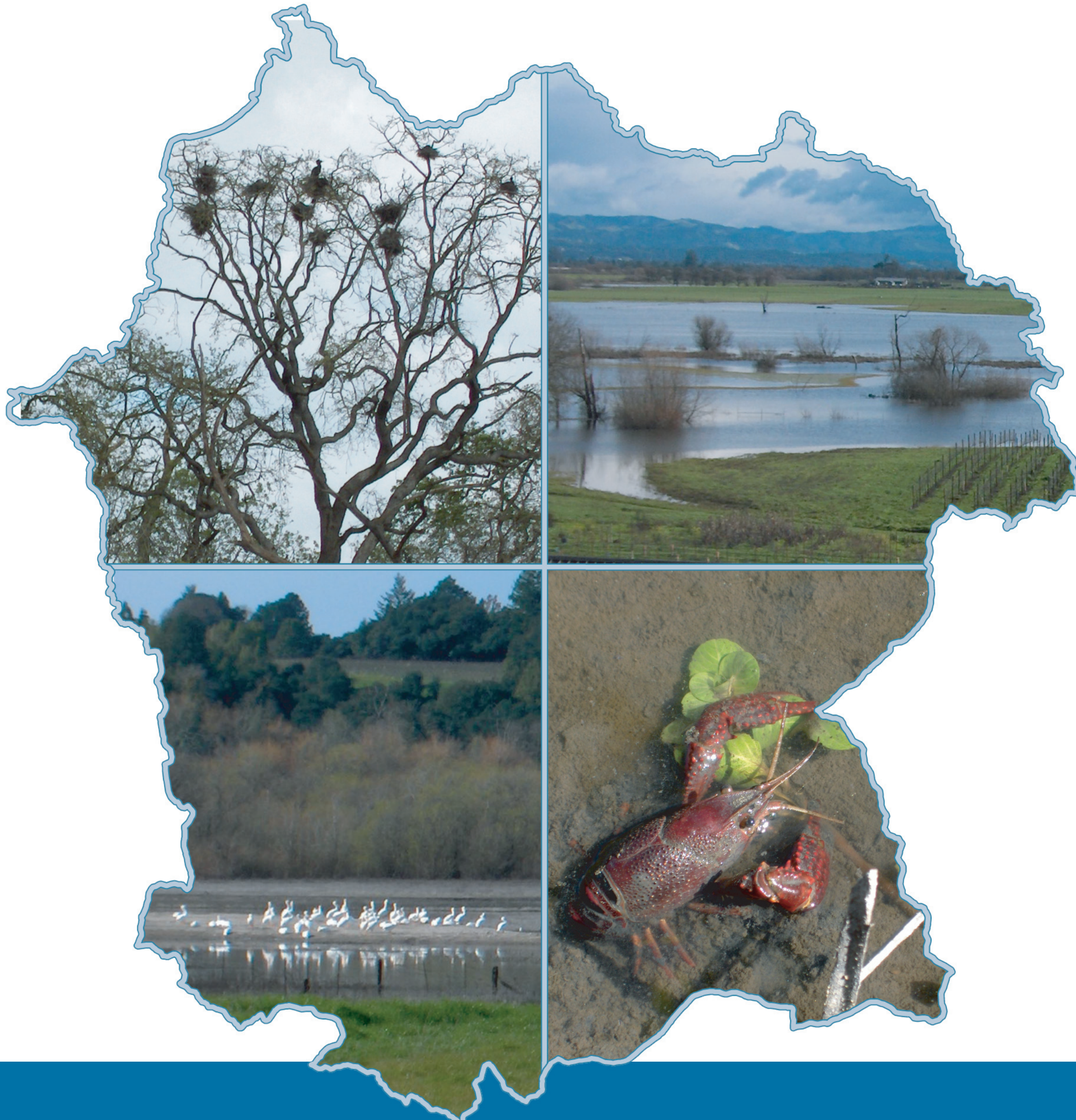
The Altered Laguna

A Conceptual Model for Watershed Stewardship



Laguna de Santa Rosa Foundation
Tetra Tech, Inc.
Philip Williams & Associates, Ltd.

Christina Sloop, Joseph Honton
Clayton Creager, Limin Chen
Elizabeth S. Andrews, Setenay Bozkurt

Contents

List of Illustrations

List of Tables

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 $G = Gmax \bullet C/(K+C)$, 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 re-aeration 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.

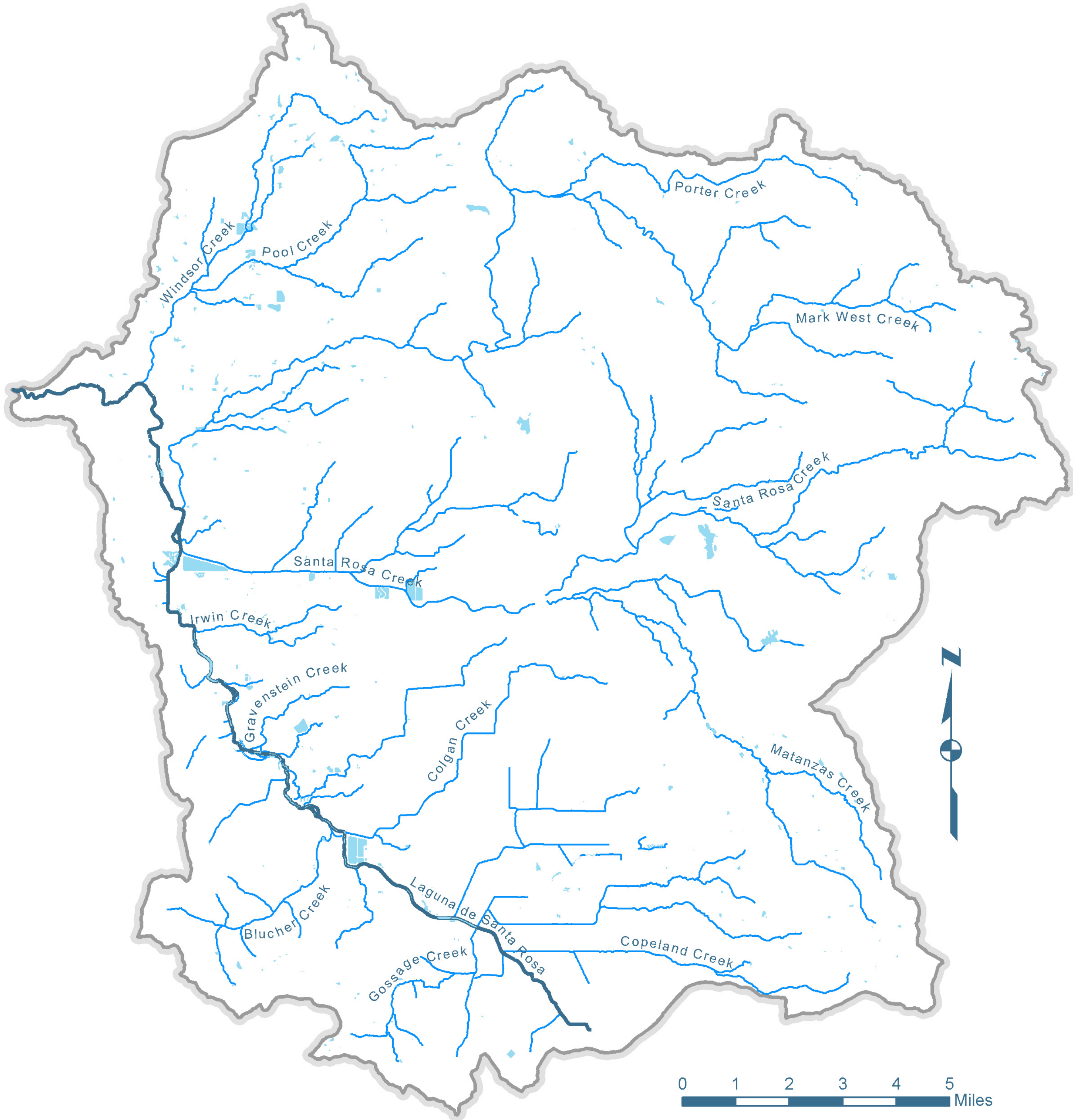


Figure 4-1 Laguna watershed and tributaries

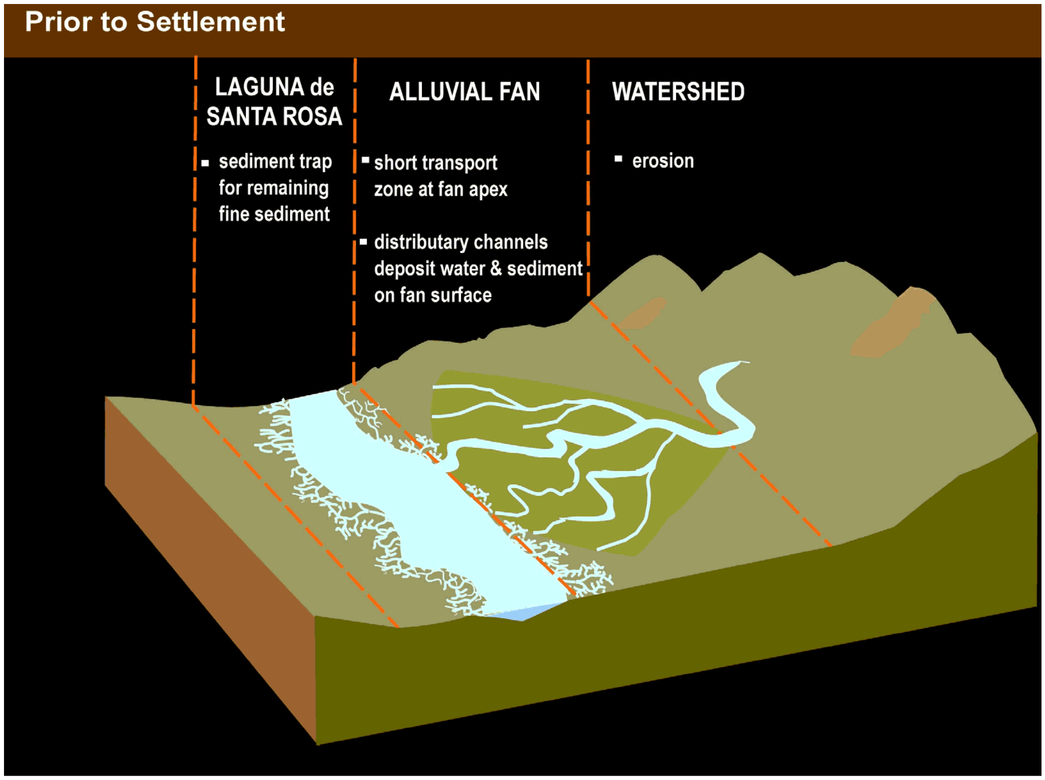


Figure 4-2 (a) Conceptual model of physical processes affecting the Laguna prior to settlement

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.

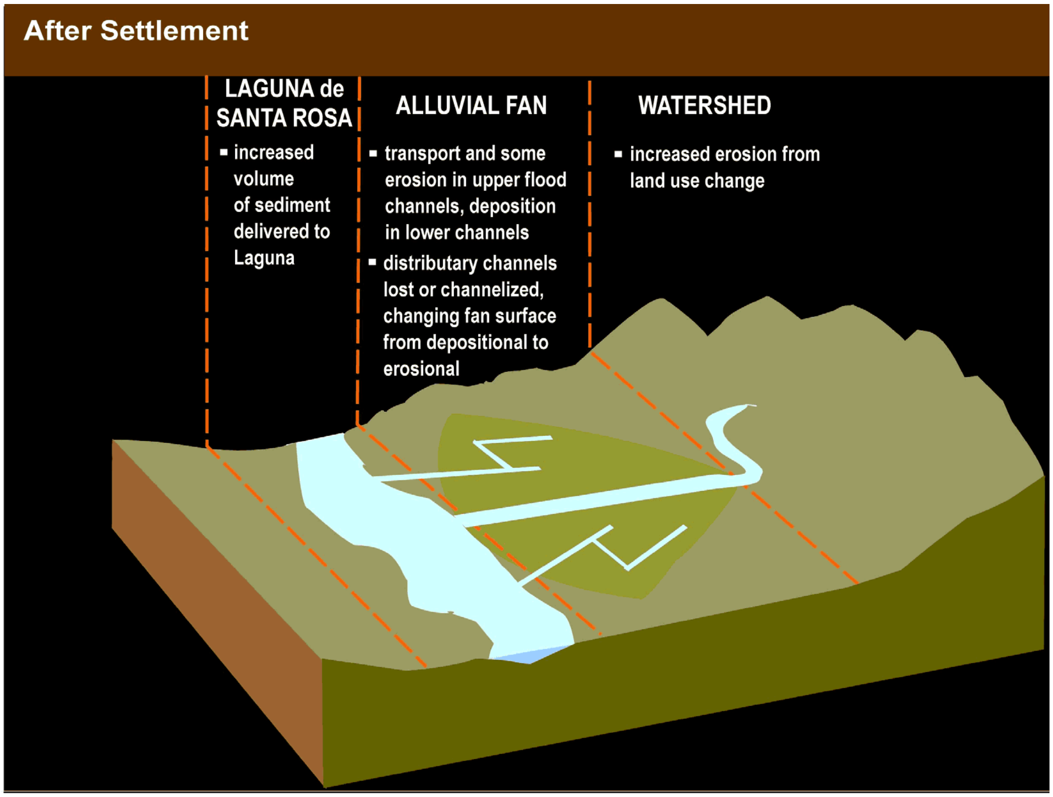


Figure 4-2 (b) Conceptual model of physical processes affecting the Laguna after settlement

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

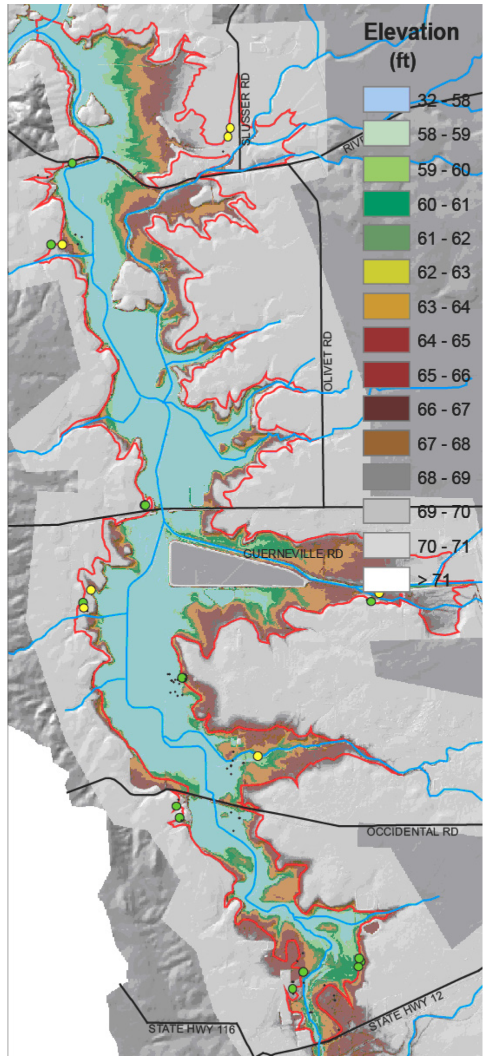


Figure 4-4 Laguna floodplain elevation map

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

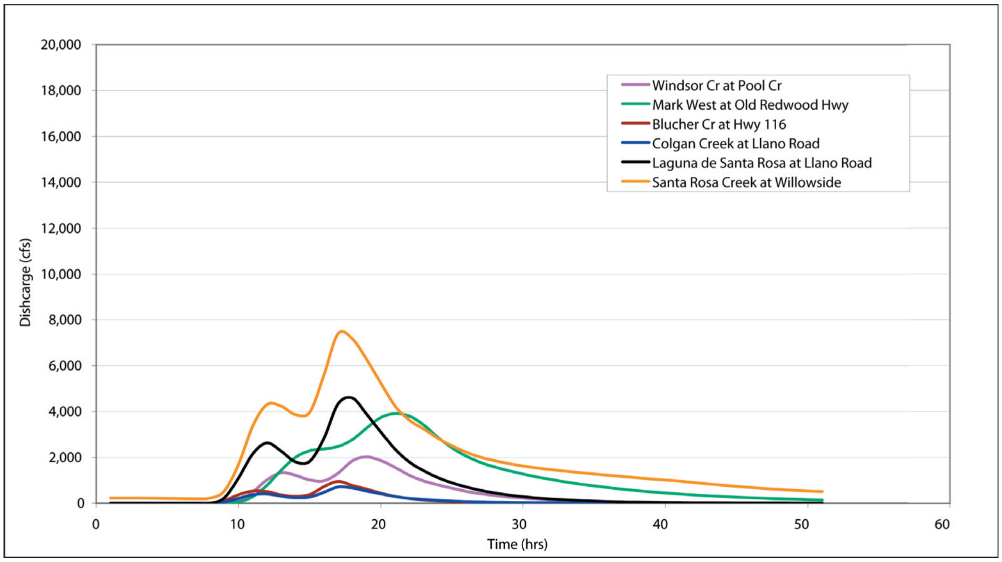


Figure 4-5 Laguna de Santa Rosa 2-year flow hydrographs
(Source: USACE. 2003. Draft Laguna de Santa Rosa Basin Hydrology Assessment. Unpublished Report)

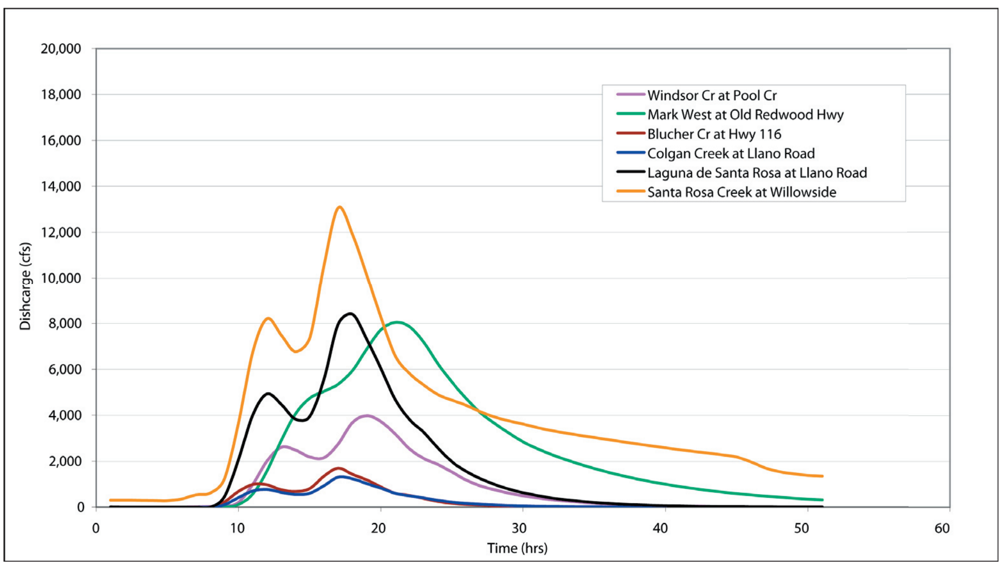


Figure 4-6 Laguna de Santa Rosa 10-year flow hydrographs
(Source: USACE. 2003. Draft Laguna de Santa Rosa Basin Hydrology Assessment. Unpublished Report)

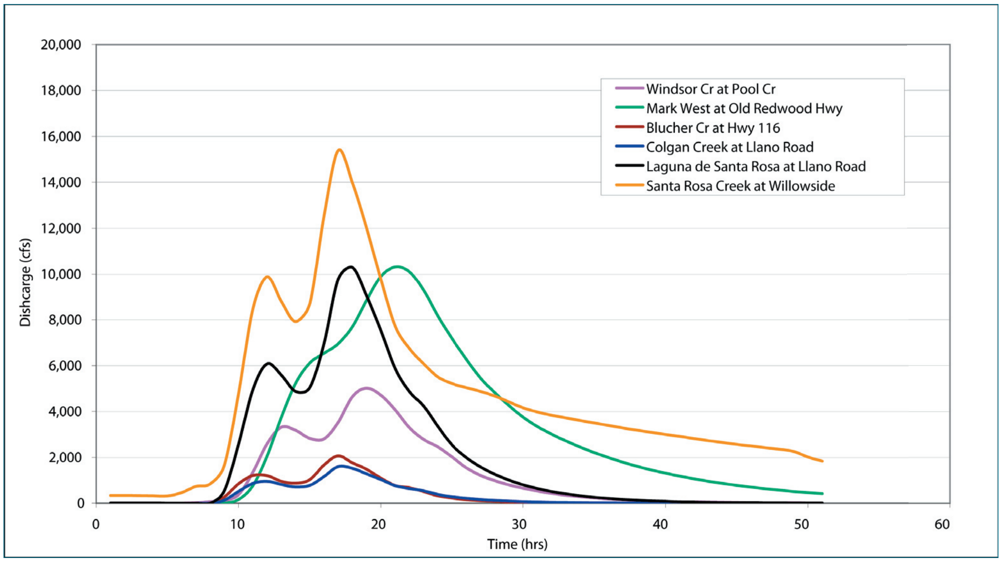


Figure 4-7 Laguna de Santa Rosa 25-year flow hydrographs
(Source: USACE. 2003. Draft Laguna de Santa Rosa Basin Hydrology Assessment. Unpublished Report)

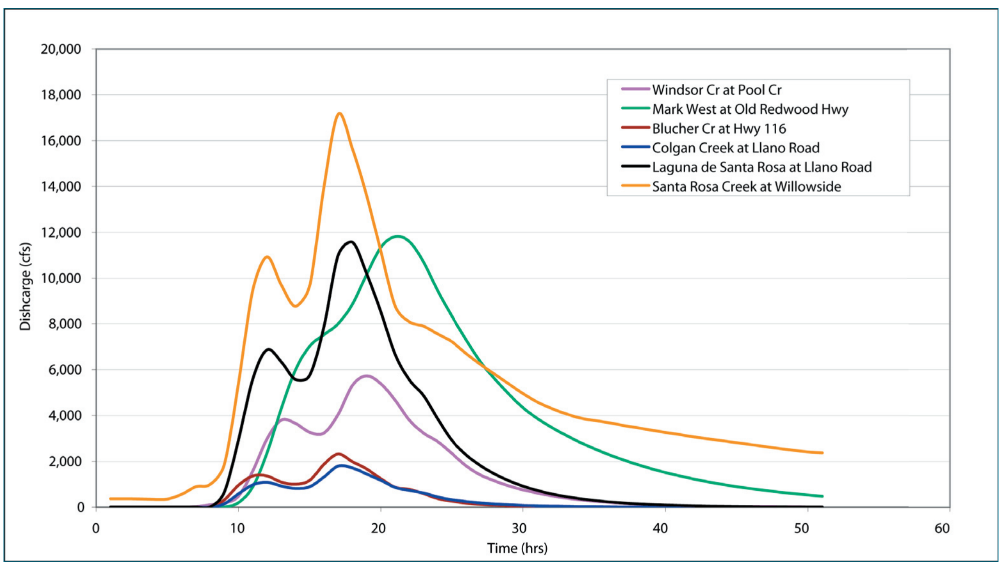


Figure 4-8 Laguna de Santa Rosa 50-year flow hydrographs
(Source: USACE. 2003. Draft Laguna de Santa Rosa Basin Hydrology Assessment. Unpublished Report)

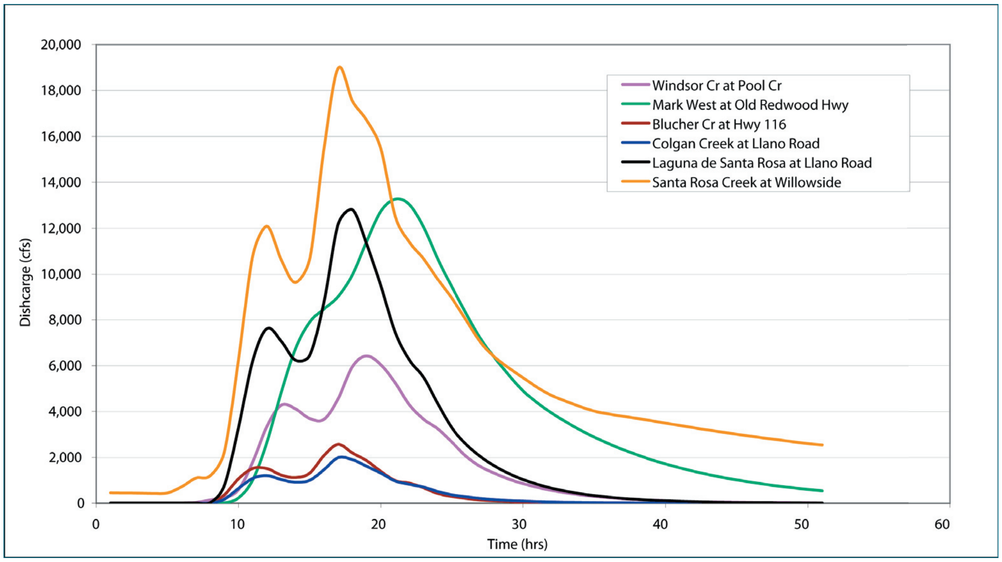


Figure 4-9 Laguna de Santa Rosa 100-year flow hydrographs
(Source: USACE. 2003. Draft Laguna de Santa Rosa Basin Hydrology Assessment. Unpublished Report)

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.

