulated pollutants may also be a human health issue. Recycled water causes a second set of stressors simply by keeping water levels artificially high throughout the year. Subsurface flow from nearby irrigated fields keeps water in areas well past their normal drying period. This stressor has allowed the shift away from species specially adapted to California's climate pattern. It also favors the late season, or year round, population of some wildlife that would otherwise seek water in the perennial streams of the montane region.

- The introduction of non-native plants such as invasive *Ludwigia* sp., Lepidium latifolium and others has caused a shift in the native plant community and the loss of natural competitive population checks. In the open-water bodies of the Laguna, especially with regard to invasive *Ludwigia* sp., this has meant a shift from a limnetic food web to a littoral marsh food web. The overall diversity of wetland communities and riparian communities has decreased with fewer types of plants and animals being found.

6.3.5 Invasive *Ludwigia* sp. model

In addition to the two watershed-scale models, we also looked in depth at the vexing problem of invasive *Ludwigia* sp., and have developed a targeted model of water quality just for this macrophyte species.

The conceptual model of invasive *Ludwigia* sp., follows basically the same layout structure as the upper and lower watershed models, but this model is confined to the processes related to this single species. Also, this model presents a three-tiered time structure which accounts for the progression of the plant from colonization to population explosion to the long list of late effects which set in when it has reached a stronghold. The model is shown as Figure 6-12.

- Altered hydrology—which in this watershed means more water than normal passing through the system (extra water diverted from the Russian River through the city's distribution system, and being flushed through the treatment plant)—provides a suitable home for invasive *Ludwigia* sp., an emergent macrophyte. Altered hydraulics, such as the construction of flood conveyance channels, provides high than normal velocities through the system, causing floating living plant fragments to break free and be distributed downstream. These alterations allow the plant to reach new locales forming nascent populations that will eventually develop along the lines described below.
- The recurrent introduction of invasive *Ludwigia* sp. into the system, occurs via the re-distribution of plant fragments during floods downstream, through natural transport by wildlife (e.g. seeds or shoots get moved via birds), and possibly through recurrent "escapes" of nursery plants from garden ponds (this has occurred with water hyacinth, *Eichhornia crassipes*). No good working hypothesis

has yet been agreed upon regarding this important question: the role of wildlife and the role of water transport in the introduction of the species to new areas deserves more attention.

- Altered channels lead to the bifurcation of the stream into sections with artificially high velocities, and sections with slow or stagnant flows. In areas of slow or stagnant flow, young invasive *Ludwigia* sp. plants take root, the uptake of readily available nutrients occurs, solar energy is at its optimum for uptake, and the stage is set for a population explosion.
- Altered growing conditions includes the high nutrient levels in the water column and in the substrate, together with access to solar radiation associated with denuded riparian habitats. This driver may cause local populations to expand rapidly. It also allows plants to spread out covering shallow open water, especially in the slow or no flow areas.
- The absence of associated invasive *Ludwigia* sp. herbivores and plant competitors from their native range means that no natural check to population growth is present. During the initial colonization phase there are no natural population growth checks, and so vast monoculture-like mats of invasive *Ludwigia* sp. establish and as an ecosystem engineer (Crooks 2002) completely change the dynamics of the system.
- Fluctuations in weather may be a toggle-type driver. If invasive *Ludwigia* sp. growth is tied to temperature and frost-free days, then warm frost-free winters will likely see ideal growing conditions and cold frosty winters will likely act as a growth inhibitor. More investigation of this phenomenon is warranted.

Indicators 7

7.1 Recommendations

The Laguna model development project is recommending the use of indicators for future monitoring and modeling assessments. Indicators are measurable components of the ecosystem that are linked to both stressors and desired outcomes. Indicators tell the user something about the status of the Laguna either in progress towards mitigating a stressor or the status of a Beneficial Use (or another desired outcome). Indicators are consistent with the emerging California Nutrient Numeric Endpoints framework that is being used to develop targets for nutrient TMDLs in EPA Region IX. Developing and monitoring a set of indicators is the primary tool for establishing hydrologic, geomorphic, and water quality conditions, as well as ecosystem health. Indicators also serve in evaluating the performance of any future studies and guide monitoring recommendations to document achievement of management goals and desired conditions.

The indicators described in the following sections were selected through the application of the overview conceptual models for hydrology, water quality, and ecosytem to identify factors that are intermediate measures (response variables C-G) between stressors and Beneficial Uses. Each indicator is briefly described including its linkage to stressors and endpoints and a recommendation is provided for communicating its status (*i.e.*, metric). This section includes more indicators than can be practically incorporated into the Laguna de Santa Rosa stewardship framework. Additional interaction among participating agencies and stakeholders is needed to prioritize and to develop a monitoring program for each indicator that is adopted in the final list.

Hydrologic indicators in the Laguna watershed are limited due to its unusual lake-like stream characteristics and its interaction with the Russian River. One management goal of our hydrologic conceptual model is related to flood hazards. Due to the complexity of hydrologic conditions in the Russian River and the Laguna, and hydraulic interactions at their confluence, there are no hydrologic indicators that would quantify future change in flood elevations. Any meaningful comparison of past, current or future flood elevations in the Lower Laguna require that base level conditions (that is water surface elevations in the Russian River) be the same for the event considered. In view of the stochasticity in precipitation and runoff events in both watersheds, comparability of flood conditions "all things being equal" is not feasible. Therefore, we are not recommending an indicator to identify flood elevations in the Lower Laguna. The recommended hydrologic and geomorphic indicators are selected to accomplish the following:

- To identify the changes in flood frequencies
- To document rapid geomorphic or habitat evolution that appears to be driven by changed or changing hydrologic or hydraulic conditions

The water quality and ecosystem indicators include several parameters that will be critical to the development of a TMDL for the Laguna. Several parameters are also already being evaluated through various programs (*e.g.*, *Ludwigia*) or have existing information and analyses that need to be supplemented (*e.g.*, nutrient concentrations, DO, and temperature).

A list of suggested general hydrologic, geomorphic, water quality, and ecosystem health indicators is provided below:

- High and low frequency flood flows / hydrographs: 2-year and 100-year flood
- Channel and floodplain cross sections
- Longitudinal channel profiles
- Bankfull flow
- Rates of bed and bank erosion or aggradation
- Dredge removal quantities
- Macrophytes (extent of Laguna with density above a selected threshold value)
- Chlorophyll a
- Minimum DO/% Saturation
- Temperature/temperature stratification
- Sediment indicator (not currently defined)
- Benthic macro-invertebrates diversity index (look at storm water data)
- Warm Water Fish – resident species
- Unionized ammonia/pH
- Nutrient concentrations in tributaries and main channel
- Organic carbon/BOD concentrations in tributaries and main channel
- Habitat condition
- Amphibians
- Birds

Each of these indicators is described in the following sections. Additional information will be provided regarding the measurement and interpretation of the proposed indicators in the monitoring recommendations as part of the final project report.

7.2 High and low frequency flood flows

We are recommending the use of both high frequency and low frequency flood flows as indicators of hydrologic change in the watershed. The 2-year flood event volume and the 100-year flood event volume are recommended as hydrologic indicators. The 2-year flood event is the flood event that has a 50 percent chance of being equaled or exceeded in any given year (or occurs on the average once every 2 years). The 100-year flood event is the flood event that has a 1 percent change of being equaled or exceeded in any giver year. The 2-year flood event is a high frequency, low magnitude event that has a considerable volume and occurs often enough to affect channel geomorphology. The variation in the 2-

year event volume over time can be used an indicator of hydrologic change. The 100-year flood event volume is recommended to represent low frequency, high magnitude events in the watershed. The 100-year flood event is FEMA's standard flood for floodplain management and flood insurance. An alternative is to compare hydrographs instead of flows which would allow comparisons of peak flow rates, time to peak, duration of flow above sediment transporting velocities and cumulative impacts from combining changes in hydrographs of tributary streams, in addition to total flood volume. Hydro graphs would allow the use of several metrics to represent the high and low frequency flood flows.

Metric – The measure of flood event volume is acre feet.

7.3 Channel and floodplain cross sections

Channel and floodplain cross sections represent the channel's ability to transport water and sediment. Variation in channel or floodplain cross sections would indicate change in overall storage capacity. Temporal variation in cross sections locations would also identify locations and magnitudes of degradation and aggradation and would indicate channel stability over time.

Metric – Cross sections are measured in length units (feet or meter).

7.4 Longitudinal channel profiles

Longitudinal profile is simply a plot of height against distance downstream. It represents the gradient of a stream at the reach or watershed scale. A profile would reveal overall geomorphic characteristics of a channel and would indicate potential erosion/ deposition zones. It is also a general indicator of sediment transport capacities along a channel because gradient strongly affects transport capacity. Variation in longitudinal profile would point to adjustments in channel gradients that can be brought about by aggradation, degradation, or changes to channel sinuosity. The process of aggradation and degradation often operates in response to changes in watershed controls or base level.

Metric – Longitudinal profiles are measured in length units (feet or meter).

7.5 Bankfull flows

Bankfull discharge is the flow of water that fills the channel and just begins to overtop the streambank in to the floodplain. River channels adjust on average to bankfull discharges which have enough stream power to erode, transport, and deposit the materials transported from upstream or contributed by banks. Bankfull discharge is commonly equated to the 2-year flood because a significant number of studies of statistical hydrology and geomorphic form in different environments have frequently found the 2-year flow (more specifically flows ranging from 1.0- to 2.5-years) to coincide with bankfull discharge. Variation in bankfull discharge is an indicator of channel geomorphic change that would point to either aggradation or degradation in the system.

Metric – The metrics for bankfull flows is discharge units in cubic feet per second or cubic meters per second.

7.6 Bed and bank erosion or aggradation

Land use modifications and changes in watershed conditions upset the continuity of sediment transport resulting in either degradation or aggradation. Degradation reflects bed load starvation and aggradation reflects excessive bed load input. Rates of bed and bank erosion or aggradation are indicators of geomorphic change due to land use modifications in the short term. Specifically they would indicate changes in sediment supply and storage capacity. Superimposed with flood volumes, they could be used to derive implications for flood storage capacity

Metric **–** Bank erosion can be expressed in terms of retreat rate, which is measured in length unit over time (such as feet per year). Bed erosion or aggradation is represented by change in bed elevation and is measured in feet per year or meter per year (or longer time frame).

7.7 Dredge removal quantities

Flood control channels in the Laguna watershed are periodically dredged. The dredged sediment volumes would indicate the magnitude of aggradational processes in the lower watershed. Aggradation in turn is an indicator of sediment supply characteristics or variations and is linked to flood elevations.

Metric **–** Dredge volumes are expressed in acre feet or cubic yard over a specified distance expressed in feet or meter.

7.8 Macrophytes

Macrophytes are rooted emergent, submergent, or floating aquatic plants (*e.g.*, *Ludwigia* sp.) that grow in or near water. Macrophytes provide cover for fish and substrate for aquatic invertebrates and are so beneficial to lakes. They produce oxygen, which assists with overall lake functioning, and provide food for some fish and other wildlife. Crowder and Painter (1991) indicate that a lack of macrophytes in a system where they are expected to occur may suggest a reduced population of sport and forage fish and waterfowl. Macrophytes can affect the designated uses of water and be ecologically important habitat. High densities of macrophytes caused by excess nutrient enrichment can impact recreational uses, such as swimming and boating, and also degrade the aesthetic value of the resource. Ecologically, an increase in macrophyte cover can provide necessary habitat for aquatic life in streams. However, decomposition and nocturnal respiration can cause oxygen depletion and low reaeration rates. Even relatively small reductions in dissolved oxygen can have adverse effects on both invertebrate and fish communities, and aerobic conditions can alter a wide range of chemical equilibria, and may mobilize certain chemical pollutants as well as generate noxious odors. Nuisance levels of macrophytes also reduce stream flows resulting in increased sedimentation and, ultimately, reduced fish spawning habitat. In addition, the absence of macrophytes may also indicate water quality problems as a result of excessive turbidity, herbicides, or salinization.

Metric **–** Macrophytes are excellent indicators of watershed health. They respond to nutrients, light, toxic contaminants, metals, herbicides, turbidity, water level change, and salt. They are easily sampled through the use of transects or aerial photography, and do not require laboratory analysis. They are easily used for calculating simple abundance metrics, and are integrators of environmental condition (USEPA 2006). The measure of aquatic macrophyte density is the percent of aerial coverage by channel reach.

7.9 Chlorophyll-a

Chlorophyll a is the photosynthetic pigment that plants use to produce cell material from sunlight and carbon. The amount of chlorophyll-a in the water column or on the substrate is a measure of phytoplankton (aquatic algae) biomass and, therefore, it is an indicator of water quality. Phytoplankton form the base of the Laguna food web and provide food for fish and other filter-feeding organisms. Changes in abundance, species composition, and productivity of phytoplankton are commonly the first biological response to nutrient enrichment and are a measure of the effectiveness of nutrient reduction strategies. These changes in phytoplankton influence the food webs of which they are a part and the fisheries that depend upon them. Too much phytoplankton, caused by overproduction and/or under-consumption, reduces water clarity and depletes oxygen in bottom waters.

Metric – The measure of chlorophyll-a in the watercolumn is micro-grams chlorophyll-a/liter water. The measure of substrate chlorophyll-a is mg chlorophyll-a/unit area.

7.10 Dissolved oxygen/percent saturation

Dissolved oxygen (DO) concentration and percent saturation in water are often used to gauge the overall health of the aquatic environment. The dissolved oxygen concentration and percent saturation are intricately linked to algal concentrations in the waterbody as well as the decomposition of organic material. When excessive amounts of algae die and sink to the bottom, bacteria decompose the material and consume oxygen. This increase in activity results in increased oxygen consumption and can deplete available oxygen. Additionally, dissolved oxygen levels change throughout the 24-hour day/night cycle, with greater concentrations being found during the day while photosynthesis is taking place and lower dissolved oxygen levels available during the night-time when respiration is taking place. As such, point measurements of dissolved oxygen are not sufficient to assess this indicator and continuous measurements are required.

Low oxygen levels generally affect bottom waters first and most severely and can result in reducing conditions within the sediments, which may cause previously bound nutrients and toxicants to be released into the water column.

Generally, dissolved oxygen concentrations above 5 mg/L are protective of most aquatic life uses. However, cold-water fishes require higher DO concentrations as do all species in stages of early development.

Metric – Dissolved oxygen concentration and percent saturation are measured by continuous reading electronic probes. The units of measurement are mg/l (concentration) and percent (saturation.)

7.11 Temperature

Stream temperatures are the net result of a variety of energy transfer processes, including radiation inputs, evaporation, convection, conduction, and advection. Stream temperatures reflect both the seasonal change in net radiation and daily changes in air temperature.

Increased temperatures are known to increase biological and chemical activity and controls the amount of dissolved oxygen that a waterbody can contain, drives certain equilibrium reactions, for example the equilibrium between ammonium and ammonia, both being toxic to aquatic life. Stream temperatures can also form a thermal barrier to anadromous cold water fish populations that use the Laguna during their seasonal migration to the colder upper reaches of the waterbody.

Metric – Temperature can be measured by either a thermometer or an electronic sensor and should be monitored continuously at the surface and bottom of the Laguna.

7.12 Sediment

Increased sediment load can greatly impair, or even eliminate, fish and aquatic invertebrate habitat, and alter the structure and width of the streambanks and adjacent riparian zone. Fine sediment can impair the use of the water for municipal or agricultural purposes. Many nutrients and other chemical constituents are sorbed onto fine particles, so sediment loads are often directly related to the load of these constituents. Indirect effects of increased sediment loads may include increased stream temperatures and decreased inter gravel dissolved oxygen.

Metric – The primary metrics of this indicator are sediment grain size, total organic carbon, nutrients, and stream embeddedness. Secondary metrics of this indicator are total nitrogen and total phosphorus.

7.13 Benthic macroinvertebrate diversity index

Benthic macroinvertebrates have several characteristics which make them potentially useful as indicators of water quality. First, many macroinvertebrates have either limited migration patterns or a sessile mode of life, and this makes them well suited for assessing site-specific impacts. Second, their life spans of several months to a few years allow them to be used as indicators of past environmental conditions (Platts et al., 1983). Third, benthic macroinvertebrates are abundant in most streams. Fourth, sampling is relatively easy and inexpensive in terms of time and equipment (USEPA 1989). Finally, the sensitivity of aquatic insects to habitat and water quality change often make them more effective indicators of stream impairment than chemical measurements (USEPA, 1990).

Metric – The primary metrics of this indicator are abundance, species richness, diversity indices, and biotic indices.

7.14 Warm water fish

Fish are a useful surrogate or integrator of a variety of physical and biological factors. Some of the factors necessary to sustain or restore a particular fish population include 1) adequate streamflow (*i.e.*, water depth and habitat space), 2) sufficient spawning habitat, 3) sufficient rearing habitat, 4) appropriate food sources at different life stages, and 5) proper environmental conditions (particularly temperature, dissolved oxygen, and turbidity). Fish permanently live in the water throughout their life, vary in their tolerance to amount and types of pollution, are straightforward to collect with the right equipment, live for several years, and are easy to identify in the field. Most fish continually inhabit the receiving water and integrate the chemical, physical, and biological histories of the waters. Fish have been used worldwide for many years to indicate clean or polluted waters, and whether conditions are doing better or getting worse.

Metric **–** The primary metrics of this indicator are the presence or absence of a particular species, numbers of a particular species, or community parameters such as productivity, density, and diversity. Fish health clearly indicates toxicity and allows assessment of root-causes (USEPA 2006). Therefore, a variety of test species should be incorporated into bioassays due to varying tolerances to specific toxins (Salop 2002).

7.15 Unionized ammonia/pH

Unionized ammonia (NH_3) is an intermediate breakdown product of organic nitrogen, fertilizers, and animal wastes. Ammonia is extremely toxic to fish and invertebrates at concentrations as low as 0.002 mg/l. The concentration of unionized ammonia in aquatic systems is driven by pH and temperature. As such, conditions that cause the temperature to rise (e.g., increased sediment load, turbidity); the pH to rise (e.g., increased CO_2 consumption during photosynthesis); or increased ammonia production (e.g., decomposition of organic material) will also cause an increase in unionized ammonia.

Metric **–** The primary metrics of this indicator are total ammonia-nitrogen (mg/l), pH, and temperature. Since pH is influenced by the algal photosynthesis:respiration cycle and changes over a 24-hour period (*i.e.*, lower pH's during the evening respiratory cycle and higher pHs during the daytime photosynthetic cycle), the unionized ammonia concentrations should be monitored continuously.

7.16 Nutrient concentrations

While nutrients (nitrogen and phosphorus) are not generally directly toxic to aquatic life, they can stimulate the growth rates of algae and macrophytes as well as the activity rates of bacteria and fungi. Excess growth of algae, macrophytes, bacteria,and fungi can result in excessive growth and a resultant over consumption of dissolved oxygen. They can also negatively affect the aesthetic quality of the waterbody and impair contact and non-contact recreational beneficial uses.

Metric – All species of nitrogen (nitrate, nitrite, particulate and dissolved organic nitrogen, TKN, total N) and all species of phosphorus (phosphate, particulate and dissolved organic phosphorus, total phosphorus) should be monitored. So that nutrient loadings can be estimated, all inputs into the Laguna should be monitored (*e.g.*, tributaries, stormwater outfalls, etc.)

