Laguna de Santa Rosa Sediment Budget

Prepared for

U.S. EPA Region 9 and

North Coast Regional Water Quality Control Board

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Contents

1 Introduction....1
2 Approach to Sediment Budget....5
3 Watershed Delineation and Spatial Data....9
4 Monitoring Data and Calculated Loads....21
  4.1 Loads Estimated from SSC Monitoring....21
  4.2 Sediment Load Estimated from Turbidity....25
    4.2.1 Prior Estimates....25
    4.2.2 Recalculated Turbidity-based Estimates....28
  4.3 Sedimentation in Matanzas Reservoir....30
5 Upland Sediment Loads....31
  5.1 Sheet and Rill Erosion....31
  5.2 Landscape Connectivity and Upland Sediment Delivery....32
  5.3 Upland Loads by Source....37
6 Other Sediment Load Sources....41
  6.1 Roads....41
  6.2 Channel Incision, Gully Erosion, and Landslides....43
  6.3 Soil Creep and Colluvial Bank Erosion....45
  6.4 Backwater from the Russian River....48
7 Sediment Sinks....49
  7.1 Sedimentation Losses....49
    7.1.1 Reservoirs and Debris Basins....49
    7.1.2 Sedimentation in the Laguna de Santa Rosa and Floodplain....49
  7.2 Channel Maintenance Activities....51
  7.3 Export to the Russian River....51
8 Sediment Budget for Current Conditions....53
9 Sediment Budget Prior to European Settlement....59
10 References....63

Appendix A Application of Modified PSIAC Method for Estimating Total Sediment Yield
Appendix B Application of RUSLE Method for Estimating Upland Sediment Loss
Appendix C Comparison of PSIAC and RUSLE Results
Appendix D RUSLE Application for Conditions prior to European Settlement

Tables

Table 2-1. Sediment Source and Sink Categories Addressed in this Report ... 6

Table 3-1. Land Cover by Subbasin from 2013 Cropland Data Layer (acres) ... 15

Table 3-2. Land Cover by Subbasin from 2013 Cropland Data Layer (percentage) ... 16

Table 3-3. Land Cover by Subbasin from 2006 National Land Cover Database (acres) ... 17

Table 4-1. Comparison of USGS Load Estimates for WY 2006-2008 to PSIAC Estimates at USGS Gage Stations (tons/yr) ... 22

Table 4-2. Comparison of Load Estimates based on USGS Monitoring ... 23

Table 4-3. Sediment Loads Calculated from Revised Turbidity – SSC Relationships ... 30

Table 5-1. RUSLE Average Annual Field-Scale Soil Loss Rates by Subbasin ... 31

Table 5-2. IC-Based vs. Area-Based Composite Sediment Delivery Ratio Estimates and RUSLE Delivered Upland Sediment Yield by Subbasin ... 37

Table 5-3. RUSLE Upland Delivered Sediment Yield Estimates by Land Use Group ... 38

Table 6-1. Road Sediment Source Analysis for Laguna de Santa Rosa Watershed ... 42

Table 6-2. Sum of Colluvial Bank Erosion, Gully Erosion, and Landslide Loading Estimates for the Laguna de Santa Rosa Watershed ... 48

Table 7-1. Sediment Removal for the SCWA Stream Maintenance Program ... 52

Table 8-1. Sediment Balance for Current Conditions in the Laguna de Santa Rosa Watershed by Subbasin (short tons/yr) ... 55

Table 9-1. Land Cover prior to European Settlement ... 59

Table 9-2. Comparison of Estimated Sediment Budgets for the Laguna de Santa Rosa Watershed for pre-European Settlement and Current Conditions ... 62

Figures

Figure 1-1. The Laguna de Santa Rosa Watershed 3

Figure 3-1. Delineation of Subwatersheds and Location of USGS Gages for the Laguna de Santa Rosa Watershed 10