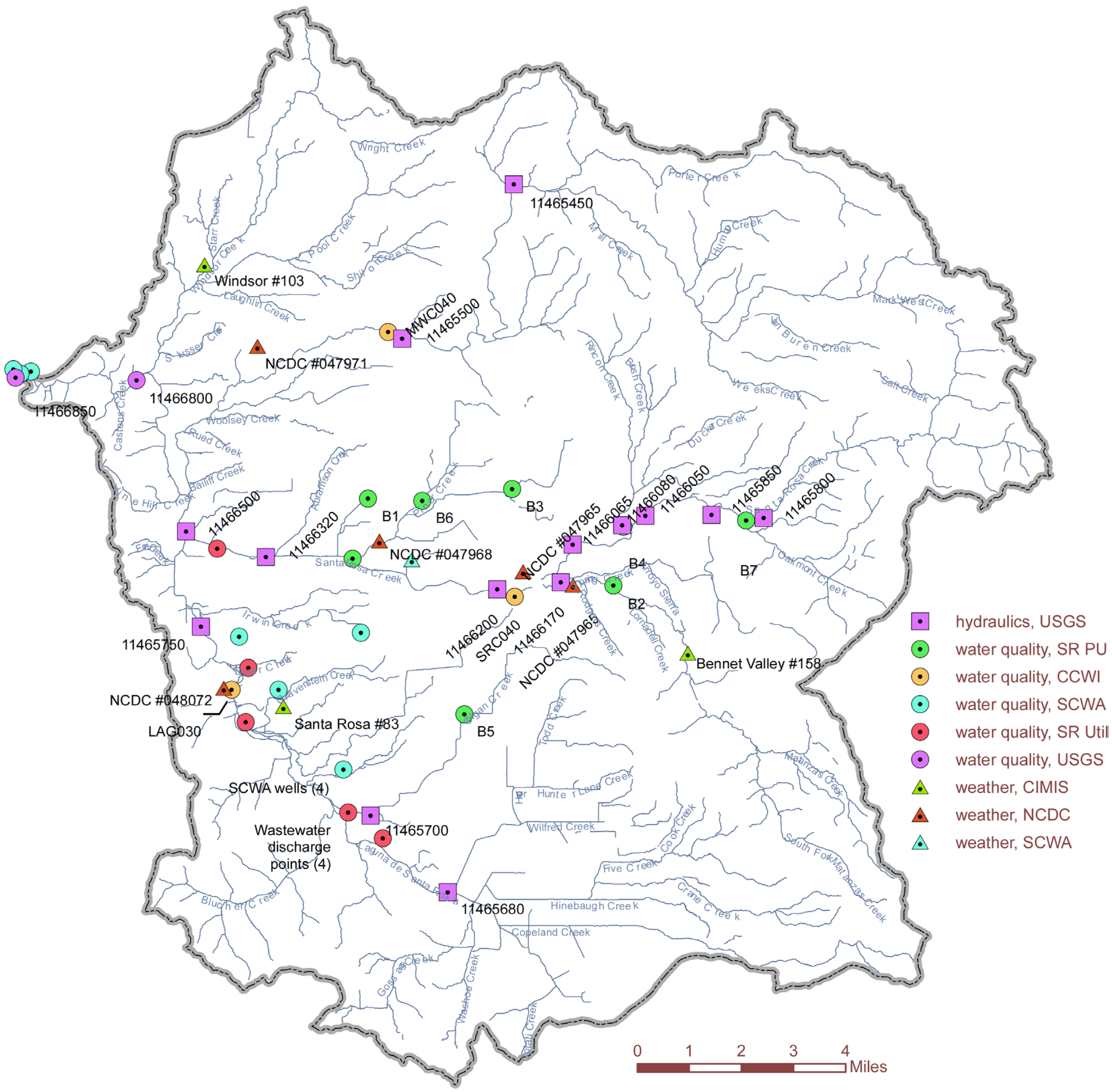
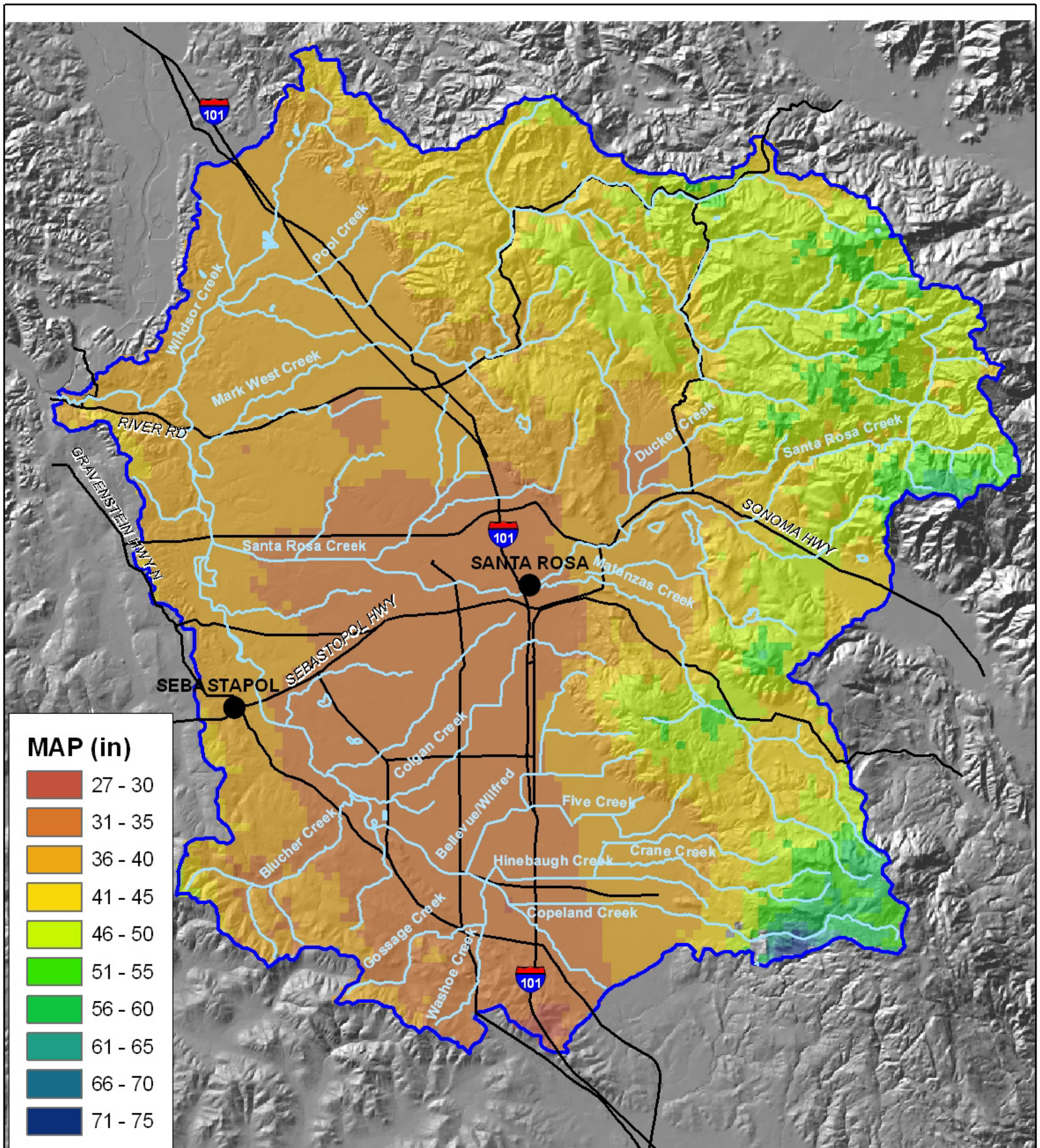


Figure 4-10 Weather and water gaging stations



Note: Mean Annual Precipitation (MAP) was converted to 270 m grid cells by USGS using the using a gradient-inverse-distance-squared approach after Nalder and Wein (1998).

Laguna de Santa Rosa

Watershed Mean Annual Precipitation (MAP)

Source: USGS (DEM, DRG), PRISM (MAP)

N

0 1.25 2.5 5 Miles

Figure 4-11 Watershed mean annual precipitation

PWA

\\Orca\pwa\Projects\1863_LdSR_ConceptualModel\Report\Figures\PRISMfig\Fig2-6.mxd

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 (mi^2)	2-year ($tons/mi^2$)	10-year ($tons/mi^2$)	25-year ($tons/mi^2$)	50-year ($tons/mi^2$)	100-year ($tons/mi^2$)
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).

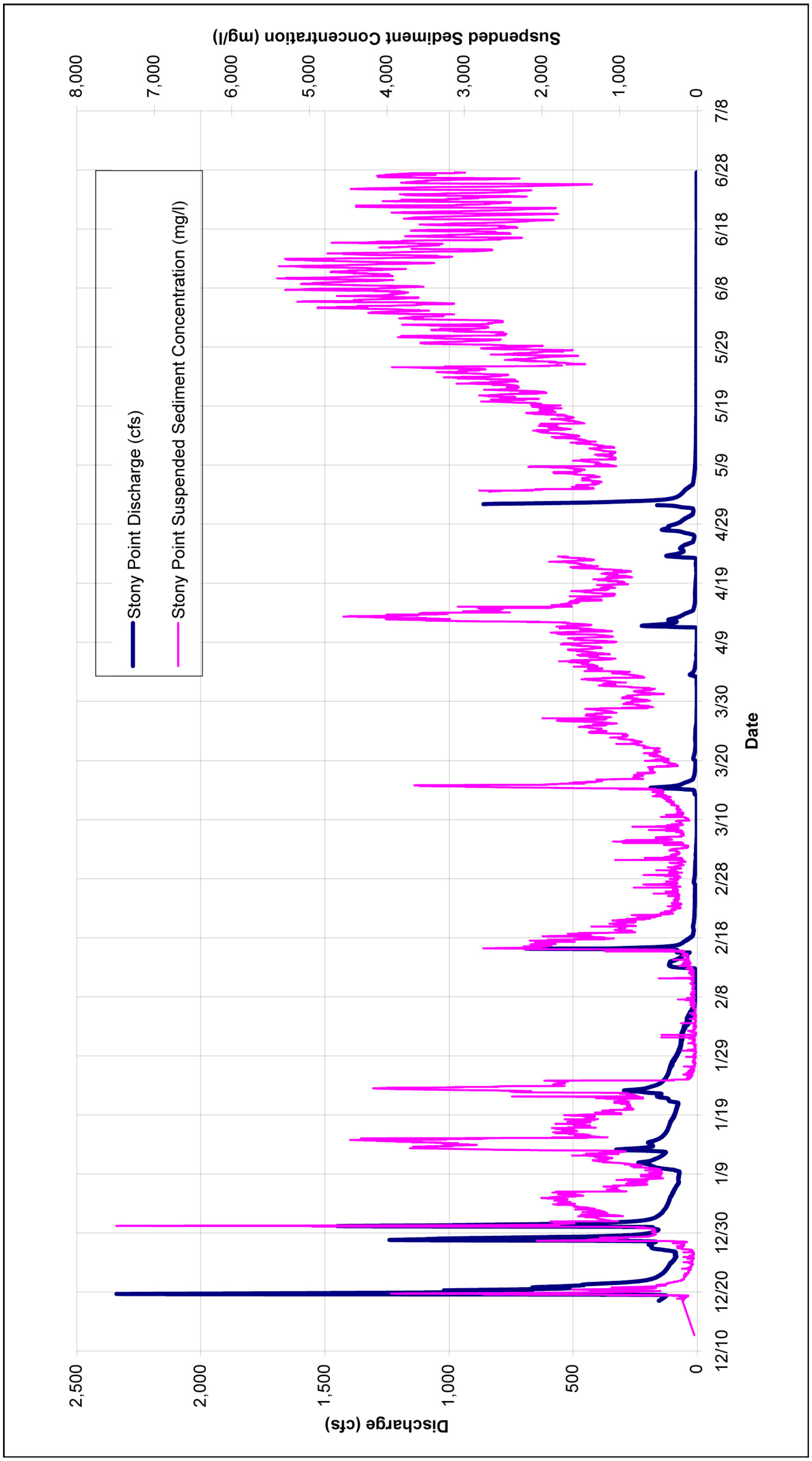


Figure 4-12
Laguna de Santa Rosa at Stony Point Road discharge and suspended sediment concentration 2002–03

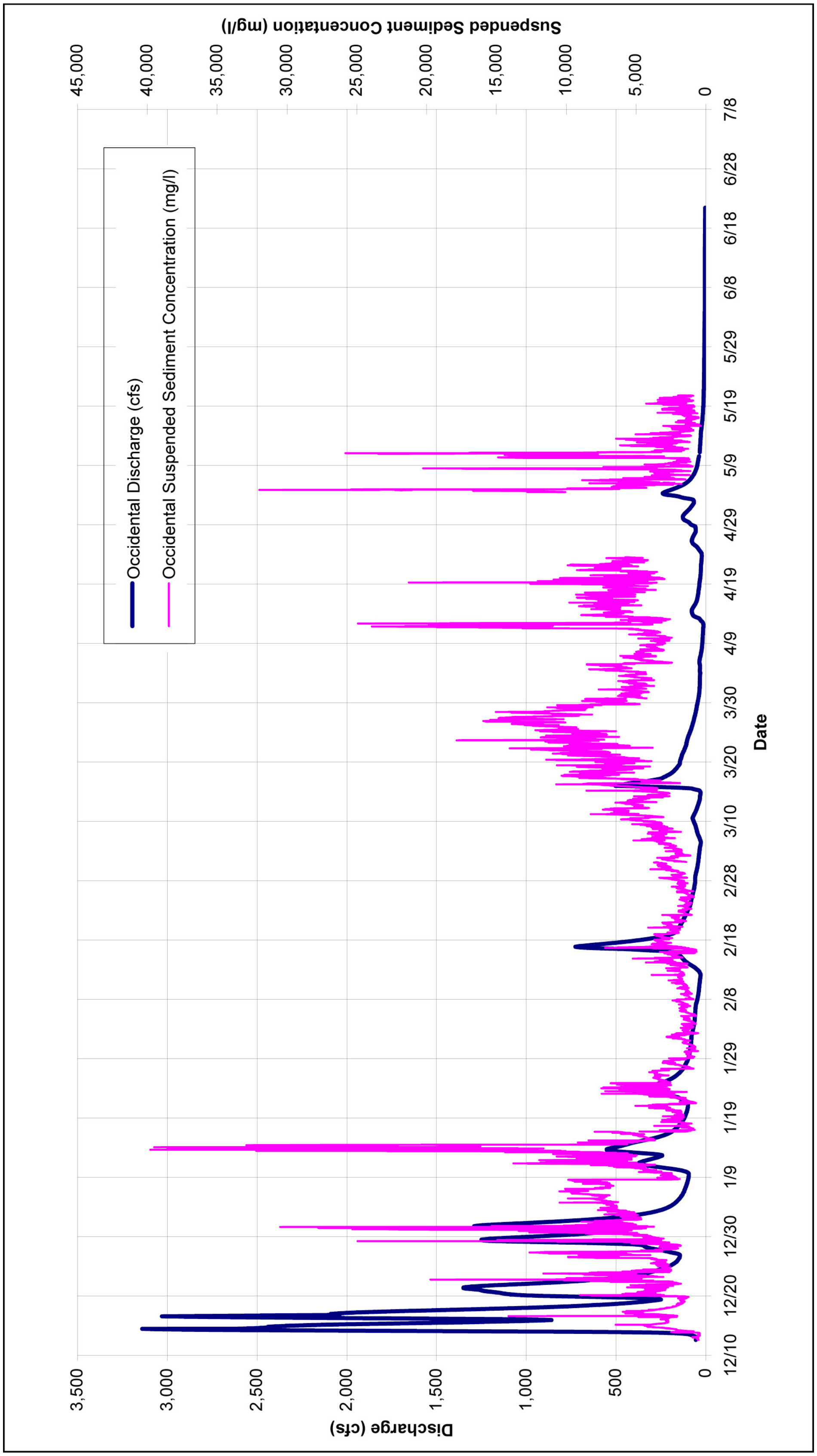


Figure 4-13
Laguna de Santa Rosa at Occidental Road discharge and suspended sediment concentration 2002-03

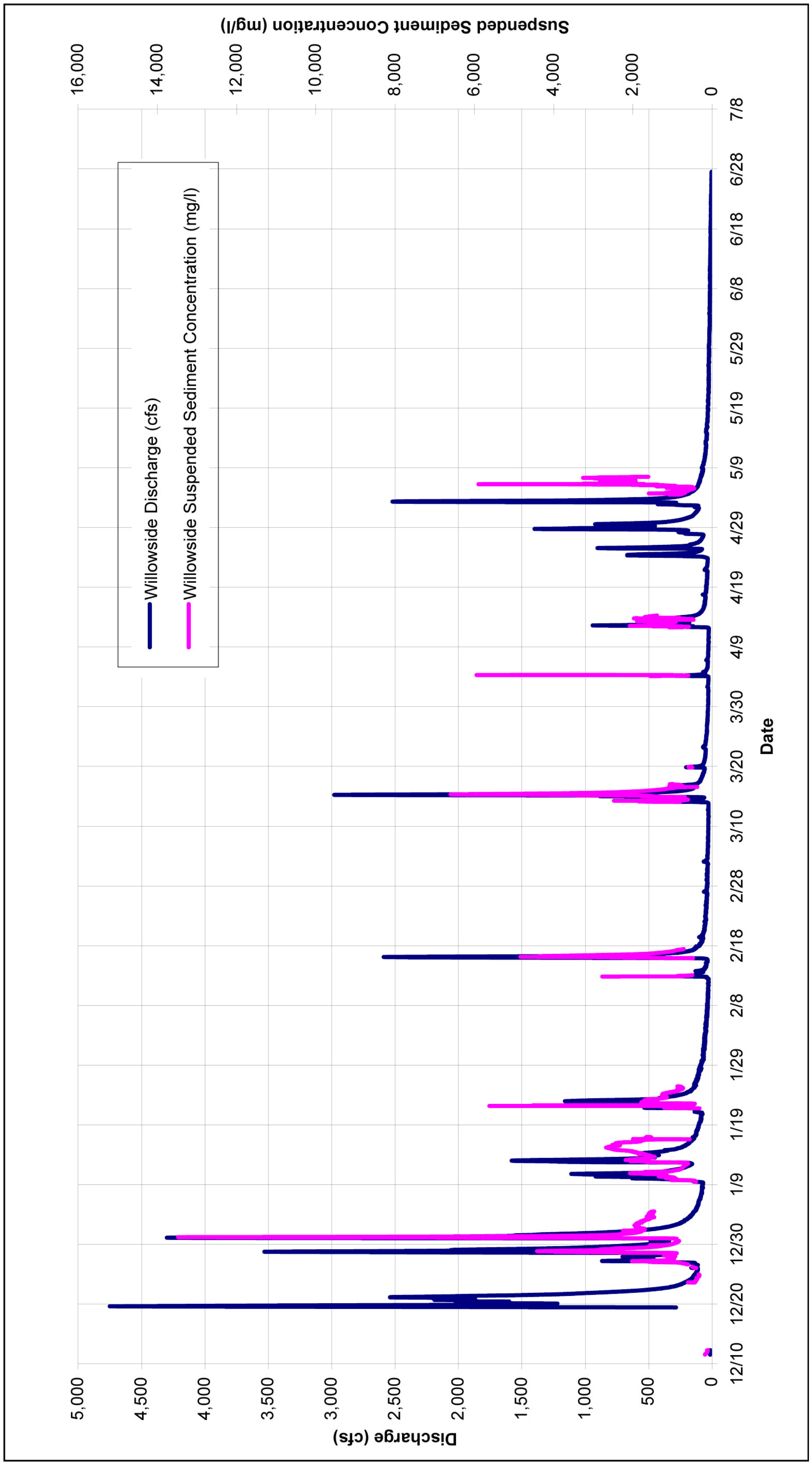


Figure 4-14
Santa Rosa Creek at Willowside Road discharge and suspended sediment concentration 2002–03

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.

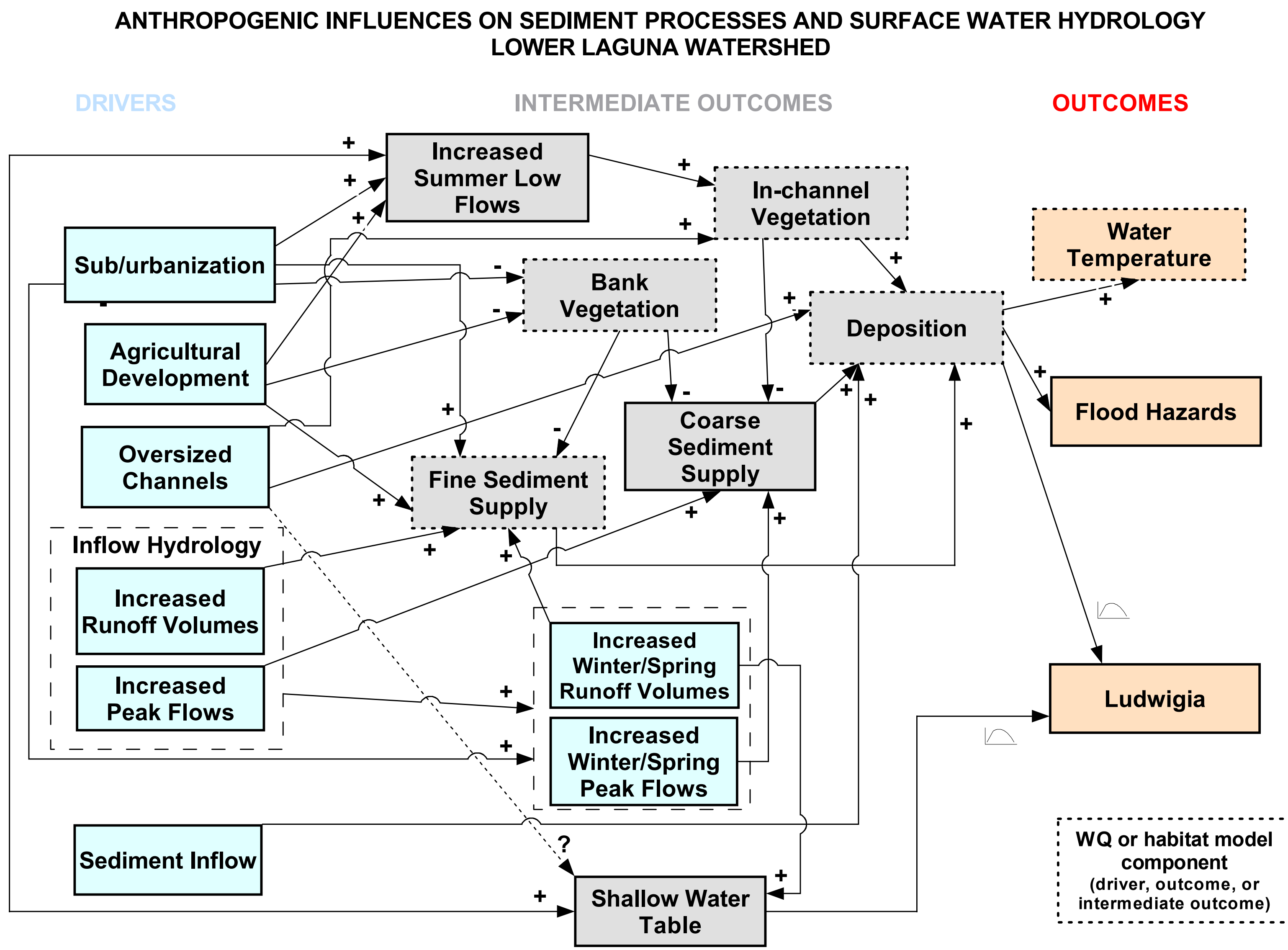


Figure 4-15
Anthropogenic influences on sediment processes and surface water hydrology in lower Laguna watershed

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-

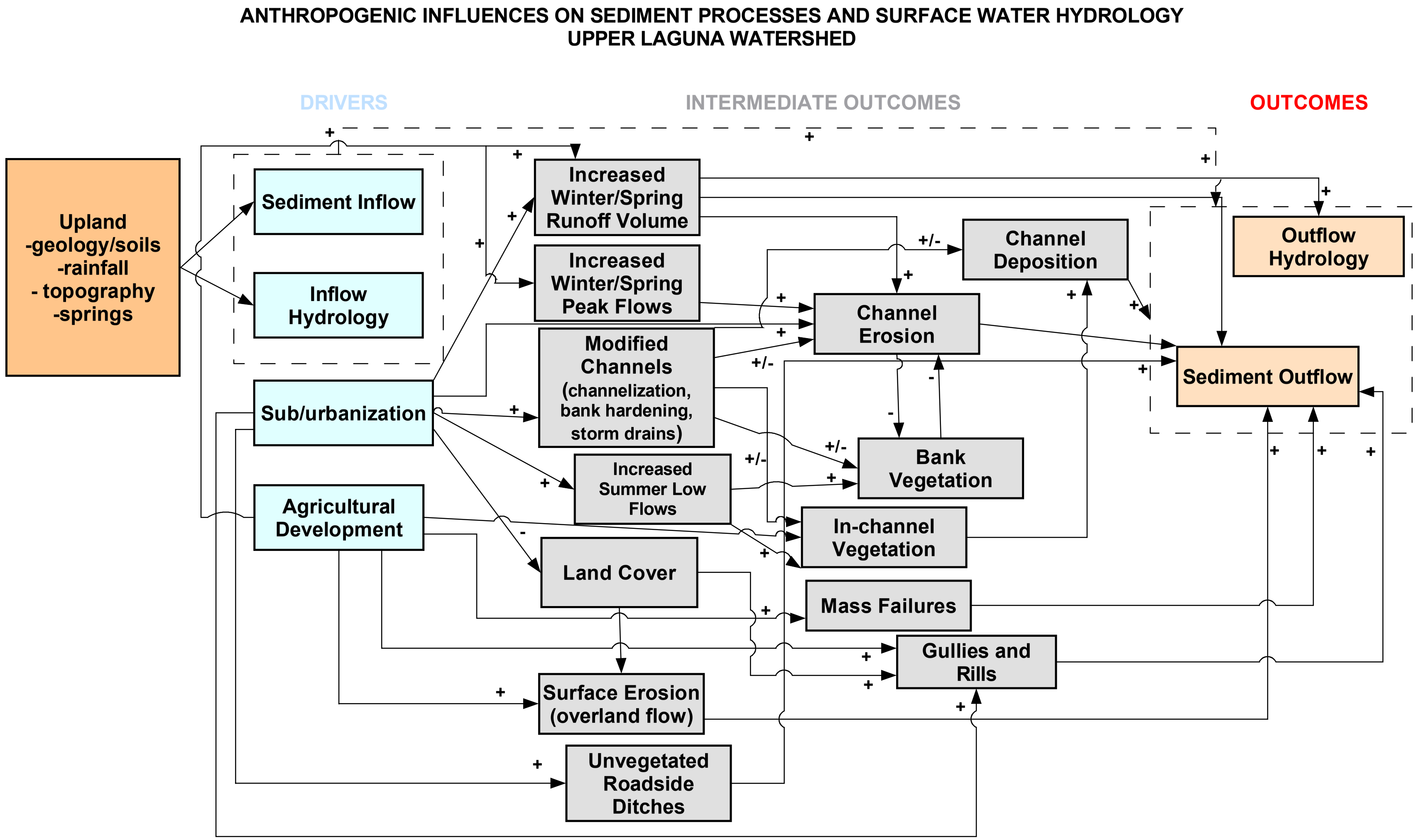


Figure 4-16
Anthropogenic influences on sediment processes and surface water hydrology in upper Laguna watershed

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.