7.17 Organic carbon concentrations / BOD

Biological/biochemical oxygen demand (BOD) is the amount of oxygen consumed by biota in water. It is a measure of the portion of organic carbon that is relatively easily oxidized by micro-organisms. It is used as an indicator of dissolved organic carbon. As such, both organic carbon and BOD loadings from both terrestrial and aquatic ecosystems are potential sinks of dissolved oxygen.

Metric - Dissolved and total organic carbon (%) and BOD 5day (mg/l) should be monitored So that nutrient loadings can be estimated, all inputs into the Laguna should be monitored (*e.g.*, tributaries, stormwater outfalls, etc.)

7.18 Habitat condition

Plants play a crucial role in invertebrate and vertebrate community diversity by providing habitat structure and essential food sources. Besides their crucial position at the food web base, the diversity of plant species, ages, shapes and sizes defines structural variety which in turn boosts the diversity of birds and other vertebrates and invertebrates (Kreitinger & Gardali 2007). Diverse vegetation structure creates a mixture of habitat niches for organisms to utilize within a given plant community, e.g. insects feed on plants and then provide nourishments to birds, which are preyed upon by other birds or mammals. Plants provide nesting sites for birds or mammals and provide shade and spawning sites for amphibians and fish along waterways. Vertical structure of vegetation ensures that bottom as well as canopy dwellers find cover and foraging habitat within a heterogeneous habitat matrix.

Riparian and oak woodlands, also improve water and air quality, absorb water runoff and slow water velocity along streams. Riparian zones support a disproportionately large amount of biodiversity compared to other landscape elements (Harris et al 1996). Terrestrial areas surrounding wetlands and streams are core habitats for many terrestrial, aquatic and semi-aquatic species (Demilitsch and Bodie 2003). Riparian zones also function as important corridors for longer-range animal movement, making riparian zones one of the most important landscape elements for biodiversity (Hilty et al 2006).

Areas where historical riparian vegetation have been lost are thus sure indicators of habitat loss/degradation, negatively affecting the entire associated aquatic and terrestrial communities. Terrestrial streamside communities are mainly impacted through the loss of cover, foraging and nesting habitat (Pearson and Manuwal 2001). Stream habitat degradation could be in the form of increased run-off and stream bank erosion, lack of shade along stream banks causing increased water temperatures, and loss of fish cover or spawning habitat. Lack of riparian vegetation may also allow adjacent livestock to enter the water, causing bank erosion, degrading the stream bottom through trampling and the introduction of increased nutrients into the stream via direct and indirect input of livestock excrement.

The loss or degradation of vegetation along streams also reduces the effectiveness of riparian buffers to improve water quality through processing and removal of excess anthropogenic nitrogen from surface and ground waters. To maintain maximum buffer effectiveness, buffer integrity should be protected against soil compaction, loss of vegetation, and stream incision (Mayer et al 2006). Restoring degraded riparian zones, and stream channels may improve nitrogen removal capacity of the stream system, making riparian buffers a 'best management practice' (Mayer et al 2006). While there is not one generic riparian corridor width to keep water clean, stabilize banks, protect wildlife, and satisfy human demands, generally the larger the width of vegetation, the better the impact on ecosystem services and biodiversity (Kreitinger & Gardali 2007, Semlitsch and Bodie 2003, Pearson and Manuwal 2001).

As exotic invasive plants, such as invasive *Ludwigia* sp., increasingly take hold in native plant communities, they threaten native biodiversity by changing the native vegetation structural diversity, often completely 'taking over,' and in some cases as "ecosystem engineers" (Crooks 2002) not only out-competing native plants and establishing an extensive and expanding mono-culture, but in the process permanently changing the habitat structure and function. This process so fundamentally changes the original native ecosystem, causing the local extinction of organisms tightly linked to the original community structure and function (National Invasive Species Council 2001). Most invasive plants were brought in by humans and initially established in disturbed sites.

Profound plant community changes can occur due to numerous anthropogenic factors. A community's ecosystem services such as preventing soil erosion and keeping water clean, may be reduced by development, over-harvesting of forest trees, trampling, unsustainable farming practices, nearby infrastructure, urban run-off etc. Once plant community structure has been altered, e.g. from high canopy forest to non-native annual grassland, the capacity of the system to hold on to top soil and to decrease run-off has diminished so that soil erosion rates will increase measurably (SEC 2006).

***Metric* -** Habitat condition can be measured by measuring vegetation, woody debris, exotic vegetation conditions and the width and continuity of habitat corridors.

7.19 Amphibians

Frogs and other amphibians are well known for their sensitivity to pollution and habitat degradation (Welsh and Ollivier 1998). They need a healthy environment, both on land and in water, to complete their life cycle from egg to larva to adult. Polluted water that may contain chemicals such as fertilizers or detergents can significantly negatively impact amphibian populations, and so have reduced amphibian populations worldwide. Pollutants commonly result in the death of the eggs or larvae, but may result in the production of abnormalities of soft and/or skeletal tissues that can later be seen in the adult frog (Howe et al 1998). Chemical synergy and life-stage sensitivity should always be addressed to properly assess the toxicity of herbicides or other chemicals to non-target organisms (Howe et al 1998).

***Metric* -** Amphibian eggs and larvae appear more sensitive to pollution or environmental change than adult amphibians or fish, making them excellent indicators of environmental toxicity (Howe et al 1998).

7.20 Birds

The usefulness of birds as indicators of ecosystem integrity has been widely discussed (e.g., Blus & Henny 1997, Temple and Wiens 1989, Morrison 1986, Reichholf 1976,). The factors that make birds attractive as indicators of wetland integrity include their ease of monitoring (usually without samples to process). Their identification is simple, allowing capable non-scientists to assist with surveys, and so birds are suited for relatively easy in situ assessments (confined or behaviorally imprinted individuals), and established survey protocols are easily available. Because of their position at the top of food chains some bird species (e.g., many raptors and wading birds) have a tendency to accumulate toxic substances in their tissue over time. Birds have a longer life span than other bio-indicators, which may make them more sensitive to some cumulative impacts and more able than other groups to integrate the effects of episodic events. The only relatively extensive nationwide data bases on trends, habitat needs, distribution, exist for birds, as well as the availability of moderately extensive bioassay data bases (USEPA 2006).

Birds can serve as indicators of hydrologic factors, changes in vegetative cover, sedimentation and turbidity, and pesticide and heavy metal contamination. Considering the current availability of data and tested protocols, birds are the only taxonomic group capable of serving as bio-indicators on a regional scale. While birds are likely to be poor indicators of the integrity of a specific wetland, their trends in species composition and relative abundance when measured throughout a region can integrate changes occurring in wetlands across the region. (USEPA 2006).

Birds as indicators of hydrologic factors

Hydrologic changes affect birds both directly and indirectly. Present water depths of the wetland can be indicated by the assemblage of breeding birds that have established nesting sites. For example, the regular presence of certain diving ducks and western grebes can indicate relatively deep water (> 2 m) and consequently, the likely seasonal persistence of water in an individual wetland (Fredrickson and Reid 1986). Species that are likely to be the most sensitive indicators of water levels might be those that (a) nest along water edges, (b) feed on mudflats (e.g., shorebirds), (c) require a particular combination of wetland hydroperiod types in a region (e.g., Kantrud and Stewart 1984). In contrast, species (e.g., marsh wren, some diving ducks) that characteristically nest well above the water level might be less directly vulnerable, and thus are probably weaker indicators (USEPA 2006).

Birds as indicators of changes in vegetative cover

Birds mostly respond strongly to changes in vegetation density and type, both within wetlands (Weller and Spatcher 1965, Lokemoen 1973) and in the surrounding landscape (Huber and Steuter 1984). Many studies have shown that reduced reproductive success in waterfowl can be a strong indicator of loss of cover in a wetland or surrounding landscape due to grazing, herbicides, cultivation, or other factors (e.g. Dwernychuk and Boag 1973).

Birds as indicators of sedimentation and turbidity

Bird species (e.g., redhead) that feed on submersed plants are likely to be affected the most by turbid conditions in wetlands. At a regional level, changes in the occurrence, frequency, or range sizes of such species might indicate overall trends in turbidity and sedimentation (USEPA 2006).

Birds as indicators of pesticide and heavy metal contamination

Declines in avian richness, and perhaps density and biomass, would be expected at wetland complexes or regions heavily contaminated by pesticides or heavy metals. Many studies have documented birds failing to reproduce or grow successfully in wetlands severely contaminated with heavy metals (e.g., Scheuhammer 1987) and particular pesticides, e.g., phorate. Selenium levels of > 0.050 mg/L, or > 0.030 mg/g of body weight, pose a potential risk to many waterbird species because selenium is rapidly accumulated in food chains and body tissues (USEPA 2006). Incidences of organochlorines, PCB's, and mercury accumulating in birds, especially raptorial and fish-eating species, have been reported (Weseloh et al 1997).

Physical condition, deformities, behavior

Eggshell thinning, physical deformities of embryos and hatching birds, and feather loss in adult birds, are symptoms of severe contamination of wetland food chains with certain chemicals, such as selenium (Scheuhammer 1987, Ohlendorf et al. 1990). Drooping wings and abnormal neck posture can indicate poisoning by carbamate or organophosphate insecticides.

Biomarkers in birds

The USFWS's Biomonitoring of Environmental Status and Trends (BEST) program has proposed use of several biomarkers, including the following relatively well-established ones (USEPA 2006):

- *Delta-aminolevulinic Acid Dehydratase (ALAD).* Elevated concentrations of this enzyme in birds and perhaps amphibians can indicate sublethal exposure, within the previous month, to lead from highway runoff or birdshot.
- *Acetylcholinesterase (AChE).* Depressed concentrations of this enzyme in birds, amphibians, and invertebrates can indicate exposure, generally within a few hours or days, to organophosphorus and carbamate insecticides (Ludke et al. 1975), and perhaps to some heavy metals.
- *Cytochrome P450 Monooxygenase System (MO).* Elevated concentrations of this enzyme in birds can indicate exposure, within the previous few days or weeks, to various organic hydrocarbons.
- *Hexacarboxylic Acid Porphyrin (HCP).* Elevated concentrations of this enzyme in birds can indicate ongoing exposure to various organic hydrocarbons.

  Retinol (Vitamin A). Depressed concentrations of this enzyme can indicate reduced viability of individual birds.

  Thyroid hormones. Depressed concentrations of various thyroid hormones in birds can indicate ongoing exposure to various organic hydrocarbons.

Laboratory costs for analysis of any of the above biomarkers generally range from $15 to $75 per sample, processed at a rate of about 20 to 30 samples per day. Other potential biomarkers for use with terrestrial vertebrates are described in Harder and Kirkpatrick (1994).

Model Selection Requirements 8

8.1 Introduction

Laguna de Santa Rosa is currently listed as impaired on California's Section 303(d) list (the TMDL list) for dissolved oxygen, temperature, nutrients and sediment. Other concerns for the management of the Laguna include flooding (partially due to backflow from the Russian River), *Ludwigia* infestation, and ecosystem/habitat integrity–all of which are linked in various ways to the impairment listing criteria. Therefore, water quality, flood protection and restoration planning are all main areas of concerns in basin management.

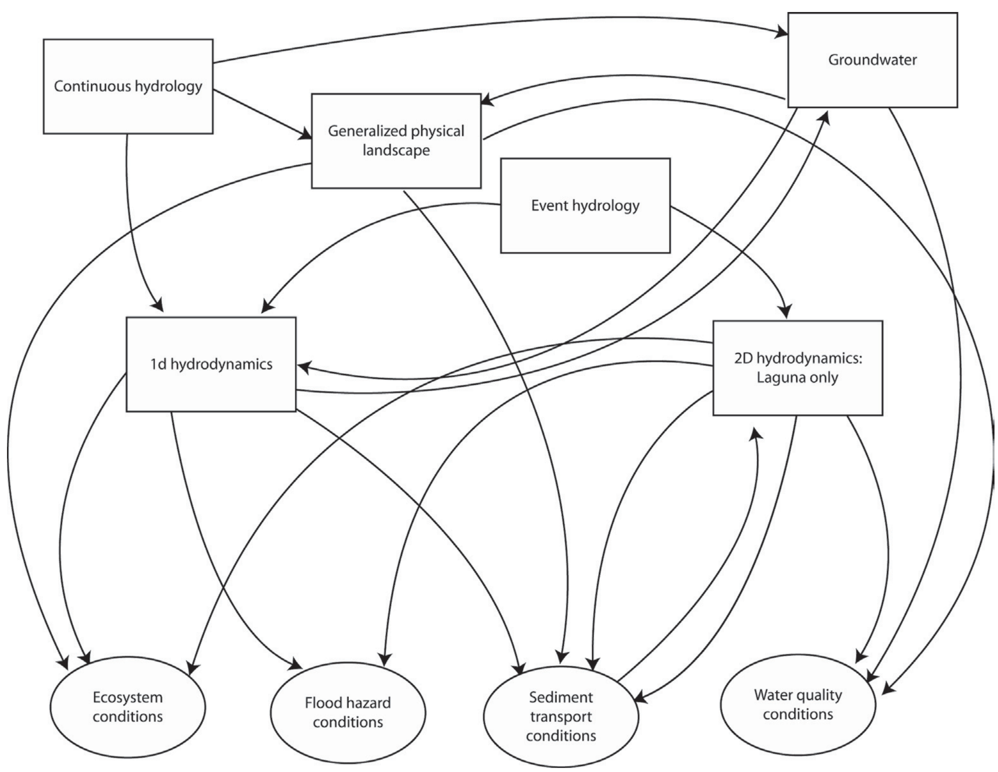


Figure 8-1 Key components and linkages among components in modeling framework

The Laguna de Santa Rosa conceptual model study has identified three major categories to be addressed in basin management and planning: hydrology, water quality, and ecosystems. Mathematical simulation models can provide a tool for evaluating and summarizing the complex interrelationships between stressors and responses in the Laguna, and are needed to assess to different management alternatives. The purpose of the this section is to discuss existing modeling efforts, evaluate requirements for a linked modeling system appropriate to address management needs, and recommend a modeling framework that can evaluate the linkages between the components identified in the conceptual models (Figure 8-1). This section includes model selection recommendations for two of the three components included in this study: hydrology and water quality. The ecosystem component is addressed partially under the water quality model component; however, some aspects of this component cannot be fully addressed through mathematical models given the current state of knowledge.

8.2 Preliminary model recommendations

The current report lays the foundation for establishing future monitoring and modeling needs for the Laguna de Santa Rosa. It is evident from the discussions in this section that there is not a single modeling tool that meets all management needs. It is also evident that there remains considerable uncertainty about which modeling tools should be chosen. Preliminary recommendations are made here; however, these should be regarded as preliminary and should be followed up with a formal model selection process.

It will also be important to develop monitoring and modeling needs in tandem. There is much that is still unknown about the functioning of this complex system that can best be answered through direct observation (rather than modeling). Further, models are, at best, only as good as the data that drive them, and the shortcomings of existing data will impede the creation of credible models unless remedied. So, developing monitoring and modeling plans in tandem will be the best way to provide for the long-term understanding and management of this unique ecosystem.

While additional data are clearly needed, the proposed schedule for the TMDL will require development and application of modeling tools in a shorter time frame that is incompatible with filling all the identified data gaps. Given this requirement, there is a clear advantage toward (1) selecting models that are not more complex than is needed to meet decision needs, and (2) choosing models already under development as part of the toolkit, where appropriate. Note that it is always possible–and often advisable–to begin with simpler models and move to more complex models later, and only as needed.

The first, and perhaps the most important, step in any modeling project is to clearly define modeling objectives (McKeon and Segna, 1987). Selection of an appropriate model or system of models involves a wide range of technical and practical considerations (Novotny and Olem, 1994). The criteria for model definition can be described in three general categories (expanding on the classification of Mao, 1992): Technical Criteria, Regulatory Criteria, and User (Functional & Operational) Criteria.

Technical Criteria comprise the match of the model to the physical/chemical characteristics of the system and contaminants. They reflect whether the model is appropriate for the system being described and supports the scientific defensibility of the results.

Physical Domain. One of the most obvious of the technical criteria for model definition is the physical domain that must be simulated, potentially including both upland areas and receiving water. For instance, different model requirements may be present for rivers versus lakes or for load generation from urban versus agricultural areas.

Constituents Simulated. A critical component of model definition is determining which constituents will need to be simulated. The more state variables that are included, the more difficult the model will be to implement and calibrate, as the model is likely to be over-specified relative to the data. On the other hand, if important state variables are omitted from the simulation the model may be unable to answer necessary questions.

Temporal Representation and Scale. Models may be classified as steady-state or dynamic in their representation of a given process. Steady-state models represent the ultimate response to a steady load and cannot capture the time course of responses to time-varying inputs. Dynamic models represent temporal variability. Where dynamic processes are represented there are usually limits on the time steps or temporal representations that are appropriate for a given model. Lumped parameter models usually have a minimum time step below which the simplifying assumptions used in model development do not permit accurate representation.

Spatial Representation and Scale. The physical representation of the watershed and waterbody is an important consideration in determining system requirements. These requirements include the manner in which different landuses and waterbodies are modeled, as well as the scale at which the model is developed. Similar to the temporal representation, there are limits on the spatial increments that are appropriate for a given model.

Regulatory Criteria reflect the fact that most watershed modeling efforts are driven, at least in part, by compliance with water quality standards and other regulatory criteria, such as floodplain delineation. The model needs to supply answers to specific regulatory questions and with a degree of defensibility acceptable to the regulatory agency. Important regulatory criteria for the Laguna include the need for FEMA-acceptable models for floodplain delineation and the use of public-domain models for the TMDL.

User Criteria comprise the functional and operational needs of the user. These criteria include the general requirements for system development and will involve consideration of such issues as available resources, ease of use, and communicability of results. Because the model may be used for planning and permitting decisions, basic functional needs include a model that is well documented, tested, and accepted. From an operational perspective, the level of effort required for model calibration must be commensurate with the project budget, without compromising the ability to meet technical criteria.

Functional needs refer to such issues as ease of use and communication of results, availability and adequacy of documentation, and extent of data requirements. The level of effort required to couple particular runoff and receiving water models can be an important functional criterion. Use of a highly complex model will increase the difficulty of understanding, communicating, and gaining acceptance of the results.

Operational needs reflect both the requisite technical ability to implement the model, and the estimate of cost and time requirements for the implementation (including data gathering). These criteria provide the cost side for any cost-benefit analysis of model selection. Both cost and time requirements of modeling can be important constraints.

Based on our current understanding of modeling needs, we believe there are considerable potential advantages in working with the existing RMA 2/RMA 11 models for the Laguna – pending completion and review of an acceptable model calibration/validation report. Consideration should be given to the need to expand to two dimensions or refine the model segmentation, but many of the basic components seem to be already in place.

Further, the RMA models should meet the requirements of both the TMDL and FEMA floodplain delineation.

A SWAT model is also in development for the watershed, and use should be made of this effort where appropriate – again pending completion and review of an acceptable model calibration/validation report. The upland component of SWAT is generally suitable for the sediment loading and pollutant loading portions of needed TMDL and watershed management (if run in sub-daily mode). On the other hand, SWAT has a number of deficiencies for simulation of transport through the stream network. SWAT is also not accepted for FEMA projects, nor is it recommended for flooding studies.

To address the watershed and upland hydrology needs of flooding studies, HEC-HMS is a well-accepted and moderate complexity tool of choice and is recommended. SWAT and HEC-HMS would then be run in parallel on the uplands – but could well share much data in common. While the MIKE family of models could handle both components simultaneously, these are – at least in theory – in appropriate for TMDL application.