Figure 3-2. Topography of the Laguna de Santa Rosa Watershed 11

Figure 3-3. Laguna de Santa Rosa Floodplain based on FEMA 100-year Flood Delineation 12

Figure 3-4. Current Land Use/Land Cover for the Laguna de Santa Rosa Watershed (USDA Cropland Data Layer, 2013) 19

Figure 3-5. Land Use/Land Cover for the Laguna de Santa Rosa Watershed (National Land Cover Database, 2006) 20

Figure 4-1. Example Rating Curve from PWA (2004a) 26

Figure 4-2. Relationship of SSC to Turbidity (NTU) in Sonoma Creek (from Appendix D to Sonoma Ecology Center, 2006) 29

Figure 5-1. Example Connectivity Estimates for Vineyard Area in Windsor Creek Watershed 33

Figure 5-2. Index of Connectivity (IC) for the Laguna de Santa Rosa Watershed 35

Figure 5-3. IC-based Sediment Delivery Ratio (SDR) for the Laguna de Santa Rosa Watershed 36

Figure 5-4. RUSLE Sediment Yield Estimates (with IC-based SDR) for the Laguna de Santa Rosa Watershed by Land Use 39

Figure 5-5. Detail from RUSLE Sediment Yield Map, North Side of Santa Rosa, CA 40

Figure 6-1. Example of Enlarging Gullies upstream of Matanzas Reservoir 43

Figure 6-2. Streams Evaluated for Colluvial Bank Erosion in the Laguna de Santa Rosa Watershed 47

Figure 8-1. Summary of the Laguna de Santa Rosa Sediment Budget for Current Conditions 57

Figure 9-1. Land Cover prior to European Settlement of the Laguna de Santa Rosa Watershed (Butkus, 2011) 60

Acronyms

AF	acre-feet
AF/mi^2/yr	acre-feet per square mile per year
AF/yr	acre-feet per year
CDL	Cropland Data Layer
cfs	cubic feet per second
cm	centimeters
cm/yr	centimeters per year
d	diameter
DEM	digital elevation model
FEMA	Federal Emergency Management Agency
ft	feet
GIS	geographical information system
IC	Index of Connectivity
kg/m^3	kilograms per cubic meter
km^2	square kilometers
lb/ft^3	pounds per cubic foot
lb/sec	pounds per second
lb/yd^3	pounds per cubic yard
LiDAR	Light Detection and Ranging
µm	micrometers
m	meters
m^3/yr	cubic meters per year
mg/L	milligrams per liter
mi^2	square miles
mm	millimeters
mm/yr	millimeters per year
MUSLE	Modified Universal Soil Loss Equation
NA	not applicable
NASS	National Agricultural Statistics Service
NCRWQCB	North Coast Regional Water Quality Control Board

ND	no data
NHDPlus	National Hydrography Dataset Plus
NLCD	National Land Cover Database
NTU	nephelometric turbidity units
NWIS	National Water Information System
PSIAC	Pacific Southwest Inter-Agency Committee
PWA	Philip Williams & Associates
RUSLE	Revised Universal Soil Loss Equation
SCWA	Sonoma County Water Agency
SDR	sediment delivery ratio
SSC	suspended sediment concentration
SSURGO	Soil Survey Geographic
t/ac/yr	tons per acre per year
t/mi/yr	tons per mile per year
t/mi^2/yr	tons per square mile per year
tons/AF	tons per acre-foot
tons/yd^3	tons per cubic yard
tons/yr	tons per year
TMDL	total maximum daily load
TSS	total suspended solids
UCL	upper confidence limit
USDA	U.S. Department of Agriculture
USEPA	U.S. Environmental Protection Agency
USGS	U.S. Geological Survey
yd^3	cubic yards
yd^3/yr	cubic yards per year