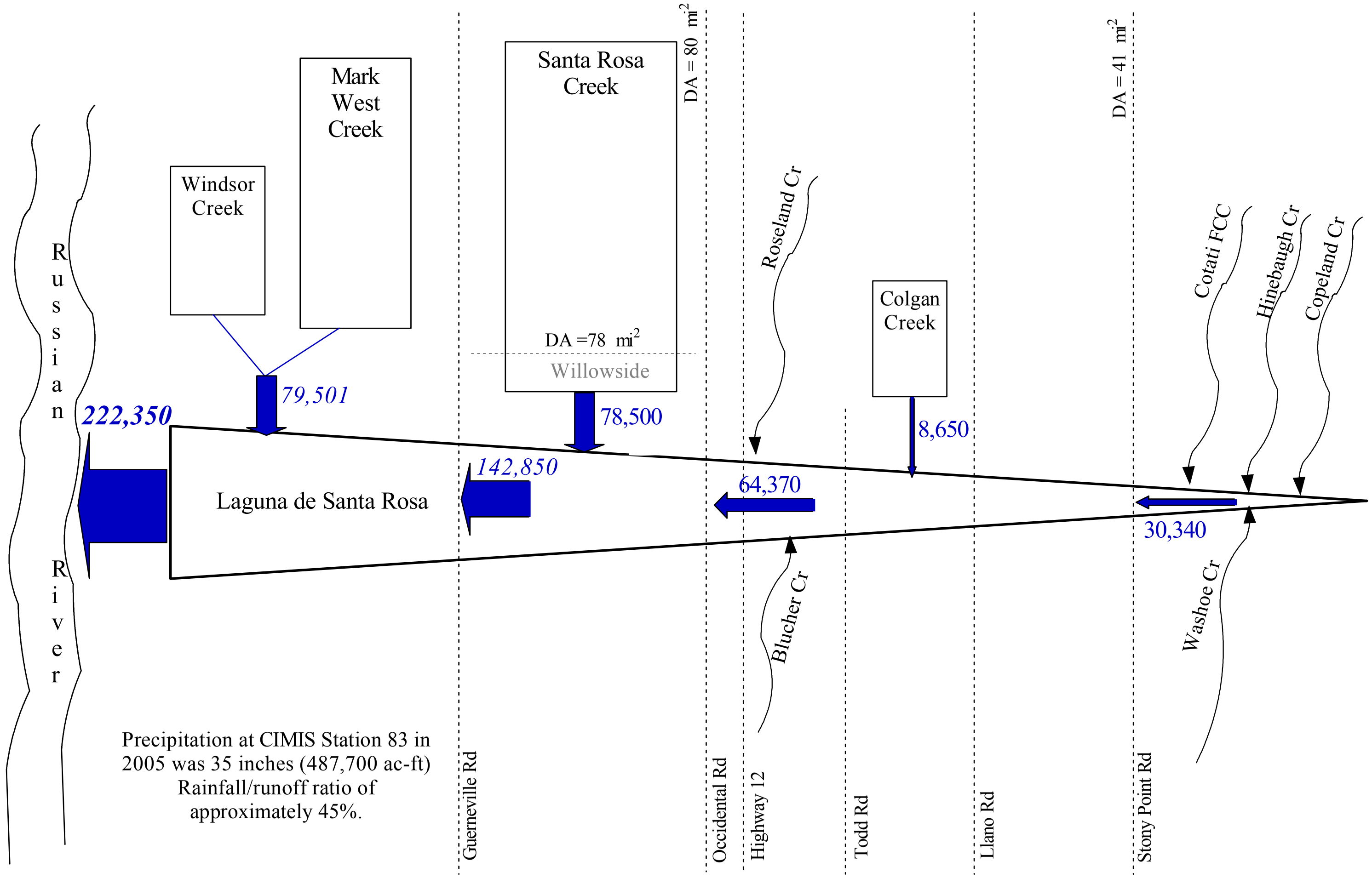
Table 4-12
Summary of USGS gauging stations in the Laguna de Santa Rosa watershed and vicinity

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)

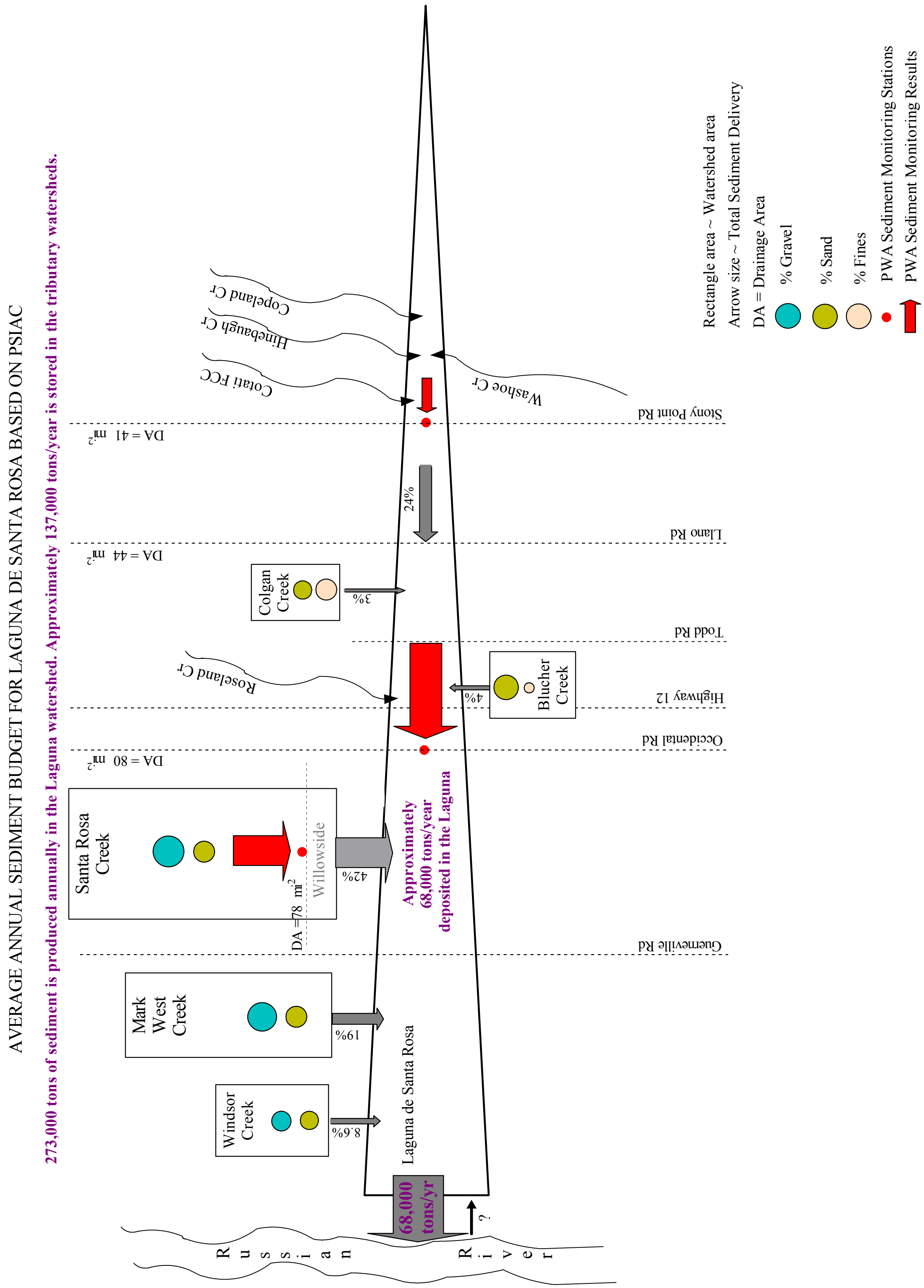


Figure 4-18 Average annual sediment budget for Laguna de Santa Rosa based on PSIAC

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).

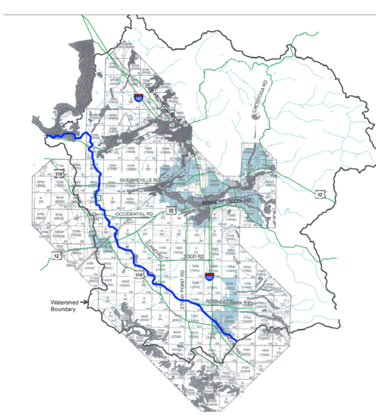


Figure 4-19
Available storage capacity and areas of natural recharge
(see full-sized inset)

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.

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.

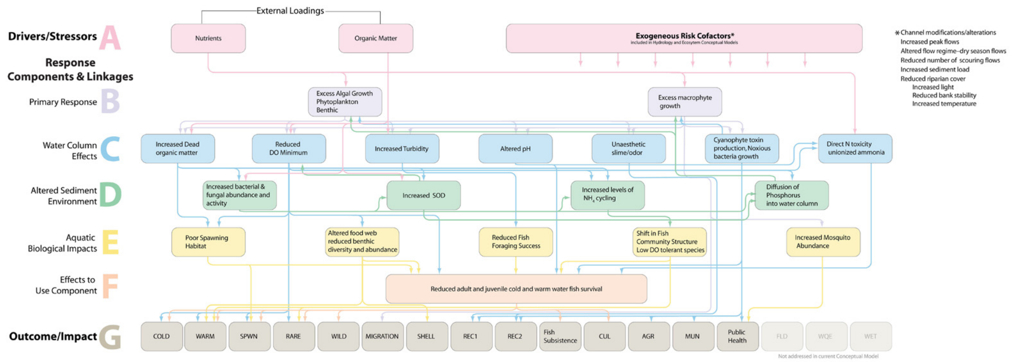


Figure 5-1 Water quality overview conceptual model
(see full-sized inset)

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.

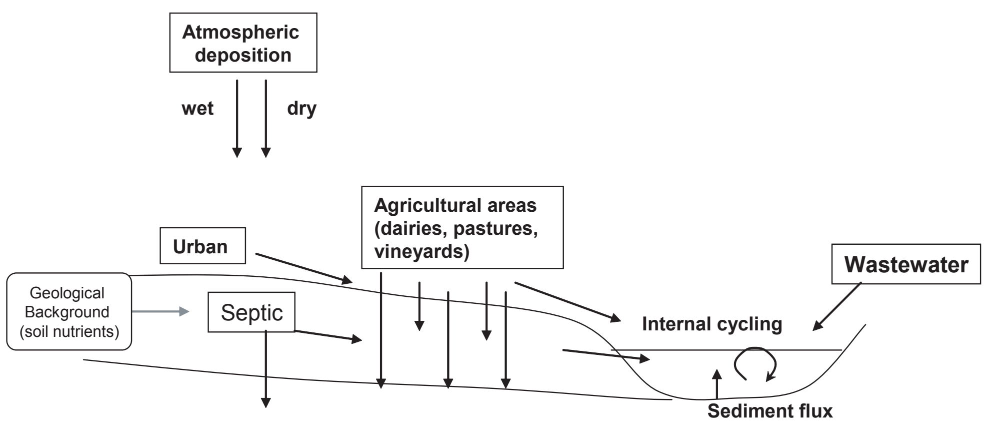


Figure 5-2 Potential point and non-point sources of nutrients/BOD in the Laguna watershed

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

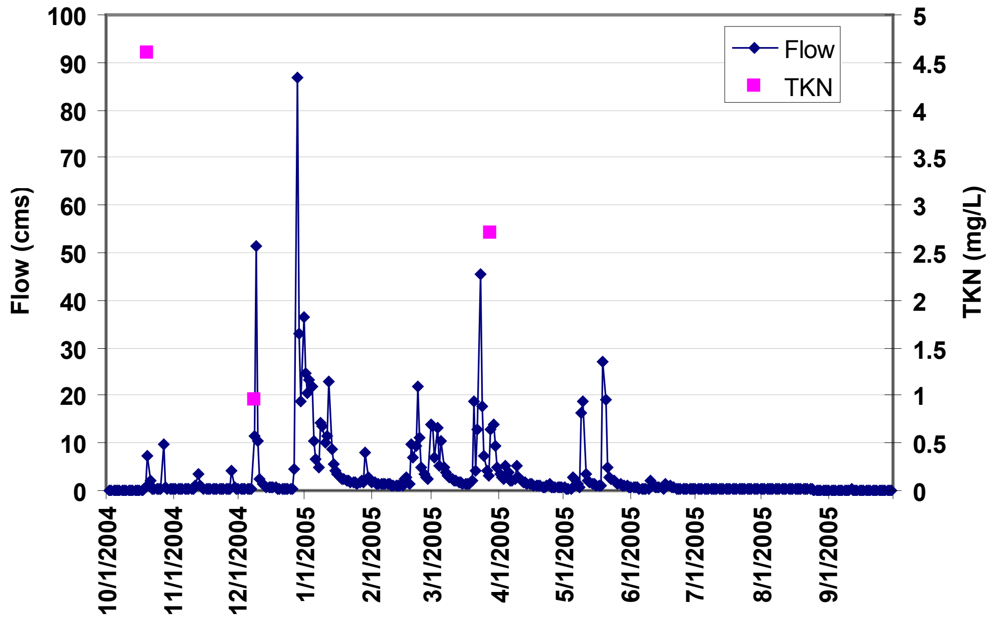


Figure 5-3 Flow at Santa Rosa Creek at Willowside Road with TKN concentrations Sampled during storm events of 2005

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.

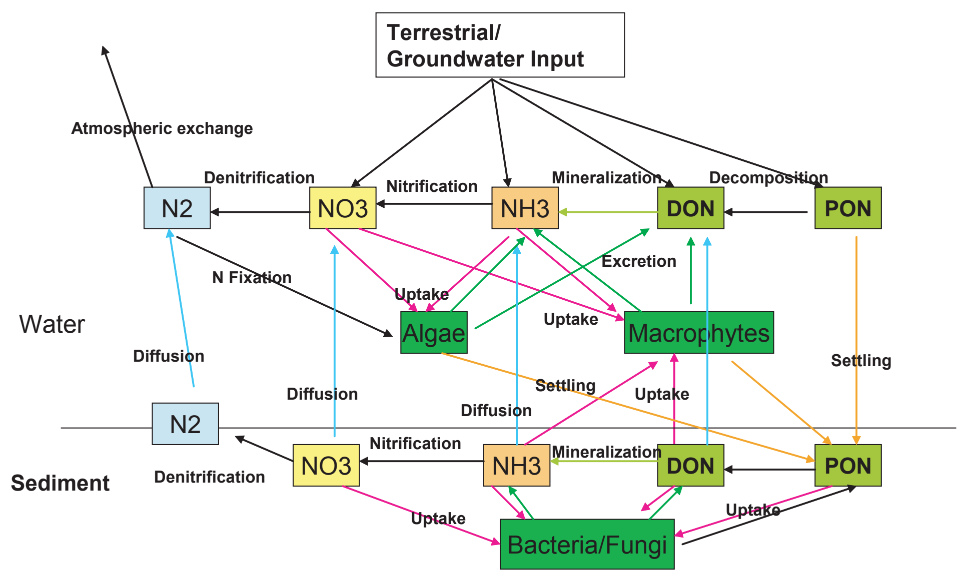


Figure 5-4 Nitrogen transformations in the water column and sediments

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.

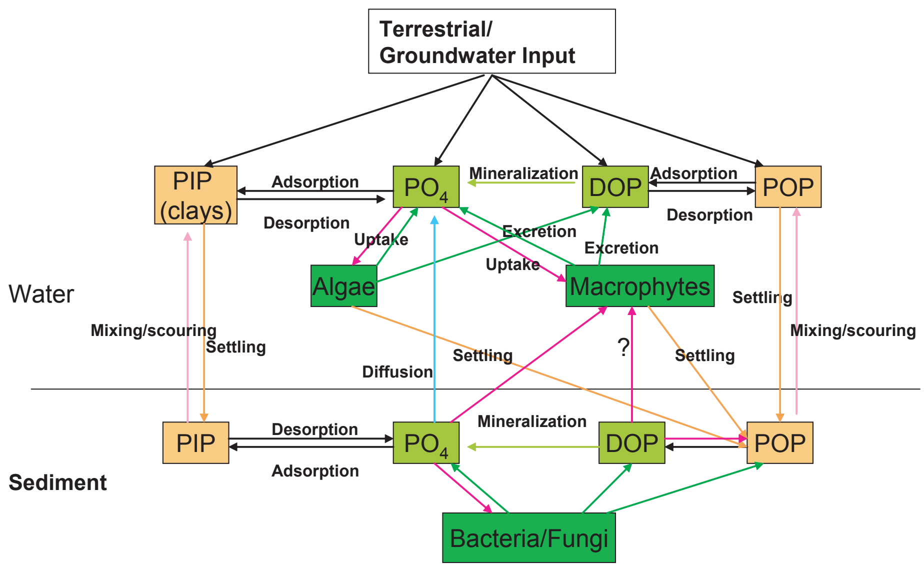


Figure 5-5 Phosphorus transformations in the water column and sediments

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 2×10^{-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

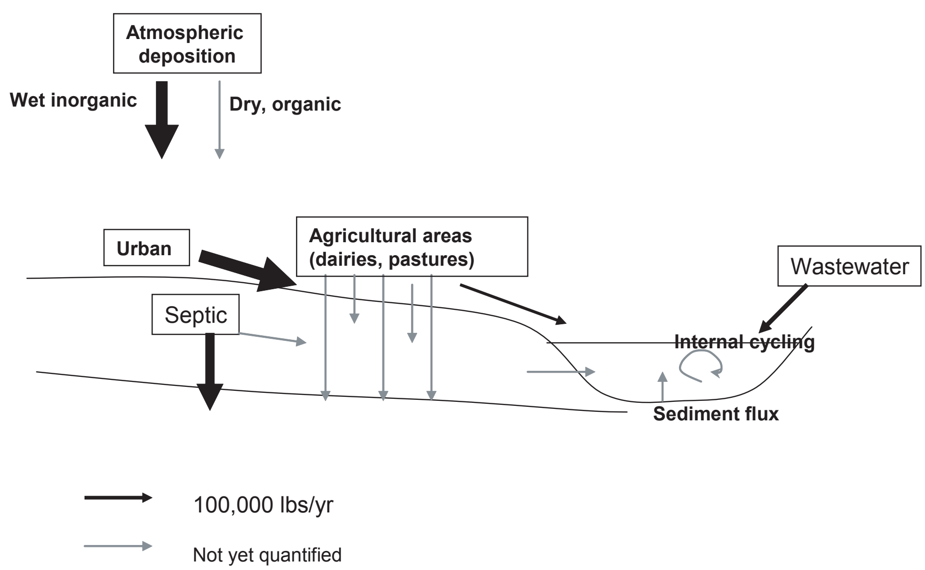


Figure 5-6 Preliminary TN loading conceptual model

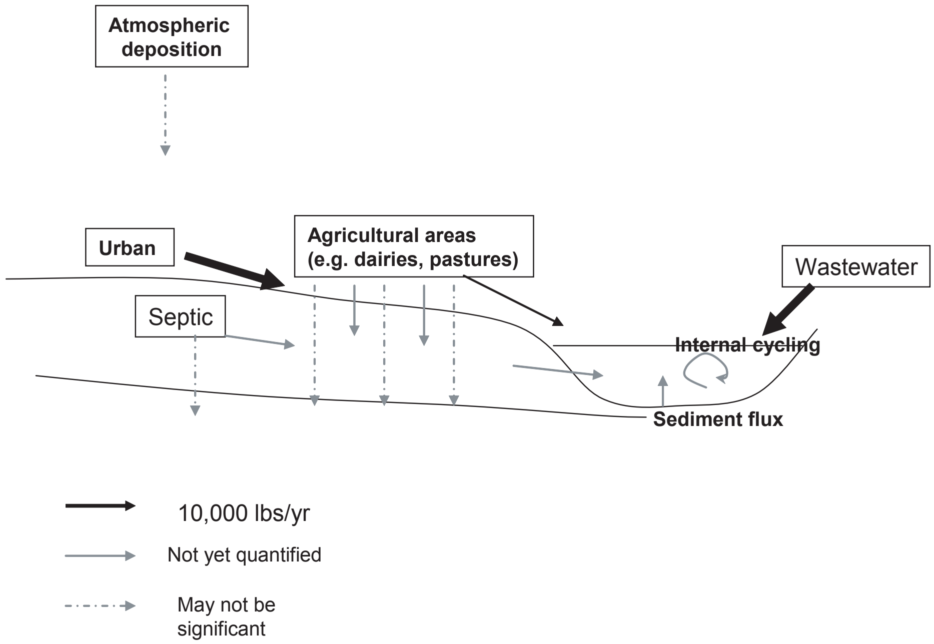


Figure 5-7 Preliminary dissolved phosphate loading conceptual model

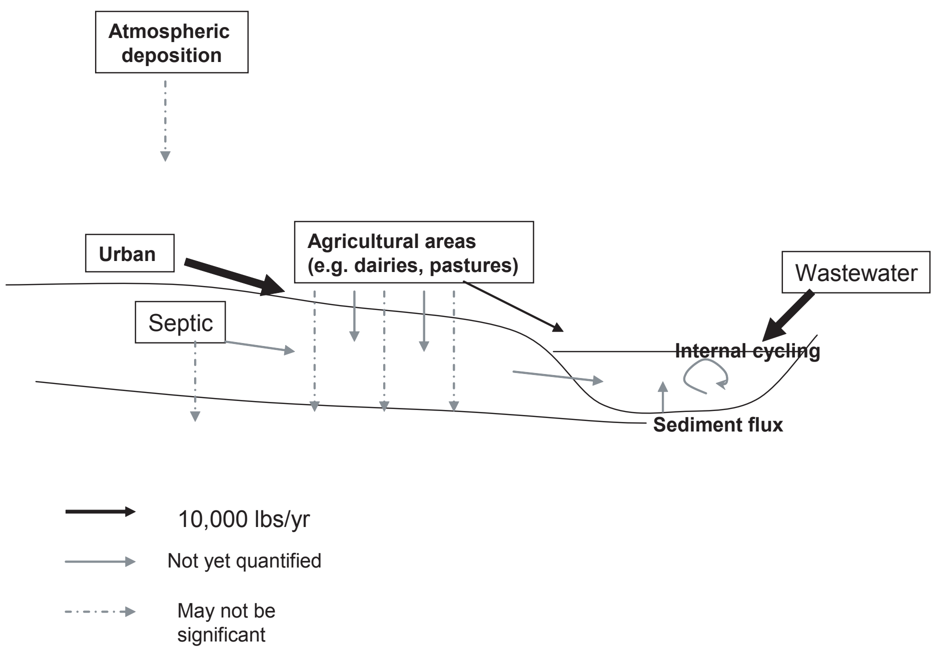


Figure 5-8 Preliminary BOD loading conceptual model

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.

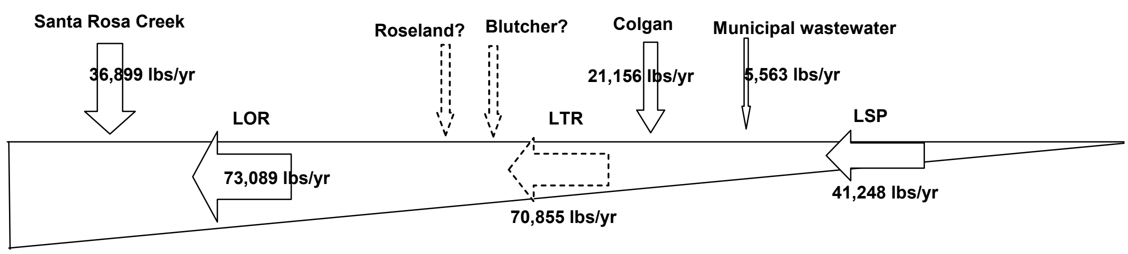


Figure 5-9 Total ammonia loadings by reaches
(note location of municipal wastewater discharge varies with year,
with most recent discharge point located below LOR)

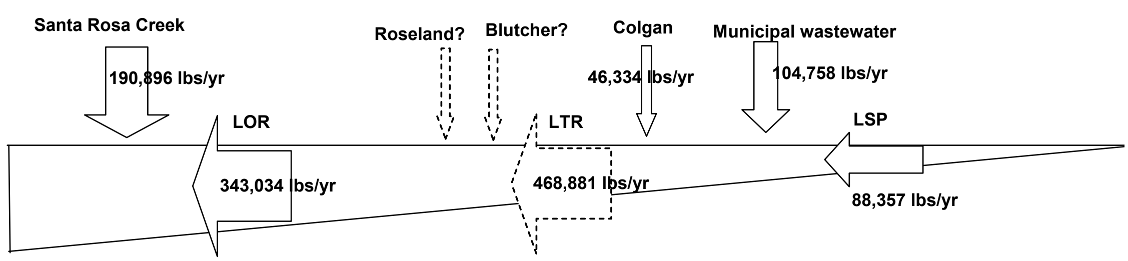


Figure 5-10 Nitrate loadings by reaches
(note location of municipal wastewater discharge varies with year,
with most recent discharge point located below LOR)

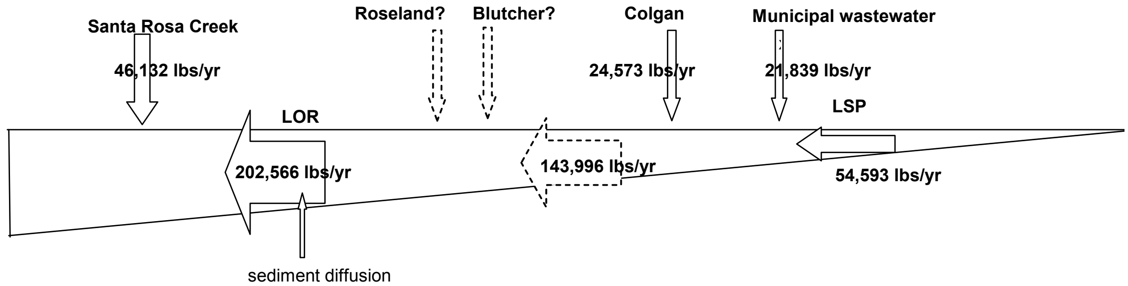


Figure 5-11 Total phosphorus loadings by reaches
(note location of municipal wastewater discharge varies with year, with most recent discharge point located below LOR)

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.