For the stream network pollutant transport component, a more thorough needs analysis should be conducted to determine if SWAT's deficiencies disqualify its use. To answer questions on the basis only of gross loading over time, SWAT is likely sufficient; however, to address instream transformations and kinetics, a more sophisticated tool is needed. This role could be supplied by HSPF's reach component, which can readily be linked to the upland component of SWAT.

HSPF can draw information from HEC-HMS. Even though, the HMS model does not directly output information used to formulate the input data to the HSPF (F Tables: relationship between reach volume and discharge), it includes the information necessary to generate F Tables if developed using a particular routing routine (Muskingum-Cunge routine). HMS input and output can be analyzed to calculate the information required to formulate the F Tables that represent hydraulics within HSPF.

In sum, a reasonable candidate modeling system to meet the variety of simulation needs in the Laguna de Santa Rosa watershed would build on existing efforts and consist of a linked set of models, incorporating HEC-HMS, SWAT, HSPF, and RMA 2/RMA 11. A conceptual strawman diagram is shown in Figure 8-2.

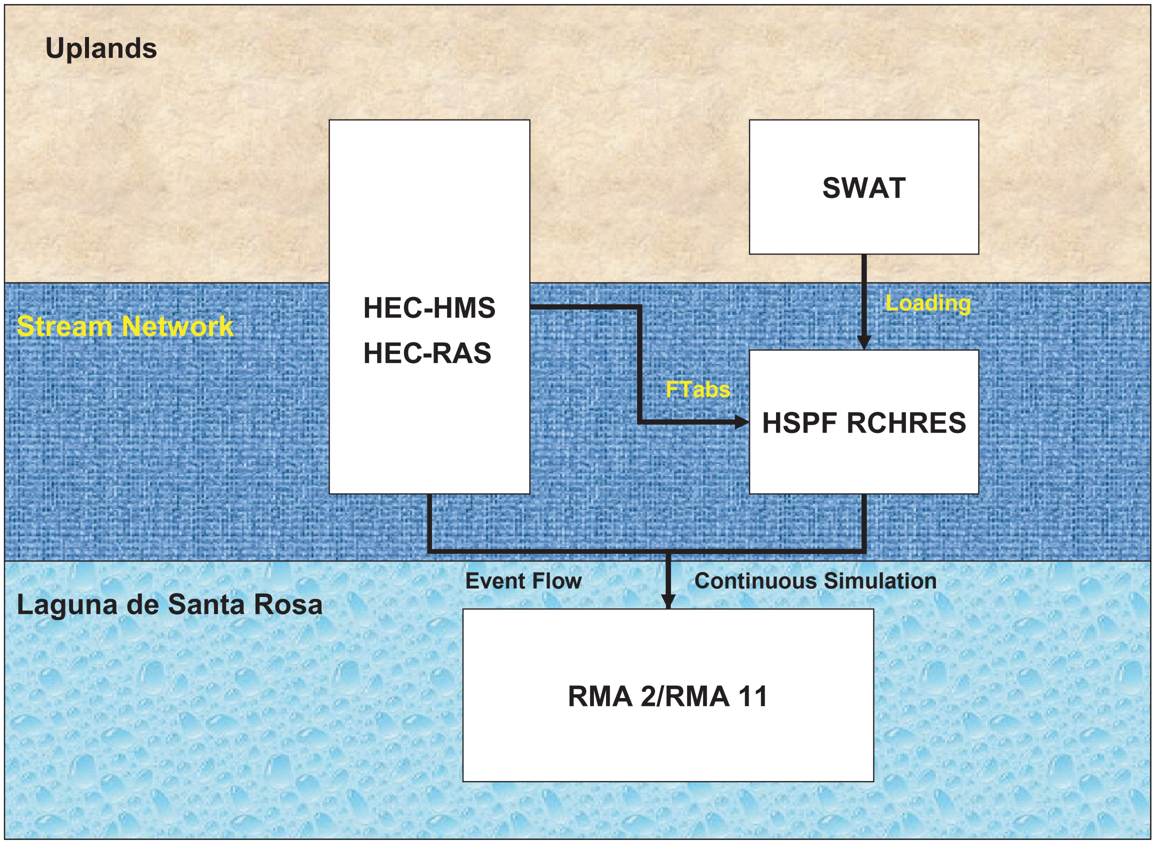


Figure 8-2 Conceptual strawman for Laguna de Santa Rosa and watershed modeling system

8.3 Existing model applications

Currently there are several ongoing modeling efforts in the basin conducted by different agencies to look at flood protection, sedimentation and water quality. These efforts include the application of SWAT model by NASA Ames and the Laguna Foundation (described below and previously in section 4.1 for hydrology and Sediment), the RMA2/11 modeling efforts by City of Santa Rosa for flow and water quality (described below) and USGS for sedimentation (described previously in Section 4.1), and hydrologic modeling using HEC-HMS being conducted by the Army Corps of Engineers (USACE; described previously in Section 4.1).

8.3.1 SWAT (NASA AMES)

SWAT is a continuous simulation watershed model developed by the USDA Agricultural Research Service that is particularly appropriate for evaluating runoff and pollutant loading from agricultural lands. (The strengths and weaknesses of the SWAT approach are discussed further in Section 8.4). The application of the SWAT model to the Laguna de Santa Rosa watershed is an ongoing effort led by NASA Ames and the Laguna Foundation (Arnold et al. 1998; C. Potter and S. Hyatt, personal communication). The model is currently implemented for the period of 2000–2006 to simulate hydrology, sediment, nutrients (nitrogen and phosphorus) and dissolved oxygen. The watershed is segmented into around 200 sub-basins. A total of five precipitation stations (with three extending back to 1948) were used in model calculation. The soil data used were an updated SSURGO soil data layer based on county-level soil surveys. The land cover dataset used is an updated National Land Cover Dataset (NLCD) in 30 meter resolution merged with the California Department of Water Resources (DWR) crop type polygons and Sonoma County Assessor's Parcel descriptions (C. Potter and S. Hyatt, personal communication). NAIP (National Agricultural Imagery Program) digital ortho imagery data were used to confirm the merged land cover product in key areas of uncertainty.

Preliminary model results indicate reasonable performance in simulating stream flow on a monthly basis ($R^2 > 0.9$; for years 2001-2006) for Santa Rosa Creek (USGS 11465800 Santa Rosa Creek near Santa Rosa, USGS 1466200 Santa Rosa Creek at Santa Rosa, and USGS 11466320 Santa Rosa Creek at Willowside Road). However, a detailed calibration report has not been prepared, and the ability of the model to simulate hydrology on shorter time steps in this watershed has not yet been demonstrated. Currently, the model is used to simulate pollutant loadings from natural vegetation, croplands, pastures, and urban storm water runoff. Loadings from fertilization and manure applications, septic systems, waste-water discharges, and irrigation of reclaimed water are yet to be added to the model. Preliminary loading estimates from the simulated land use categories (i.e. vineyard, residential, commercial/transportation, evergreen forest/shrub, deciduous forest/shrub, orchard, pasture, range, and grassland) indicated that 5-10% of the nitrogen load in the watershed was attributable to vineyards with 5-35% contribution from upland grass rangelands for nitrogen. For sediment loads, preliminary predictions suggest that greater than15% of the total load was contributed by vineyards with greater than 25% contributed by the upland grass rangeland cover. One caveat of these loading estimates is that a full water quality calibration/validation has not been completed.

The SWAT application is an ongoing effort that has not been fully calibrated and validated for hydrology and water quality simualtions. Before water quality calibration can be completed there are more loading source categories to be added to the model. One of the issues encountered in the modeling effort is the difficulty to simulate access to over-bank floodplain and the potential effects on nutrients and sediments due to this wetting and drying process. Another issue of the model application is that the model represents streams and other bodies in a very simplified manner, and specifically lacks mechanisms to simulate backwater effects from the Russian River. These issues however will also exist for other watershed models. Although in its preliminary development stage, the SWAT modeling effort is currently the only watershed modeling effort in the Laguna watershed. The model also has detailed land management options (e.g. manure application) which are part of the land use in the watershed. In general, SWAT is a potential candidate for simulation of flow and loading from the watershed, however a more detailed in-stream model is preferred to simulate the response in Laguna main channel, especially when these models have been applied to he Laguna (discussed below in section 8.3.2). For example, SWAT represents stream channel as one dimensional complete mix compartment, while a 2-D model may be more suitable for the Laguna.

8.3.2 RMA (City of Santa Rosa and USGS)

The City of Santa Rosa is applying sophisticated finite element hydrodynamic and water quality models originally developed by the USACE (RMA-2 and RMA-11) to assess flow and water quality conditions in the Russian River and Laguna (M. Deas, Watercourse Engineering, Davis, CA, personal communication). The models have open source code, but have a user fee.

The Russian River-Laguna flow and water quality model (RRL) extends from the USGS gage at Cloverdale to the USGS Gage at Hacienda on the Russian River, from the Laguna at Stony Point Road to the confluence with the Russian River, and includes a representation of Dry Creek as well. RMA models were selected for river reaches because they are capable of accurately simulating flow and transport in river reaches. The RMA suite includes RMA-2 and RMA-11, along with various utility programs. RMA-2 computes water surface elevations and horizontal velocity components for subcritical, free-surface flow in two dimensional flow fields using a finite element solution of the Reynolds form of the Navier-Stokes equations for turbulent flows. Friction is calculated with the Manning's or Chezy equation, and eddy viscosity coefficients are used to define turbulence characteristics. Both steady and unsteady state (dynamic) problems can be analyzed. The model can also be applied in one-dimension with depth and laterally averaged conditions. Output from this hydrodynamic model (including velocity, depth, and representative surface and bed areas) is passed to the water quality model RMA-11. RMA-11 is a finite element water quality model simulating the fate and transport of a wide range of physical, chemical, and biological constituents.

These two linked river models are applied on hourly or sub-hourly time steps to capture the short-term response of state variables such as temperature and dissolved oxygen. For this application, the RMA models are applied in one-dimension, representing variations along the longitudinal axis of the river while averaging vertical and lateral details. Water quality constituents simulated included in RMA-11 are: conservative tracer, dissolved oxygen (DO), organic matter (OM), ammonia (NH_3), nitrate (NO_3), nitrite (NO_2), orthophosphate (PO_4), algae as phytoplankton and benthic algae, and temperature.

For the Russian River application, the model was calibrated for water temperature, dissolved oxygen, nutrients, and algae. Data were only available during discharge months. Comparisons of simulated and observed temperature, dissolved oxygen, nutrients, and algae were completed for each of the five simulation years (2000-2004). Results of calibration-validation show that the RRL model represents the majority of system processes and translates water quality conditions downstream through the system with significant accuracy. This modeling tool, as it now stands, is capable of assessing complex questions about how discharge operations in the basin and various meteorological, hydrological, and water quality conditions influence the environment of the Russian River. Issues identified during model application include a general lack of data during summer and a lack of geometry data.

The U.S. Geological Survey, together with the USACE, is also using RMA-2 and SED-2D to develop preliminary tools for management applications in the floodplain. In addition to water quality constituent modeling, RMA can also simulate sediment transport and deposition in the Laguna de Santa Rosa floodplain from Highway 12 to Mark West Creek at Trenton Road. The coupled RMA-2 and SED-2D models will be calibrated to four gages along the Laguna and to the flood inundation extent estimated from observations following the 2006 New Year's Flood. Peak discharges having 2-, 5-, 10-, 25-, 50-, and 100-year recurrence intervals as determined by the USACE will be used to estimate by interpolation the peak discharges at the upstream and downstream study reaches. The RMA-2 model will be used to simulate stage at specified locations throughout the study reach and will simulate changes in flow and sediment transport under operations representing management schemes to control *Ludwigia*.

8.4 Hydrologic models to address flood protection and sedimentation

8.4.1 Model simulation requirements

For the purposes of simulating hydrologic and sediment processes to help address key management questions, several different types of models can be considered: 1) event simulation hydrologic models that can predict flood event streamflows; 2) continuous simulation hydrologic models that can predict long-term streamflow conditions, typically more critical to environmental conditions; 3) hydraulic models that can predict the physical characteristics of streamflow, including unsteady (time-variant) flow conditions; 4) either a sediment yield or sediment transport-based (assuming modeled system is transport-limited) system to estimate sediment inflows to the portion of the watershed of interest; and 5) sediment transport models to predict erosion, deposition, and delivery through the system. In addition, if surface water - groundwater interactions are important to the management questions of interest (a point that is not yet clear), a model addressing these aspects of the hydrologic system is also needed. No model includes all of these functions.

There are many runoff and sediment generation and transport models available. Each model typically was designed to serve a particular purpose. Time and budgetary constraints being the same, the selection of a model typically reflects the emphasis being made on either the processes at work or the output. In this context, it is important to remain focused on the goal of hydrologic modeling within the context of integrated management of the Laguna de Santa Rosa watershed: an understanding of the processes that is sufficient to answer the identified management questions. A consideration of rainfall-runoff models indicated that "over-parameterisation can prevent models from reaching their potential level in their ability to simulate streamflow" (Perrin et al., 2001). The study noted that models with a larger number of parameters simulate flows better during calibration compared to simpler models, though this trend is not consistent during the verification phase. Simpler models tend to be more robust. Models with a large number of processes considered run the risk of having a high degree of uncertainty associated with model input, which is translated through the model output. A model's value is best manifested by its simplicity relative to its explanatory power (Steefel and Van Cappellan, 1998). For purposes of the Laguna's management, we argue that simplicity must be construed to also include the simplicity of incorporating interaction between key processes in the modeling environment. Using an array of models to simulate an array of processes can be cumulatively complex if the interactions between those models and processes are difficult linkages to make.

In selecting models of hydrology, hydraulics, and sediment transport to assist in management of the Laguna, two general questions should be kept in mind:

- What modeling approaches will best address the key management issues of concern?
- What opportunities exist to use a common modeling framework (directly integrated or designed for sequential usage) or datasets to improve efficiency and consistency?

Two important user criteria should also be addressed in the selection of an approach for modeling hydrology, hydraulics, and sediment transport that will support flood analysis and water quality analysis in the Laguna de Santa Rosa. First, because flood hydrology and hydraulics are key to the issue of flood management, a criterion for any model for simulation of flood hydrology and hydrologic conditions is that the model or models must be acceptable to FEMA for floodplain studies. FEMA provides a website with a listing of such models at http://www.fema.gov/plan/prevent/fhm/en_modl.shtm. Second, TMDLs are required to be developed to address water quality impairment in the Laguna. The Regional Water Quality Control Board requires that any model used to develop a TMDL be in the public domain. Therefore, only numerical models that meet these minimum criteria are supported for consideration in this document for development in the Laguna de Santa Rosa.

8.4.2 Model evaluation: hydrology and sediment transport

There are three primary spatial domains to be addressed in a complete simulation of hydrology and sediment transport affecting conditions in the Laguna. These are the watershed (where runoff is generated), the stream network (which conveys flows to the Laguna), and the Laguna itself (where the primary impacts occur). It is useful to think about the stream network and Laguna separately, because the hydraulic processes in tributary streams are primarily one-dimensional with uni-directional flow, while the Laguna is fundamentally two-dimensional and may experience backwater effects (and even occasional reversing flow) from the Russian River.

There are also competing temporal domains for the hydrologic simulation. To address flooding, a highly-detailed evaluation of response to individual major storm events is most relevant. However, many of the water quality issues in the Laguna are driven by long-term loading, and low flow, non-event conditions are important for responses.

It would be desirable to have a hydrologic simulation model that could address all three physical domains of interest, while being capable of both long-term continuous and event-based (i.e., flood condition) hydrologic simulation. Unfortunately, there are also inherent conflicts. Use of a fine temporal and spatial scale to support detailed flood analysis would mean that model runtimes and data requirements are large, while use of a simplified watershed model that is adequate to assess pollutant loading may not supply the necessary resolution to model a flood wave. Similarly, it would be advantageous to use a hydrology model that also supported sediment delivery, sediment transport, and water quality simulations – but these simulations may have different functional needs than hydrology to support flood analysis. Accordingly, it may be appropriate to use more than one model or link several models to address the different spatial and temporal scales implicit in management questions.

Watershed Models

The hydraulic/flooding objective requires generation of subdaily runoff hydrographs for analysis of flood wave propagation. Sediment transport simulation would also benefit from subdaily simulation of the hydrograph, because transport processes are highly nonlinear. In particular, simulation of channel erosion generally requires an accurate resolution of flows and shear stresses in the channel.

SWAT, HSPF, SWMM and MIKE SHE are among models that can provide continuous sub-daily hydrologic simulation and also support sediment and water quality simulation, though they use different approaches to simulate these processes. The SWAT model is a continuous watershed model developed by USDA and is in the public domain. SWAT is designed to predict the impact of management on loading and transport of water, sediment, and nutrients. The model can operate either at a daily time step (using a curve number approach) or at a sub-daily time step (using Green-Ampt infiltration). It is not accepted by FEMA. SWMM is comprehensive watershed-scale model developed by EPA (Huber and Dickson, 1988) to address urban storm water runoff and pollutant transport. The model is generally of limited suitability for rural applications. It is in the public domain and is acceptable to FEMA. HSPF is a comprehensive package developed by EPA that simulates watershed hydrology, point and non-point loadings, and receiving water quality (Bicknell et al., 1993). It is in the public domain, but is not accepted by FEMA. However, it could likely be used in acceptable flood studies if coupled to an approved channel hydrology model. Both SWAT and HSPF are part of the EPA BASINS (Better Assessment Science Integrating Point and Nonpoint Sources) package, designed to support watershed analysis and TMDL development. MIKE SHE is a proprietary model developed by DHI Water and Environment. It is a physically-based, distributed parameter model for three-dimensional simulation of hydrologic systems. MIKE SHE is not directly on the FEMA list, but integrates seamlessly with the MIKE-11 channel model which is accepted by FEMA; however, MIKE-SHE does not meet the public domain criterion for TMDL development.

The capabilities of three of the hydrologic models that can be used to simulate processes in the Laguna Watershed are summarized below in Table 8-1.