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1 Introduction

Tetra Tech is providing support to the U.S. Environmental Protection Agency (USEPA) Region 9 and California's North Coast Regional Water Quality Control Board (NCRWQCB) for completion of total maximum daily loads (TMDLs) for the Laguna de Santa Rosa in Sonoma County, CA. The Laguna de Santa Rosa watershed is located within the 8-digit Hydrologic Unit 18010110 (Russian Watershed), and occupies a total area of 255.5 square miles (163, 528 acres), including the city of Santa Rosa (Figure 1-1). Note that the streams shown on this and subsequent maps are the medium resolution streams from the National Hydrography Dataset Plus (NHDPlus, version 2; McKay et al., 2012). The medium resolution coverage is used to provide a clear picture of major drainages, but various small and mostly intermittent stream channels are omitted. As described below in Section 3, the area of interest for this study is confined to the portion of the Laguna de Santa Rosa watershed upstream of Ritchurst Knob, a bedrock constriction just downstream of the confluence with Windsor Creek that defines the slowly moving portion of the Laguna de Santa Rosa. The area of the watershed upstream of Ritchurst Knob is 251.7 square miles (161,075 acres).

The Laguna de Santa Rosa is the largest tributary to the Russian River. It is home to threatened and endangered anadromous fish species and contains the largest freshwater wetlands complex on the northern California coast. The Laguna de Santa Rosa is a series of low gradient channels and wetlands that developed along the western edge of a tectonic depression formed between two tilting crustal blocks (the Santa Rosa block and Sebastopol block). Over geologic time, tilting, uplift, and erosion of these blocks resulted in erosion of the higher elevations in the watershed with deposition in alluvial fans on the Santa Rosa Plain to the east of the Laguna and sedimentation in the Laguna itself. While these represent natural geologic processes, land use changes in the Laguna and widespread channelization of streams on the Santa Rosa Plain have resulted in greater sediment erosion and greater delivery of eroded sediment into the Laguna de Santa Rosa.

The watershed of the Laguna de Santa Rosa consists of three Hydrologic Subareas within the Russian River Hydrologic Unit:

114.21	Laguna Hydrologic Subarea
114.22	Santa Rosa Hydrologic Subarea
114.23	Mark West Hydrologic Subarea

The Basin Plan (NCRWQCB, 2011) assigns existing and potential beneficial uses to these Hydrologic Subareas as follows:

Municipal and Domestic Supply (MUN): existing for 114.22 and 114.23; potential for 114.21
Agricultural Supply (AGR): existing for all three subareas.
Industrial Service Supply (IND): existing for all three subareas.
Industrial Process Supply (PRO): potential for all three subareas.
Groundwater Recharge (GWR): existing for all three subareas.
Freshwater Replenishment (FRSH): existing for 114.21 and 114.23.
Navigation (NAV): existing for all three subareas.
Hydropower Generation (POW): existing for 114.21; potential for 114.22 and 114.23.
Water Contact Recreation (REC-1): existing for all three subareas.
Non-Contact Water Recreation (REC-2): existing for all three subareas.
Commercial and Sport Fishing (COMM): existing for all three subareas.
Warm Freshwater Habitat (WARM): existing for all three subareas.
Cold Freshwater Habitat (COLD): existing for all three subareas.
Wildlife Habitat (WILD): existing for all three subareas.

Rare, Threatened, or Endangered Species (RARE): existing for all three subareas.
Migration of Aquatic Organisms (MIGR): existing for all three subareas.
Spawning, Reproduction, and/or Early Development (SPWN): existing for all three subareas.
Shellfish Harvesting (SHELL): potential for all three subareas.
Aquaculture (AQUA): potential for all three subareas