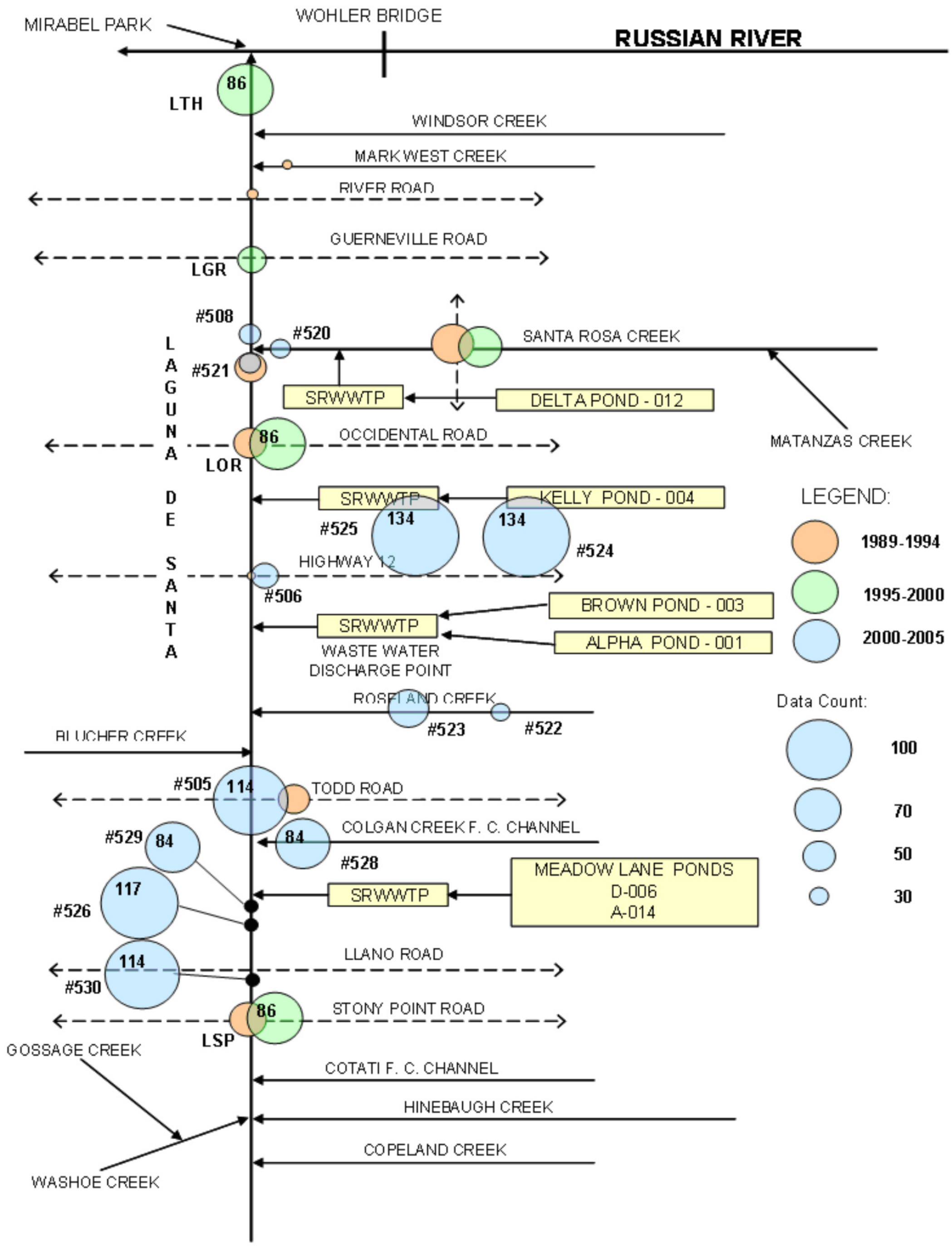


Figure 5-12 Total number of data points for the samples during 1989-1994, 1995-2000, and 2000-2005.

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.

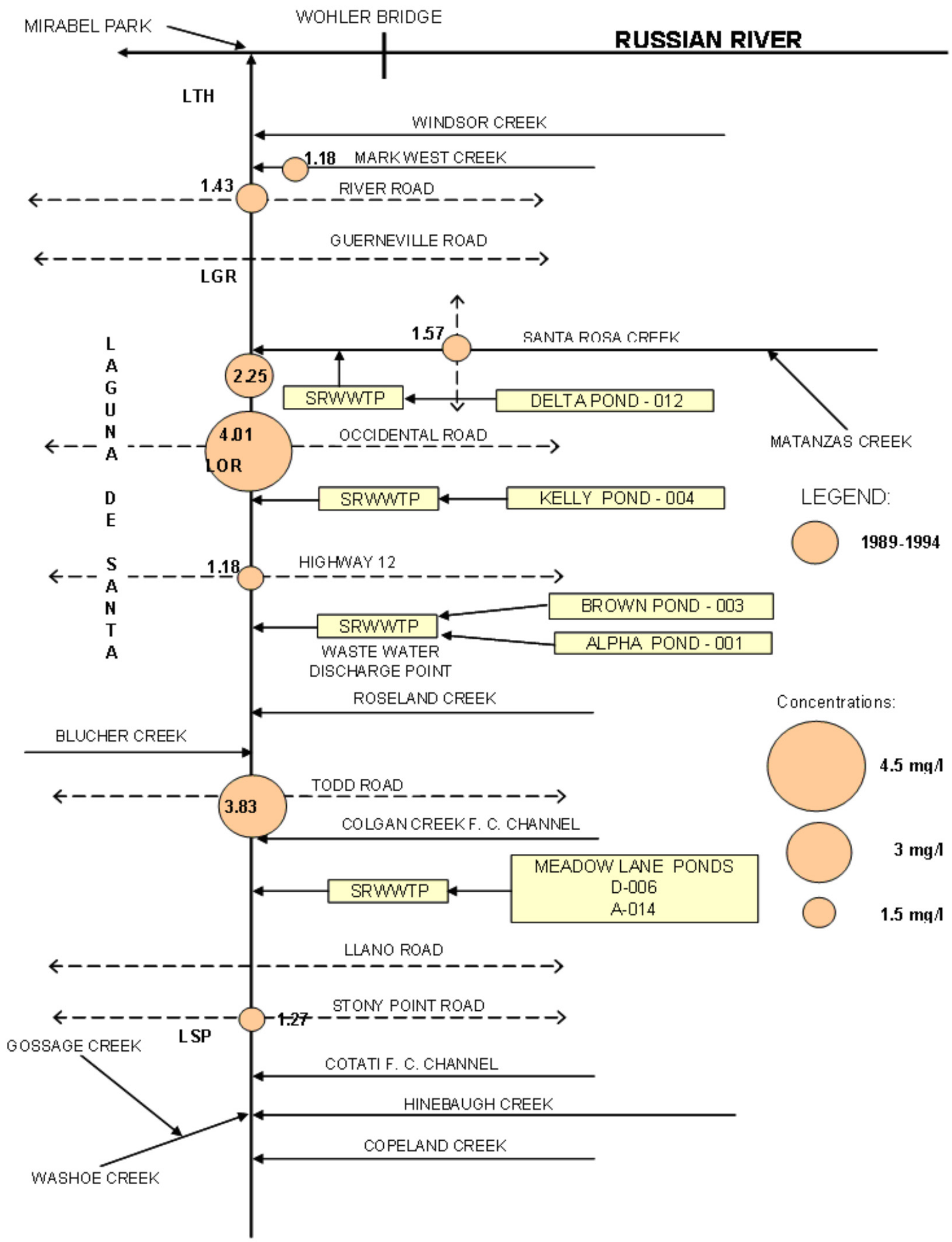


Figure 5-13 Mean NO_3 concentrations for 1989-1994

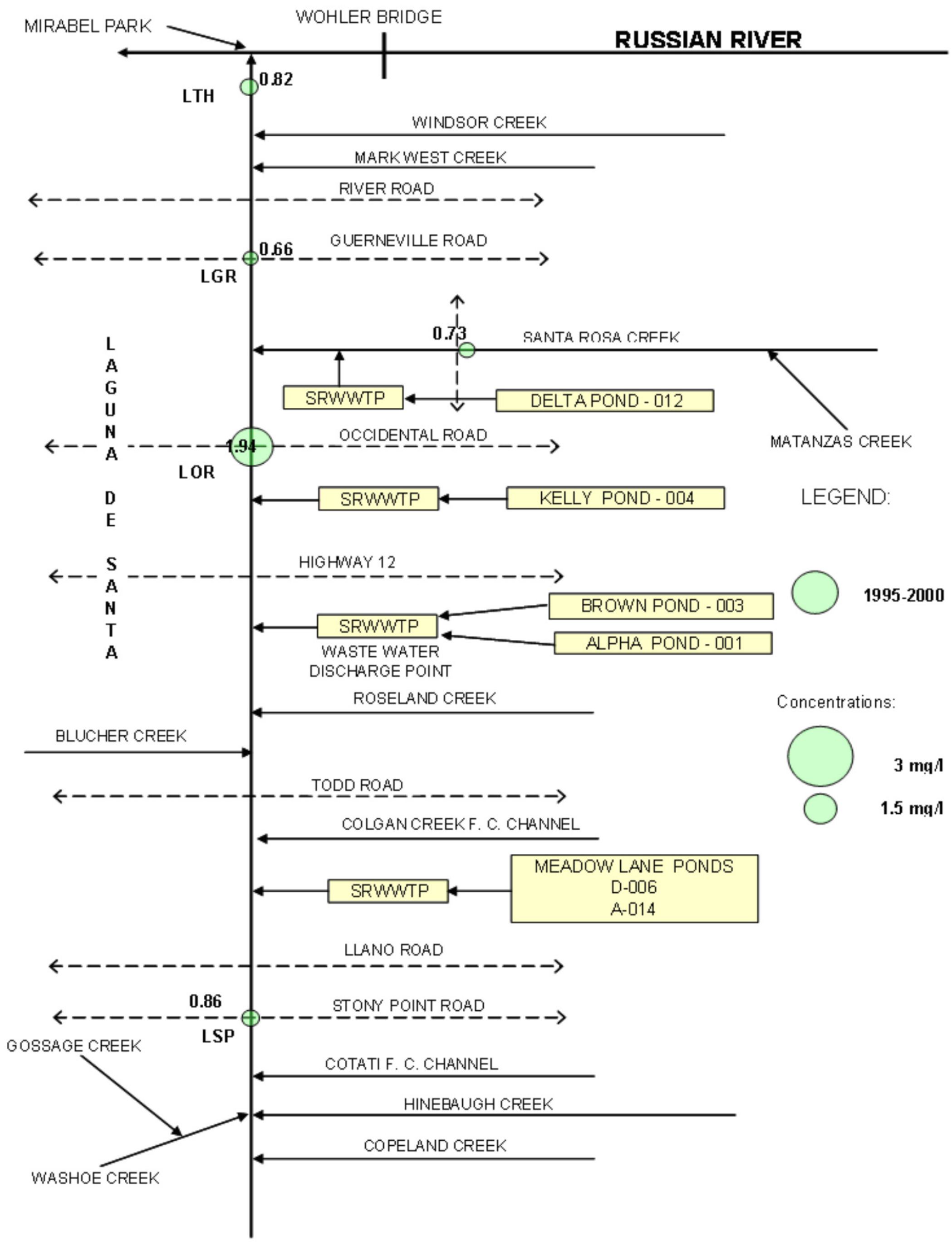


Figure 5-14 Mean NO_3 concentrations for 1995-2000

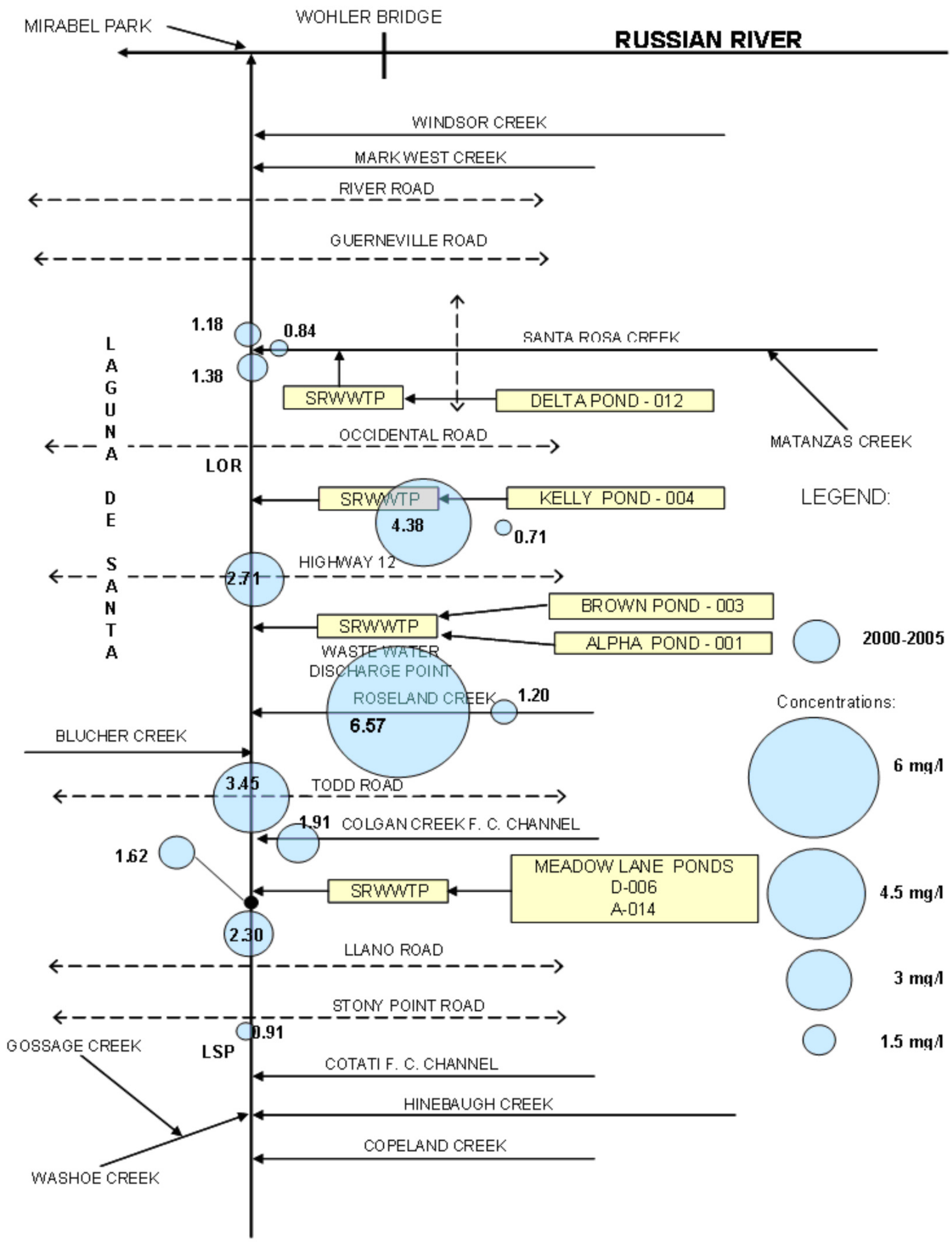


Figure 5-15 Mean NO_3 concentrations for 2000-2005

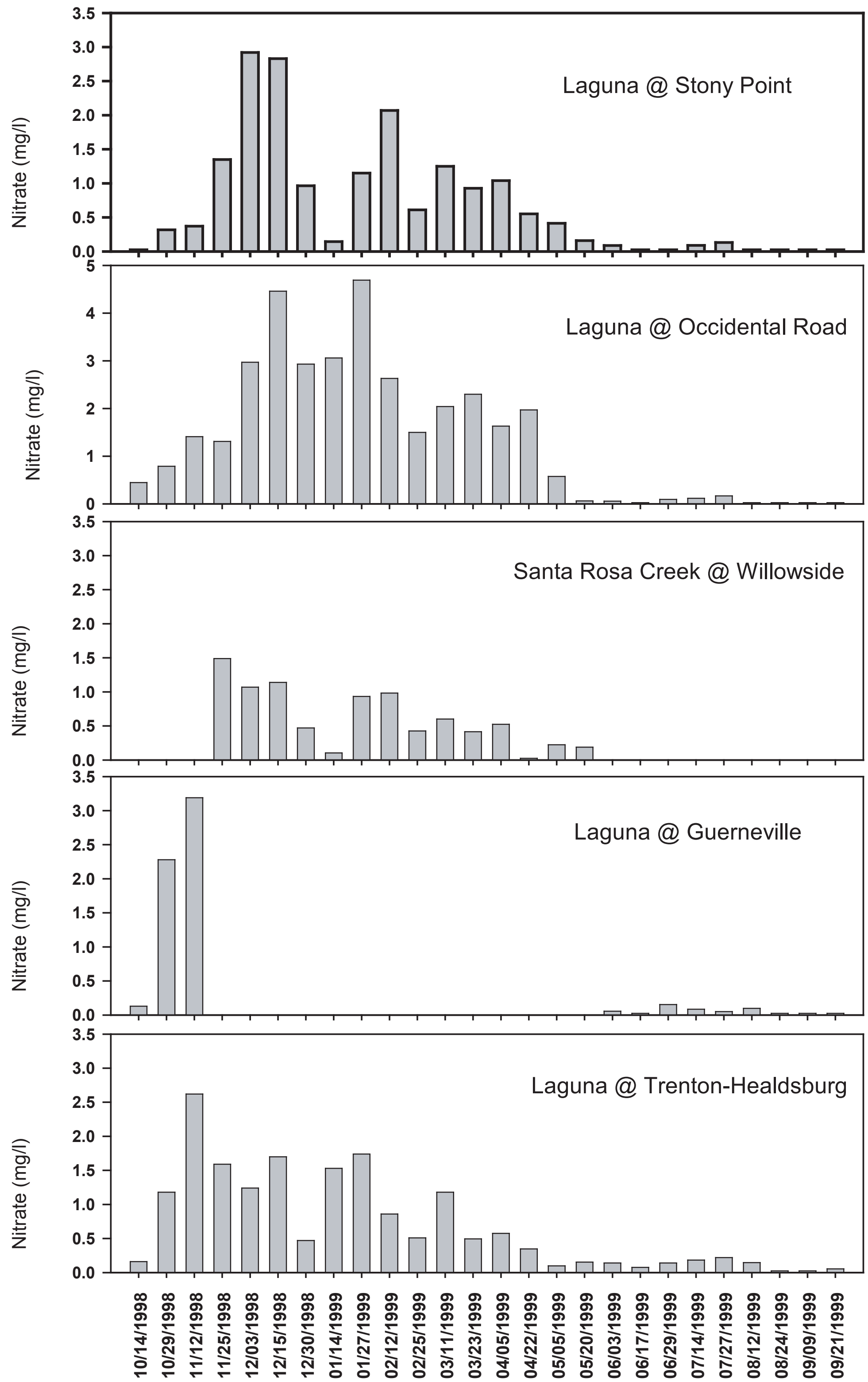


Figure 5-16 Seasonal pattern of NO_3 concentrations

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.