Table 8-1
Watershed-scale continuous hydrology and sediment models

Description /Criteria	HSPF	MIKE SHE	SWAT
Model Components/ Capabilities	Computes streamflow hydrographs. Simulates interception soil moisture, surface runoff, interflow, base flow, evapotranspiration, groundwater recharge, sediment detachment and transport, sediment routing by particle size, channel routing. GIS platform.	Simulates interception, evapotranspiration, overland and channel flow, groundwater flow, exchange between groundwater and streamflow, soil erosion. GIS compatibility.	Hydrology, weather, sedimentation, sediment loading. GIS platform.
Temporal Scale	Long term; variable constant steps (hourly or sub-hourly).	Long term and storm event; variable steps depending numerical stability.	Long term; daily steps.
Watershed Representation	Lumped pervious and impervious land areas, stream channels, and mixed reservoirs; 1-D channel simulation.	2-D rectangular/square overland grids, 1-D channels, 1-D unsaturated and 3-D saturated flow layers.	Sub-basins grouped based on climate, hydrologic response units (lumped areas with same cover, soil, and management), ponds, groundwater, and main channel.
Rainfall Excess on Overland/ Water Balance	Water budget considering interception, ET, and infiltration with empirically-based areal distribution.	Interception and ET loss and vertical flow solving Richards equation using implicit numerical method.	Daily or sub-daily water budget; precipitation, runoff, ET, percolation, and return flow from subsurface and groundwater flow.
Overland Runoff	Empirical outflow, Depth to detention storage relation, and flow using Chezy-Manning equation.	2-D diffusive wave equations solved by an implicit finite-difference scheme.	Runoff volume using curve number and flow peak using modified Rational formula or SCS TR-55 method.
Subsurface Flow	Interflow outflow, percolation, and groundwater outflow using empirical relations.	3-D groundwater flow equations solved using a numerical finite-difference scheme and simulated river-groundwater exchange.	Lateral subsurface flow using kinematic storage model and groundwater flow using empirical relations.
Runoff in Channel	All inflows assumed to enter one upstream point, and outflow is a function of reach volume or user-supplied demand.	1-D diffusive wave equations solved by an implicit finite-difference scheme.	Routing based on variable storage coefficient method and flow using Manning's equation adjusted for transmission losses, evaporation, diversions, and return flow.
Overland Sediment	Rainfall splash detachment and wash off of the detached sediment based on transport capacity as function of water storage and outflow plus scour from flow using power relation with water storage and flow.	Soil erosion add-on module using EUROSEM.	Sediment yield based on Modified Universal Soil Loss Equation (MUSLE) expressed in terms of runoff volume, peak flow, and USLE factors.
Channel Sediment	Non-cohesive (sand) sediment transport using user-defined relation with flow velocity or Toffaleti or Colby method, and cohesive (silt, clay) sediment transport based on critical shear stress and settling velocity.	Simulated in MIKE 11 using cohesive and non-cohesive transport modules.	Bagnold's stream power concept for bed degradation and sediment transport, degradation adjusted with USLE soil erodibility and cover factors, and deposition based on particle fall velocity.
Code Availability	Public domain	Proprietary	Public domain

Stream network models

The stream network is simulated to connect runoff generated by the land surface to downstream areas of interest. The stream network models may be part of an integrated package with the upland watershed model, or a separate watershed model may be used to drive the stream model. To meet the flood analysis objective, the stream network model should be on the FEMA approved list; however, it is believed that a pairing of a non-FEMA upland model with a FEMA-approved channel model could be acceptable.

For the analysis of the flooding objective, HEC-HMS is the most commonly used hydrologic model that links the upland runoff generation and stream network transport. HEC-HMS is, however, most commonly used for storm event and not continuous simulation, as it lacks a detailed subsurface flow component. It also does not have capabilities for sediment and pollutant transport simulation.

The MIKE-SHE/ MIKE-11 pair also provide a unified simulation of watershed runoff and stream transport, and also integrate water quality components. From a technical perspective, these models appear suitable to meet all hydrologic, hydraulic, and sediment transport needs – although the modeling framework may be more complex than is needed. However, MIKE-SHE/ MIKE-11 are proprietary and do not meet the public domain criterion for TMDL development.

The SWMM model is capable of and approved for simulating channel hydrodynamics, but has only limited sediment transport capabilities. Further, as noted above, it is generally not appropriate for rural watersheds.

Neither HSPF nor SWAT is FEMA-approved. While the SWAT model is capable of sub-daily simulation of runoff, the channel routing is simplistic and pollutant transport in channels is constrained to a daily time step. As noted in the manual, "the model is not designed to simulated detailed single event flood routing." HSPF can do full sub-daily routing of sediment and pollutants, but does not calculate detailed hydraulic routing. Rather, the hydraulic response of a stream channel is input through an externally specified "functional table" (FTab). In many applications, the FTabs are generated from HEC-HMS models, providing a linkage between the two representations.

In terms of sediment transport, the better models use detailed hydraulic modeling to address the physics of sediment movement. The MIKE-11 component in MIKE SHE provides this capability, though the other hydrologic models discussed above do not.

However, in the case of the Laguna, it may be appropriate to consider the nature of the key sediment volume-related management issues in selecting a modeling approach. We argue that the simulation requirements for sediment transport may be different for the portions of the tributaries upstream of the lower Laguna than for the lower Laguna main channel itself. The Laguna's sediment production zone lies primarily in the steep lands to the east of the Santa Rosa Plain. Simulation of sediment conditions in the steep zones may potentially be estimated by a simplified model or by empirical methods rather than attempting a detailed continuous simulation of both delivery to a channel and then transport under the rapidly varying hydraulic conditions. Given the substantial uncertainty associated with sediment transport modeling in general, development of greater detail in the steep reaches might be of limited utility. Transport of sediment from the upper watershed to the Laguna is most likely transport-limited: supply can generally be assumed to be available in excess of the transport capacity in the channels that cross the Santa Rosa Plain. For this reason, use of a sediment transport capacity-based analysis system to evaluate depositional reaches and volumes, a fairly simple analysis requirement, may be entirely sufficient for analysis of sediment deposition and transport to the lower Laguna main channel. Options for this type of model model include simple spreadsheet models to evaluate sediment transport equations appropriate to the conditions in the channels, or the US Army Corps of Engineers (USACE) SAM model, either stand-alone or as incorporated in the USACE 1D network hydrodynamic model, HEC-RAS.

Based on our understanding of surface water-groundwater linkages at this time, it is not clear how significant this interaction is to the key management questions identified for the Laguna, or what type of interaction of these elements is most important to represent. A limited number of full surface water-groundwater models exist; on the other hand, many watershed hydrology and some groundwater-specific models have limited representation of surface water – groundwater interactions. For these reasons, we have not recommended any particular modeling approach to modeling surface water – groundwater interactions at this time.

Receiving water models

The Laguna itself will require a different modeling approach from the upland streams. The Laguna has multiple channels, with significant storage capacity, and is also affected by backwater from the Russian River. A fully two-dimensional approach to hydraulics might be needed to fully resolve flood delineation issues.

Both the RMA and MIKE family of models are acceptable for FEMA purposes and can be used for both one-dimensional and two-dimensional simulation. If a full two-dimensional simulation is needed, MIKE 21 of MIKE FLOOD would be needed rather than MIKE 11. The current RMA application is also one-dimensional, but could be expanded to two dimensions relatively easily.

At the lower Laguna main channel (perhaps from Stony Point Road downstream) and its connection to the Russian River, the hydrodynamics of the system become far more subtle and variable, and we recommend that sediment transport though this part of the system be addressed in the context of a more detailed hydrodynamic modeling tool. Options for this tool might include models that integrate the sediment transport component in the hydrodynamic model dynamically, such as MIKE 21C (curvilinear version of the 2D hydrodynamic model from DHI Water and Environment), MIKE FLOOD (linked MIKE 11 – MIKE-21 floodplain analysis model), or a model that has a sequential sediment transport analysis tool such as RMA-2 with SED-2D. All of these hydrodynamic models meet the FEMA floodplain analysis acceptability requirement and are capable of modeling sediment erosion and depositional processes in a 2D environment. The RMA-2/SED-2D system cannot reflect change in hydraulic conditions in the system over time as a result of sediment deposition processes and requires use of a single representative grain size, but we do not consider either of these impediments as fatal flaws to its use for simulation of hydraulics or sediment transport processes in the lower Laguna de Santa Rosa. For example, the model could be run in a step-wise fashion to look at the effects of sediment deposition on hydraulics and sediment transport processes in the Laguna over time. In addition, it is probably not unreasonable to assume a single representative grain size for sediment processes in the

Laguna. Either RMA-2, MIKE-21C, or MIKE FLOOD should provide a reasonable basis of analysis for ecosystem conditions.

8.5 Watershed and water quality models for TMDL

8.5.1 Model simulation requirements

The primary focus of the water quality model recommendations is the simulation of nutrients, dissolved oxygen, and temperature for the purpose of TMDL development. The regulatory requirements for establishing TMDLs include some key elements of identifying the impairment, the pollutants, and the source categories or subcategories for load allocations. Establishing TMDLs also requires consideration of seasonal variations so that water quality standards will be met during all seasons of the year. As suggested by the protocols for developing TMDLs established by U.S. EPA (EPA, 1999), key components of TMDL developments include source assessment, linkage between water quality targets and sources, and load allocations. Watershed and water quality models can be useful in the TMDL processes for establishing the linkage between water quality targets and sources and for load allocation.

The impairments identified in the Laguna include nutrients, DO, temperature and sediments. The identified pollutants contributing to these impairments include nutrients (nitrogen and phosphorus), biochemical oxygen demand (or organic enrichment), and sediments. Therefore the minimum requirements for a watershed model are to be able to simulate different species of nitrogen (ammonia, nitrate, organic nitrogen) and phosphorus (dissolved and total), as well as transport dynamics of biochemical oxygen demand, DO, temperature and sediments. The source categories of pollutants identified for the watershed include both point sources of wastewater discharge and various non-point sources that can originate from various land uses including urban, agricultural (e.g. pastures, vineyards, dairies) and rural areas (e.g. shrubs, grasslands, forests), as well as atmospheric deposition. Characterization of pollutant loadings from various sources is needed for establishing the linkage between sources and the resulted water quality. Therefore another requirement for the model is to be able to simulate loadings of various pollutants from various land uses (i.e. urban, agricultural, and rural areas). Pollutant loadings are largely associated with runoff and sediment transport, and therefore simulation of hydrology and sediments is also very important in pollutant loading estimates. The TMDL requirement for consideration of seasonal variations also requires the selected model(s) to be able to simulate continuously (and in shorter time steps such as daily). An interpretation of the TMDL as a daily load is now required by court ruling, but does not necessarily require a daily-scale simulation. As some of the impairments such as temperature and DO that can vary during short period, sub-daily time steps may be ideal.

Besides addressing loadings from the watershed, the responses in water bodies to loadings which can have significant impacts on achieving water quality standards can also be important. As suggested in the preliminary conceptual model (Section 5.1), the Laguna main channel is a slow-moving water, which has large impacts on water quality. Low flow and channel geometry were believed to influence reaeration and water residence time which can impact dissolved oxygen level. Although a conceptual model on temperature has not been developed, flow, channel geometry, and riparian vegetation should also have impacts on stream temperature, which is important for cold water fishery survival. Therefore, the model selection process also takes into account the response in receiving waters (in-stream processes). Minimum requirements for a receiving water model include simulation of flow, sediment transport, and algae/plant growth, DO dynamics and temperature for the TMDL purposes.

The three main categories of model evaluation criteria (i.e. hydrology and sediment, watershed processes, and in-stream processes) as well as the sub-categories as shown in the first two columns of Table 8-2 are listed below:

1. Hydrology and sediment – which can have significant impacts on pollutant loadings and transport

- Time step – for evaluation of the extent of temporal variations accounted for by the model
- Watershed segmentation – for evaluation of the extent of spatial variations accounted for by the model
- Runoff – for evaluation of the mechanism of runoff generation
- Groundwater – for evaluation of interaction of surface and groundwater and groundwater as a source of pollutant loadings
- Sediment erosion and transport – for evaluation of sediment yield and transport as well as pollutants associated with sediments (e.g. phosphorus, BOD)

2. Watershed processes

- Species of nitrogen simulated – for evaluation of the completeness of the species simulated
- Pollutant loadings- for evaluation of pollutants originated from various sources including atmospheric deposition, urban/residential/agricultural runoff, septics, as well as from some agricultural practices such as fertilization and irrigation
- Pollutant transport – for evaluation of phosphorus transport with sediments and terrestrial organic carbon/BOD sources

3. In-stream processes

- Flow/sediment routing – for evaluation of in-stream channel routing and sediment transport
- Plant/algae growth – for evaluation of algae/plant growth simulation that influences dissolved oxygen dynamics. Some processes of particular interests to Laguna include aquatic species simulated (whether it includes macrophytes) and releases of phosphorus bottom sediment
- DO - for evaluation of simulations of DO diurnal cycle, DO source/sinks, BOD and SOD
- Temperature – for evaluation of methods for water temperature calculation and whether effects of shading, flow and geometry are accounted

Some other issues to consider in the model selection may include model availability (whether the model is in public domain), model data requirements (whether the model data requirements can be met), model performance (whether reasonable calibration can be achieved) and model run time.

8.5.2 Watershed model evaluations

SWAT, SWMM, HSPF and WARMF

A few watershed models that address watershed pollutant loadings and in-stream responses, and are commonly used for TMDL applications, are evaluated here. There include several detailed watershed models that are available in the public domain such as SWAT, SWMM, HSPF (USEPA, 1997), and WARMF (Chen et al. 2001). All of these models are able to simulate the existing mixed land uses in the Laguna.

- SWAT is a watershed model developed by USDA to simulate hydrologic, sedimentation, nutrient, and pesticide movement in large, complex rural watersheds and receiving water quality (Neitsch et al. 2002). It has particular strengths in simulating plant growth and management operations in agricultural land uses; however, the stream transport components are simplistic and operate only at a daily time step.
- SWMM is a comprehensive watershed-scale model developed by EPA (Huber and Dickson, 1988) to address urban storm water runoff. Although SWMM was upgraded to simulate mixed land uses, it is mainly applied to address urban storm water issues.
- HSPF is a comprehensive watershed and receiving water simulation package developed by EPA that simulates watershed hydrology, point and non-point loadings, and receiving water quality (Bicknell et al., 1993).
- WARMF is a decision support system developed under the sponsorship from the Electric Power Research Institute (EPRI) for watershed management. Its Engineering Module is a GIS-based watershed model that simulates hydrology, pollutant loading and receiving water quality.

Both SWAT and HSPF are part of the EPA BASINS (Better Assessment Science Integrating Point and Nonpoint Sources) package designed to support watershed analysis and TMDL development. WARMF is currently compatible with BASINS, using BASINS to generate inputs. All the three models have been used in TMDL applications.

The SWMM model was eliminated from further consideration because it is generally not appropriate for simulation of rural watersheds. SWAT, HSPF and WARMF were compared for their capabilities in simulating hydrology and sediments, watershed processes for pollutant loadings and transport, and in-stream processes for simulating algal growth, dissolved oxygen and temperature (Table 8-2). Overall HSPF offers finer temporal resolution and more detailed representation of in-stream processes. HSPF can be run on an hourly or shorter time step, which allows for more accurate simulation of time of concentration during flood events. An hourly time step also allows simulation of the DO diurnal cycle.

Although different algorithms are used, all three models have been reported to be able to simulate hydrology and sediment transport reasonably well in other applications (Borah and Bera, 2004; Chen et al. 2005). SWAT typically uses an empirical method (the curve number method) for simulating surface runoff and MUSLE method for simulating sediment yield, which can lead to errors in certain types of soils and precipitation regimes. HSPF uses a storage-routing method for hydrology and simulates sediment as a result of accumulation, detach and transport. WARMF uses a more physically based approach for simulating runoff and simulates sediment as a result of rainfall and overland flow impact. Results from all three models are unreliable without a detailed calibration effort.

The three models also have similar capabilities for simulating pollutant loadings and transport from the watershed to streams, although processes are represented differently. All models are able to simulate pollutant loadings to waterbodies from atmospheric deposition, urban runoff, septics, fertilization and irrigation. In all models, the transport of phosphorous can be simulated as a function related to sediment transport (required in SWAT and WARMF, optional in HSPF). In simulating organic nitrogen, SWAT simulates organic nitrogen as active, stable and fresh pools. HSPF simulates both the labile and refractory particulate and dissolved organic nitrogen. Although included in the TKN and TN simulation, organic nitrogen is not currently explicitly tracked in WARMF. In terms of simulating terrestrial sources of organic carbon/BOD, SWAT simulates BOD as a function of sediment loading. HSPF can simulates both particulate organic carbon, potentially as a function of sediment, and dissolved phase loading. WARMF simulates organic carbon from direct surface loadings as well as particulate and dissolved organic carbon as a result of litter decay. In general, SWAT is preferable for conducting detailed simulations of agricultural practices, while HSPF provides a more comprehensive and flexible representation of pollutant loading and transport. The two models can be combined, or SWAT agronomic simulations can be used to fine tune an HSPF watershed model.

The receiving water transport portions of the three models all use one-dimensional completely mixed segments. An important distinction is that SWAT simulates instream transport only at a daily time step, preventing detailed resolution of kinetics. Both SWAT and WARMF simulate stream water temperature as a function of ambient air temperature and can provide poor results for thermal simulations. HSPF uses a more sophisticated algorithm to calculate in-stream temperature based on heat balance from meteorological data, shading, boundary condition, flow, water body geometry and inflow temperature

All three models meet the general requirements for simulating hydrology, sediments, and terrestrial loadings of pollutants of the Laguna watershed. However, the in-stream processes of SWAT and WARMF are much less sophisticated than HSPF.

The data requirements for the three models are similar in some aspects. All of the models require meteorological and hydrologic data, land use distribution and characteristics, and receiving water characteristics. The SWAT model always uses soil data as input, while this is optional for HSPF. Generally the SWAT model has less data requirements and calibration needs. If HSPF is run on an hourly time step, hourly meteorological data is required. Limitations of the models have also been reported. For example, SWAT has been reported to perform better on monthly bases than shorter time steps in previous applications (Borah and Bera, 2004). HSPF has been reported to be more difficult to calibrate due to more data requirements (Borah and Bera, 2004). WARMF also has more data/parameterization requirements for calibration.

At the third TAG meeting, several models (i.e. WEND, GEM, and MIKE-SHE) were suggested by TAG members as models of interests for further evaluation and therefore an evaluation of each of these three models for suitability of TMDLs was summarized below:

WEND

Watershed Ecosystem Nutrient Dynamics (WEND) is a dynamic model that was developed by the Natural Resources Conservation Service in conjunction with the University of Vermont to model phosphorus in watersheds (Cassell et al. 2001). The model is based on a mass balance approach to track input and output of phosphorus through agriculture, forest and urban sectors. The model has the advantage of having a detailed representation of processes that influence phosphorus dynamics in poultry and vegetable farms (e.g. chicken litter, feed, irrigation, fertilizer, harvest, manure, atmospheric deposition). However, the model is mainly a phosphorus mass balance model and lacks functionalities to simulate hydrology and nitrogen cycle, which are considered to be the key components in nutrient and DO TMDL development. Information on how model represent phosphorus processes in urban and forest sectors is also lacking. The model so far has been applied to four watersheds in the US, all of which have animal feeding operations. Despite of its advantage in representing phosphorus dynamics in farms in great detail, the model is not sufficient enough for a full simulation of hydrology, sediment transport, and nitrogen and carbon loadings from watersheds and therefore does not meet the needs for TMDL development.

GEM

The General Ecosystem Model (GEM) is an ecosystem model designed to simulate the response of algal and macrophytes communities to the simulated levels of nutrients, water and environmental inputs within different ecosystems (e.g. wetland, terrestrial; Fitz et al. 1996). The model includes processes considered to be most important in influencing plant production and ecosystem properties. The model assumes hydrology as the critical process in controlling plant growth and nutrient cycling, with hydrology, plant production and nutrient cycling being the key components of the model. The model assumes spatially homogeneous (or cell based). Scaling up to landscape will require the model to be incorporated into other spatially distributed models. One advantage of the model is that it does include hydrology, nutrient cycling and dynamics of both algae and macrophytes. However the model is only a cell model or a single ecosystem type model with very simplified representation of processes, and therefore is most suitable for hypothesis testing for long-term ecosystem responses. It does not account for pollutant loadings from non-vegetated areas (e.g. urban areas) nor is it spatially distributed to account for the spatial variation existed in the watershed. The model also lacks representation of detailed in-stream processes. Currently the model is still under testing for simulations in different ecosystem types. And a spatially distributed version is not readily available for use. Therefore the use of GEM for TMDL purpose is not appropriate in its current form.