Support for beneficial uses in the Laguna is threatened by a variety of interlocking historical and ongoing sources of impairment, including reduced storage capacity, low dissolved oxygen, elevated nutrients and temperatures, and overgrowth of the invasive aquatic weed, *Ludwigia* (Sloop et al., 2007). All three of the Hydrologic Subareas that constitute the Laguna de Santa Rosa watershed have been identified as impaired by sedimentation/siltation on the Clean Water Act Section 303(d) list (http://www.waterboards.ca.gov/northcoast/water_issues/programs/tmdls/303d/). Other impairment listings are present for dissolved oxygen, phosphorus, water temperature, aluminum, manganese, mercury, and indicator bacteria. These other impairments are variously related to excess loads and deposition of sediment in the Laguna de Santa Rosa. For instance, the sedimentation in the Laguna brings with it phosphorus and oxygen-consuming organic material. The accumulation of sediment and resulting infill and shallowing tends to raise water temperature, encourages the growth of *Ludwigia*, and creates conditions under which mercury methylation and release to the water column is more likely to occur. Thus, quantifying the sources and status of sediment in the system is a key component for the successful completion of the full suite of pending TMDLs for the Laguna de Santa Rosa – both for sediment and for other stressors.

The Basin Plan does not specify numeric targets for sediment; however, it does establish narrative objectives applicable to all inland surface waters (NCRWQCB, 2011): “The suspended sediment load and suspended sediment discharge rate of surface waters shall not be altered in such a manner as to cause nuisance or adversely affect beneficial uses.” Application of this narrative objective requires understanding how the sediment balance has been “altered” relative to natural conditions (defined as conditions prior to European settlement) and how the current sediment regime may “adversely affect” beneficial uses. The adverse effects have been previously documented and are summarized in Sloop et al. (2007).

This report documents the estimated sediment budget for current land use and pre-settlement conditions in the Laguna de Santa Rosa watershed, using a variety of methods. This information may be used to develop TMDL targets and load allocations for the protection of beneficial uses.