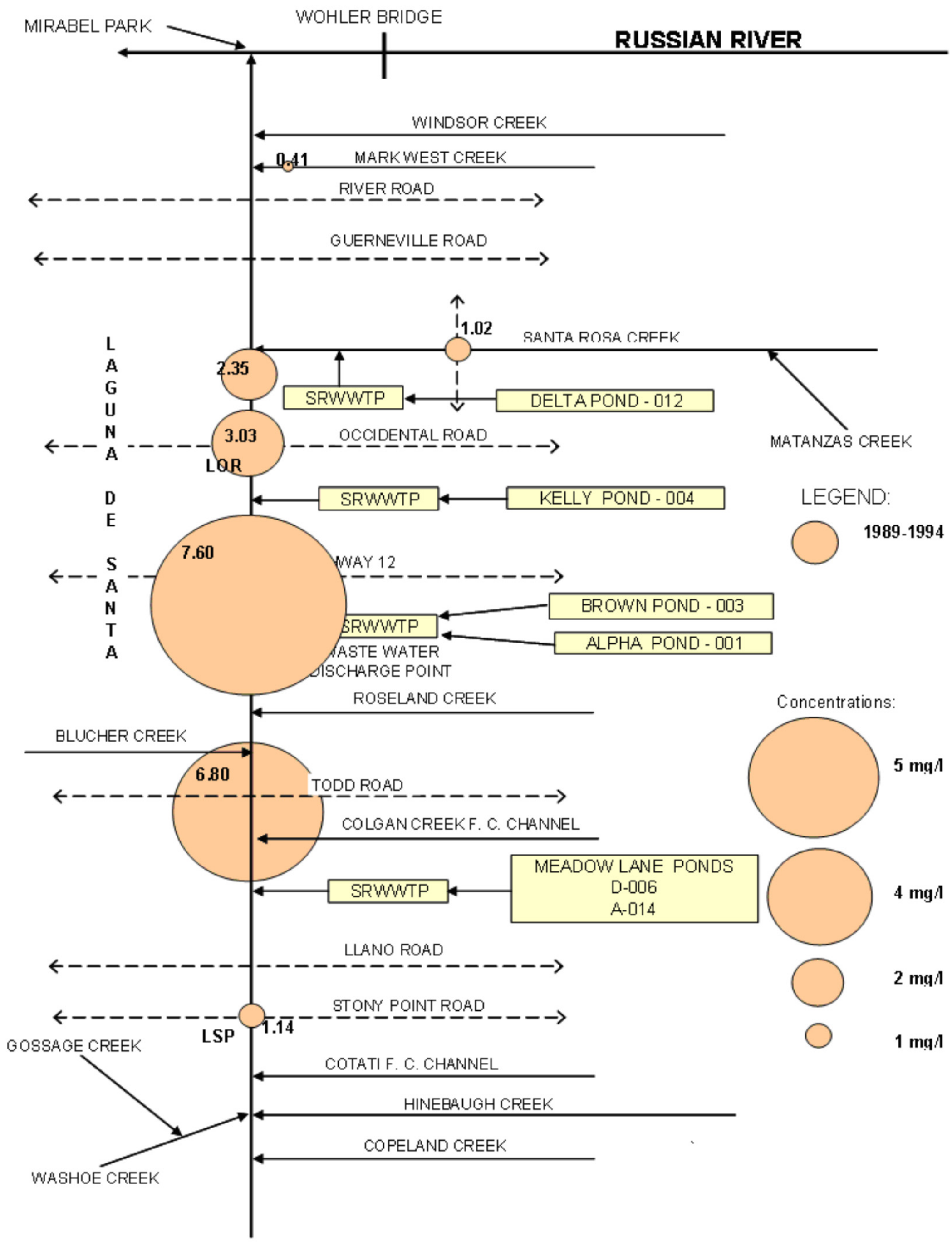


Figure 5-17 Mean TKN concentrations for 1989-1994

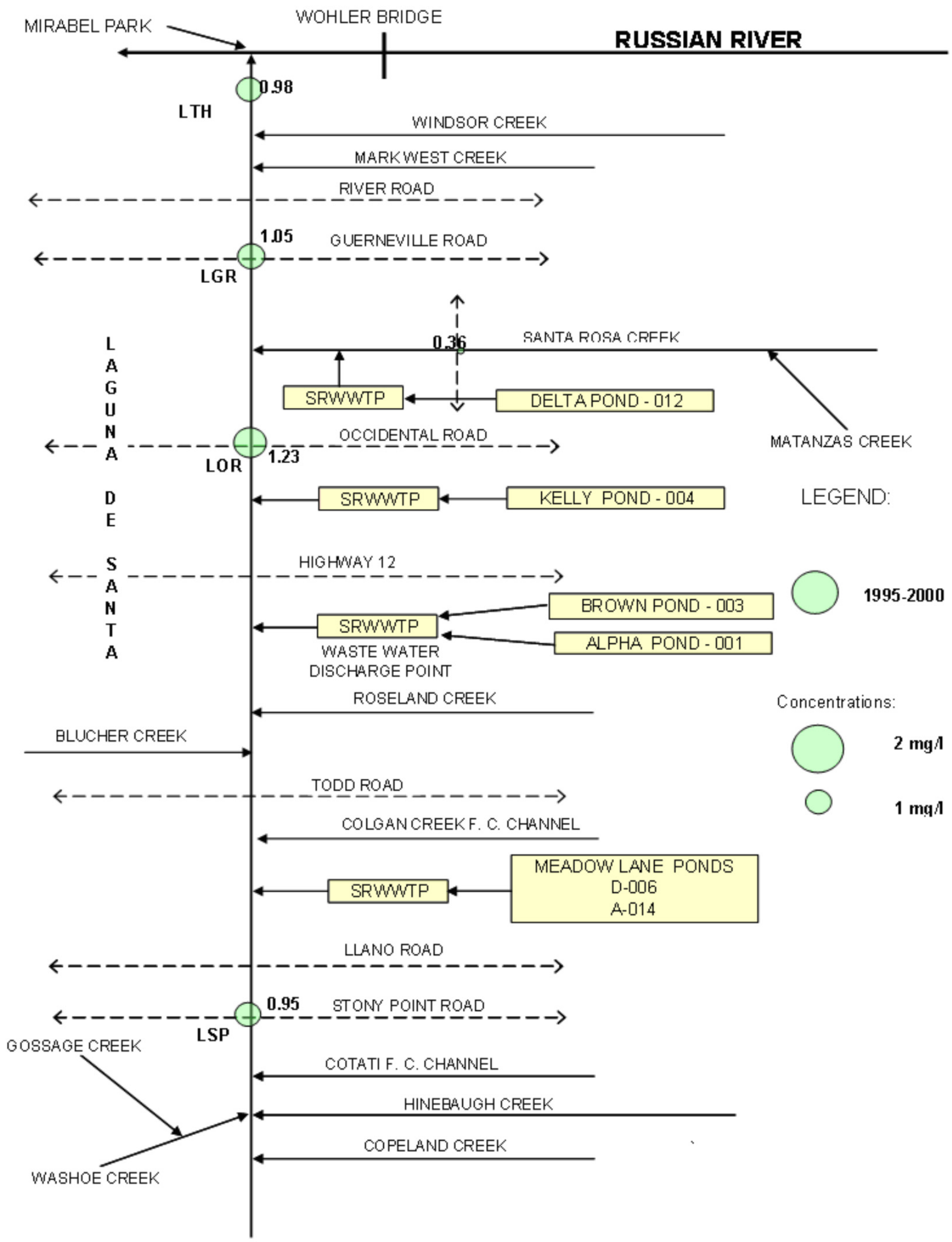


Figure 5-18 Mean TKN concentrations 1995-2000

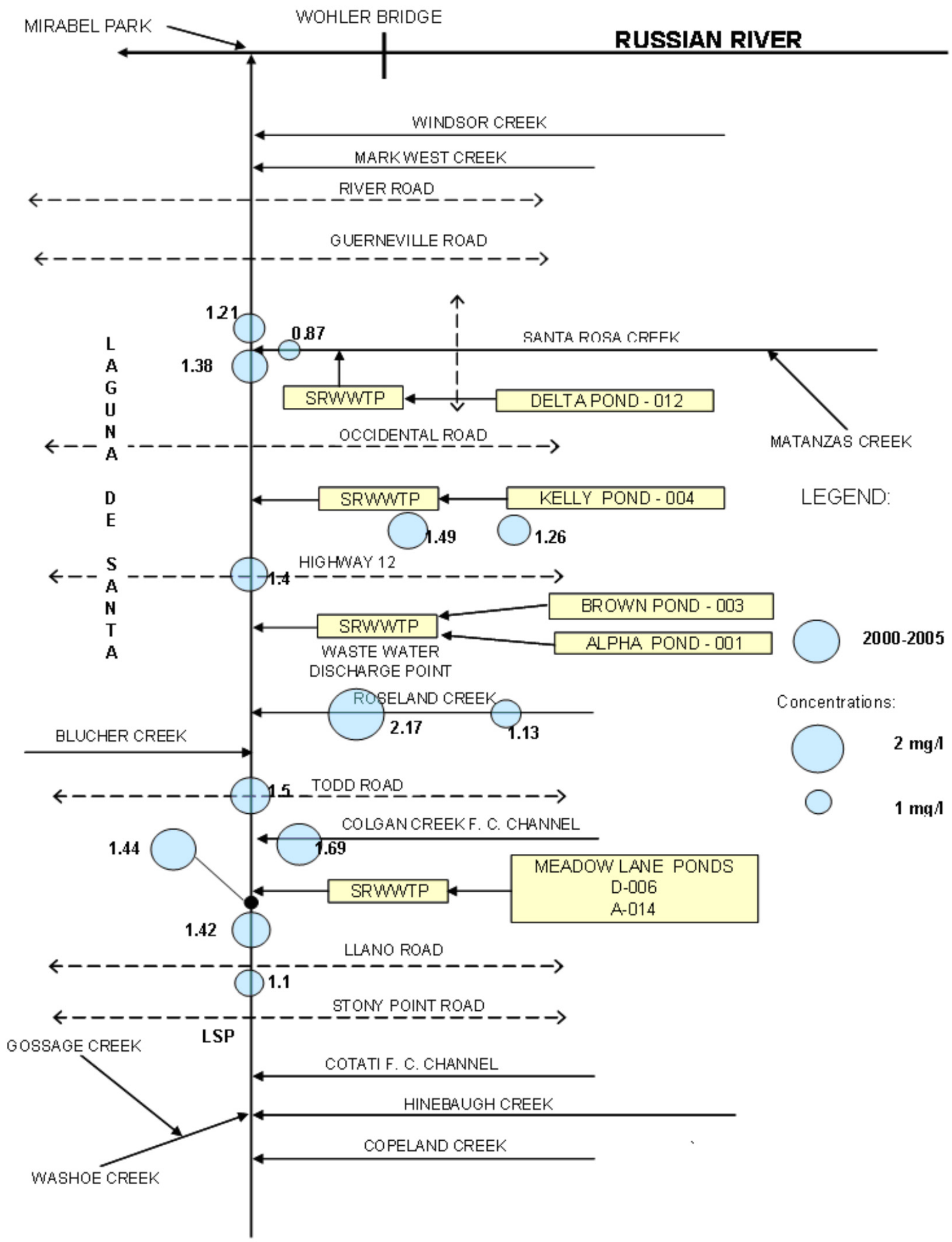


Figure 5-19 Mean TKN concentrations for 2000-2005

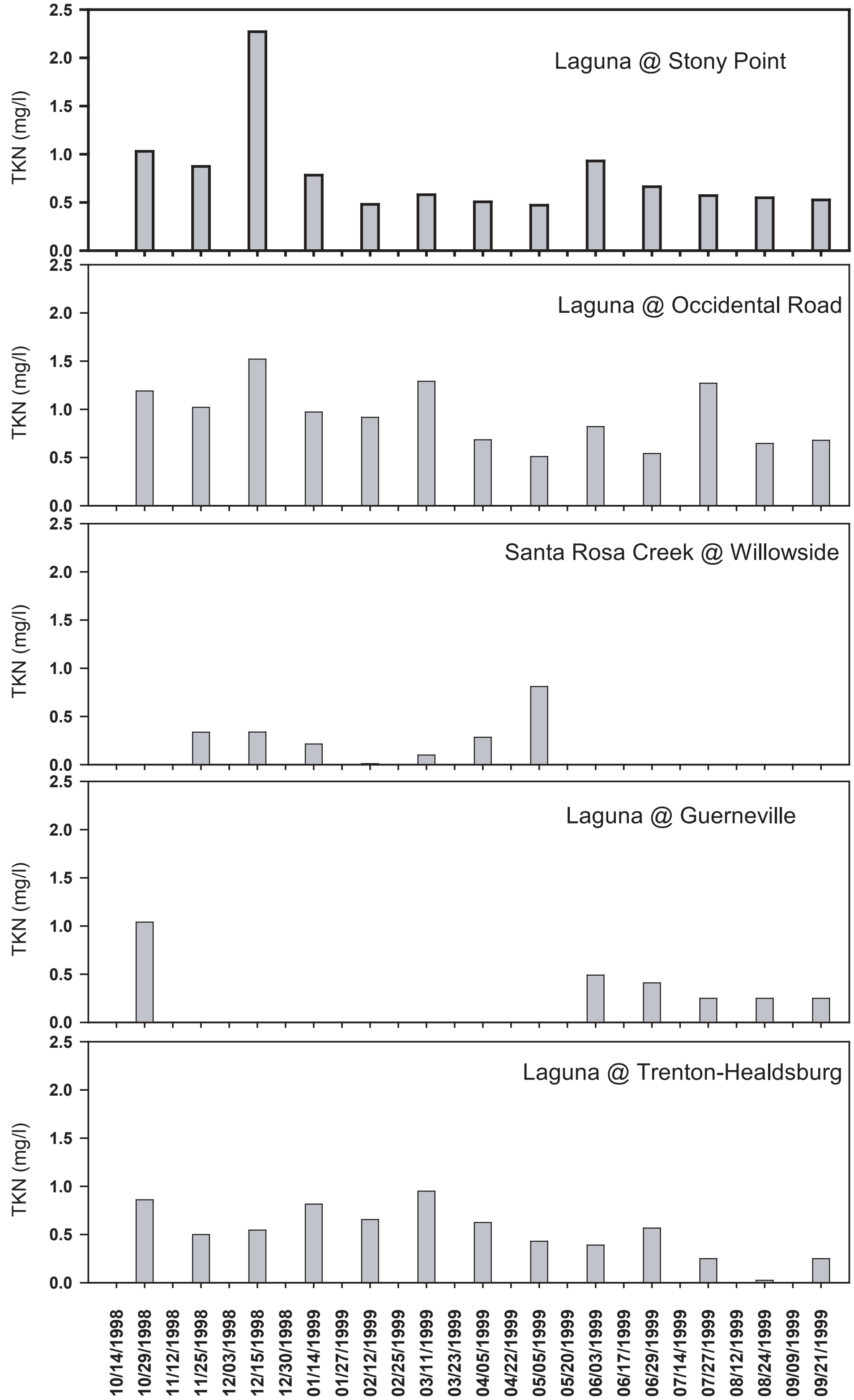


Figure 5-20 Seasonal Pattern of TKN

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.

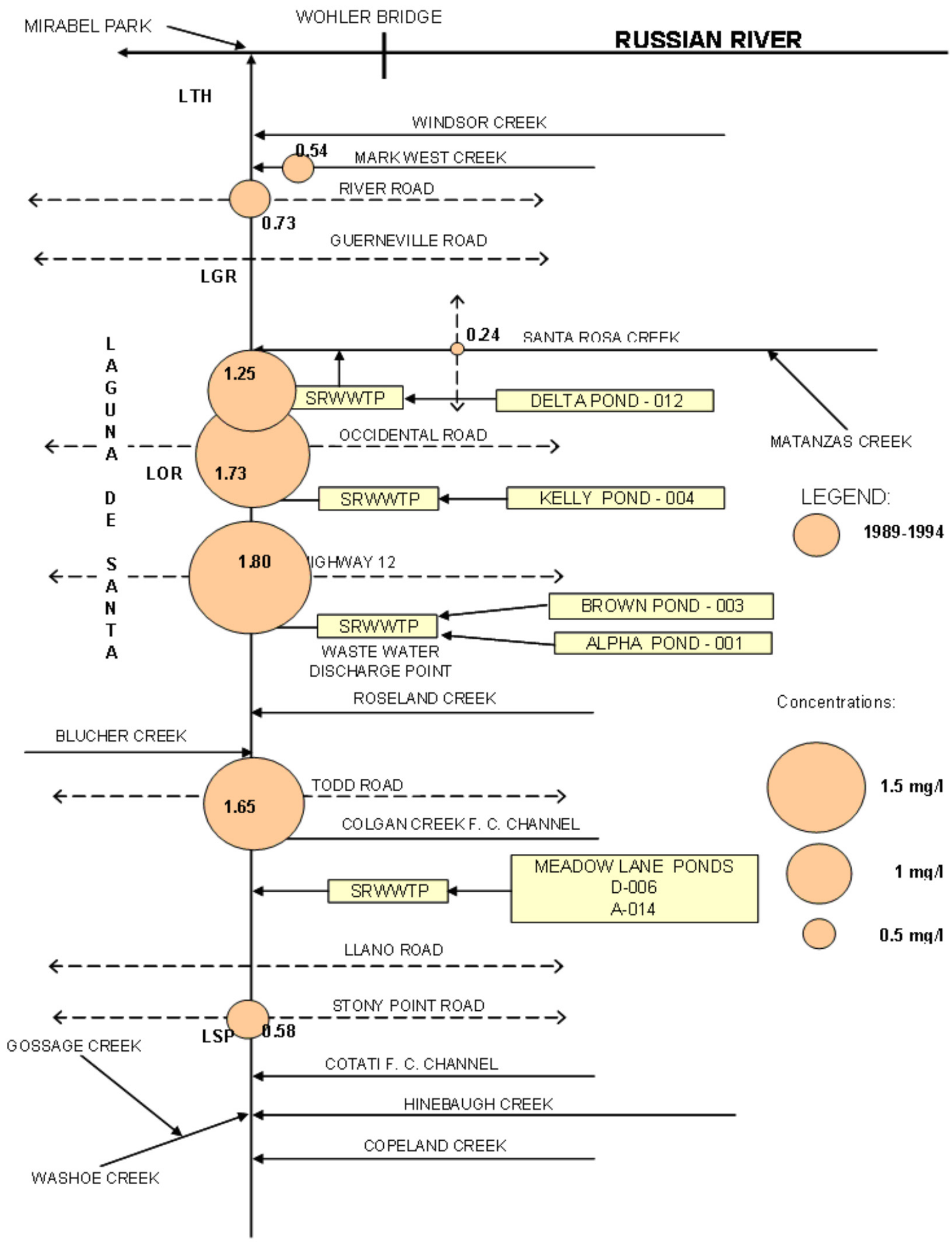


Figure 5-21 Mean TP concentrations for 1989-1994

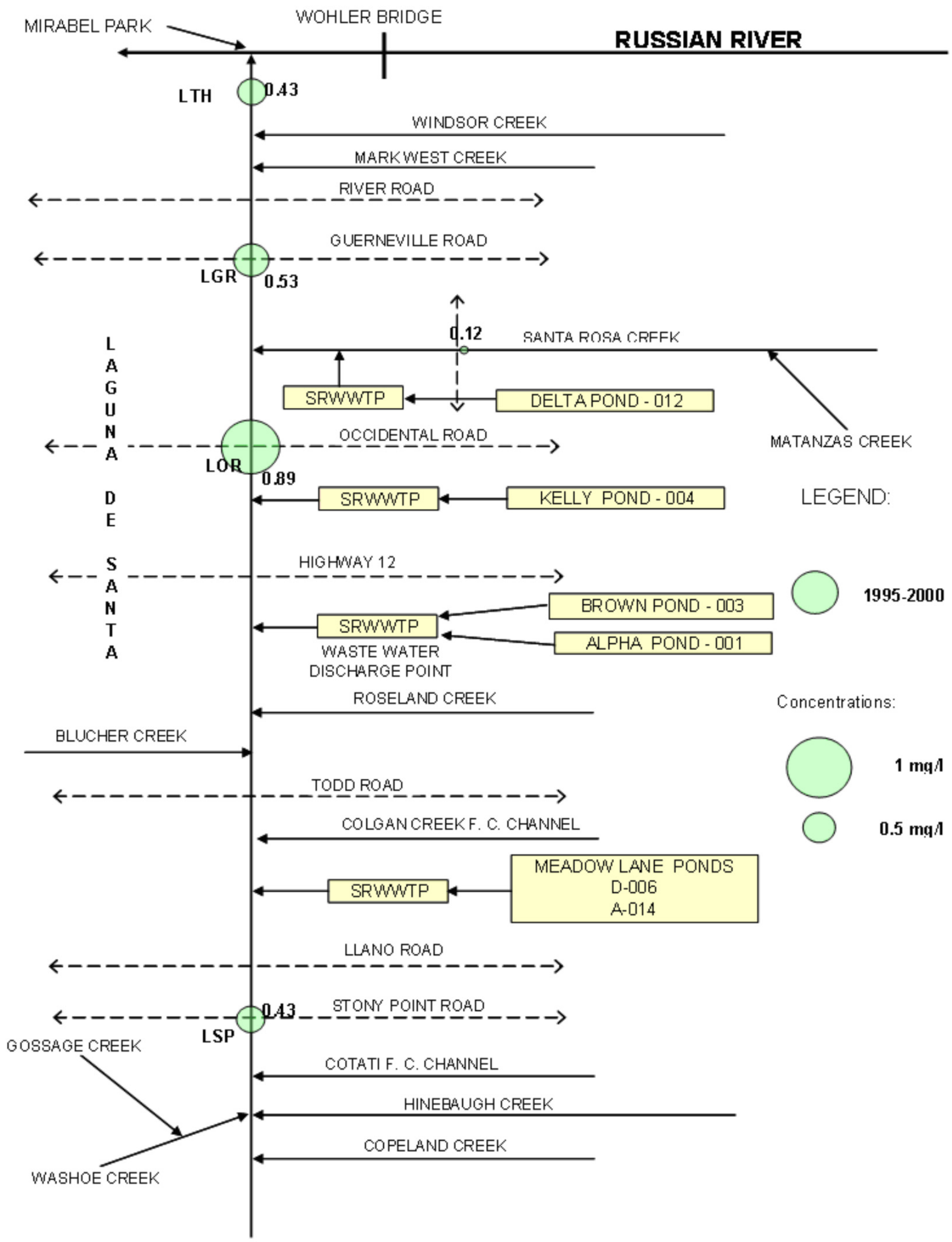


Figure 5-22 Mean TP concentrations for 1995-2000

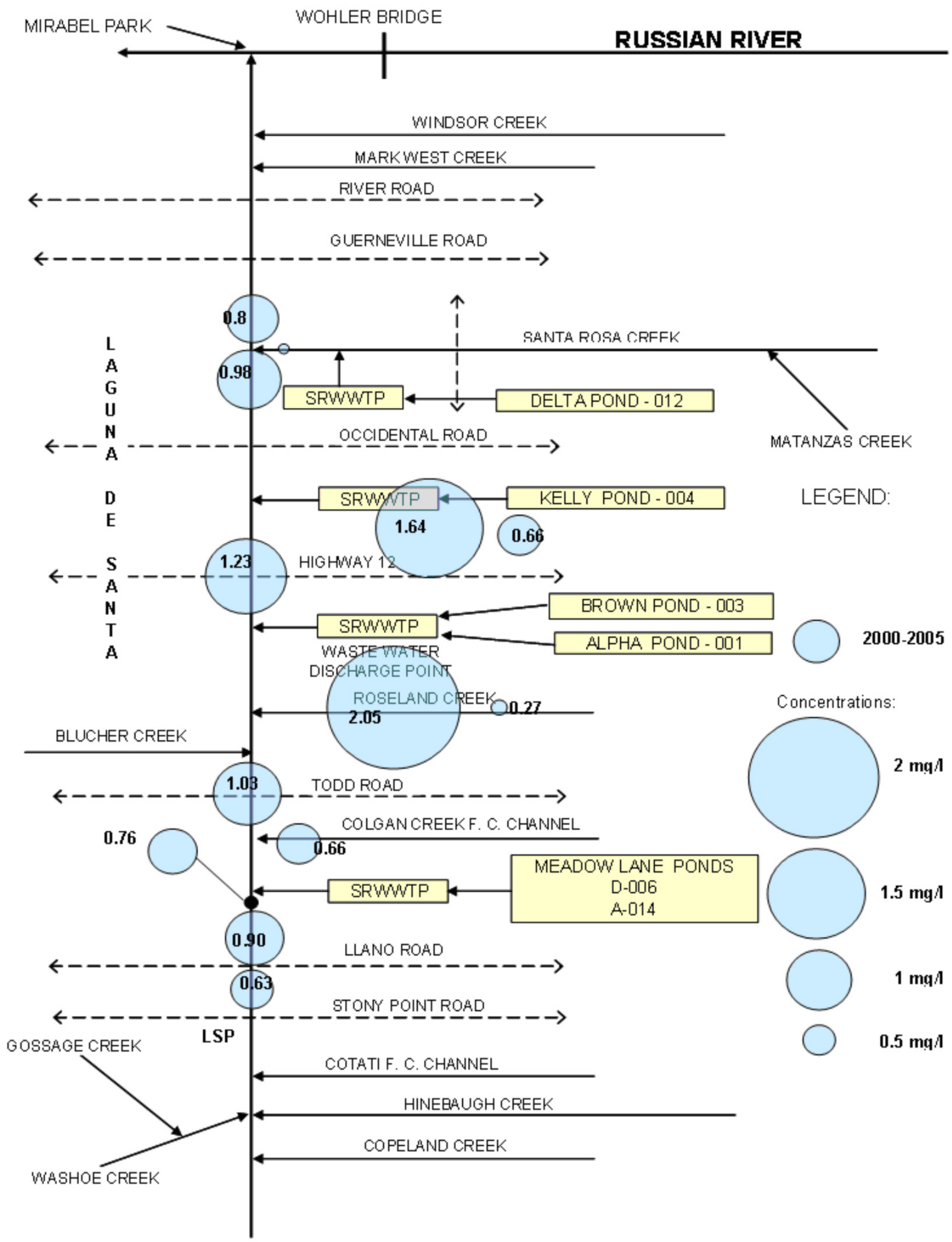


Figure 5-23 Mean TP concentrations for 2000-2005

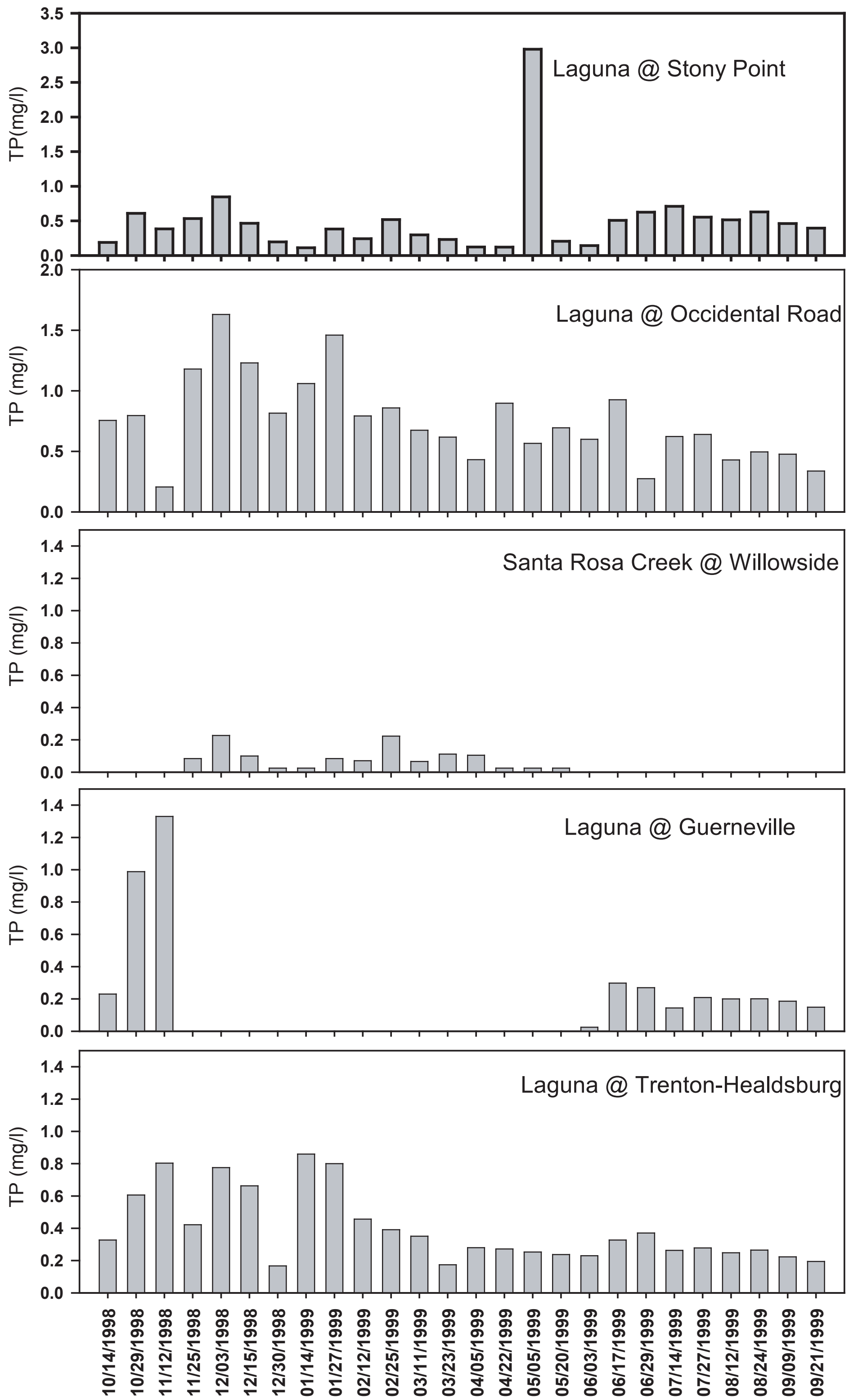


Figure 5-24 Seasonal pattern of TP

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.