MIKE-SHE

MIKE-SHE is a spatially distributed and physical based modeling system for hydrology and pollutant simulation, developed by Danish Hydrology Institute (DHI; Refsgaard and Storm, 1995; Abbott et al. 1986). The model simulates full hydrological cycle of interception/ evapotranspiration (ET), overland and channel flow (OC), unsaturated zone and saturated zone flow, snowmelt, and exchange between groundwater and surface water. The model has a detailed representation of groundwater component (3-D grids) and spatially distributed overland and unsaturated zone flow (1-D grid cells). The model simulates both event and long-term hydrological response. The temporal scale of the model simulation is flexible and can range from minutes to days. Besides hydrology, the model has several add-on modules that can be used to simulate advection and dispersion of solutes, geochemical processes, crop growth and nitrogen processes in the root zone, soil erosion, and irrigation. MIKE-SHE has been widely applied in Europe for groundwater pollution, flood forecasting and leaching of nitrogen from agricultural lands. MIKE-SHE was coupled to DAISY (Hansen et al. 1990) model to simulated crop production and water and nutrient dynamics in the root zone.

MIKE-SHE is the only model that fully integrates groundwater and surface water simulations and is able to simulate the groundwater and surface water interaction. The nitrogen simulated by DAISY primarily focus on nitrate only. There is not enough information regarding the functionality of the model to simulate in-stream water quality processes (e.g. DO, temperature). The spatially distributed model also requires extensive data input, for many cases only limited existing information is available. The main limitation of MIKE-SHE is that it is not public domain and the availability of the code is questionable.

8.5.3 Water quality model of the Laguna

None of these watershed models is optimal for simulating responses in the Laguna itself, with its complex, slow-moving hydrology and important interactions with sediment and macrophytes. The receiving water portion of the HSPF model could be applied to the Laguna, except under conditions of reversing flows, and would meet many of the requirements for the study. SWAT and WARMF are inadequate for simulation of the Laguna itself and would need to be linked to a more detailed receiving water quality model if used for watershed simulation. A variety of additional receiving water quality models are available that could simulate responses of the Laguna at different levels of detail, each with their own specific advantages and disadvantages (USEPA, 1997; Table 8-2). Among these, CE-QUAL-W2 and RMA-11 may be good candidates at a moderately high level of sophistication. WASP model is also a detailed model developed by EPA. However, the temperature and sediment routine in WASP is less sophisticate for TMDL purposes. Previous attempts to apply CE-QUAL-W2 to the Laguna by City of Santa Rosa suggested problems in mass conservation among the reaches and problems with applying a reservoir model to streams.

Table 8-2 Comparison of watershed model functionalities

Category	Laguna Model Needs	SWAT	HSPF	WARMF
Hydrology and Sediment	Time Step	Daily or subdaily on land surface; daily only in waterbodies	Daily, hourly, subhourly	Daily
	Watershed segmentation	Subbasin / HRU (multiple subbasins)	Subbasin / HRU	Subbasin
	Runoff	Surface runoff simulated using curve number method or Green-Ampt infiltration method; other flow components include bypass and lateral flow	Philip infiltration with full simulation of interflow and groundwater	Runoff from soil layers is simulated based on soil moisture, soil saturation and field capacity, soil thickness and hydraulic conductivity
	Groundwater	Shallow, deep (as sink)	Shallow, deep (as sink)	Shallow
	Sediment erosion and transport	MUSLE, erosion/sediment as a function of rainfall/ runoff	Accumulation and detachment based on Negev model and comparable to USLE; transport limited by flow capacity	Sediment erosion from rainfall and overland flow. Simulate sand, silt and clay separately. Transport limited by transport capacity
Water quality-processes	Nitrogen	NH4, NO3, ON (active, stable, fresh)	NH4, absorbed NH4, NO3, labile and refractory PON and DON	NH4, NO3, TKN, TN; ON not explicitly tracked
a. pollutant sources	Atmospheric deposition	Wet only	Wet and dry (time-series, monthly)	Wet and dry (time series)
	Urban / residential	Build-up/wash off or USGS regression equations	Impervious runoff, build-up/wash off	Surface loading, impervious runoff
	Septic Systems	Not explicit: Either as point source or as fertilization rate	Not explicit: Either as point source or loads applied to land surface	Total septic flow volume of each catchment is applied to a specific soil layer
	Point Sources	Partial (no BOD or temperature)	Full flexibility	Full flexibility
b. operations/ BMPs	Fertilization	User specified amount of fertilizer applied/auto-fertilization	Application rates/loads	Monthly loading rates applied to different land uses, routed through soil
	Irrigation	User scheduled or auto application	Multiple options (including time series)	Time series of flow added to specific land use of the catchment
	Filter strips	Trapping efficiency calculated as a function of width	Removal efficiency (constant/vary monthly), various width	Model as a rectangular catchment with user specified slope, length and width
c. pollutant transport	Phosphorus transport with sediment	Loading function, proportional to sediment	Use a potency factor to relate to sediment or simulate independently via buildup/washoff	Partition coefficient, related to sediment
	Terrestrial organic carbon/BOD source	Function of sediment loading and plant growth/ soil organic carbon simulation	Potency factor, surface built-up/wash-off, subsurface concentration for dissolved phase	Product of litter decay, surface loading
Water Quality-In-stream processes	Dimension	1D, completely mixed (daily)	1D, completely mixed (sub-daily)	1D,completely mixed (daily)

Category	Laguna Model Needs	SWAT	HSPF	WARMF
a. Flow/ sediment routing	In-stream sediment transport	Deposition/degradation, related to max velocity	Deposition /scour, based on shear stress. Sand, silt, and clay	Deposition/scour, based on shear stress. Sand, silt, and clay.
	Bank stability	Channel erodibility factor	As a function of bed erosion based on shear stress	Bank erosion (a stability factor)
b. Algae growth	Aquatic species	Algae, macrophytes not simulated	Benthic algae, phytoplankton, zooplankton, no macrophytes	Phytoplankton (green, blue-green, diatom), periphyton, no macrophytes
	Algal growth	Affected by temperature, nutrient, light (self shading) – limited by daily time step	Affected by temperature, nutrients, light (turbidity/ self-shading))	Affected by temperature, nutrient, light extinction (function of suspended sediments, detritus and algal biomass)
	Release of phosphorus from bottom sediment	Not available	Benthic release under aerobic and anaerobic condition	Not available
c. DO	DO diurnal cycle	Not available	Full simulation	Not available
	DO source/ sinks	CBOD decay, nitrification, SOD, reaeration, algae photosynthesis/respiration	CBOD decay, nitrification, SOD, reaeration, photosynthesis/respiration	Reaeration, algal photosynthesis/respiration, DOC decay, SOD, nitrification
	Biochemical Oxygen Demand (BOD)	CBOD modified by deoxygenation and settling	CBOD, Benthic release of BOD, benthic algae death, zooplankton, phytoplankton death, decay, settling	BOD as a result of organic carbon decay, BOD decay
	Sediment Oxygen Demand (SOD)	Constant	Constant or exponential function of DO. Benthic release of BOD under low oxygen/anoxic condition	Reach-specific constant (user input)
d. Temperature	Water temperature	Function of air temperature	Heat balance based on meteorological data, area of water exposed to radiation (shade), boundary condition, hydrodynamic (flows and water body geometry), and inflow temperature.	Function of inflow temperature and air temperature
	Shading/light extinction	Temperature not affected by shading	Shading due to riparian cover is accounted for and will impact in-stream temperature	Shading due to riparian vegetation is not considered and will not impact temperature
Other considerations	Availability	Public – code available	Public – code available	Public, some limitations on code
	User-interface	User-friendly	User-friendly	Most user-friendly
	TMDL Applications	Moderate number	Most frequently used	Limited number

Table 8-3
Receiving water quality models

Model	Organization	Water Body	Time Scale	Dimension	Pollutants	Summary
AQUATOX	USEPA	Reservoir/ Lake, Stream	Dynamic	1-D	Sediments, Nutrients, Toxic Substances, BOD/ DO	Predicts the fate of various pollutants, such as nutrients and organic chemicals, and their effects on the ecosystem, including fish, invertebrates, and aquatic plants.
BATHTUB	USACE	Reservoir/ Lake	Steady state	1-D	Nutrients	Steady state model that simulates nutrient mass loading and algal response in lakes and reservoirs
CE-QUAL-W2	USACE	Reservoir/ Lake, Stream, Estuary	Dynamic	2-D	Nutrients, BOD/DO, Bacteria	A two-dimensional, laterally averaged, hydrodynamic and water quality model.
EFDC	EPA & Tetra Tech, Inc.	Reservoir/ Lake, Stream, Estuary	Dynamic	1, 2, 3-D	Sediments, Nutrients, Toxic substances, Metals, BOD/DO, Bacteria	State of the art hydrodynamic model that can be used to simulate aquatic systems in one, two, and three dimensions
QUAL2K	Steve Chapra, USEPA TMDL Toolbox	Streams/River	Dynamic	1-D	Nutrients, BOD/DO, Bacteria	River and stream water quality model that simulates conventional constituents
RMA-11	USACE	Estuaries, bays, lakes, and rivers	Dynamic/ Static	3-D	Nutrients, BOD/DO, algae, sediments	Finite element water quality model for simulation of three-dimensional estuaries, bays, lakes and rivers.
WASP	USEPA	Reservoir/ Lake, Stream, Estuary	Dynamic	1, 2, quasi-3-D	Sediments, Nutrients, Toxic substances, Metals, BOD/DO, Bacteria	A dynamic model for aquatic systems, including both the water column and the underlying benthos that simulates pollutants dynamics in 1, 2, and 3 dimensions.

All of these models lack the capability to simulate overbank access to the floodplain and macrophyte (i.e. *Ludwigia*) growth, which can have significant impacts on water quality. Currently there are models available for submerged aquatic species in some of the water quality models (e.g. CE-QUAL-ICM). However, *Ludwigia* is an emergent aquatic species, and development of new model routines may be needed for full simulation. A full analysis of model requirements in light of information needs for management and decision needs to be carried out before final selection of modeling tools for the Laguna.

Monitoring Recommendations 9

The purpose of this section is to provide general guidance on proposed monitoring activities to provide information for several of the recommended indicators and key uncertainties / data gaps identified in this report, and to support the next phase of model development. A more detailed Laguna monitoring and quality assurance plan will need to be prepared as part of the next steps in this process.

Key hydrologic, geomorphic, water quality, and ecosystem data to understand the Laguna de Santa Rosa system are either absent or sparse. Expanding the data set will support future TMDL studies and will assist in achieving management goals. Table 9-1 lists our recommendations for future hydrologic and geomorphic monitoring efforts.

Table 9-1
Monitoring recommendation summary

Indicator	Method	Frequency of Analysis
Channel cross sections	Identify and monument cross sections that would best reflect geomorphic change without being affected by hydraulic conditions. Resurvey the cross sections periodically.	Once every 5 years or before and after dredging if applicable
Floodplain cross sections	Field surveys of cross-sections using a total station or survey floodplain topography using ground-based LIDAR.	Once every 10 years or after major (1:100) flood events
Longitudinal profiles	Detailed field surveys using a total station.	Once every five years if no future dredging activity; otherwise before each dredging activity
Bankfull flow	Identify bankfull conditions in the field and estimate the associated discharge based on flow calculations.	Once every 10 years or after major (1:100) flood events
Rates of bed and bank erosion and aggradation	Baseline channel reconnaissance survey to locate and record bed and bank erosion and aggradation locations. Resurvey periodically to measure bank rates of change.	Once every 10 years or after major (1:100) flood events
Dredge removal volumes	Clearly identify the extent of the dredged reach. Record timing of the dredging. Estimate the magnitude of dredged volume.	Undetermined; based on dredging

Indicator	Method	Frequency of Analysis
Macrophytes	Determine the area covered by macrophytic growth using walking GPS surveys, grids and photographic documentation – calculate percent of the area covered by aquatic plants. Samples from representative locations to quantify biomass.	Minimum: once at peak of growing season (summer) and again during the winter when growth is minimal
Chlorophyll-a	Several locations -- Standard Methods 10200-I, or equivalent	Minimum: once at peak of growing season (summer) and again during the winter when growth is minimal
Minimum DO/ % Sat / REDOX	Several locations - Electronic probe – multiple depths	Continuous at 15 minute increments
Temperature/ Temperature stratification	Several location - Electronic probe – multiple depths	Continuous at 15 minute increments
Sediment	Grain size: wet-sieve/laser diffraction TOC: ASTM D4129-82M (or equivalent) Embeddedness: Survey ring/grid method Nutrients: Total P (EPA 365.3) Total N (EPA 351.3)	Grain size/TOC during high & low flow conditions. Embeddedness during low flow as conditions allow.
Benthic Macroinvertebrate Diversity Index	Rapid Bioassessment in both upper reaches of watershed and reaches within cities	Initial five years every Spring, then every other year
Warm and Cold Water Fish	Electro-shock and release, initial detailed community surveys in main stem and reaches not yet surveyed, then monitor communities at set locations within watershed at regular intervals	Low and high flow conditions (as conditions allow)
Unionized ammonia pH	Calculated from temperature, pH, and total ammonia Electronic probe	TBD Continuous at 15 minute intervals
Nutrient (e.g., PO4, TP, NO3, NO2, TN, Total ammonia)concentrations	EPA 365.3/EPA 351.3	TBD
Organic carbon/BOD concentrations	Organic Carbon: ASTM D4129-82M (or equivalent) BOD5day: SM5210B	TBD
Atmospheric deposition	USGS Method described in: Water-Resources Investigations Report 03–4241	During the wet season
Run-off from dairies, pastures, vineyards, and land application of tertiary treated wastewater	Collection of runoff from drainage ditches, culverts, and storm water drains and analysis for nutrient constituents and BOD. This monitoring should also include shallow wells to monitor infiltration rates from irrigated fields to the streams.	Ditches and culverts should include three samples, each, during the wet and dry seasons. Shallow wells sampling regime to be determined.

Indicator	Method	Frequency of Analysis
Riparian buffer habitat condition	GIS mapping and regular geographic survey to identify alterations to buffer width and habitat connectivity; shade cover / density; on the ground assessments of vegetation & fauna condition throughout watershed, including determination of non-native/invasive components. Riparian Buffer study should also include monitoring of uptake and trapping efficiency of various buffer types and widths.	Once every 5 years
Amphibians	Calling and Crossing surveys	Yearly during spring
Birds	Area search, point count and nesting surveys in riparian zones and along waterways	Summer and spring

In addition, we recommend the installation of an acoustic Doppler sensor at the River Road Bridge to record flow direction and velocity so that inflows form the Russian River can be quantified. This would provide a greater understanding of sediment and water movement and would be key to verify and calibrate a hydrodynamic model of the Laguna and the Russian River confluence.

If there is a desire to develop a more complete hydrologic and sediment budget of the system, future monitoring and analysis of the Laguna de Santa Rosa should also include:

- Discharge data at more locations over a longer period of record;
- Approximate amount of sediment contributed by each type of sediment source in each subwatershed;
- Grain size distribution along the Laguna;
- Grain size distribution of sediment contributed from each tributary;
- Approximate volume and grain sizes of sediment stored along streams; and
- Approximate transport rate of sediment through stream channels and valley floors.

In terms of water quality and ecosystem parameters, we recommend the following special studies to be preformed:

9.1 Sediment Oxygen Demand

Sediment oxygen demand (SOD) is the rate of the dissolved oxygen consumption in a water body (river, lake or ocean) due to the decomposition of organic matter deposited on the bottom sediment. In shallow nutrient-rich waters where algal blooms frequently occur, very high SOD (due to the decomposition of settled algal detritus) has been measured. This may lead to severe oxygen depletion, resulting in fish kills. The SOD is often a significant component of the dissolved oxygen budget; its determination provides an important input to mathematical models used in water quality control and environmental impact assessment studies. SOD is quantified using an *in situ* SOD chamber, which continuously measures the dissolved oxygen in a chamber placed over the sediments.

The objective of this study will be to measure the SOD in the Laguna's sediments during low and high flow conditions.

9.2 Sediment nutrient flux

It is well-recognized that sediments play an important role as both a source and a sink of nutrients in lakes and reservoirs (Nürnberg 1987; James 1991). The forms and quantity of phosphorus (P) and nitrogen (N) in aquatic ecosystems are a function of such factors as the external nutrient inputs and outputs, and their interchange between the sediment and the water compartments (Reddy et al. 1996). The exchange rate of nutrients at the sediment–water interface is a highly complex phenomenon that depends on several factors and processes, including temperature, dissolved oxygen (DO), redox potential, pH and microbial activities (Bostrom et al. 1988). The organic matter content of the sediments also influences nutrient flux rates

The objective of this study will be to measure the sediment nutrient flux in the Laguna's sediments during low and high flow conditions.

9.3 N/P limitation

The ratio of nitrogen (N) to phosphorus (P) in stream water impacts lotic ecosystem structure and function. Low N:P ratios (<16) often result in N limitation of algae growth and high N:P ratios (>16) often result in P limitation of algae growth. The objective of this study will be to measure the nitrogen and phosphorus ratios in the Laguna during low and high flow conditions.

Recommended algal growth potential methodology

The bioassay method is important for a better understanding of the relation between nutrient concentration and phytoplankton dynamics in aquatic systems. Based on the concept of algal nutrient limitations, the algal assay is a responsive test designed to examine algal growth response to nutrient enrichment (Miller et al., 1978; Downing et al., 1999). Nutrient enrichment bioassays are a useful indicator as to which nutrient has the potential or is most likely to limit phytoplankton growth at a particular time and place (Diaz and Pedrozo, 1996; Ault et al. 2000). Nutrients of primary concern are nitrogen and phosphorus compounds (Verhoeven et al., 2001; Wetzel, 2001). Since the growth rate of phytoplankton in eutrophic waters is usually limited by nitrogen and/or phosphorus (Olde Venterink et al., 2002), the addition of these nutrients causes a growth response of algal cells proportional to the magnitude of limitation of the particular nutrient. Accordingly, the interpretation of the degree of algal growth response to nutrient enrichment leads to a sharper definition of the concept of nutrient limitation by providing a quantifiable definition of nutrient limitation (Downing et al. 1999). Algal biomass and overall ecosystem productivity may be controlled by the type and intensity of nutrient limitation (Dodds et al., 2002). Therefore, the magnitude of nutrient limitation has implications for population dynamics, species interactions, and ecosystem processes and thus many measures reported in published experiments can be converted to a single biologically meaningful measure of nutrient limitation that is comparable across studies (Downing et al., 1999; Osenberg et al., 1999).