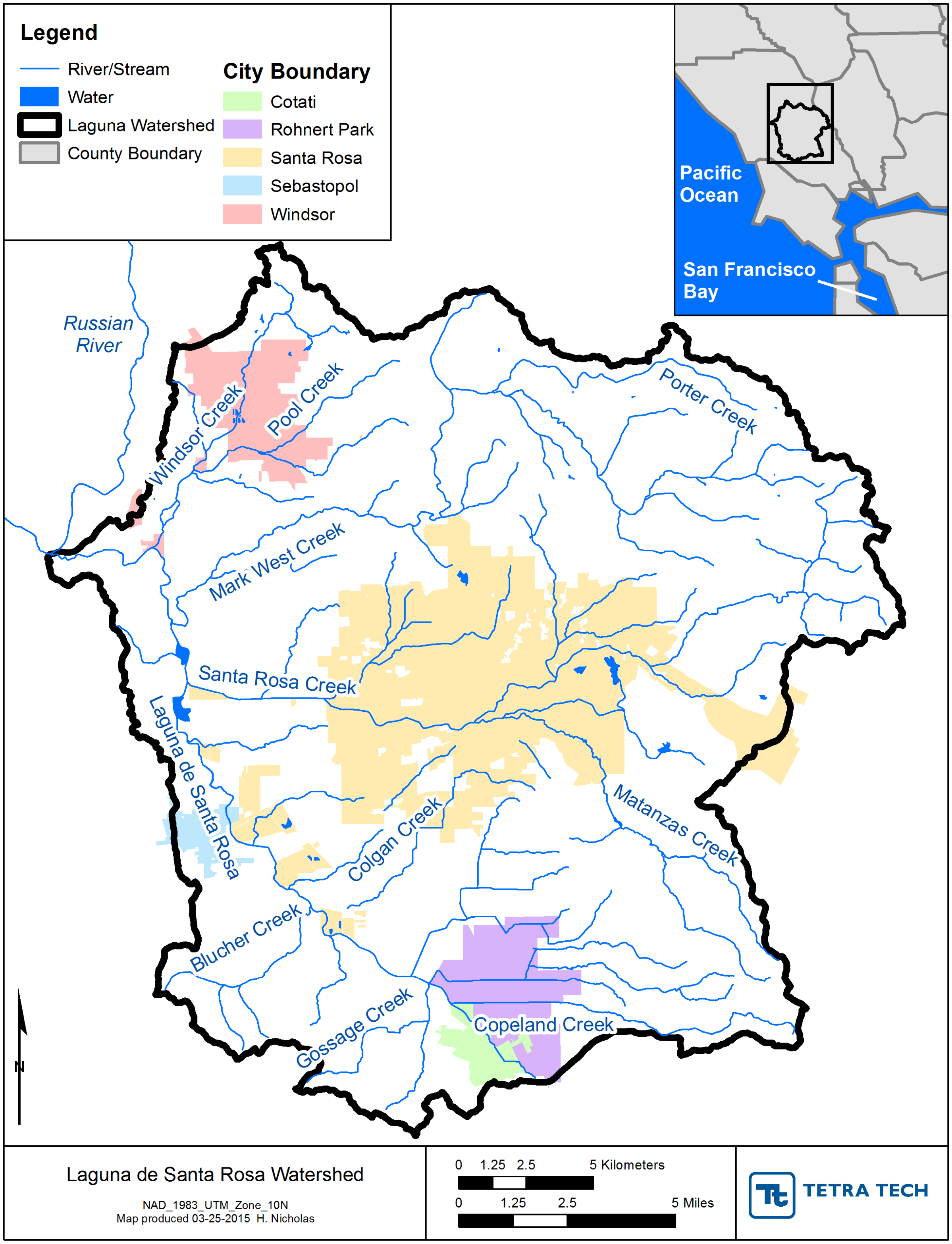

Figure 1-1. The Laguna de Santa Rosa Watershed

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2 Approach to Sediment Budget

A sediment loading and budget analysis for the Laguna de Santa Rosa was previously completed by Philip Williams & Associates, Ltd. (PWA) under contract to the U.S. Army Corps of Engineers (PWA, 2004a, 2004b). That report was based on extensive field data and application of several analytical methods that provided an initial basis for developing a long-term sediment budget for the Laguna. The conceptual understanding of processes in the watershed is expanded by Sloop et al. (2007).

PWA (2004a) provides a comprehensive evaluation of the then available sources of information on sources of sediment from the watershed to the Laguna. However, while the PWA report provides estimates of sediment yield by tributary basin, it does not track sediment back to individual land uses, processes, or source areas, and so does not provide a complete basis for implementation planning. Additional information has become available since 2004, as have new analysis techniques that warrant revisiting the sediment budget.

PWA calculated sediment budgets by several methods and concluded that the PSIAC method (Pacific Southwest Inter-Agency Committee, 1968) provided what appeared to be the most realistic estimates of sediment yield for the Laguna. The Sloop et al. (2007) report concurred with this analysis. PWA (2004a) also performed estimates of sediment yield with MUSLE (Modified Universal Soil Loss Equation; Williams, 1981), but this appeared to grossly over-estimate sediment yields.

The current analysis commenced with the idea that PSIAC likely provided the best existing framework for estimating total sediment yields to the Laguna at the tributary scale and the PSIAC estimates are revisited based on current spatial data in Appendix A. PWA stated that the PSIAC estimates of sediment load were supported by analyses relating turbidity monitoring to delivered sediment load (PWA, 2004a); however, studies of three years of suspended sediment monitoring data by the U.S. Geological Survey (USGS; Curtis et al., 2012) provided estimates of delivered load that were an order of magnitude lower than PSIAC. These estimates are also uncertain and have been reanalyzed in this study along with additional estimates of load from Sonoma County Water Agency (SCWA) stormwater permit monitoring (Section 4.1), but the reanalyses continue to suggest that the PSIAC estimates of delivered sediment load are too high. In addition, PWA's method for the reported validation of the PSIAC estimates based on turbidity data turns out to have significant uncertainties and is likely biased high, as described in Section 4.2.