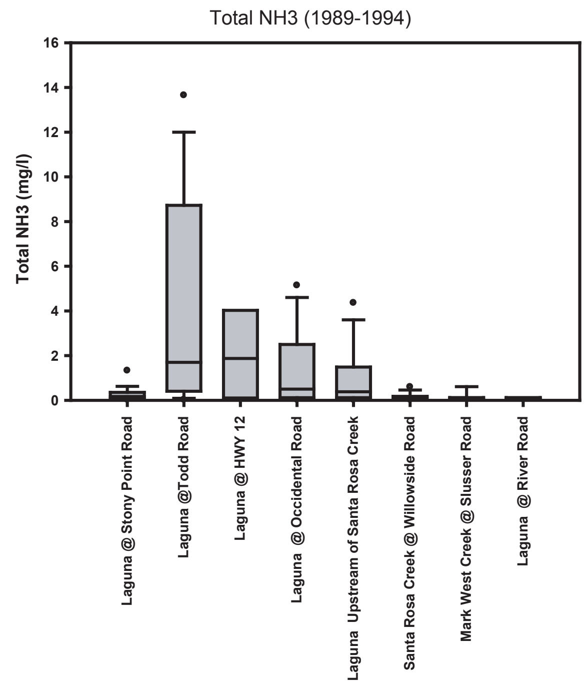


Figure 5-25 Total NH_3 concentrations for 1989-1994 by sampling locations

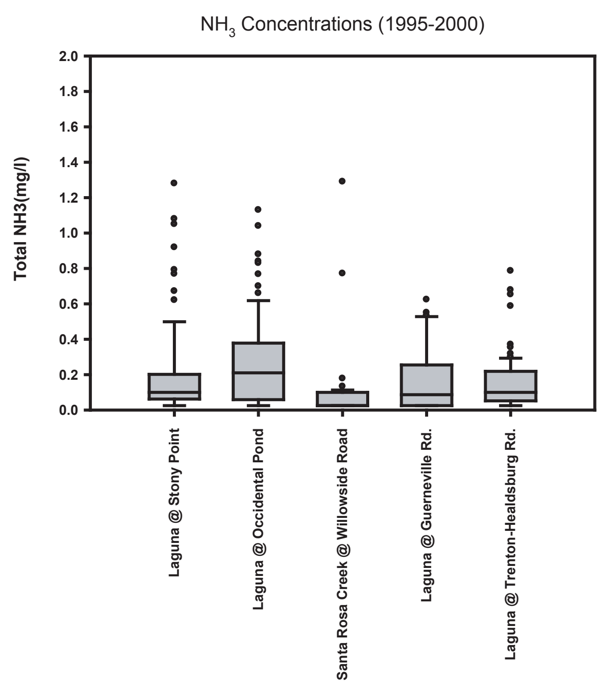


Figure 5-26 Total NH_3 concentrations for 1995-2000 by sampling locations

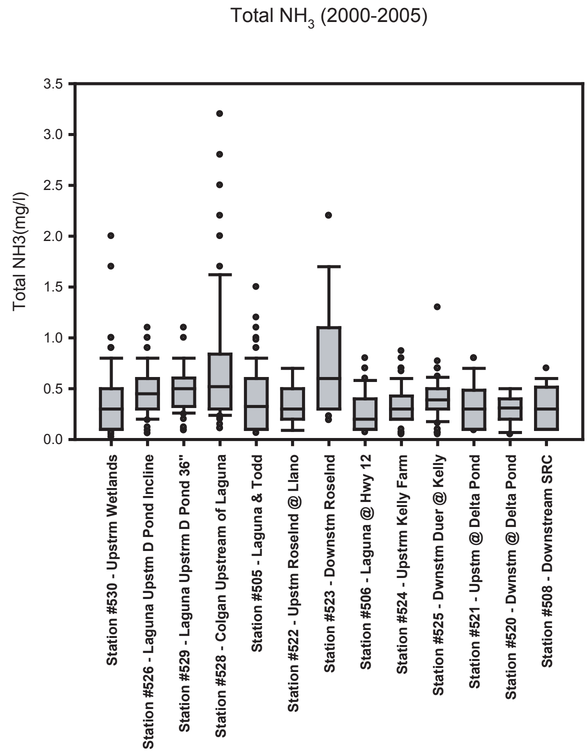


Figure 5-27 Total NH_3 concentrations for 2000-2005 by sampling locations

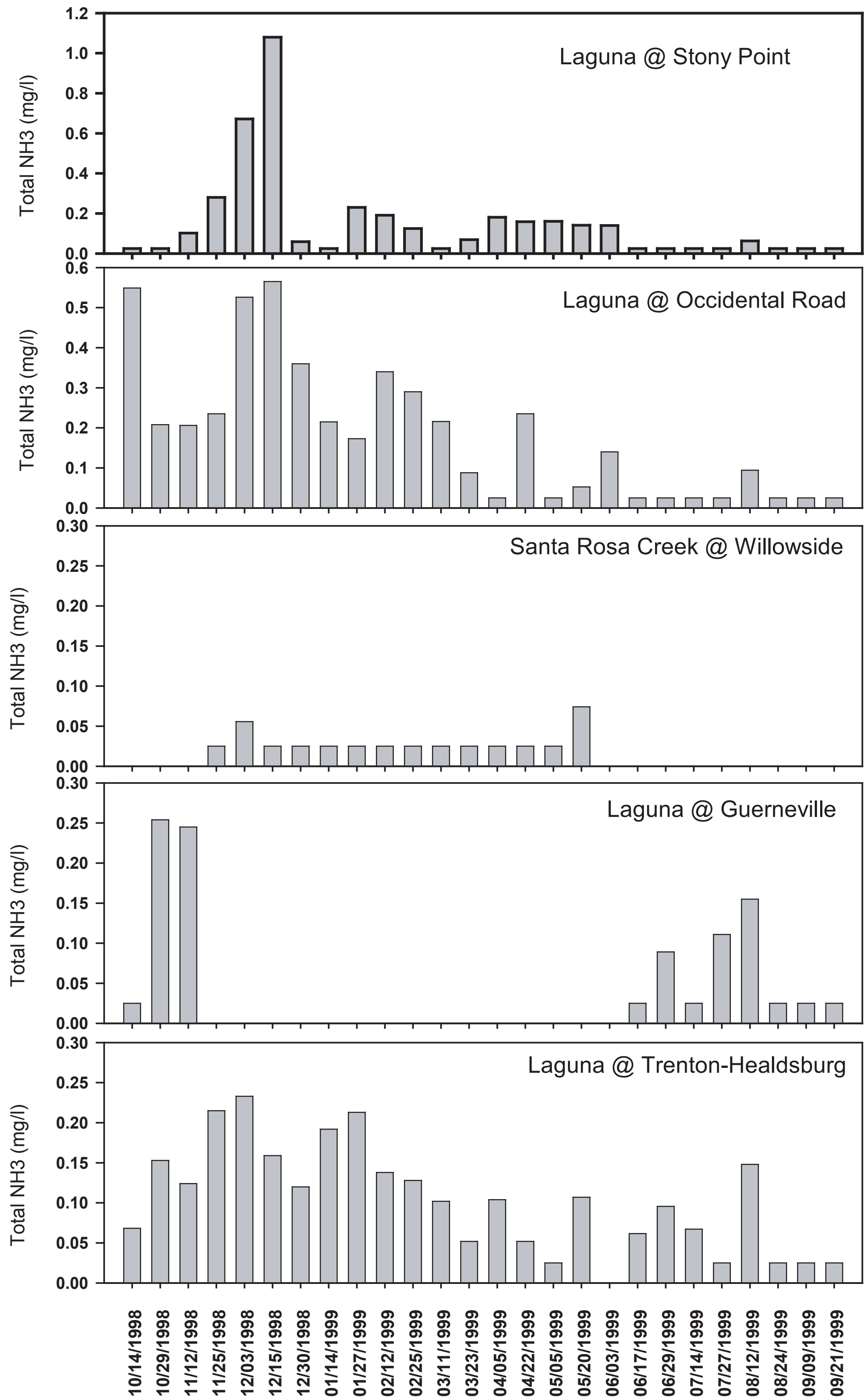


Figure 5-28 Seasonal pattern of total NH_3 concentrations

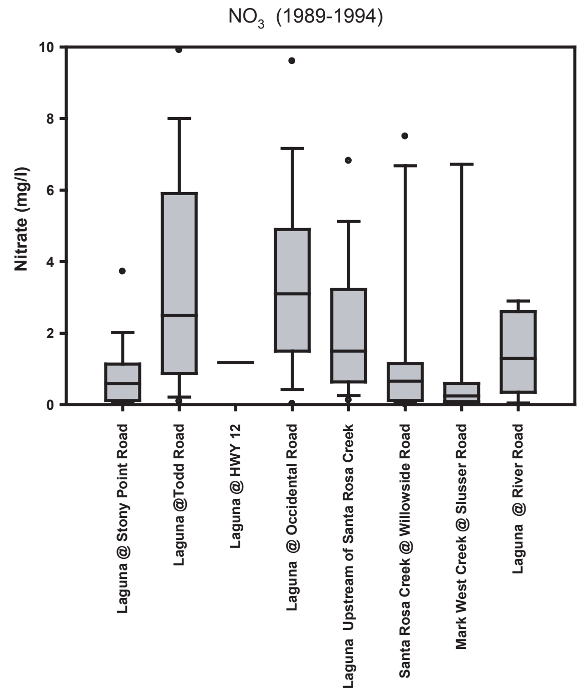


Figure 5-29 Total NO_3 concentrations for 1989-1994 by sampling locations

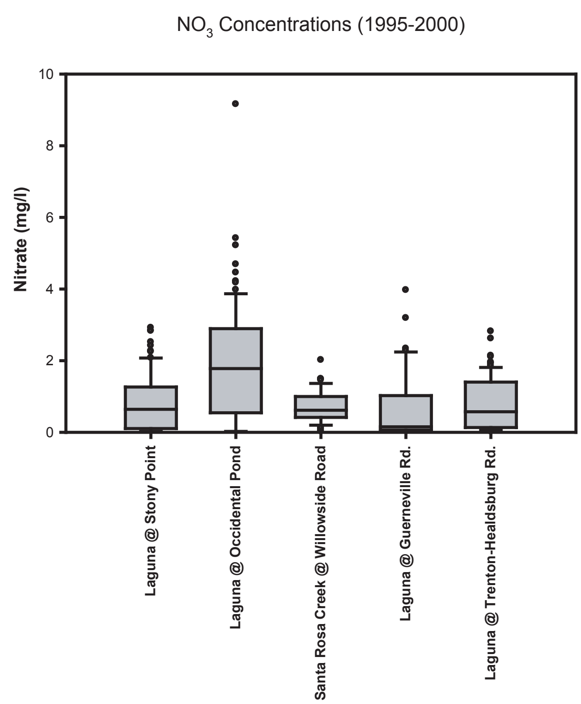


Figure 5-30 Total NO_3 concentrations for 1995-2000 by sampling locations

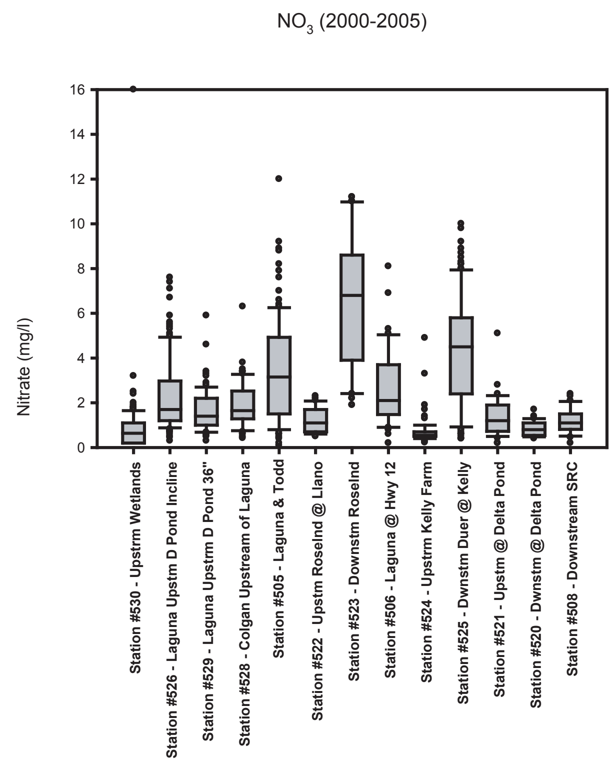


Figure 5-31 Total NO_3 concentrations for 2000-2005 by sampling locations

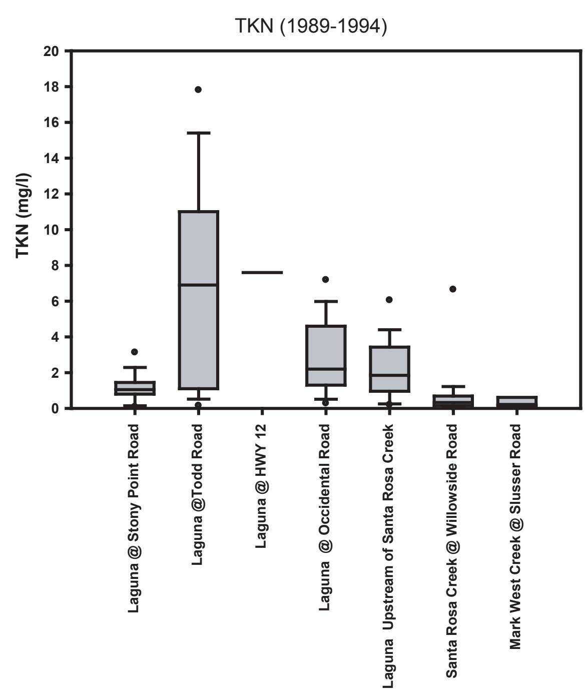


Figure 5-32 TKN concentrations for 1989-1994 by sampling locations

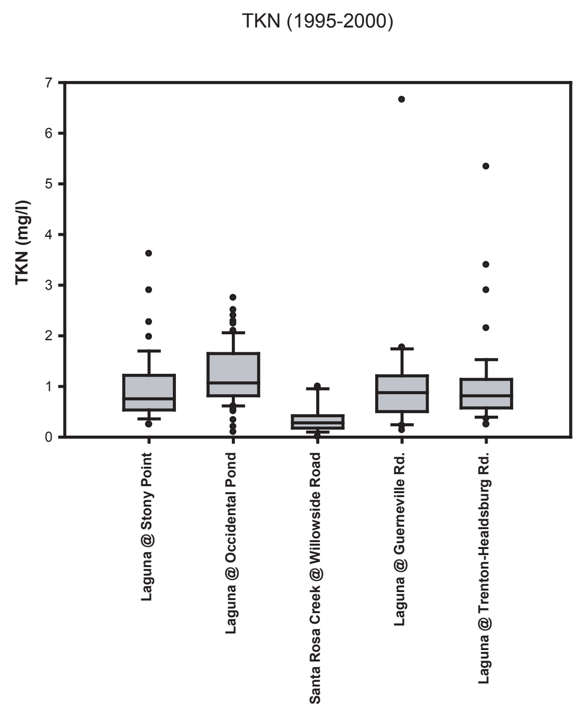


Figure 5-33 TKN concentrations for 1995-2000 by sampling locations

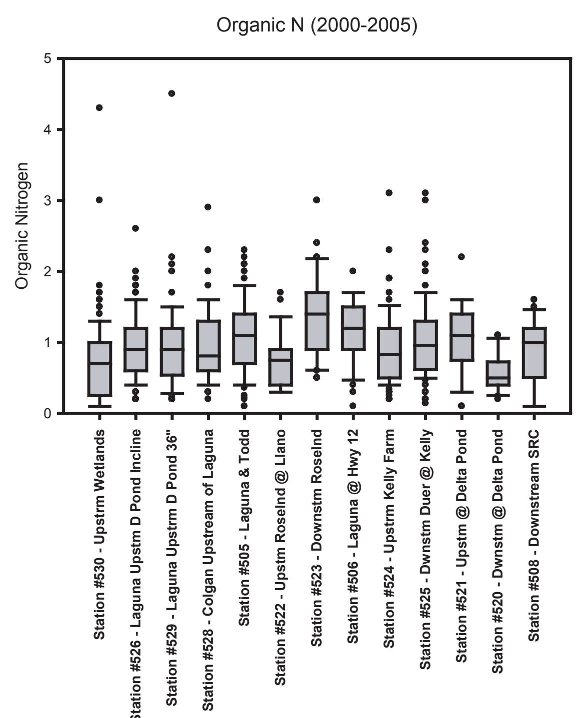


Figure 5-34 Organic nitrogen concentrations for 2000-2005 by sampling locations

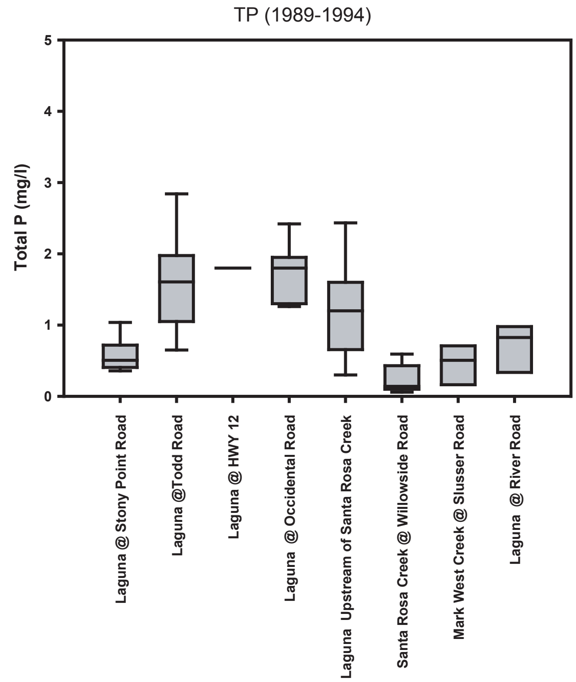


Figure 5-35 TP concentrations for 1989-1994 by sampling locations

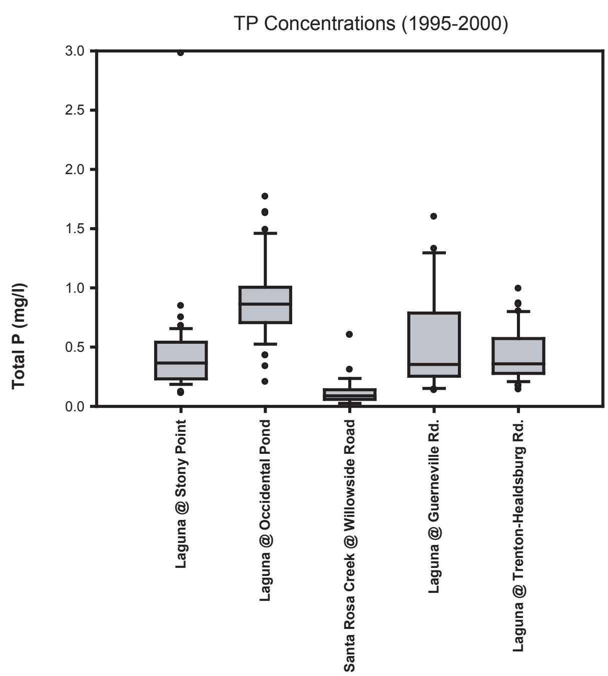


Figure 5-36 TP concentrations for 1995-2000 by sampling locations

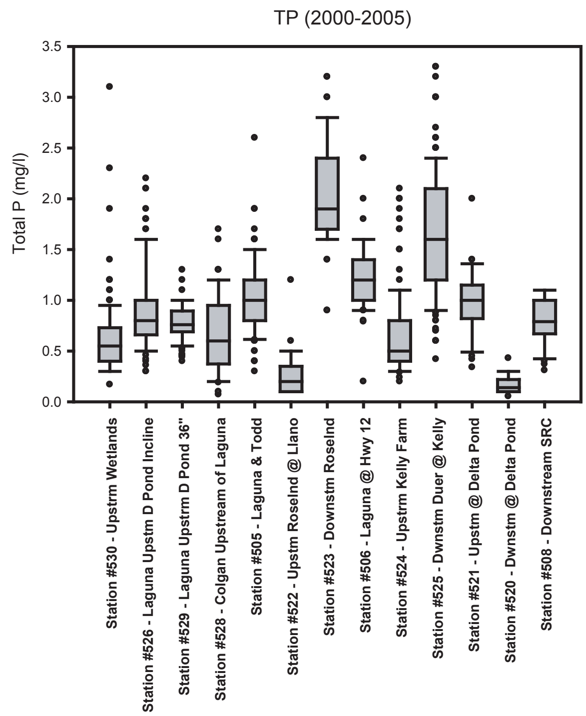


Figure 5-37 TP concentrations for 2000-2005 by sampling locations

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.

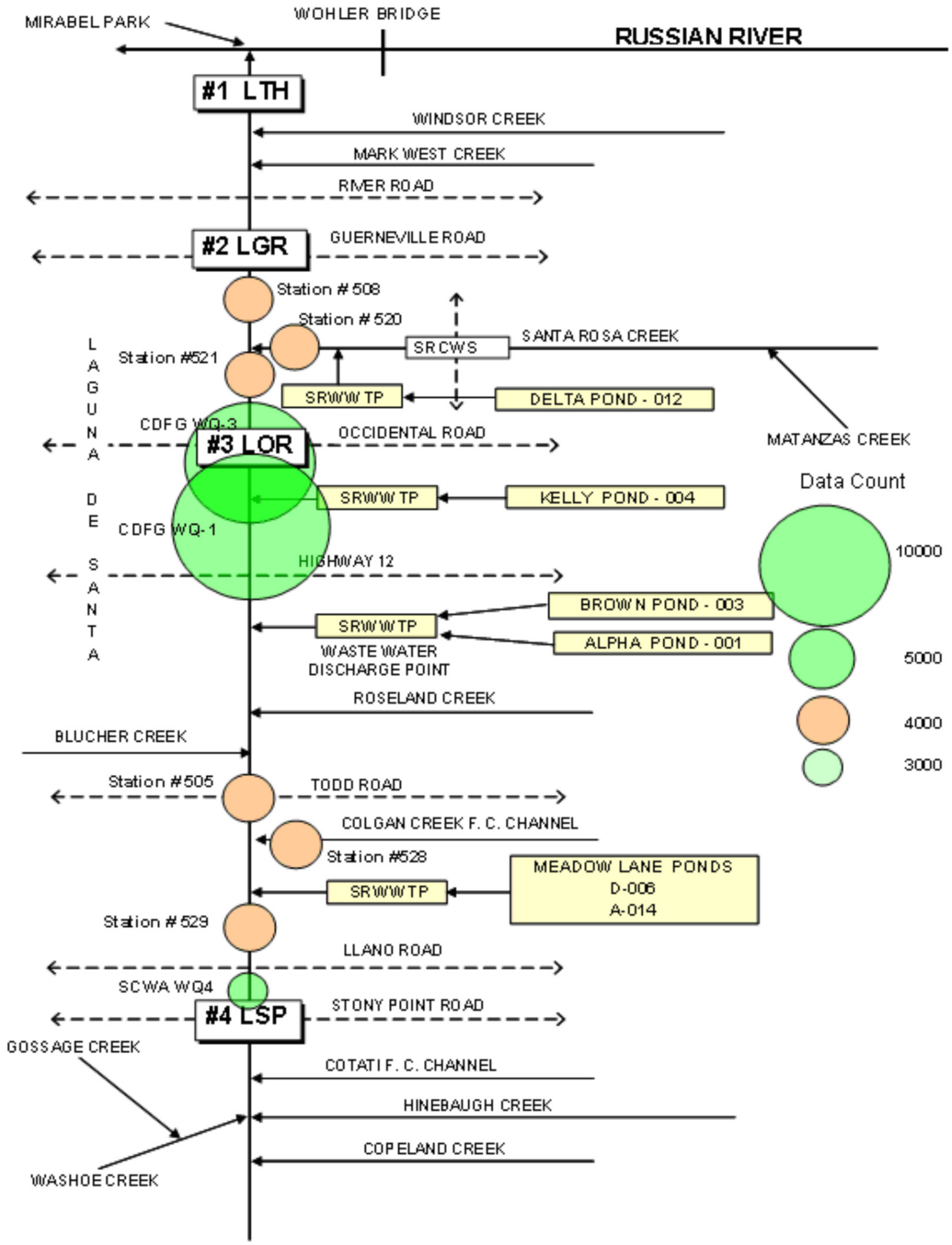


Figure 5-38 Locations and total number of data collected for dissolved oxygen.
Short-interval (15 or 30 minutes) DO monitoring
Orange: City of Santa Rosa (spring/winter 2005 and 2006)
Green: *Ludwigia* Control Project team (summer 2005 and 2006)

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.

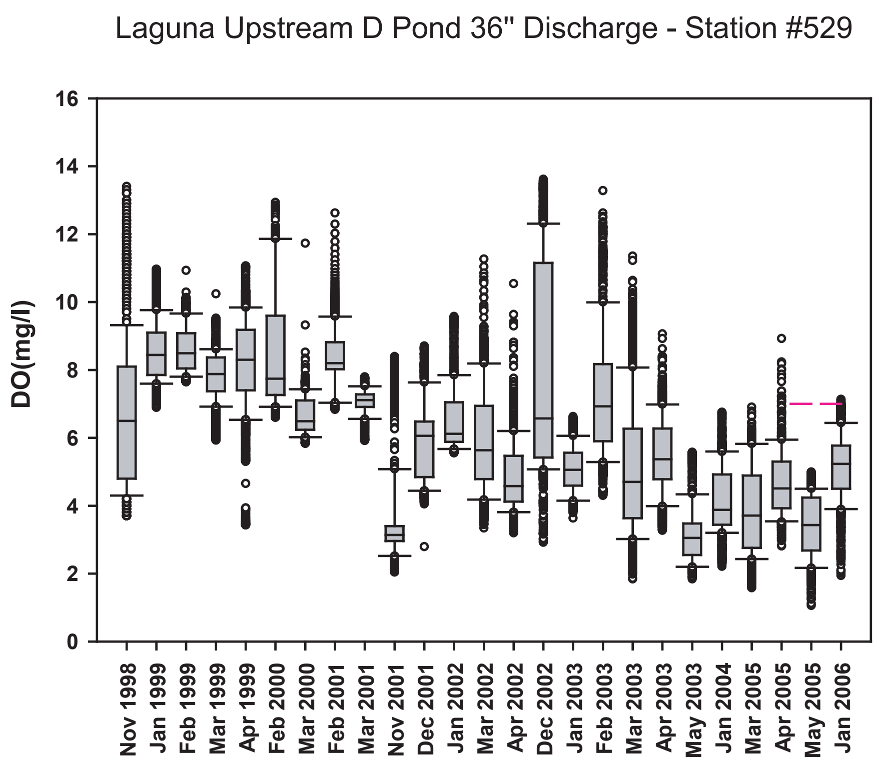


Figure 5-39 Range of DO concentrations by sampling months at Laguna upstream of D Pond 36" discharge

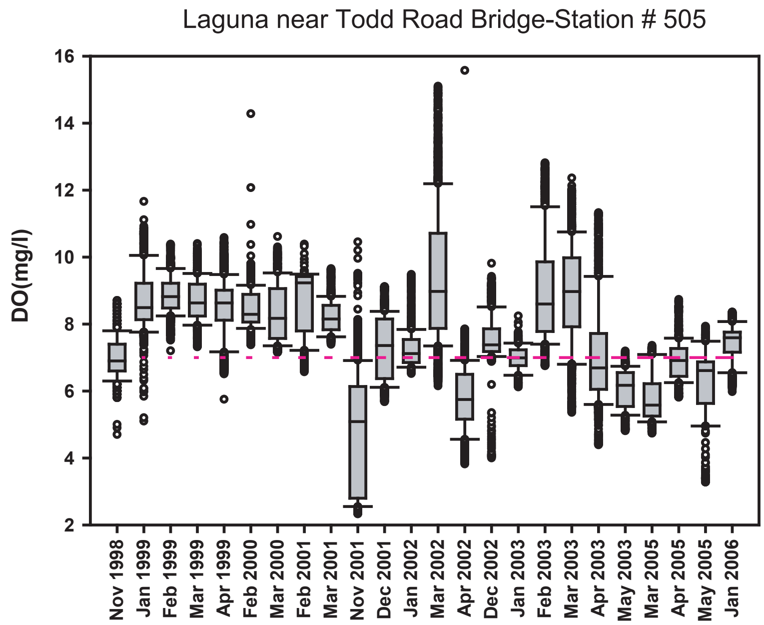


Figure 5-40 Range of DO concentrations at Laguna near Todd Road bridge

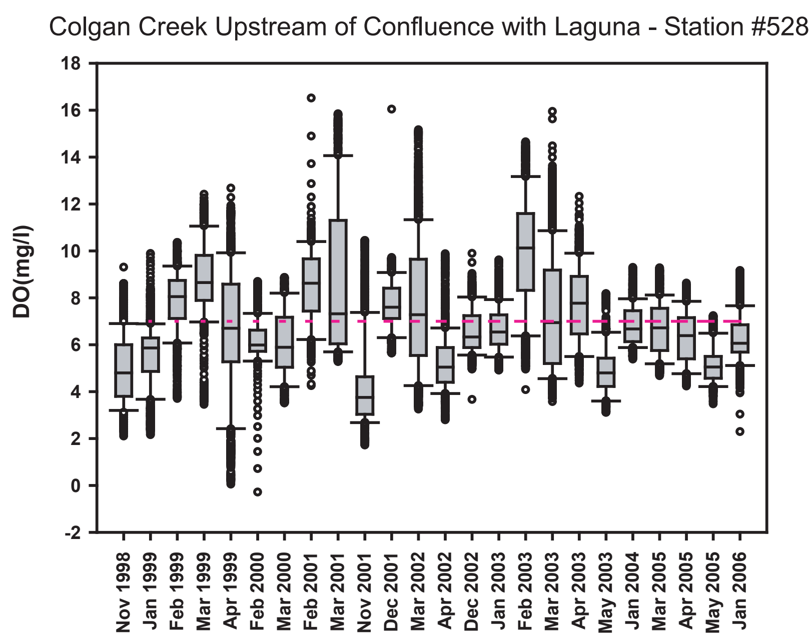


Figure 5-41 DO at Colgan Creek upstream of confluence with Laguna

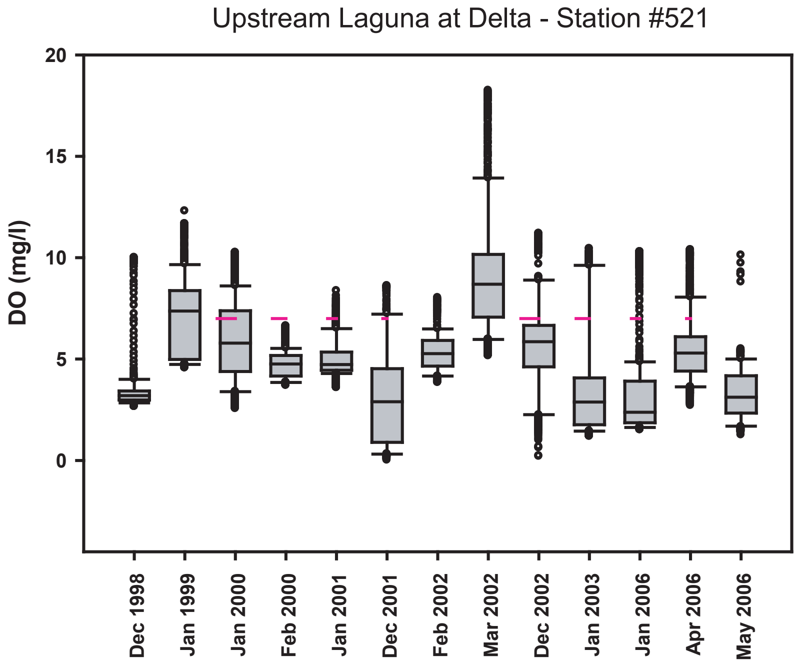


Figure 5-42 DO at Laguna upstream of Delta Pond

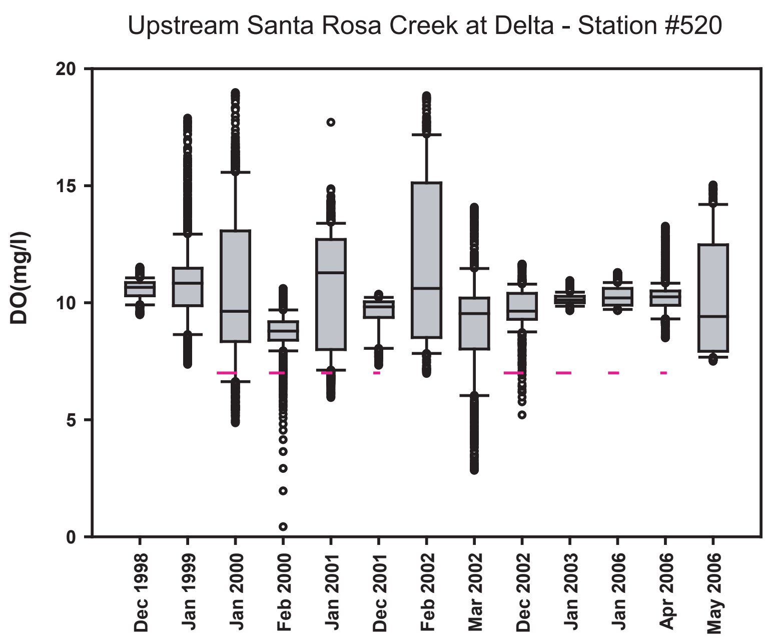


Figure 5-43 DO at Laguna near Santa Rosa Creek

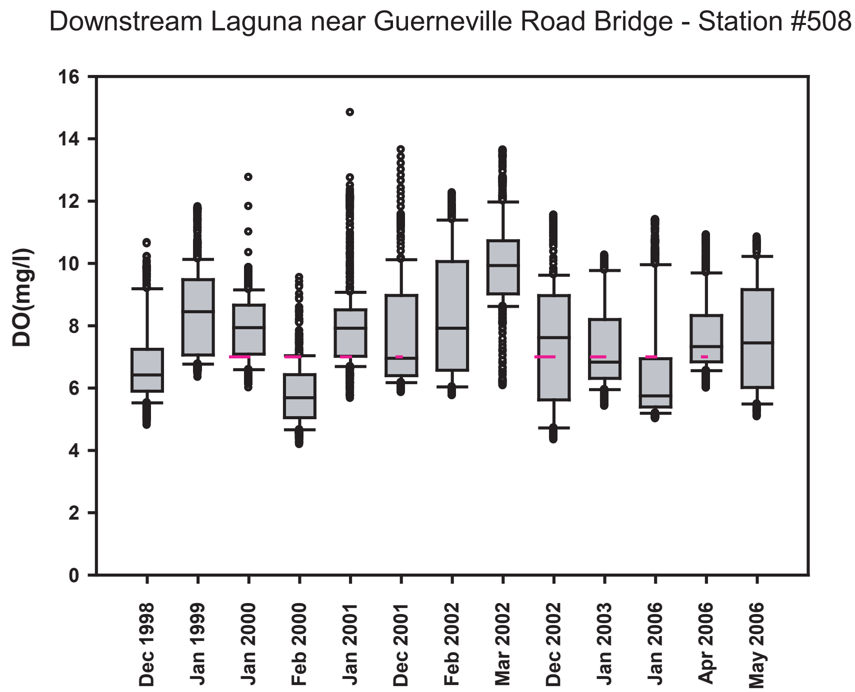


Figure 5-44 DO at Laguna near Guerneville Road

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.