Horvatić et al (2006) describes a method of nutrient addition to determine nutrient limitation. A modification of this method using a laboratory cultured green alga (Selenastrum capricornutum) and nutrient spiked/not-spiked sterile-filtered water from the Laguna could be used to determine the AGP of the Laguna. A brief overview of the method is provided below:

1. Prior to testing, laboratory cultured green alga (*S. capricornutum* or equivalent) is acquired, rinsed and starved in sterile-filtered distilled water for three days to eliminate any stored nutrient reserves that the algae have accumulated.
    - Using a single species of known health reduces the uncertainty of using "naturally" collected algae of unknown species and health.
    - Allows for an accurate initial inoculation of algal cells into the test chambers
2. Laguna sample is collected, sterile-filtered (0.45 micron cellulose filter), analyzed for nutrient concentrations, and placed into sample flasks.
    - Removes bacteria, predators, competing algae species, and detritus
    - Provides a test environment having known concentrations of background nutrients and water quality.
3. One set (six replicates) remains unspiked; one set contains a spike of KNO_3 (final concentration = 0.16 g-N/l); another set contains a spike of K_2HPO_4 (final concentration = 0.02 g-P/l); a control set contains algal growth media.
    - Provides control over the concentration of nutrients in solution. Nitrogen and phosphorus are added in excess so that neither nutrient becomes limiting during the experiment
4. Inoculate each test chamber with a known number of algal cells as described in "*Short-term Methods for Estimating the Chronic Toxicity of Effluents and Receiving Waters to Freshwater Organisms*" (EPA/600/4-91/002 – July 1994).
    - Provides a known initial quantity of algal cells.
5. Perform test as described in EPA/600/4-91/002 – July 1994), with the following exception:
    - Quantify growth of S. capricornutum from one replicate from each treatment daily for 14 days (until the stationary phase of growth) [per method described by Horvatić et al (2006)
6. Calculate AGP according to Horvatić et al (2006)

This method of addition allows for the calculation of AGP by using the test indicator species' growth rather than the depletion of nutrients. This method does have uncertainties. The primary uncertainty is that it provides only an approximation of *in situ* conditions; an uncertainty that is present in all laboratory bioassay tests.

9.4 Baseline faunal surveys

In addition to surveying and regularly monitoring the above listed faunal indicators (e.g. fish, amphibians, birds), it is important to get a better idea of the full spectrum of the current faunal diversity (including invertebrates, mammals, reptiles) within selected degraded and non-degraded reaches in the watershed. This will serve as baseline information to help assess the direction and success of future restoration efforts.

Response to Comments 10

A complete draft of this report was published on August 7, 2007 and distributed, in electronic form, to the Technical Advisory Group. Paper copies of the publication were also prepared and sent to the San Francisco Estuary Institute (SFEI), for technical peer review. The reviewers at SFEI were Rainer Hoenicke, Mike Connor, Lester McKee, Robin Grossinger, and Josh Collins. Upon review of this document by SFEI, comments were prepared and submitted to the authors. A discussion between the authors and the reviewers occurred on September 27,2007 at the offices of the San Francisco Estuary Institute, Oakland, California.

The table below enumerates the September 27, 2007 comments from SFEI, and the responses to those comments by the authors. When given, page numbers refer to the publication dated August 7, 2007.

SFEI Peer Review Comment	Project Team Response
1.1 - What is the end product of the conceptual model? How will it be used? To inform a more "fully automated and dynamic model?" Perhaps mentioning this future computational model more clearly in the beginning would constitute another reason to build a conceptual model first, especially given that there is a chapter dedicated to models.	The previous Introduction provided inadequate guidance to the reader on what to expect in the report. The introductory chapter has been reworked.

SFEI Peer Review Comment	Project Team Response
1.1 – I do not fully understand the organization of this section and what, in particular, I should expect in the report. There are several lists: objectives (which is clear), "specific management decisions" to be evaluated, and "components necessary to develop a comprehensive assessment." How does the report approach each of these and in what sequence? Based on the first two paragraphs, I understand the main focus of the report is to develop conceptual models for a better integrated understanding of the watershed.	The reworked Introduction provide a better summary of what the reader should expect.
1.6 – "Each section…has been divided into three topical areas" – Hasn't the report (rather than each section) been divided into three topical areas? (The first three main headings in the table of contents are the three identified topical areas).	Correct. This has been reworded.
It would be good to have a map showing the Upper and Lower Laguna Watershed areas.	There is not an exact boundary between the Upper and Lower Laguna Watersheds, therefore a map delineating these distinct areas can't be provided. In addition, the boundaries vary across different tributaries (depending on where depositional processes become significant along a given tributary). However, a description of what processes define these areas would help in roughly delineating the downstream boundary of each tributary adjacent to the mainstem Laguna. The Upper Laguna Watershed consists of headwater zones of tributary channels to the Laguna and the main stem tributary channels and represents sediment production and transport zones. This domain is the source for sediment through hillslope processes but also serves as the transport link between headwater zones and the Lower Laguna. The Lower Laguna Watershed consists of the main channel of Laguna and its floodplain, including the lower reaches of the tributary channels and floodplains. The Lower Laguna Watershed represents the depositional zone in the Laguna system where stream channels act as sediment sinks.

SFEI Peer Review Comment	Project Team Response
Are there problems that arise during periods of low flows – what are the important factors to concentrate on at different times of the year? Should the seasonality of problems and how they relate be clarified?	Increased summer flows from irrigation likely increase in-channel vegetation growth? In winter, increased peak flows from development result in increased channel erosion and sediment transport.
Link to the anthropogenic causes are not clear from the studies discussed. How is the link going to be clearly made between hydrologic regimes and sedimentation processes and anthropogenic influences? More clearly, I don't necessarily see the report summaries and associated data at the beginning of this chapter leading directly into and informing the discussions of the conceptual models.	PWA's 2001 study on Geomorphic Investigation in the Laguna Watershed detailed the anthropogenic influences on hydrology and sedimentation in the Laguna. The report included a chapter titled "Assessment of Historical Changes" that addressed issues such as land use changes in the watershed, early river management, river management associated with flood control, and recent river management activities in the watershed along with chapters on assessment of hydrology, geology, and channel sediment character. The PWA 2004 study summarized those findings and reinterpreted earlier observations based on more detailed technical analyses. Both of these reports can be requested from the US Army Corps of Engineers. We incorporated a summary discussion of land use changes and their effect on hydrology and sediment processes in the introduction to Chapter 4.
Should anthropogenic causes of sedimentation be mentioned in the introduction to the chapter? They are discussed extensively in the discussions of the conceptual models, starting at 2.3.	Yes. We incorporated a summary discussion of land use changes and their effect on hydrology and sediment processes in the introduction to Chapter 4.

SFEI Peer Review Comment	Project Team Response
"2002-2003 Turbidity Measurements:" Upon what parameters is suspended sediment concentration dependent on? It's partially a function of discharge—what else? I would be interested in more explanation of Fig 2-10 through 2-12.	The mainstem Laguna channel is a transport-limited system whereas downstream reaches of the tributary channels are either transport- or supply-limited. Please refer to the PWA (2004) report on the geomorphic reconnaissance of the tributary channels and observed sediment transport characteristics. Figures 4-12 and 4-13 (in this final report) are mainstem Laguna locations where the channel is transport-limited (capacity-limited) and represent reaches where many variables such as discharge, depth, velocity, width, slope, and bed topography influence sediment transport. Figure 4-14 shows the suspended sediment concentration at Santa Rosa Creek at Willowside Road, where the suspended sediment transport is primarily supply-limited (except the sand-sized materials, which are occasionally transported in suspension). Therefore, in addition to the rate of supply and discharge, seasonal differences and hysteresis (where sediment wave is not synchronous with the water wave) also affect suspended sediment concentrations. Please note this effect and the closer correlation of concentration with discharge on Figure 4-14 compared to Figures 4-12 and 4-13.
2.3 – Change "the Laguna system or its physical and ecological" to "the Laguna system and its physical and ecological?"	Modified as suggested.
2.3.1 – Identified the distinct difference between pre- and post-European influence. May also want to discuss differences due to the agricultural shift to vineyard and the parallel expansion of urban areas in the latter part of the 20th century.	Please refer to PWA (2004) and Laguna de Santa Rosa Foundation (2006) studies for more discussion of land use changes and their effects on the temporal variability of hydrologic and sediment delivery.

SFEI Peer Review Comment	Project Team Response
p. 39 – Agriculture can also cause dewatering of the channel depending on water extraction practices (location and depth of wells), the balance of urban influence, and the location of the groundwater table. This, however, may only occur in upper reaches. This comment relates to a general need for distinction between the Upper and Lower watershed. That is, when are comments addressing the whole watershed, and when do they only apply to the lower Laguna system?	Groundwater pumping for agriculture primarily occurs in the Lower Laguna. Comment noted. However, typically the processes for Upper and Lower Watersheds are discussed in separate sections.
p. 39 – Can increases in low flows also be due to channel incision (streambed closer to groundwater table)?	This could conceivably be true. However, incision is predominant in the upper part of the system and would not explain increases in low flows in the Lower Laguna Watershed.
p. 39 – Is it possible to link the elevated groundwater table (and subsequent increased low flows) to the increased summer water supply in the mainstem Russian River as a result of management practices at the dams and the Eel River diversion?	The groundwater movement is toward the Russian River (p.39: "the Santa Rosa Plain subbasin drains northwest to toward the Russian River"). It is not likely that increases in groundwater levels along the Russian River would translate back very far toward the Laguna groundwater elevations, limiting the effect of this mechanism. The USGS groundwater model would provide a more definitive answer if queried on this point.
p. 41 – The effect of geology and soils – What is the Laguna dominated by and where? (Impervious and resistant or permeable and loose?)	Please refer to PWA (2004) and Laguna de Santa Rosa Foundation (2006) studies for more discussion on the geology and soils of Laguna, as well as the groundwater section in this report.

SFEI Peer Review Comment	Project Team Response
p. 39-41 – How have the discussions of hydrologic modifications due to (sub)urbanization in the Lower versus Upper Watersheds been distinguished? Has the Lower Watershed not been influenced by land cover change and stream channel alteration, given that this is discussed in the Upper watershed section? Should the differences be brought out more clearly and perhaps linked to the physical differences between the Lower and Upper Watersheds (different types of development and agriculture leading to different types of consequences)?	Given the distinguishing characteristic that defines the Upper and Lower Laguna Watersheds as different zones (source/transport zone versus depositional zone) by our definition, we have discussed the aspects of (sub)urbanization that support each of those characteristics as appropriate to the region being discussed. While aspects of development could support increases in sediment production in the Lower Laguna (depositional) zone, for example, the predominant processes of concern in this zone will be those that support deposition. There are not strict physical landscape (or development) distinctions between the two zones, as described above, so discussion of these differences has not been included in the text.
p.46 – Figure 2-16 needs a title	Comment noted.
2.3.4, p50-51 – Why is the project rate of water supply by 2030 expected to decrease to 3,000 acre-feet? Secondly, are these figures part of the 29,700 acre-feet figure listed in the preceding paragraph, or is it in addition?	This number references groundwater that is expected to be used in 2030. The number is expected to decline as a result of increased surface water supplies becoming available. The 29,700 acre-foot value is an estimate of total pumping, both public and private, and would therefore include the portion of these "total groundwater and local supplies" that represent groundwater pumping from the Santa Rosa subbasin. The numbers come from two different sources and are getting at somewhat different things, but help to identify the scale of total pumping versus the much smaller scale of pumping for public water supply.
Question 3, p. 54 – This question seems to be more clearly focused on the Lower Laguna area – should this be specified (summer flows may not be elevated in upper reaches).	The question is indeed focused on the Lower Laguna. Modified the question as suggested to: "Is it likely that present and/or expected future condition low flows, especially in the Lower Laguna Watershed, do or will impair beneficial uses?"
Question 6, p. 56 – This seems to be a key question, especially in terms of management implications.	Question 6 asks, "What is the magnitude of bedload contribution from each source (e.g., roadside ditches, landslides, gullies, creek banks, etc.) and each geographic subregion, and how are these expected to change in the future?" We agree that this is a key question in terms of its management implications.

SFEI Peer Review Comment	Project Team Response
p10 – ac-ft per year is an off unit for sediment yield. 25% delivery to the Russian R. seems too high – I would expect more like 10%. Please justify.	The sediment yield estimates were derived from the PWA (2004) study, the focus of which was to estimate sediment deposition rates and volumes in relation to flood storage. Typically, flood storage issues are discussed and reported in acre-feet. Since, one of our focus areas is flood management for the current report, the units from the original estimates were not revised. In addition, the PSIAC method estimates sediment yield in units of acre-feet per year. 25% delivery to the Russian River is derived from estimates of sediment storage in the upper watershed and the trap efficiency of the Laguna. We estimated that 50% of sediment from the watershed is coarse sediment and is stored in the upper watershed and upper tributary channels (based on observed particle size distributions, delivery patterns, and a limited record of channel sediment removal activity at one location –Hinebaugh Creek). We estimated the trap efficiency of the Laguna as 50% based on Brune's empirical relationship to estimate long-term trap efficiency in normally impounded reservoirs based on the correlation between the capacity to inflow ratio. Therefore, 25% (50% of 50%) of sediment is deposited in the Laguna, while the remaining 25% is delivered to the Russian River.
p11 – median flows of 500 cfs seems too high. I looked up the data and it appears more like <10 cfs (9.2). Please check.	We rechecked the statistics for the Laguna de Santa Rosa near Sebastopol station from the USGS website. Median of daily mean values for each day is typically less than 10 cfs from May to December. However, median flows go up to 490 cfs in the first couple of days in January and are typically higher than 100 cfs from January to mid-March.
p20 – it would be helpful to the reader to have main creek names on this map as well as an outline of the position of the Laguna.	Figure modified.
p23 – do you mean tables 2-3 to 2-5? These figures do not show flow-duration curves – wrongly referenced? Please check.	Text deleted. The flow duration curves are not included in this report. Please refer to PWA (2004) study for flow duration relationships.
Table 2-6. Number of significant figures detracts from the information.	Deleted significant figures.

SFEI Peer Review Comment	Project Team Response
p26 – last paragraph and in the table – mixing units is at best odd and at worst ambiguous and leads to the likely misuse of the data by a future reader. (metric tons per year v tons/sq-mi/yr). Please consider being consistent or being very thorough of stating the units with definitions	Comment noted. Tons/year is adopted.

SFEI Peer Review Comment	Project Team Response
p27 – These are v. high sediment yields. Given the style of the channel – I have to wonder how transport is supported. Is it possible that floodplain storage is a large and unquantified term? Please add a comment as you see fit.	As indicated in Section 2.3.3 "Perspective on Sediment Yield Estimates", based on our understanding of sediment production in the watershed, field observations, and comparison to other studies, we concluded that the MUSLE method significantly overestimated sediment yields in the Laguna watershed. The MUSLE results are only presented to provide a range and a high upper limit for sediment yield estimates. Below discussion further explains this conclusion and is extracted from the discussion in the PWA (2004) report: "The MUSLE estimated sediment yield is much larger than the value produced by PSIAC… These estimates are significantly out of line with both the Matanzas reservoir and Russian River basin measurements, suggesting this method overestimated sediment yield for the Laguna watershed. In addition, using our own data for sediment deposition in the Laguna, we would require a trap efficiency of 50 percent and a delivery ratio of less than 10 percent to arrive at a convergence between sediment deposited and sediment yield. Based on rough calculations of channel area length and width it is apparent that to store this amount of sediment in the channel system would require tens of feet of storage (channel bed aggradation) across the whole river system, which is clearly not the case. There are three possible explanations for the inconsistency of our findings with the high MUSLE figures. "Firstly, we could have miscalculated the sediment deposition depth and thus the volume in the Laguna. Assuming a sediment delivery ratio of 50 percent and a sediment trap efficiency of 50 percent the MUSLE figures would result in 12,500 ac-ft of deposition over the recorded time period, as opposed to our estimate of 1,806 ac-ft. Based on our depth-volume calculations this would require approximately 7 feet of sediment deposition. Even given the caveats we presented regarding inaccuracies in survey locations and depths, it is extremely unlikely that the assessment could be this inaccurate, or indeed that 7 feet of deposition on

SFEI Peer Review Comment	Project Team Response
(continued)	the floodplain (adjacent to infrastructure such as roads and bridges) would go unnoticed. We therefore reject this possibility. "Secondly, we could have made incorrect assumptions regarding the horizontal extent of sediment deposition (e.g. sediment could have accreted as layers parallel to the ground surface rather than horizontally. This is more plausible than a large error in depth calculation, but even doubling the horizontal extent of our depositional area would leave the estimated sediment volume greatly below the figure estimated by MUSLE. We again reject this possibility. "Lastly, sediment produced in line with the MUSLE could have been eroded, but not transported into the channel system (i.e. stored in the fields where it was generated). To match our sediment volume figures approximately 90 percent of all eroded sediment would have to be stored on site for this to be possible. This may be possible, but is unlikely. Once sediment is detached we would expect more than 10 percent of it to reach the drainage system over a 46-year period. "Therefore it is likely that the MUSLE figures are an overestimation of sediment production. The inaccuracy of the MUSLE estimation may be due to USACE generated high runoff figures. Using regional runoff curves from the USGS rather than the HEC-HMS values used for the MUSLE analysis gives much lower predicted runoff values, suggesting a potential reason for the higher soil erosion estimates. In addition, use of MUSLE for such large watershed areas is questionable, given its intended use as a tool for estimating erosion at the farm field scale".

SFEI Peer Review Comment	Project Team Response
p28 – The data may be bad. Please provide the reader with more detail on what probe was used and how it was able to measure turbidity >1800 ntu. What influence did water color have on the turbidity measurements given you mention earlier in the report that the water is tea-colored. Please clarify and comment. What was the brand and model probe that was used?	Figures 4-12 through 4-14 (in this final report) show discharge versus suspended sediment concentration (not turbidity) at the gauged locations. Maximum turbidity values were observed in the beginning of the monitoring period and ranged from 800 NTU at Occidental Road, to 950 NTU at Stony Point Road, to 400 NTU at Willowside Road (PWA, 2004). We used an optical backscatter turbidity sensor (OBS-3 by D&A Instruments), a pressure transducer (PT-1230 from Druck), and a date logger (CR-510 by Campbell). OBS-3 can measure turbidities up to 2,000 NTU (http://www.d-a-instruments.com/obs3+.html).
It appears that none of the references in hydrology and sedimentation chapter are in the reference list. Miliman is spelt [sic] incorrectly.	All of the references have been added to the reference list; the incorrect spelling of Milliman has been corrected.
p43 – discharge seems high but reasonable – I convert your number to 400 mm of runoff (about the same as Sonoma Creek).	Comment noted. Please also note that the average annual runoff in the watershed based on Rantz's 1974 mean annual runoff distribution map in the San Francisco Bay region results in approximately 360 mm of runoff for the watershed.

SFEI Peer Review Comment	Project Team Response
p45 – When several estimates converge, that has no bearing on the quality of the estimate. It is how they compare to your conceptual model of magnitude and process. Please remove the comment and justify you estimate from the basis of your understanding of sediment loads in other bay area landscapes or some other conceptual models.	We agree that the convergence of several estimates has no bearing on the quality of the estimate. However, if the quality of the estimates is adequate and the estimates themselves are deemed reliable based on a solid understanding of the watershed processes, comparison to nearby systems, and best judgment, the convergence of estimates is meaningful. We concluded that a sediment yield estimate of 0.6 to 0.8 ac-ft/sq-mi/yr, that is 1,000 to 1,400 tons/sq-mi/yr (using a specific weight of 90 lb/ft^3) is representative of sediment yield in the Laguna watershed. Please refer to PWA (2004) report for details on different assessment methods, assumptions, and caveats. Sediment yield estimates in the nearby watersheds or in Northern California watersheds also underlain by Franciscan complex are comparable to our estimates. Sonoma Ecology Center has published a sediment budget of the Sonoma Creek watershed in which an annual sediment yield of approximately 1,100 tons/sq-mi was estimated. Ritter and Brown (1971) evaluated suspended sediment transport in the Russian River basin. For the years 1965 to 1968, Ritter and Brown found a suspended load of 1,150 to 14,000 tons/sq-mi/year, the highest being in the very wet 1965 water year. Griggs and Hein (1980) estimated average erosion rates for a number of Northern California watersheds based on off-shore sedimentation studies. Their study suggested an erosion rate of approximately 1,600 tons/sq-mi/yr in the Russian River watershed. California Geological Survey (CGS) prepared a technical memorandum reviewing the EPA's July 2002 analysis of impacts of timberland management on water quality (2002). It concluded that from a review of the literature and analysis of recent studies conducted by the CGS watersheds underlain by Franciscan mélange are likely to have natural/background sediment loads of approximately 1,000 tons/sq-mi/year or greater (Bedrossian and Custis, 2002). Therefore, we believe that our sediment yield estimates are representative of a Northern California coastal watershed that is underlain by Franciscan mélange and that has undergone land use changes. The above comparative information has been included in the revised text.