Sediment Mass and Volume

This report focuses on sediment mass, but various data sources and estimation techniques (including PSIAC) instead report sediment volume. Volume and mass are related by the bulk density, which is the dry weight mass per unit of volume. The bulk density varies as a function of sediment size fraction, porosity, fraction of organic matter, and degree of compaction, so the relationship is not constant. Different authors have used different assumptions about bulk density of sediment in the Laguna watershed. To provide a consistent basis of comparison, this report assumes a bulk density of 1,400 kilograms per cubic meter (kg/m^3) or 1.4 grams per cubic centimeter (g/cm^3), which is equivalent to a weight of 1.18 short tons per cubic yard or 87.4 pounds per cubic foot (lb/ft^3). This is slightly less than the typical bulk density of clay loam soils on the Santa Rosa Plain (around 1.5 g/cm^3 according to the county soil survey), but is a reasonable approximation because most recently delivered sediment will not be fully compacted.

Given the difference between PSIAC predictions and measured values, along with the apparent lack of validation from the turbidity analysis, a modified approach was devised for completing the Laguna de Santa Rosa watershed sediment budget analysis. In addition to the earlier work by PWA (2004a), this revised approach draws significantly on work carried out in an adjacent watershed and reported in the Sonoma Creek Sediment TMDL (Low and Napolitano, 2008) and the accompanying sediment source analysis (Sonoma Ecology Center, 2006). The sediment balance is developed by assembling available information on the major sources and sinks of sediment in the watershed, comparing the results to data, where available, and ensuring that the resulting mass flux estimates are consistent with a physically realistic balance. The major sediment source and sink categories addressed in this report are summarized in Table 2-1.

Table 2-1. Sediment Source and Sink Categories Addressed in this Report

Category	Report Section	Notes
Major Sediment Sources		
Upland Sheet and Rill Erosion	5	RUSLE estimates of soil loss combined with landscape-based estimates of sediment delivery
Roads	6.1	Based on analyses conducted for Sonoma Creek TMDL
Soil Creep / Colluvial Bank Erosion	6.3	Expanded from analyses conducted for Sonoma Creek TMDL
Channel Incision, Gully Erosion, and Landslides	6.2	Expanded from analyses conducted for Sonoma Creek TMDL and PWA (2004a)
Major Sediment Sinks		
Deposition in Reservoirs and Debris Basins	7.1.1	Data analysis
Deposition in the Laguna de Santa Rosa and Floodplain	7.1.2	USGS (Curtis et al., 2012)
Channel Maintenance Activities	7.2	Analysis of data from SCWA
Export to Russian River	7.3	Data analysis

These various components are assembled into a sediment budget for current conditions in Section 8. Although there are many acknowledged sources of uncertainty regarding various components, this sediment budget provides a reasonable and physically plausible representation of the movement and storage of sediment in the Laguna de Santa Rosa system. It will be feasible to further refine individual components as additional data are collected, but the general conclusions are expected to remain firm. A parallel analysis of the sediment budget under conditions prior to European settlement is provided in Section 9.

Although this report addresses only the sediment budget, NCRWQCB is interested in integrating sediment and nutrient analyses in the watershed. A more accurate sediment budget will help provide the foundation for an improved phosphorus loading analysis, as inorganic phosphorus is particle-reactive with relatively low solubility and moves primarily in conjunction with the movement of sediment. A common approach to modeling nonpoint loads of phosphorus is to simulate phosphorus load based on a sediment potency factor (e.g., pounds of phosphorus per ton of sediment). Even in the absence of a completed comprehensive watershed model, combining an improved sediment budget with potency factors (from the literature and/or based on local soil tests) should provide a good basis for evaluating the significance of different sources of phosphorus load. It is worthwhile to note that the most elevated soil phosphorus levels are primarily associated with surface soil layers in land that has been fertilized for agriculture or subject to intensive manure inputs from livestock at some point during recent history. Loading from these sources will primarily be associated with sheet and rill erosion, and buried sediments accessed by enlargement of channels and gullies are much less likely to contribute excess phosphorus loads – which is an important reason to attempt to separate upland and gully/channel erosion sources in the analysis.