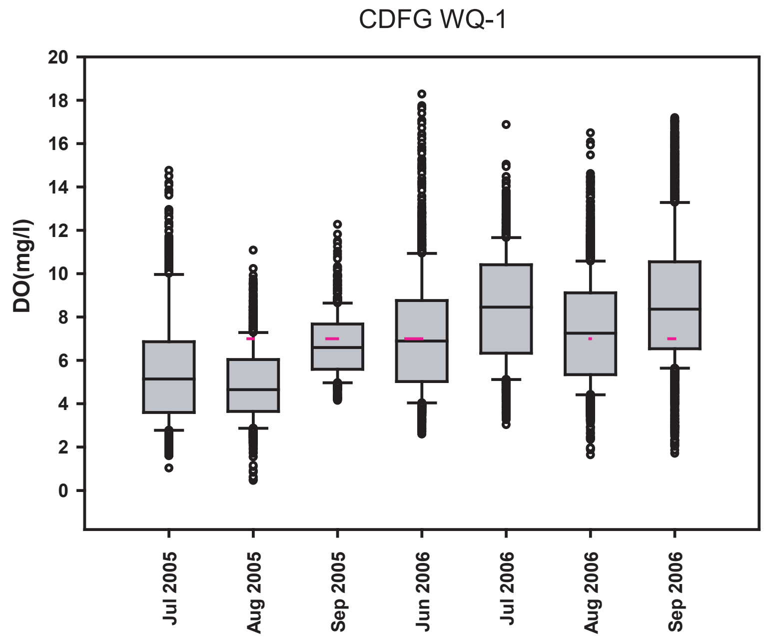


Figure 5-45 DO at CDFG WQ-1 during summer 2005 and 2006

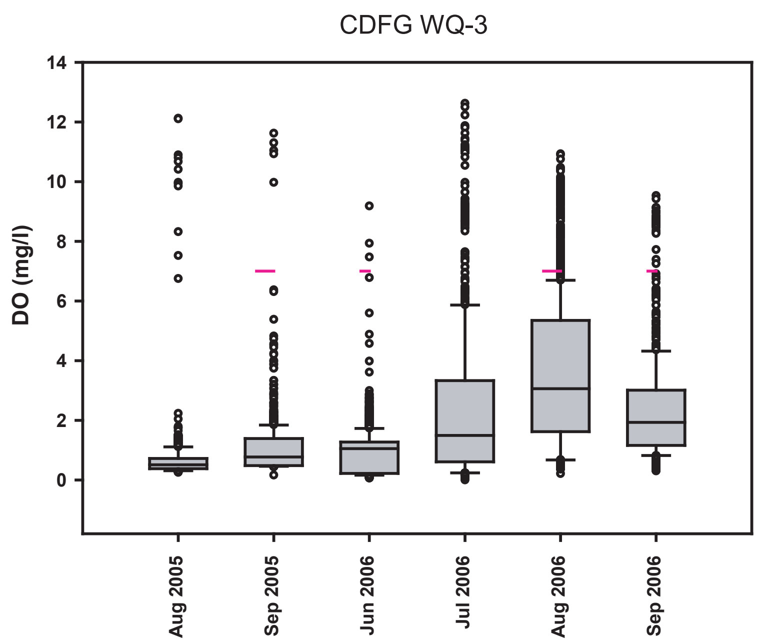


Figure 5-46 DO at CDFG WQ-3 during summer 2005 and 2006

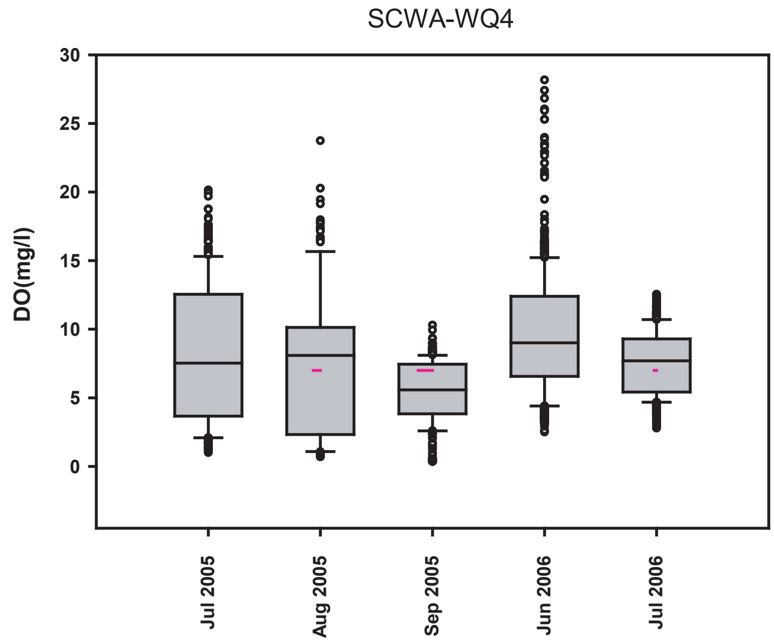


Figure 5-47 DO at SCWA-WQ4 during summer 2005 and 2006

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.

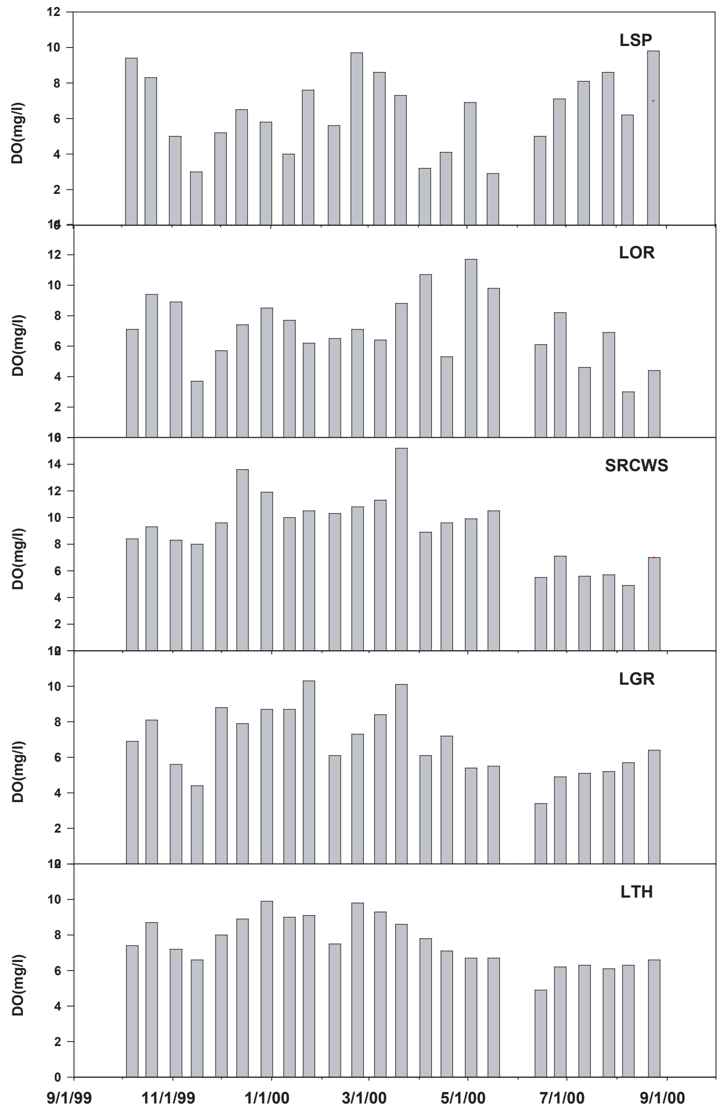


Figure 5-48 Seasonal Pattern of DO

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

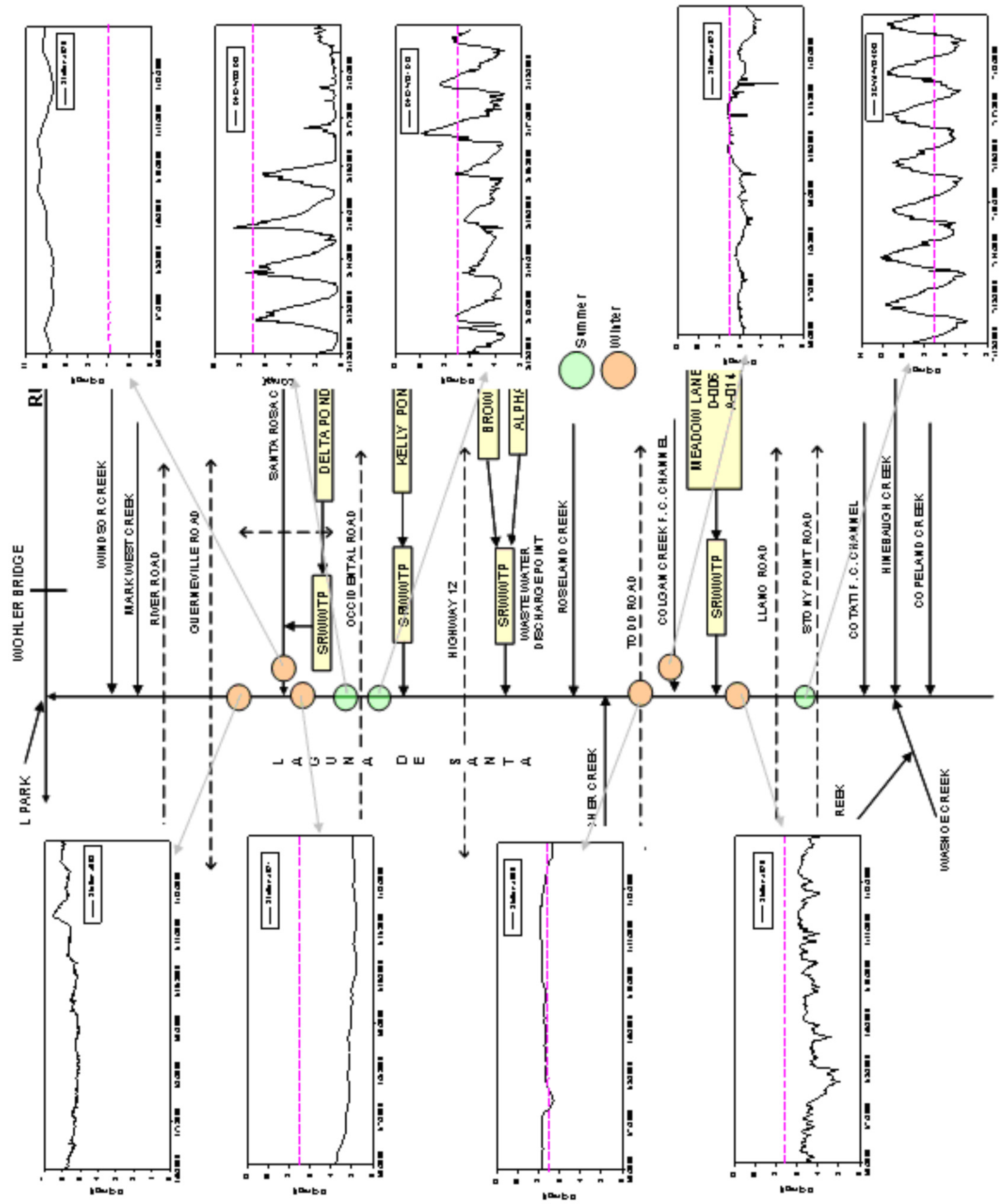


Figure 5-49 Examples of DO diurnal cycle at various locations of Laguna during winter and summer season respectively.

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.

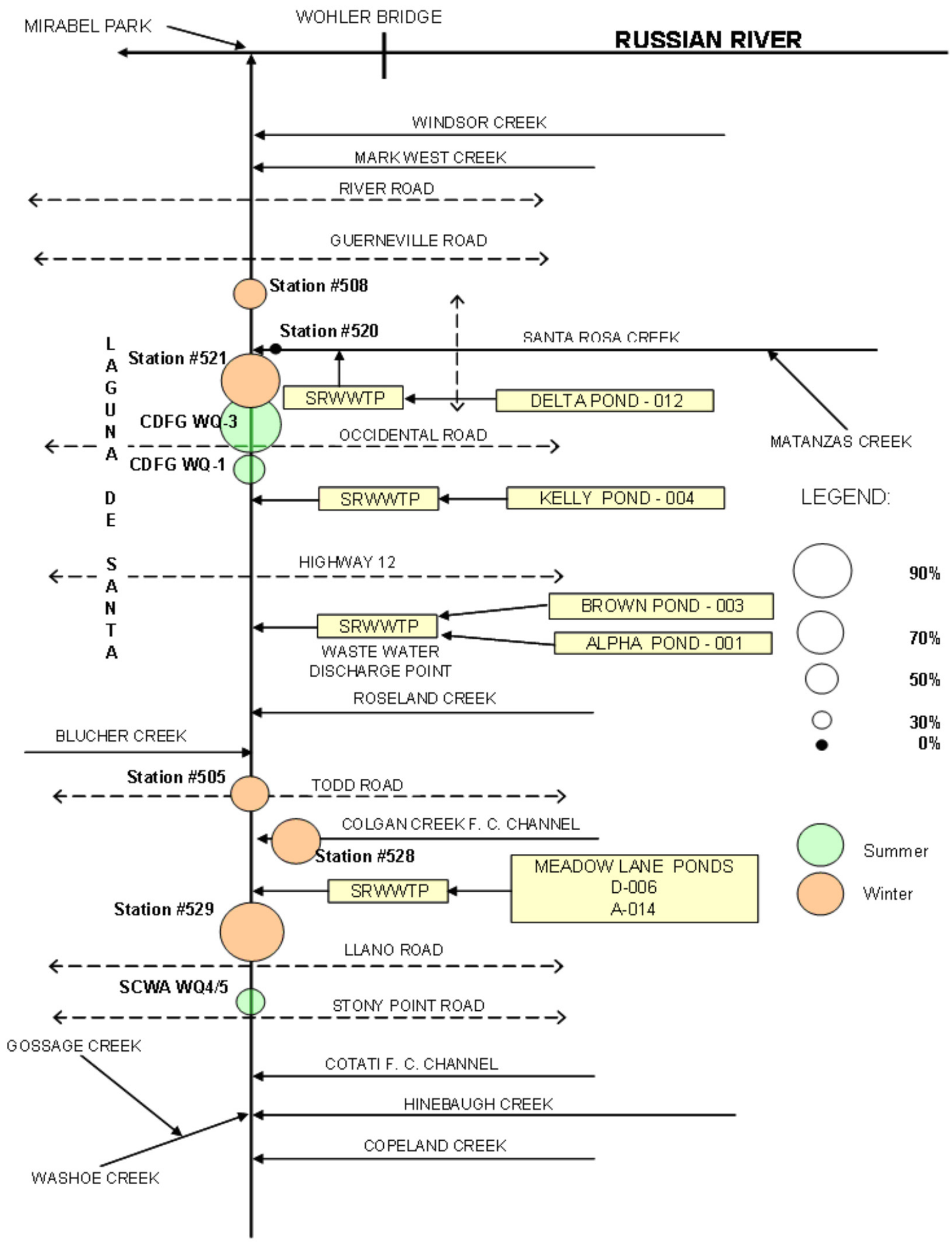


Figure 5-50 Percent of time below Basin Plan Objective (7 mg/l)
for all the samples collected in 2005 and 2006

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.

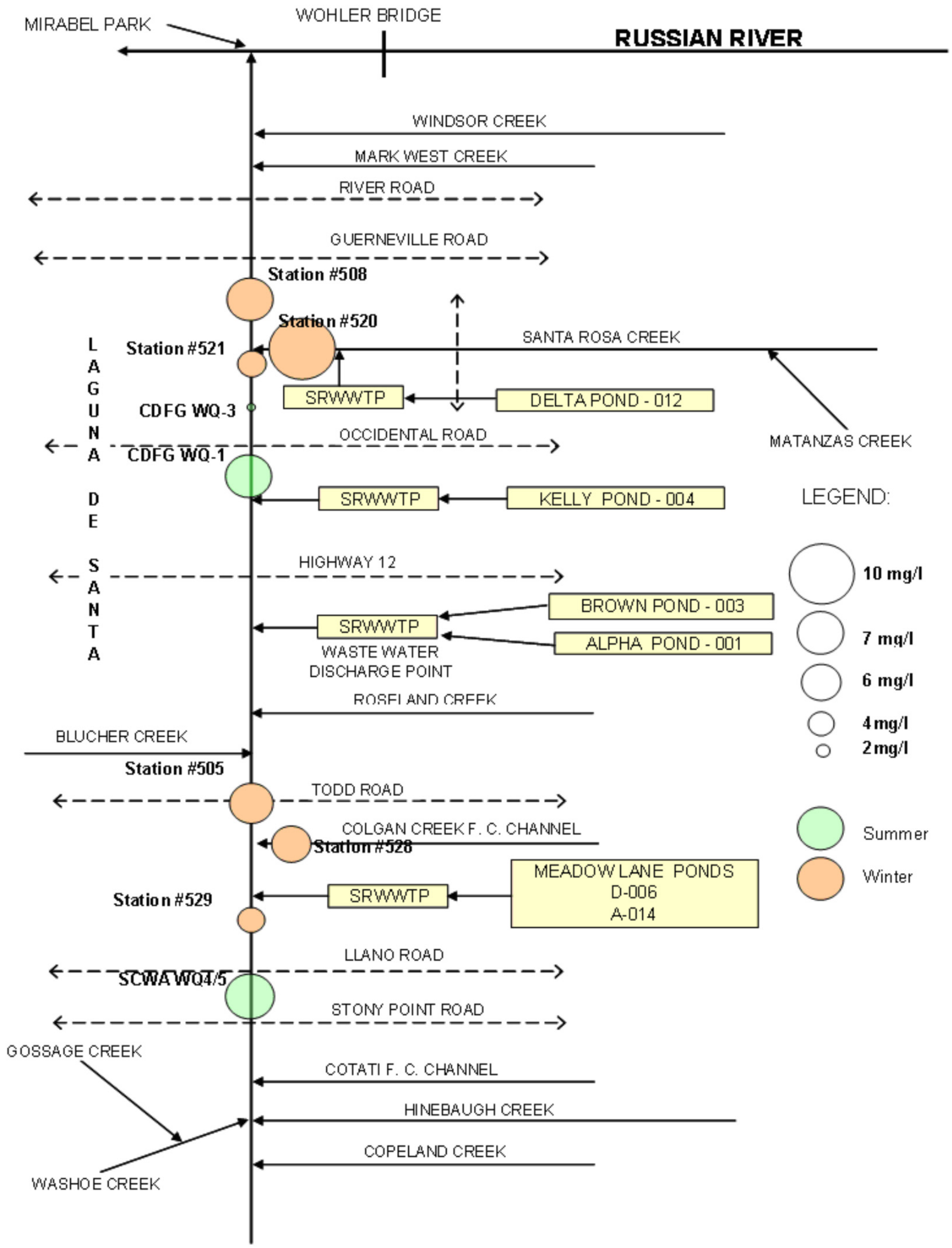


Figure 5-51 Median (50th percentile) DO concentrations
for all the short-interval samples collected in 2005 and 2006.

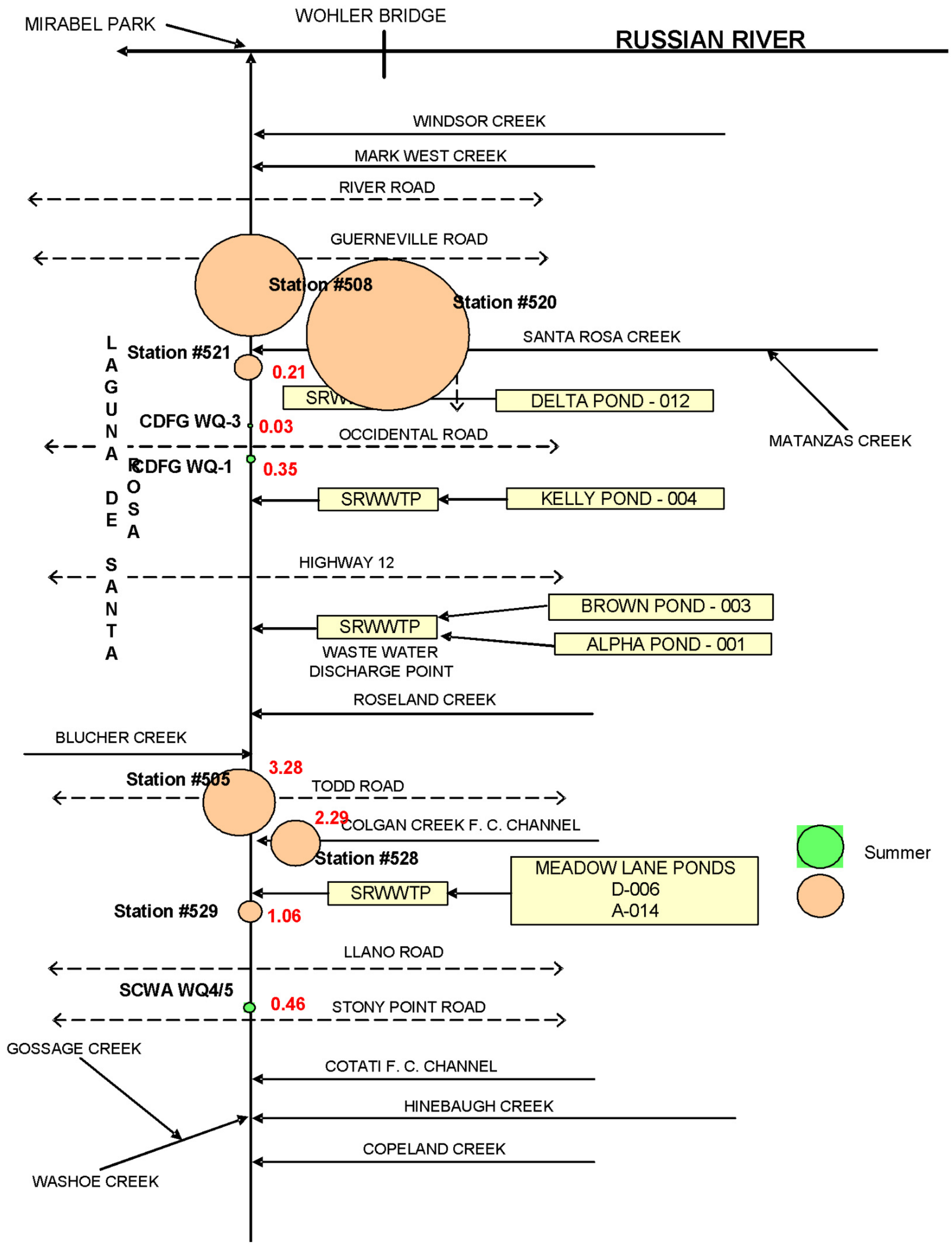


Figure 5-52 Minimum DO observed in 2005 and 2006

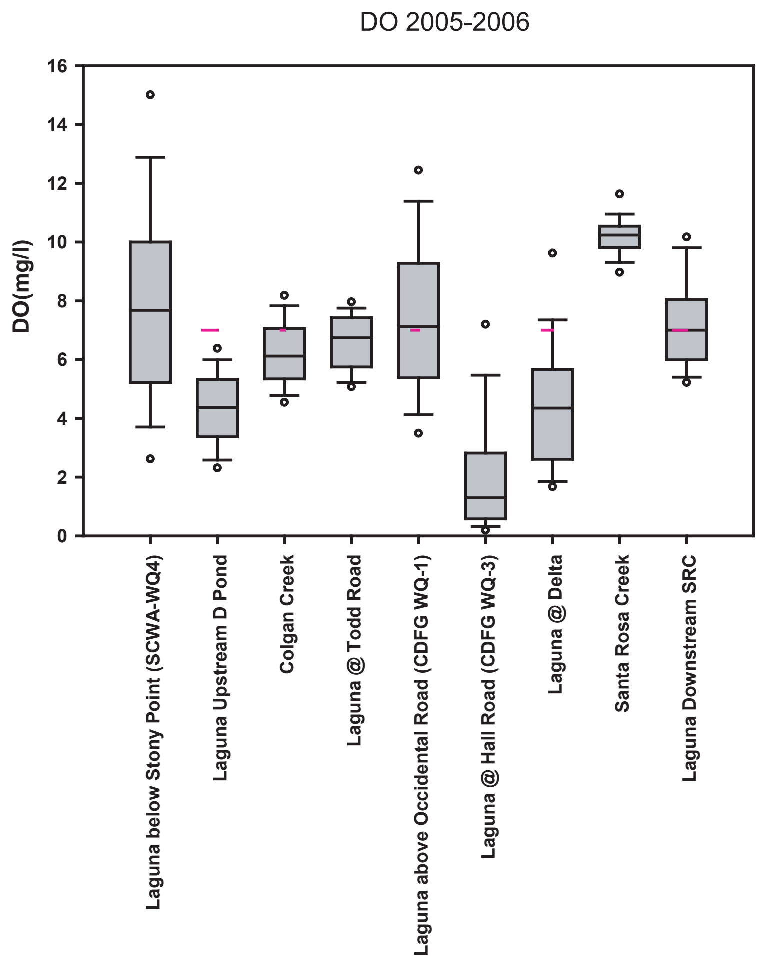


Figure 5-53 Ranges of DO observed in 2005 and 2006 at the continuously monitored locations (number of samples were shown in Figure 5-38)

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.