SFEI Peer Review Comment	Project Team Response
p46 – Please remove this figure so that there is no confusion on your recognition that the number are off.	Figure 2-16 removed.
p52 – Key uncertainties and data gaps paragraph. I agree, in terms of the academic question on sediment transport through the Laguna, the largest data gaps appear to be the influence of bi-directional flow and over-bank flow on storage. As it related to storage of nutrients and flooding, it may be an important management question as well.	Comment noted.
p56 – Question 7 seems to be a priority question.	We agree that locations of present sediment deposition areas within stream channels and floodplains is an important unknown (there is no hierarchical arrangement of questions in terms of priority). The current USGS study will address this question for the studied reach along the Laguna. Anecdotal reporting from SCWA maintenance staff, monitoring data, as well as future hydrodynamic models of the mainstem Laguna and tributary channels would help to address this critical question.

SFEI Peer Review Comment	Project Team Response
p61 Geological sources of phosphorus have been overlooked in the conceptual model. I have found that P concentrations in Napa, Sonoma and Pinole Creek in some sub-watersheds seemed likely associated with geological sources no land use / management.	We agree that it is possible that geological sources of phosphorus could be a providing a significant background load. The conceptual model figure has been modified to include this as a potential source. The Santa Rosa Plain is largely comprised of Clear Lake Series Soils. These soils contain high percentage of clay (35-59%) and are susceptible to erosion. Clay particles bind with phosphorus and certain metals. Therefore during winter storms, phosphorus inputs associated with sediment erosion can be a source to the Laguna. However we have been unable to identify any information providing the nutrient content of soils within the Laguna. Therefore, at the conceptual model level, we are not able to quantify the geological background source of nutrient loading. We believe that the Laguna is a naturally eutrophic system due to its low gradient, its surrounding productive terrestrial environment, and possibly high background levels of nutrient loading. However the Laguna has extremely high nutrient levels when compared to other waterbodies within the ecoregion (see Table 10-1) and the historical anthropogenic point sources and non-point sources of nutrients have played an unmistakable role in creating the hypereutrophic conditions that exist today.
p63 Please provide a justification to the reader why medians are greater than means. Is it because the system is point-source dominated? If so, figure 3-20 would suggest that the point sources are triggered by rainfall process because we still see high concentrations in the wet season – normally not what would happen if dilution was at play. The ammonia and nitrite numbers seem very high – please justify the data quality.	The Laguna is dominated by nonpoint sources in some locations and point sources in others. For this specific dataset, the medians are greater than means. Depending on which direction the data are skewed, medians can be higher than the mean. For this case, the median and mean are actually very close (0.38 vs. 0.36) and should not be a cause for concern. The dataset is also limited by its number of data points (i.e. 9). We believed the ammonia concentrations to be real as they also correspond to high TKN and TN values. The dataset was provided by the City of Santa Rosa, which has a demonstrated track record of excellent QA procedures.
Table 3-5. It would be helpful to normalize these numbers to area so that they can be compared to world literature by a reviewer and in the text. Please add some comparisons to other systems as a justification for data quality.	Please see the new Table 5-5b "Loadings normalized to area."

SFEI Peer Review Comment	Project Team Response
p71 – I think the ammonia number for urban runoff are high – my own data set for Sonoma and Napa downstream of the urban areas maxed out at <86 ug/L. Please justify your data quality.	Santa Rosa has an intermixing of horse pastures, fairgrounds, and dairies within the urban stormwater boundary. In addition the stormwater monitoring data collected by the City of Santa Rosa is subject regular quality assurance checks. The project team believes that the reported values are real.
Table 3-9 Nutrient numbers for urban stormwater in this table seem believable except those of ammonia which seem to be perhaps 10x too high. I did not check the other numbers, but it would be great if the author could compare them to the literature on dairying watersheds to see if they are believable.	These loading estimates for dairies were developed using source values that were extrapolated from literature provided by the local University of California Agricultural Extension Service agent who has been conducting research on local conditions (i.e. Lewis et al. 2001).
Figure 3-16. Please turn the y axis captions 180 degrees.	Comment noted – Axis captions for all figures have been rotated 180 degrees.
Figure 3-20. These patterns suggest a non-point source dominance in some parts of the watershed and a point source (but perhaps still wet-season influenced) dominance in other areas.	Agree. High background NH3 concentrations (might be due to manure).
p93 – Figure 3-25 very high NH3 – seems like secondary treated sewage or dairy shed overflows.	These values are in close proximity to dairies prior to the implementation of the Waste Reduction Strategy. The success of the program has resulted in lower concentrations for the period of 1995 to 2000 (Figure 5-26).
p96 – very high TKN also. Please justify to the reader that the ammonia and TKN numbers are not caused by bad data.	The high values for NH3 and TKN are due to the close proximity to dairies prior to the implementation of the nutrient management strategy. The monitoring and analytical programs were both subject to rigorous quality assurance guidelines.
p130 – Q2 – has DO always been that low? Perhaps management will not get it about 3 mg/L or some other target.	It is clear that the Laguna is a low elevation eutrophic system that is subject to hot summers. However there are several impacts that if addressed would result in improved overall DO results in the Laguna. These impacts include high loads of organic matter, high loads of nutrients, riparian canopy removal, and degradation of stream channel habitat. The project team believes that current conditions do not reflect historical or future potential conditions.

Table 10-1 Water quality monitoring data

Laguna de Santa Rosa compared to other waterbodies within Ecoregion 6

Chemical	Stream Type	Most Sensitive BU (Tier I/II)	Most Sensitive BU (Tier II/III)	Median	Average	First Quartile	Second Quartile	Third Quartile	Fourth Quartile	No. of data points
NH3	Minimally Impacted			0.02	0.05	0.01	0.02	0.04	3.25	261
(mg/l)	Unimpaired			0.02	0.41	0.01	0.02	0.07	32.94	1229
	Impaired (nutrient)			0.05	0.34	0.01	0.05	0.14	12.10	907
	Impaired (other)			0.05	0.47	0.02	0.05	0.12	17.10	1279
	Laguna de Santa Rosa			0.40	1.16	0.10	0.40	0.90	15.00	279
	Nutrient Target Matrix									
NO2	Minimally Impacted			0.00	0.01	0.00	0.00	0.00	0.06	110
(mg/l)	Unimpaired			0.02	0.15	0.01	0.02	0.13	12.00	1500
	Impaired (nutrient)			0.04	0.09	0.01	0.04	0.10	5.00	861
	Impaired (other)			0.02	0.14	0.01	0.02	0.09	2.95	1160
	Laguna de Santa Rosa			0.09	0.41	0.02	0.09	0.40	4.30	66
	Nutrient Target Matrix									
NO3	Minimally Impacted			0.05	0.16	0.05	0.05	0.15	2.85	112
(mg/l)	Unimpaired			0.36	4.45	0.05	0.36	3.70	48.09	1301
	Impaired (nutrient)			4.74	5.02	1.17	4.74	7.50	31.84	600
	Impaired (other)			2.2	4.71	0.56	2.20	4.80	48.10	1037
	Laguna de Santa Rosa			2.30	0.32	0.80	2.30	5.20	26.70	285
	Nutrient Target Matrix									
TKN	Minimally Impacted			0.25	0.31	0.13	0.25	0.41	1.20	156
(mg/l)	Unimpaired			0.40	1.01	0.20	0.40	0.93	42.70	1425
	Impaired (nutrient)			0.7	1.06	0.40	0.70	1.20	11.00	868
	Impaired (other)			0.6	0.97	0.30	0.60	1.10	33.00	1486
	Laguna de Santa Rosa			1.11	1.09	0.81	1.20	6.10	19.00	67
	Nutrient Target Matrix									
PO4	Minimally Impacted			0.04	0.05	0.02	0.04	0.07	0.23	260
(mg/l)	Unimpaired			0.08	0.49	0.02	0.08	0.50	28.73	1671
	Impaired (nutrient)			0.22	0.60	0.03	0.22	0.90	8.10	1056
	Impaired (other)			0.05	0.45	0.02	0.05	0.26	40.00	1793
Total PO4	Laguna de Santa Rosa			0.82	1.38	0.46	0.82	1.80	6.20	68
Ortho PO4	Laguna de Santa Rosa			0.75	1.93	0.37	0.75	1.90	46.0	66
TP	Minimally Impacted			0.08	0.08	0.03	0.08	0.09	0.30	34
(mg/l)	Unimpaired			0.07	0.36	0.01	0.07	0.27	24.80	633
	Impaired (nutrient)			0.13	0.77	0.05	0.13	1.07	7.94	525
	Impaired (other)			0.07	0.34	0.03	0.07	0.22	45.10	1069
	Laguna de Santa Rosa			0.64	0.66	0.47	0.66	0.70	1.20	27
	Nutrient Target Matrix									

Chemical	Stream Type	Most Sensitive BU (Tier I/II)	Most Sensitive BU (Tier II/III)	Median	Average	First Quartile	Second Quartile	Third Quartile	Fourth Quartile	No. of data points
TOC	Minimally Impacted									
(mg/l)	Unimpaired									
	Impaired (nutrient)									
	Impaired (other)									
	Laguna de Santa Rosa			12.00	14.72	9.80	12.00	16.00	84.00	51
	Nutrient Target Matrix									
DOC	Minimally Impacted									
(mg/l)	Unimpaired									
	Impaired (nutrient)									
	Impaired (other)									
	Laguna de Santa Rosa			11.00	12.13	8.80	11.00	13.00	52.00	50
	Nutrient Target Matrix	<3 (MUN)								
Chl-A	Minimally Impacted									
(ug/l)	Unimpaired									
	Impaired (nutrient)									
	Impaired (other)									
	Laguna de Santa Rosa			20.0	42.37	8.00	20.00	50.00	564.00	157
	Nutrient Target Matrix	<5.0 (COLD/ MUN)	>10 (COLD/ MUN)							
Benthic Algal Density	Minimally Impacted									
(mg/m2)	Unimpaired									
	Impaired (nutrient)									
	Impaired (other)									
	Laguna de Santa Rosa									
	Nutrient Target Matrix	<100 (COLD/ MUN/ SPWN)	>150 (COLD/ MUN/ SPWN)							

SFEI Peer Review Comment	Project Team Response
p131 – restoration of light limitation may be the most cost effective management measure in areas where full canopy can be achieved.	The project team agrees that in many cases riparian and channel restoration may be the most cost-effective approach to address nuisance conditions. However long-term nutrient reduction strategies must be retained as a core part of the ecosystem recovery strategy.
p132 – last hypothesis – yes likely – monitoring at a key USGS gauge should easily provide the data.	DOC is not included in the parameters monitored at the USGS gauge station. It is important that both forms of organic carbon inputs to the Laguna be reduced to ensure restoration of Beneficial Uses.
p133 – reduced and oxidized forms.	The oxidized form was added to the text.
p135 – Q11. What was it like historically? Perhaps no amount of management can influence the way it naturally (?) functions.	The Laguna was historically a eutrophic system of high productivity. Historical accounts of water quality and fish populations suggest that there has been a recent and significant decline in conditions. Small improvements have been achieved through the nutrient management strategy. The recent influx of sediment (Shallowing), high organic matter and nutrient inputs have impacted DO conditions. It stands to reason that removing excess organic and nutrient inputs and restoring habitat integrity will improve conditions beyond existing conditions.
p136 – Key uncertainties – Historic information needed.	The development of the document "Enhancing and Caring for the Laguna" pulled together a large amount of source material that could be used to develop historical ecology framework. The project team agrees that this is a key uncertainty and that it should be addressed.

SFEI Peer Review Comment	Project Team Response
p136-140 – Given that there is likely a natural supply of phosphorus from geological sources, it would seem reasonable to hypothesize that P would not have been limiting historically. Given nutrient sources in a modern system like this one, excess nitrogen relative to phosphorus is likely from dairying (because N is the dominant nutrient applied and consumed in grass-based dairying systems) and treated sewage (because phosphorus is removed through sludge). However, since the Laguna is loaded with nutrients, it seems just as likely that light or competition are limiting. Without a detailed process-based evaluation, it is hard to make further comments. In the absence of such knowledge, managers typically have to "pick the low-hanging fruit" and watch to see how the system changes through time. Usually the low-hanging fruit are those under control of public agencies and the higher effort level is private property and stewardship. It comes down to a stakeholder decision. I think a key data gap is learning what is currently supplying and limiting nutrient-based ecosystem function in the Laguna. A model could then be used to predict how long it will take after management measures are implemented before the system becomes either N or P limiting.	The project team believes that due to the high concentrations of both nitrogen and phosphorus that neither is limiting within the Laguna ecosystem. However we agree that any "low hanging fruit" should be taken to reduce nutrient loads regardless of whether it is nitrogen or phosphorus. It is also likely that even implementing nutrient controls within the Laguna today that the Laguna sediments will be a substantial source of nutrients for many years. Because of factors like sediment banked nutrients any restoration strategy will be subject to a long recovery timeline.
p142 – Hypothesis – atmospheric and GW could be sources during storms – yes, but minor compared to direct human sources such as fertilizers and animal and pet manures entrained by rainfall induced surface runoff during storms.	The project agrees with the suggestion and will make the necessary change to the text.

SFEI Peer Review Comment	Project Team Response
Evaluation of what is known about flood capacity is extensive, and data requirements for scenario-planning are well explained. The brief section on anticipated climate change impacts could reference any estimates of upward migration of tidal influence in the Russian River and how that may affect hydrology at the Laguna-Russian River confluence.	DWR's 2006 report on climate change titled "Progress on Incorporating Climate Change into Management of California's Water Resources" (available at http://baydeltaoffice.water.ca.gov/) is the most recent study on anticipated climate change impacts that we are aware of that specifically addresses anticipated precipitation changes in California. The report does not make quantitative predictions of how precipitation and runoff amounts and patterns will change in different parts of California. However, it elaborates on historic changes and trends in runoff volumes for selected river basins in California. Table 2-4 of the report indicates that in the Russian River basin, runoff has increased negligibly for the period of April through July and has increased by approximately 1,000 acre-feet since 1941. This is not a significant change. Based on current state of knowledge and assuming similar trends for the future, climate change is not expected to significantly impact runoff volumes in the watershed. In terms of sea level rise projections, Independent Science Team to CALFED estimated a sea level rise of up to approximately (8 feet). Upward migration of tidal influence along the Russian River may be possible due to sea level rise of such extent and climate change; however, it is not likely that this effect will be felt more than 20 miles upstream at the Laguna confluence.

SFEI Peer Review Comment	Project Team Response
The report doesn't make it obvious how the compiled information can or should be used in decisions pertaining to WHERE and HOW flood peak attenuation features can be restored or created, how water management planning activities can benefit water quality attainment strategies, or how land use decisions can be improved to achieve better integration of beneficial uses, restoration/ protection, management and prevention of biological invasions, water supply reliability enhancements, achievement of flood protection goals, and restoration of watershed functions and processes. This is one of the key areas where additional funding could be pursued to improve the value to environmental managers. The report only takes the first, albeit most important, step toward a planning and management framework - understanding the system and formulating hypotheses that should be tested with short-term special studies or tracking progress toward specific environmental goals or targets.	Water Management Planning is not an *objective* of this study. It was listed in the original proposal as an objective that a basin-scale model should *support* (and therefore can not be an objective, for a planning and management framework). Additional funding will be required to achieve this objective. The paragraphs in Section 1 of the original report which discuss this have been modified to clarify this.
Add larger-scale maps showing the key watershed features along the lines of the figure on the small fact sheet accompanying the report, the natural and artificial drainage network including stormdrains, land cover and land use, land slide hazard maps, and any other easily obtainable data layers that could help the reader follow some of the interpretive text.	Larger scale maps are incorporated into this final document.

SFEI Peer Review Comment	Project Team Response
The report could benefit from a thorough copy-editing job. There are numerous typos and syntax errors sprinkled throughout, but particularly in the latter third of the report. Someone needs to check that all figures have titles (e.g. 2-16), improve resolution of some of the figures that are barely readable, and insure all citations and references are actually listed in Section 8.	The final report has been copy-edited.
The end use of the conceptual model could be better explained. Is it designed as an education and communication tool, as a tracking tool during the anticipated years of prioritized data collection activities, to allocate resources for future sensitivity analyses, or all of the above and possibly more?	This has been addressed in the executive summary and has been changed in the introduction of the final report.
The report organization is a bit confounding at first. The Introduction identifies objectives, specific management decisions to be evaluated, and components necessary to develop a comprehensive assessment. How does the report approach each of these and in what sequence? The first two paragraphs in the Introduction make it sound as though the report's overall goal is to develop conceptual models for a better integrated understanding of the watershed, but it really does much more than that. Why not say right up-front that it also serves as a summary of our current understanding of how the system works, what we don't know, and what needs to be done to inform restoration and protection decisions?	The introduction has been changed to reflect a better integration of the new report organization and includes a more comprehensive statement of the report's overall goals.

SFEI Peer Review Comment	Project Team Response
The description of 1.6 can be improved. The first three sections represent more or less characterization of conditions and human-caused or –induced alterations of the physical, chemical, and biological integrity of water (which is the definition of pollution in the Clean Water Act) and the watershed as a whole.	This section has been updated to give a more accurate description of each section of the document.
Explore in more detail the implications of the lack of suitable models capable of accounting for reverse flood flows from the Russian River into the Laguna system.	Suitable models capable of accounting for reverse flood flows do exist; however, there is a lack of data to develop such models. Quantifying the volume of water and the amount of sediment that is delivered to the Laguna by the Russian River is hard in the absence of good long-term flow records for the lower Laguna, and sediment and flow records for the Russian River in the vicinity of the confluence. We recommend the installation of an acoustic Doppler sensor at the River Road Bridge to record flow direction and velocity so that inflows form the Russian River can be quantified. In addition, a two-dimensional hydrodynamic and sediment transport modeling of the Laguna and the Russian River confluence is recommended to gain a greater understanding of sediment and water movement. Such a model can simulate a range of typical flood events to assess the volume of sediment delivered under different return frequency events. Beyond its use in assessing Russian River inputs, developing such a linked model is desirable for the insights it would offer on deposition in the lower Laguna and in quantifying how sediment deposition affects flood stage in both the Laguna and the Russian River.
The report could be significantly enhanced via an Executive Summary with the following suggested outline:	An executive summary has been added to the final report according to the reviewers' suggested outline.

SFEI Peer Review Comment	Project Team Response
(1) Characterization of the watershed in terms of physical geography, historical and current conditions, current stressors, and the kinds of management intervention steps at the policy, program, and project levels that have already been taken to move undesirable trends in condition or watershed processes toward a more desirable state. This approach could pull together the pertinent elements currently dispersed throughout the report in each of the sections on hydrology/geomorphology, water quality, and valued ecosystem components and can set the stage for later recommendations. An Executive Summary might be one way to link all the individual chapters together better.	This is addressed in the executive summary.

SFEI Peer Review Comment	Project Team Response
(2) Management questions and resulting assessment questions arranged in hierarchical order. What is described as "management questions" in the report are really "assessment questions" that could be more logically arranged along a "critical path" (answers to some questions are required prior to being able to tackle the next). Management questions might better be expressed in terms that decision-makers at the policy and program level can relate to, such as: "What options exist for enhancing flood protection now and under various climate change scenarios?" "What range of management intervention steps (e.g. BMPs) have already been implemented to reduce nutrient and sediment inputs into the drainage network, and what is their geographical coverage?" So, the Executive Summary could include a table that identifies half a dozen or so broad management questions with corresponding assessment questions linked to them in critical path fashion (e.g. MQ: "What options exist for enhancing flood protection now and under various climate change scenarios?" Corresponding AQs: 1) "What is the current flood storage capacity?" 2) What are current flood peaks, durations, and volumes and their recurrence intervals?" 3) "How will future land use change and hydromodification affect flood conditions and the future hydrologic regime?"	Management questions are now in a separate section at the beginning of the document.

SFEI Peer Review Comment	Project Team Response
(3) Bits and pieces of references to historical conditions are sprinkled throughout the report and could be summarized in a section of the Executive Summary, including key unknowns that should be explored further if they affect restoration or protection options (e.g., has low DO always represented a migration barrier to salmonids in the southerly tributaries? If so, salmonid restoration attempts in Copeland Creek may not make much sense). Also, historical information could inform the need for recovery target adjustments or for site-specific water quality objectives.	This is included in executive summary.
(4) Model descriptions and modeling needs are not very well linked to either management or assessment questions. The Executive Summary could contain a table that makes it apparent how data requirements relate to management and assessment questions, how models relate to forecasting and scenario-planning activities, and how proposed data collection activities could serve to parameterize or calibrate models to increase their predictive power.	The project team agrees that such a table would be very informative and helpful, but at this point in time we need more interactions with decision makers before we can go through this analysis step. We agree that this is high on the priority list for next steps.
(5) Recommendations for next steps should go beyond monitoring recommendations included in the final chapter of the report. While the report's goal is to provide a planning and modeling framework, its focus is currently too narrow and seems to emphasize primarily data collection activities for model calibration and uncertainty reduction without balancing that focus with a planning framework for strategic early actions that might proceed in light of uncertainty and paucity of data.	The project team agrees that this is a high priority for next steps in the planning process. We have changed the introduction to reflect a more realistic set of goals for this body of work.

Reviewer's response to questions agreed upon to guide review process

Questions were posed to the peer review team, by the authors, to guide their review. The authors' questions together with the reviewers' comments are provided in the left-hand column. The authors' response to these comments are provided in the right-hand column.

Authors' questions with reviewers' comments	Response to comments
Question 1. Does the report adequately address the objective outlined in Section 1 of the document?	This is addressed individually, by objective, immediately below.
Objective 1: Baseline Characterization. The report succeeds in bringing together in one place all pertinent data and to a large extent succeeds in transforming raw data into information. The report also succeeds in pointing out inter-relationships between human-caused or human-induced alterations in the physical, chemical, and biological integrity of water and desired environmental conditions.	Agreed.
Objective 2: Restoration Planning. A key element for setting restoration planning guidelines is missing from the report and is the basis for a MAJOR recommendation addressing questions 7, 8, and 10 below. Our experience with restoration planning is that without having a picture of how the watershed functioned during times prior to massive modifications of the landscape and hydrologic regime, restoration opportunities can easily be overlooked, or alternatively, restoration targets may not be realistic or optimal.	The Laguna de Santa Rosa Restoration and Management Plan entitled "Enhancing and Caring for the Laguna" contains some of the basic historical information referred to here. However, we agree with the reviewers comments that a more extensive comparison of specific historic and current conditions would be beneficial for the whole planning effort. We also agree that sensitivity analyses could be beneficial in prioritizing data gaps.

Authors' questions with reviewers' comments	Response to comments
Objective 3: Flood Protection Planning. Evaluation of what is known about flood capacity is extensive, and data requirements for scenario-planning are well explained. The brief section on anticipated climate change impacts could reference any estimates of upward migration of tidal influence in the Russian River and how that may affect hydrology at the Laguna-Russian River confluence.	DWR's 2006 report on climate change titled "Progress on Incorporating Climate Change into Management of California's Water Resources" (available at http://baydeltaoffice.water.ca.gov/) is the most recent study on anticipated climate change impacts that we are aware of that specifically addresses anticipated precipitation changes in California. The report does not make quantitative predictions of how precipitation and runoff amounts and patterns will change in different parts of California. However, it elaborates on historic changes and trends in runoff volumes for selected river basins in California. Table 2-4 of the report indicates that in the Russian River basin, runoff has increased negligibly for the period of April through July and has increased by approximately 1,000 acre-feet since 1941. This is not a significant change. Based on current state of knowledge and assuming similar trends for the future, climate change is not expected to significantly impact runoff volumes in the watershed.

Authors' questions with reviewers' comments	Response to comments
Objective 4: Water Quality Assessments. This section addresses the key issues adequately. However, it is very difficult for someone not intimately familiar with the geography to follow the locations of identified "trouble spots." A map with dots indicating the "good, bad, and ugly" would be very helpful in following the rationale behind some of the hypotheses and would let the reader make associations between land use characteristics and areas where standards are not being met or beneficial use impairment has been documented. This would also assist with following the rationale behind monitoring and assessment recommendations, which currently appear overwhelming and difficult to evaluate and prioritize in relation to undesirable conditions and management goals. While the assessment of impacts is quite exhaustive, it isn't yet in a form that is very useful to decision-makers and water quality managers. A key next step could be to sort through the information and conduct initial sensitivity analyses on the range of management options for remediation and restoration. Do sufficient data exist in some reaches or areas where the relative importance of each of the sources of nutrients and sediment could be evaluated, so the range of data collection activities could be prioritized? Currently, the implied message that the report conveys is "We need everything and the kitchen sink" before we can begin implementation of remediation steps in adaptive fashion. Reduction of nutrients and sediment inputs (essential in tackling the D.O. issue as well) can occur in two and three key ways, respectively: (1) reducing anthropogenically mobilized sediment and nutrients to natural background levels, enhancing or restoring sediment storage and nutrient transformation/uptake outside the channel network, and (3) in the case of sediment, restoring the hydrograph to minimize bed and bank erosion in the higher-velocity reaches and maximize sediment transport in the lower-velocity reaches. Where do opportunities present themselves to pursue any or all of these general goals?	In terms of sea level rise projections, Independent Science Team to CALFED estimated a sea level rise of up to approximately (8 feet). Upward migration of tidal influence along the Russian River may be possible due to sea level rise of such extent and climate change; however, it is not likely that this effect will be felt more than 20 miles upstream at the Laguna confluence.

Authors' questions with reviewers' comments	Response to comments
Objective 5: Water Quality Assessments. The report doesn't make it obvious how the compiled information can or should be used in decisions pertaining to WHERE and HOW flood peak attenuation features can be restored or created, how water management planning activities can benefit water quality attainment strategies, or how land use decisions can be improved to achieve better integration of beneficial use restoration/protection, management and prevention of biological invasions, water supply reliability enhancements, achievement of flood protection goals, and restoration of watershed functions and processes. This is one of the key areas where additional funding could be pursued to improve the value to environmental managers. The report only takes the first, albeit most important, step toward a planning and management framework - understanding the system and formulating hypotheses that should be tested with short-term special studies or tracking progress toward specific environmental goals or targets.	Water Management Planning was listed in the original proposal as an objective that a basin-scale model should support (and therefore can not be an objective for a planning and management framework). We agree that additional funding will be required to achieve this objective. This objective was taken out of Section 1 as an objective of the current study.

Authors' questions with reviewers' comments	Response to comments
Question 2. Does the report adequately outline a clear course of action for what steps should be taken next in the watershed to achieve the stated objectives? The report is organized in a fashion that puts considerable (and almost exclusive) emphasis on what is known and not known about the system and documents how useful (or not) various simulation models may be for purposes of forecasting water and pollutant transport and storage scenarios and various aquatic/riparian habitat recovery trajectories. The information is likely to be overwhelming to three key audiences of the report: Land use decision-makers, public works and stormwater managers, and private land stewards in the urban, ex-urban, and agricultural communities. A clear course of action emerges only with regard to filling huge data gaps (in non-prioritized fashion) and parameterizing recommended scenario-planning models. Much of the suggestions for an Executive Summary could remedy the "bottom-up" approach the report takes and work more from the "top-down," starting with a prioritization of management questions, identification of adaptive management opportunities, where incremental and pilot-level early implementation steps could be taken and then evaluated through targeted data collection and monitoring efforts in a watershed context. While the proposed list of indicators and monitoring recommendations seems sound and reasonable, their implementation is unlikely to proceed without first evaluating the likely "bang for the buck." Without an explicit linkage of monitoring recommendations to their management and policy-making relevance, decision gridlock and much "hand-wringing" is likely to emerge.	This is addressed in the executive summary.

Authors' questions with reviewers' comments	Response to comments
Question 3. What uncertainties should be assigned the highest priority to be addressed in our monitoring recommendations? Our experience with finding an "acceptable" level of uncertainty is that the lower the implementation costs are to society as a whole (through taxes or fees) or individual stakeholder groups (via fees, loss of use, or compliance with regulations), the greater the comfort level with relatively large uncertainties and vice versa. Without first conducting an analysis of uncertainty "comfort levels" (plus or minus 50% chance of moving a condition onto a more desirable trend line; plus of minus 5% chance) by involving groups with a vested interest in the status quo, this question is hard to answer definitively. However, the data compilation seems to suggest that one of the most important unknowns in the nutrient budget is the relative importance of external loadings compared to the internal cycling of accumulated nutrients between the sediment and biomass. Since the creation of riparian buffer zones, for example, through zoning changes, land use ordinances, or easements/acquisitions falls into the category of "high costs" to both society and individual stakeholder groups, the burden of proof is likely very high to support a "menu" of external nutrient control strategies and management measures versus alternative, possibly cheaper in the short term, management strategies involving reduction of internal "sources" through continuous maintenance (e.g. dredging) or increased nutrient exports out of the Laguna system via the Russian River (e.g. enhancing flushing).	The proposed modelling framework and monitoring recommendations were provided to address uncertainty regarding relative loading from the various categories that have been identified. Internal cycling is likely to be a key source of loading and its impact will be exerted on the Laguna for a long period of time. Any recovery strategy will need to accurately represent and communicate a long-term recovery trajectory to realistically manage expectations regarding the time frame required to achieve water quality improvements. Therefore any restoration strategy will require a combination of approaches that both reduce external loadings to the system and mitigate / reduce internal loading within the Laguna (e.g., low flow channels to reduce water column exposure to nutrient rich sediments). The external load reduction strategies have additional benefits to the ecosystem that should be incorporated into the management option rationale. Restoring the Laguna will require a substantial investment over a long period of time regardless which source is the largest.

Authors' questions with reviewers' comments	Response to comments
Question 4. Have we identified the relevant loading categories and the uncertainty regarding their potential relative magnitude? Are the relative orders of magnitude assigned to the various nutrient inputs appropriate? The report does identify the relevant loading categories and does an excellent job at identifying the relative contribution from various sources. The estimated pollutant loading tables may give the false impression to some readers that the numbers are more precise than they are. They could benefit from including coefficients of variation in parentheses behind each number. Also, for comparison purposes, it would be useful to estimate natural background loadings to the Laguna under natural land cover condition or, at a minimum, reference the TMDL loading or reduction targets. As a next step, it would be important to determine which of the loading categories would be most sensitive to load reduction efforts, which could then make a compelling case for data collection prioritization. For example, by how much would one expect urban stormwater contributions to decrease via broadly accepted urban retrofitting techniques during re-development and applying low-impact development principles in areas expected to be converted from agricultural or open space to urban or ex-urban land uses?	The project team does not have sufficient information to realistically quantify estimates for the loading categories. We prefer the qualitative characterization as a relative order of magnitude comparison of categories. The estimates were developed using different inputs. For some of the point sources actual monitoring data was used while for others loading coefficients were extrapolated to land use information. The estimates are intended to be useful for a first order assessment of the potential relative importance of the various loading categories. A consistent uncertainty assessment for each category is not possible and the project team prefers to retain the qualitative statements that limit the use of the information to broad comparison of categories. The project team requested natural background loading information from an ongoing application of the SWAT model within the watershed. These estimates may be available in the future but were not available at the time the conceptual model report was being written. More precise loading estimates will be developed as part of the TMDL source characterization work, which will then be used to optimize loading reduction strategies as part of the allocation phase of the TMDL.

Authors' questions with reviewers' comments	Response to comments
Question 5. How well do the individual sections of the report link together? Wherever there is a lack of linkage, how could better linkage be achieved? It is apparent that the three main sections of hydrology/geomorphology, water quality, and ecosystem were prepared by different groups of authors as more or less "stand-alone" chapters. The Ecosystem chapter has the potential of being the "integrative" section of the report but doesn't quite fulfill that potential. Internal linkage between the information compilation and review, the anthropogenic causes of impairment, and the discussion of the conceptual models in each chapter could be achieved relatively easily by highlighting the management relevance of the data evaluations, and to what extent the existing data do are do not show associations that could be used to weight the relative importance of the conceptual model boxes. Expanding on the knowledge bases and incorporating findings and key elements from the water quality and hydrology sections into both text and schematics in the Ecosystem Conceptual Model could improve the linkages. Alternatively, the Executive Summary could take major findings from each section and serve as the place for an integrative "bottom line."	The executive summary serves as the integrative "bottom line."

Authors' questions with reviewers' comments	Response to comments
Question 6. For which sections of the report could additional funding be pursued in order to improve findings? As alluded to above, the whole planning effort could benefit from a much more extensive comparison of historical and current conditions, which probably would require additional funding. There is likely a substantial amount of historical information (publicly available but not yet compiled) that could inform interpretations of system hydrology, appropriate habitat and TMDL targets, water supply reliability enhancement opportunities, and the relative importance of key stressors. Also, sufficient data exist both within the Laguna system and from similar watersheds to conduct sensitivity analyses on some of the water quality issues (including sediment impairment), so that additional data collection activities can be prioritized. The monitoring chapter could benefit from additional funding as well. The current list of data gaps appears daunting and needs to be prioritized. The state's surface water monitoring strategy, located on the Waterboards' website (http://www.waterboards.ca.gov/swamp/docs/cw102swampcmas.pdf) could serve as a guidance document for the development of a monitoring and special study design and implementation plan over the next five to ten years. Integration of TMDL implementation monitoring activities, NPDES monitoring requirements for both Phase I and Phase II municipal permittees and the POTW, WDR and/or waiver conditions, 401 certification conditions, and implementation guidance for the forthcoming stream and wetland protection policy could all be strategically aligned to work with the Surface Water Ambient Monitoring Program and forthcoming Proposition 84, and 1E grants to fill data gaps in prioritized fashion. This will likely require considerable resources. The forthcoming SWAMP Assessment Framework or "business plan" could serve as a template. Increased and consistent participation in SWAMP activities by a NCRWQCB staff member as the tech transfer and coordination resource might defer some of the costs.	The Laguna de Santa Rosa Restoration and Management Plan entitled "Enhancing and Caring for the Laguna" contains some of the basic historical information referred to here. However, we agree with the reviewers comments that a more extensive comparison of specific historic and current conditions would be beneficial for the whole planning effort. We also agree that sensitivity analyses could be beneficial to the need for prioritization of addressing data gaps.

Authors' questions with reviewers' comments	Response to comments
Question 7. What advice do you have for the Foundation regarding next steps? Next steps are alluded to above but can be summarized as follows: 1) Convene appropriate stakeholders to prioritize data collection activities via special studies and status and trends monitoring. 2) Evaluate and develop a list of "early actions" that promise to meet TMDL targets and habitat goals, where they exist. 3) Conduct a thorough compilation of historical condition records, put them in digital format (GIS data layers) and explore the feasibility of a watershed goals process that is informed by a picture of the past, a picture of present conditions, and change, with subsequent identification of tradeoffs among potentially conflicting goals (urban development vs. floodplain protection and enhancement of water supply reliability). 4) Identify and analyze barriers to implementation beyond scientific uncertainties and data gaps (e.g., counterproductive policies; financial barriers; education and awareness gaps; etc.)	This project has already served one purpose: to speed up the schedule for the development of Laguna TMDLs. The TMDL process has now been started using the final report document as the conceptual background. The project team agrees with all the steps outlined here for next steps in the process to improve the Laguna watershed with regard to natural and human-related functions.
Question 8. Which indicators and monitoring recommendations should be considered highest priority? An answer to this question is possible AFTER sensitivity analyses have been conducted and considerable effort has been put into implementation of the steps outlined in the Statewide Surface Water Monitoring Strategy.	Agreed.
Question 9. What recommendations can you offer for moving forward with a comprehensive planning and stewardship management framework in five areas: key questions, uncertainties, stewardship indicators, monitoring program activities, and model development?	
1) Work with key decision-makers in the various environmental management agencies (public works, stormwater, water recycling, water supply, natural resource trustees) and in the land use arena to fine-tune the management and assessment questions and arrange them hierarchically and along a critical path.	1) Agreed.

Authors' questions with reviewers' comments	Response to comments
2) Estimate societal and individual costs of the range of policy, program, and project implementation options that have shown environmental benefits and prioritize data collection and modeling efforts based on the anticipated "burden of proof" that is required to move ahead in adaptive fashion.	2) We believe the report, with sufficient study, provides much of the information that is needed to support these discussions. These discussions would be most productive if they included key agencies and stakeholders who would be involved in the implementation of restoration options and who would be impacted by these options.
3) Conduct analyses of anticipated relative benefits of various implementation options (e.g., would urban retrofits reducing imperviousness and enhancing stormwater retention capacity provide greater benefits than widespread implementation of agricultural BMPs?).	3) The driver for model capabilities is to be able to simulate various restoration scenario options for as many categories as possible. This would include (but not limited to) pollutant reduction strategies, riparian and channel improvement projects, stormwater management practices. It is likely that a combination of several possible mitigation approaches will be required to restore the Laguna to a "proper functioning condition." This is why the model framework includes compartments for watershed processes, hydrology, sediment processes, and water quality. It is not clear whether the modeling framework itself is feasible but the goal is the evaluation of multiple implementation options.
4) Focus model development on scenario planning tools that have the greatest utility for decision-makers in selecting courses of action.	4) It is possible that the development of a comprehensive model capable of detailed scenario simulation may not be feasible. But the model development goal is directed to achieving exactly the recommendation stated in this comment. It is possible that the scenarios will need to be more conceptual in nature. The development of conceptual scenarios would be supported through additional monitoring conducted within the Laguna.

Authors' questions with reviewers' comments	Response to comments
5) Incorporate available, but not yet compiled and digitized, historical records into the uncertainty analyses, identification of opportunities for beneficial use protection and restoration, and evaluation of tradeoffs among possibly conflicting goals.	5) The project team agrees that a more complete historical ecology analysis is needed, but the requested analysis will need to be included in the next phase of this process. The Laguna Foundation has compiled much of the information that would be used in the next phase of any historical ecology analysis.

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