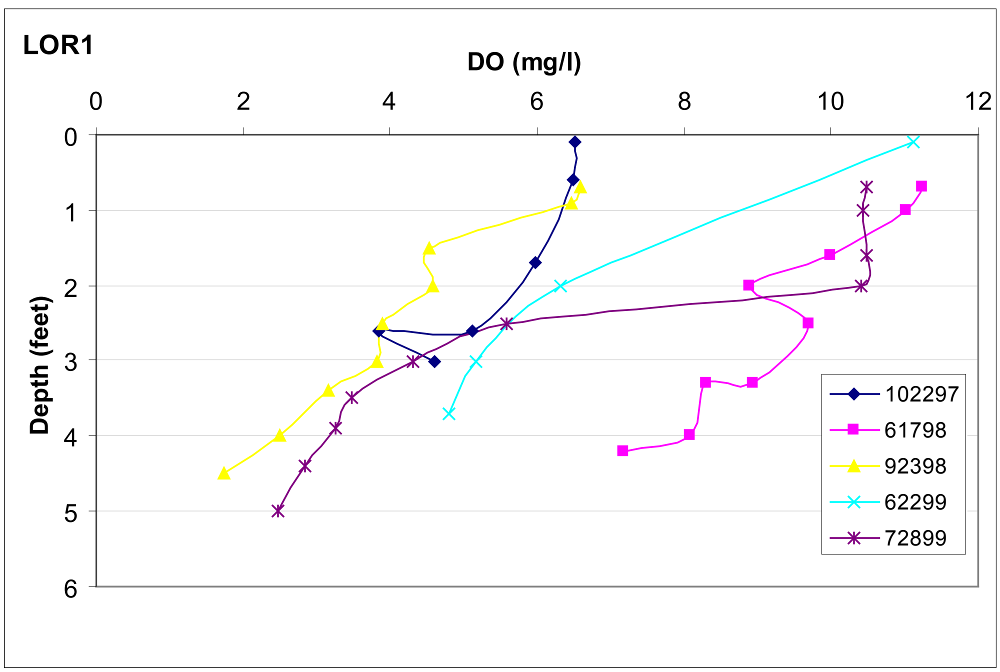


Figure 5-54 DO profile at LOR1 for summer 97, 98 and 99
(Otis, 2006)

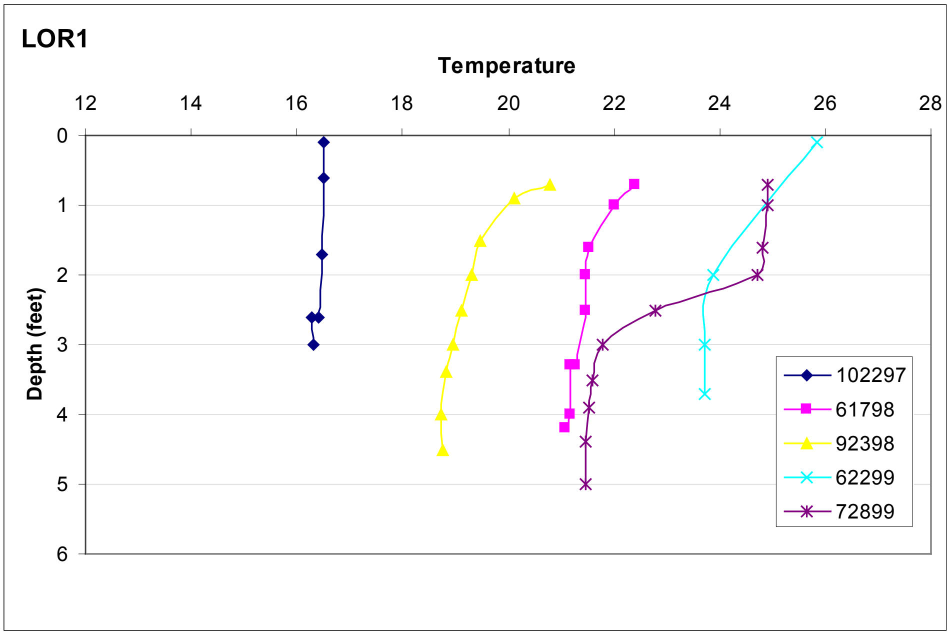


Figure 5-55 Temperature profile at LOR1 for summer 97, 98 and 99
(Otis, 2006)

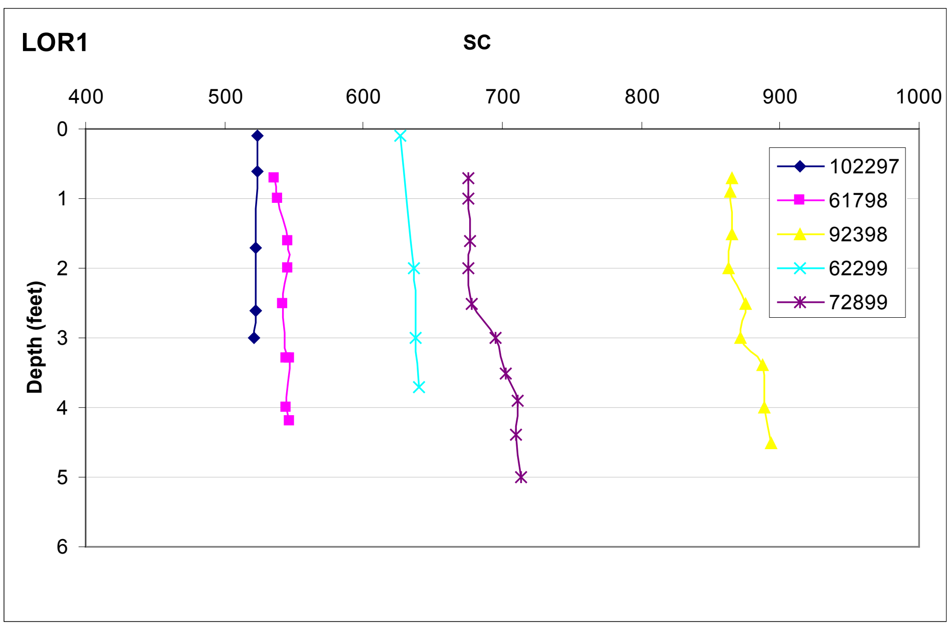


Figure 5-56 Specific conductivity profile at LOR1 for summer 97, 98 and 99
(Otis, 2006)

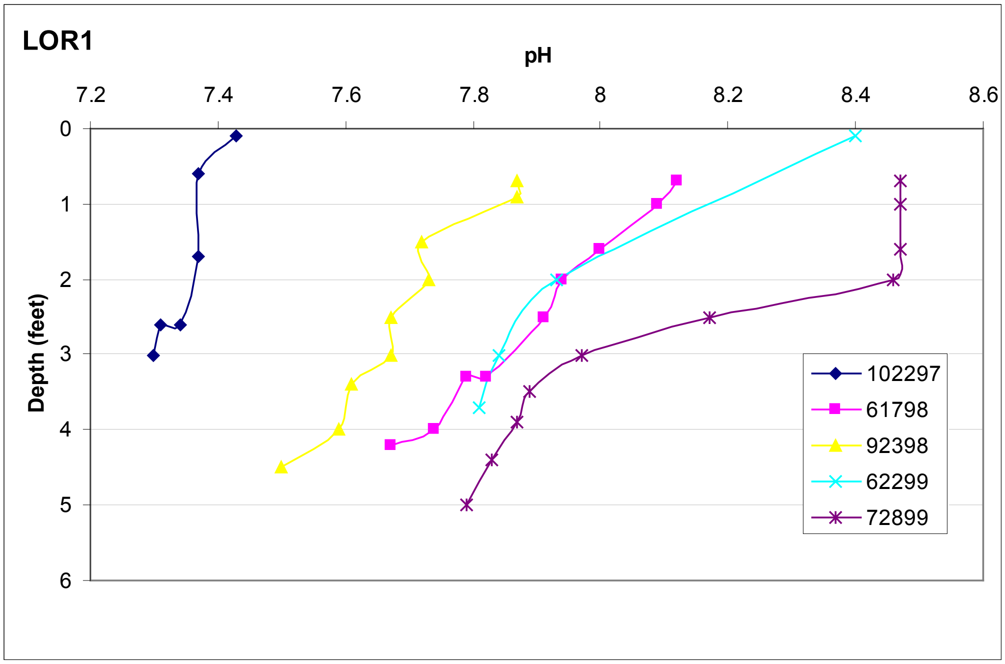


Figure 5-57 pH profile at LOR1 for summer 97, 98 and 99
(Otis, 2006)

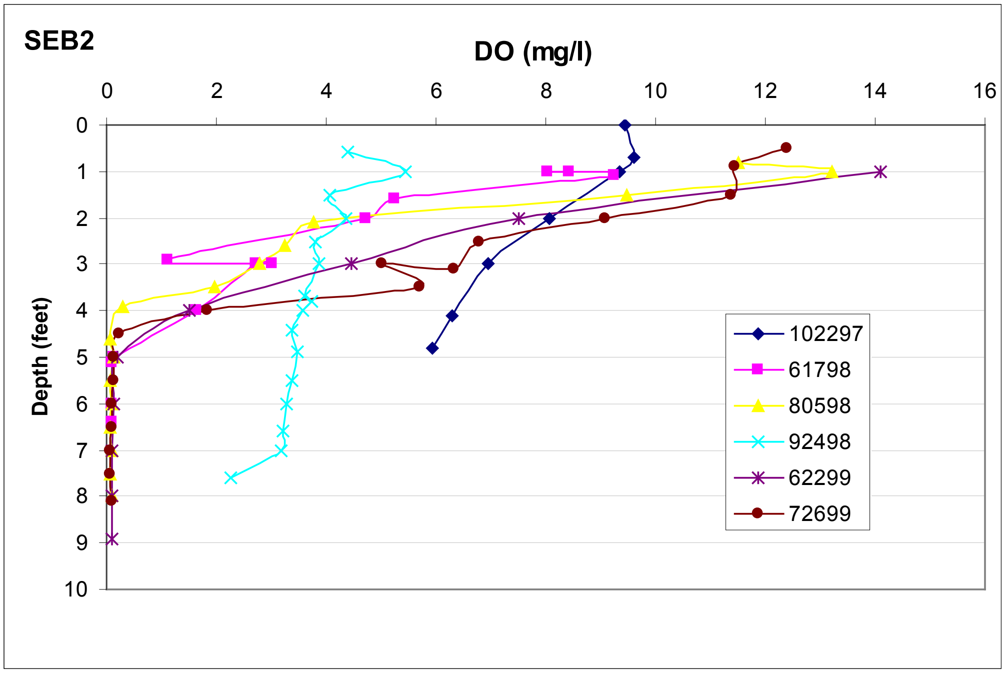


Figure 5-58 DO profile at SEB2 for summer 97, 98 and 99
(Otis, 2006)

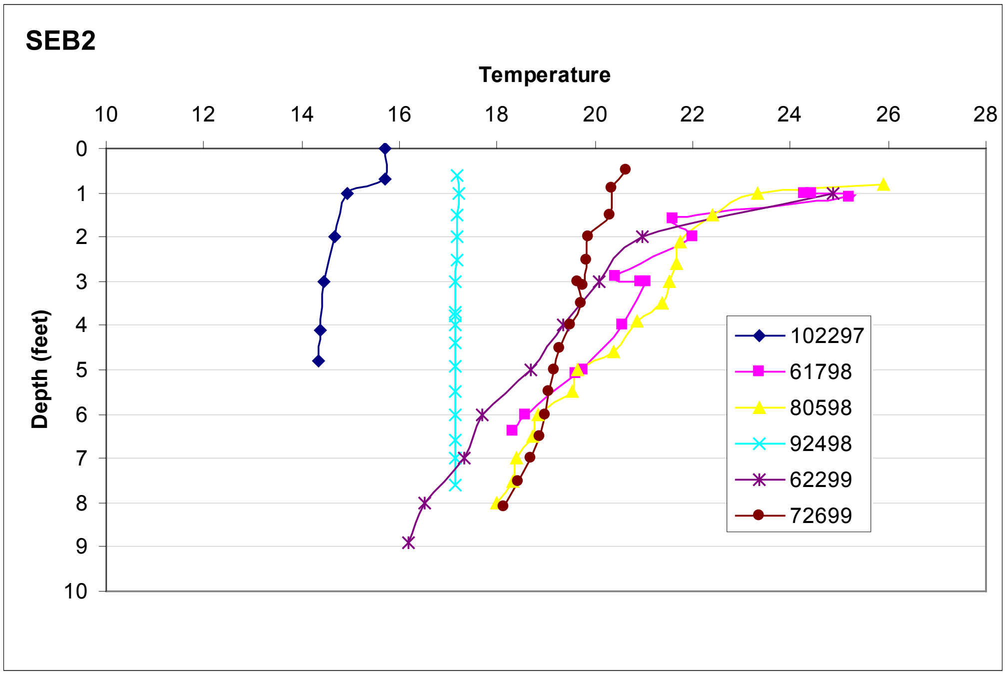


Figure 5-59 Temperature profile at SEB2 for summer 97, 98 and 99
(Otis, 2006)

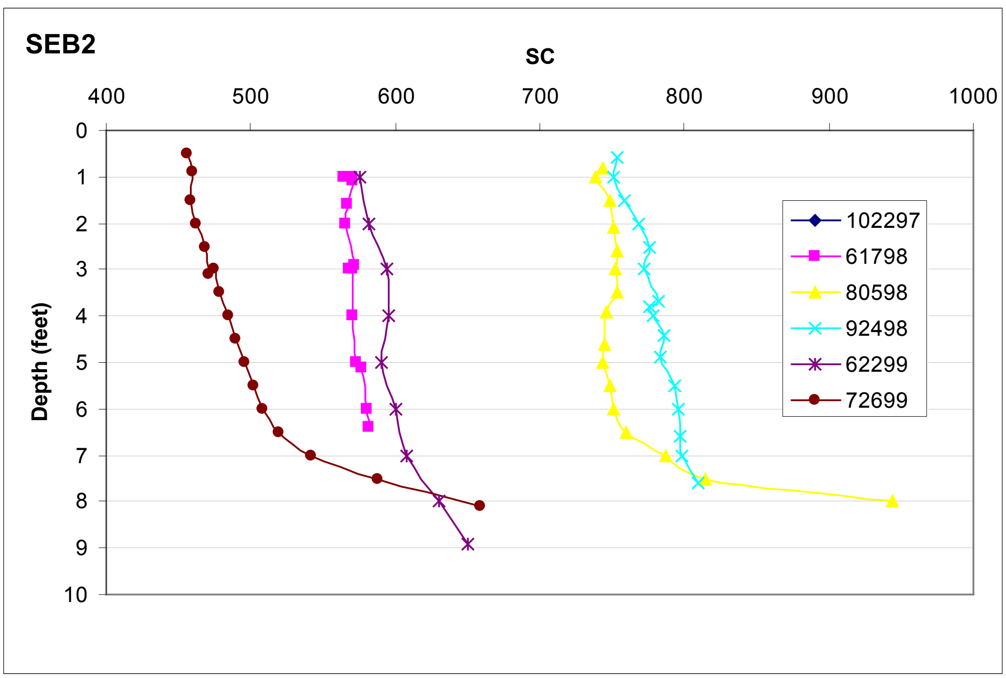


Figure 5-60 Specific conductivity profile at SEB2 for summer 97, 98 and 99
(Otis, 2006)

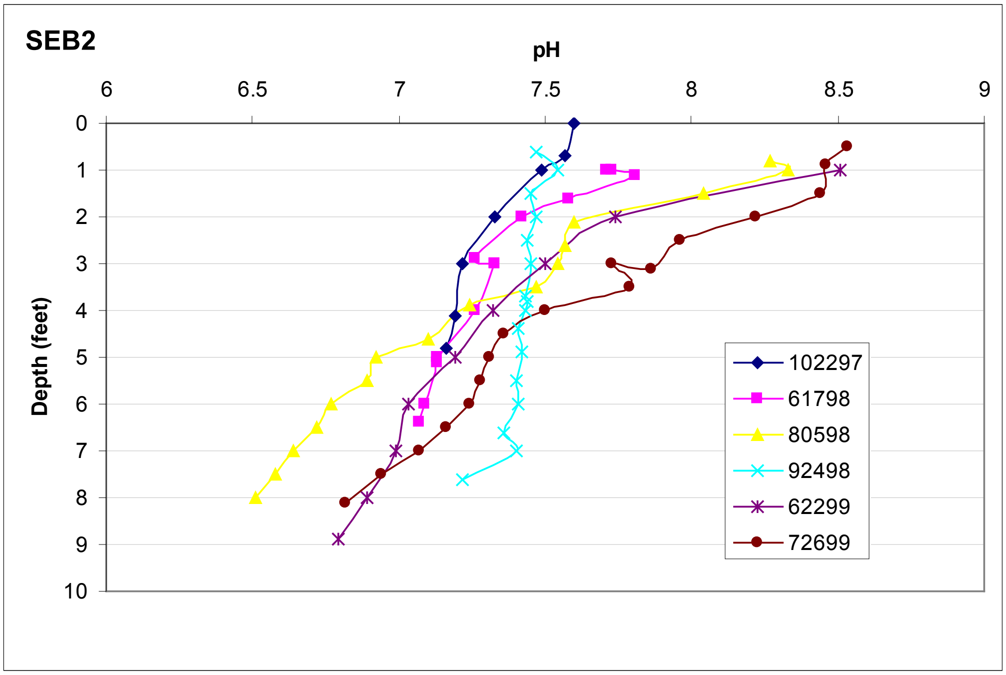


Figure 5-61 pH profile at SEB2 for summer 97, 98 and 99
(Otis, 2006)

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.

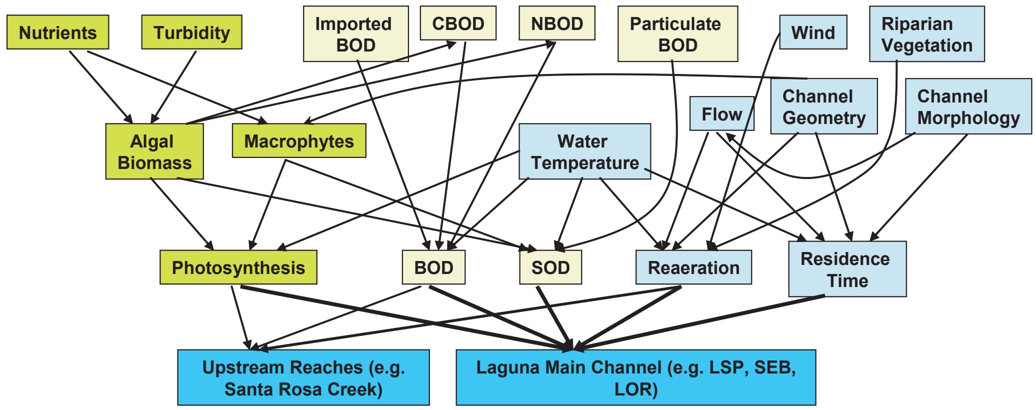


Figure 5-62 Physical, biological and chemical factors impacting DO dynamics

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).

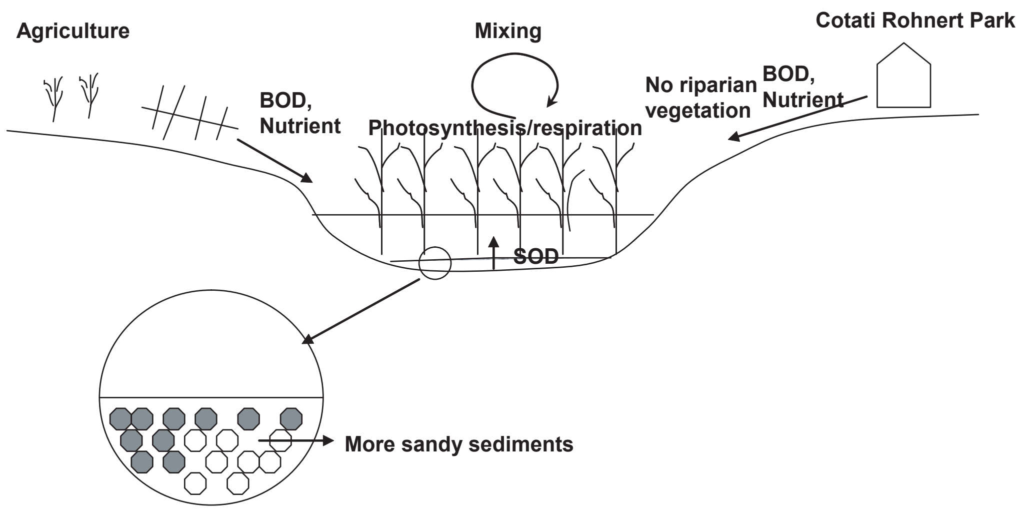


Figure 5-63 Preliminary DO conceptual model at the Laguna at Stony Point (LSP)

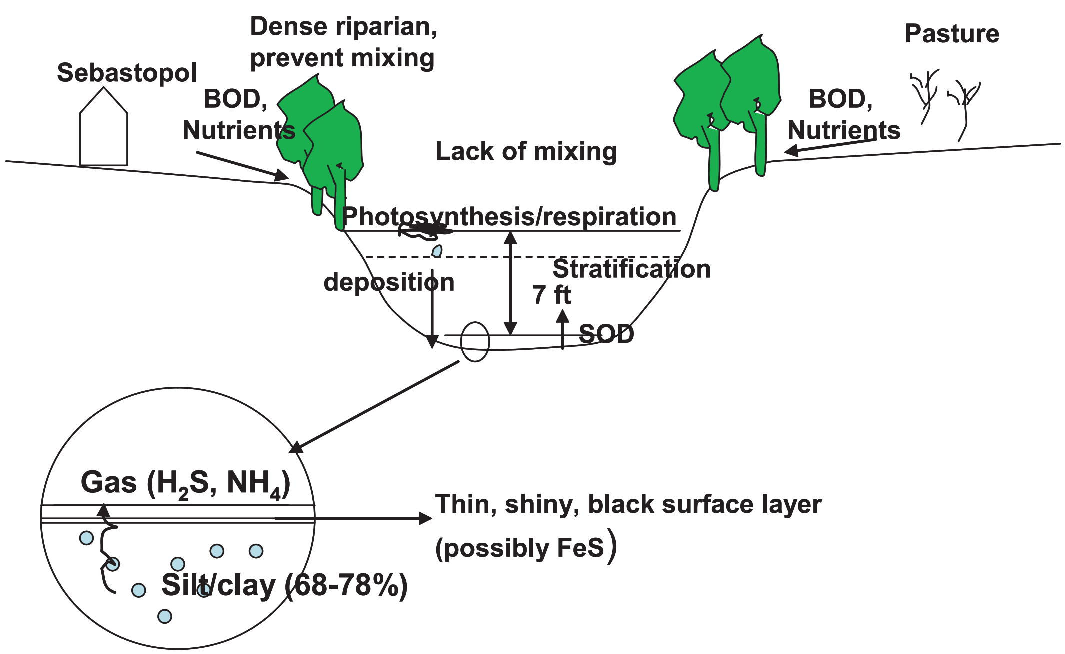


Figure 5-64 Preliminary DO conceptual model for the Laguna at Sebastopol Pond (SEB)

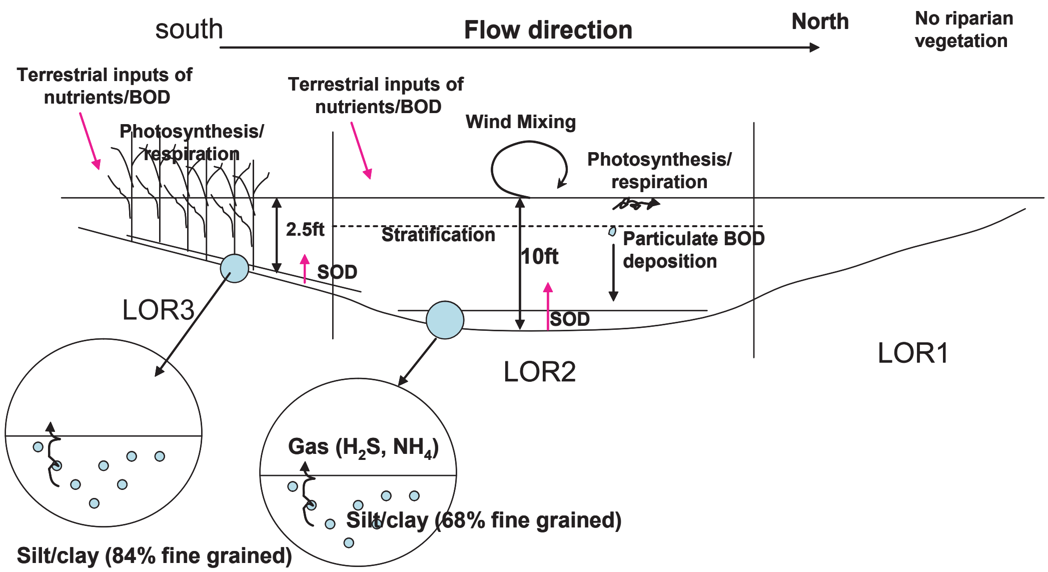


Figure 5-65 Preliminary conceptual model for the Laguna at Occidental Road (LOR)

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.