The sediment budget is likely to be less informative as to nitrogen loads, as nitrogen movement is typically dominated by dissolved forms. It is believed, however, that control of phosphorus loading is essential to reducing adverse nutrient impacts in the Laguna due to the high potential for nitrogen fixation in the system (Butkus, 2012).

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3 Watershed Delineation and Spatial Data

The Laguna de Santa Rosa watershed discussed in this study is defined as the area upstream of the pour point of Mark West Creek into the Russian River (Figure 3-1). Water elevation in the historical lake and wetland complex that constitutes the Laguna de Santa Rosa is controlled by a bedrock outcrop at Ritchurst Knob, just downstream of the confluence with Windsor Creek. It is the area upstream of this point (totaling 161,075 acres) that is of specific interest for the development of a sediment budget for the Laguna de Santa Rosa. While it is likely that much of the coarse sediment load from Windsor Creek is delivered directly to the Russian River, fine sediment and nutrient loads from Windsor Creek often back up into the Laguna during flood events on the Russian River. Regardless, the only available monitoring location from which output from the Laguna de Santa Rosa system may be measured is located downstream of Windsor Creek (Mark West Creek near Mirabel Heights, USGS gage 11466800); thus Windsor Creek must be included within the overall sediment balance.

The Laguna de Santa Rosa watershed was divided into a series of subwatersheds for the purpose of analysis of sediment sources and sinks. A detailed investigation of the sediment budget of the Laguna de Santa Rosa watershed was previously undertaken by PWA (2004a, 2004b). This served as a starting point for the present study, and there was a desire to maintain consistency with the spatial analyses presented in that earlier work. Subwatershed boundaries were thus delineated for the Laguna de Santa Rosa watershed to fit with the boundaries described in the PWA (2004a) analyses. Because the watershed has high spatial variability of parameters such as soils and slope, several of the larger PWA-matched subwatersheds were subdivided further to allow for greater precision of parameter/factor estimation (Figure 3-1). Note that the Copeland subwatershed is subdivided from the greater Upper Laguna to allow for separate comparison with the 2004 Copeland Creek Watershed Assessment (Laurel Marcus and Associates, 2004). The area that contains the Laguna de Santa Rosa, its floodplain, and various tributaries that cross the Santa Rosa Plain is subdivided into the Lower Floodplain and the Upper Floodplain at the break point of USGS station 11465750 (Laguna de Santa Rosa near Sebastopol, CA).

The topography of the watershed, shown in Figure 3-2 from high resolution (1-m) Light Detection and Ranging (LiDAR) laser surveys provided by the Sonoma County Vegetation Mapping and LiDAR Program, exhibits a strong gradient in elevation, from mountains in the northeast to the flat Santa Rosa Plain in the south and west. Prior to European settlement, much of the sediment generated at higher elevations was deposited in alluvial fans on the Santa Rosa Plain and did not reach the Laguna.

The Laguna de Santa Rosa floodplain is defined for the purposes of this report as the Federal Emergency Management Agency (FEMA) 100-year floodplain about the Laguna de Santa Rosa and the portion of Mark West Creek between the confluence with the Laguna and the confluence with Windsor Creek, omitting the floodplains assigned to tributaries. This boundary is generally consistent with the estimated extent of open water and wetlands prior to European settlement (see Section 9) and also largely corresponds to the limit of less developed land. When this report refers to estimates of sedimentation within the Laguna de Santa Rosa it specifically refers to sedimentation within this polygon, which includes both the functioning and potentially restorable extent of the waterbody.

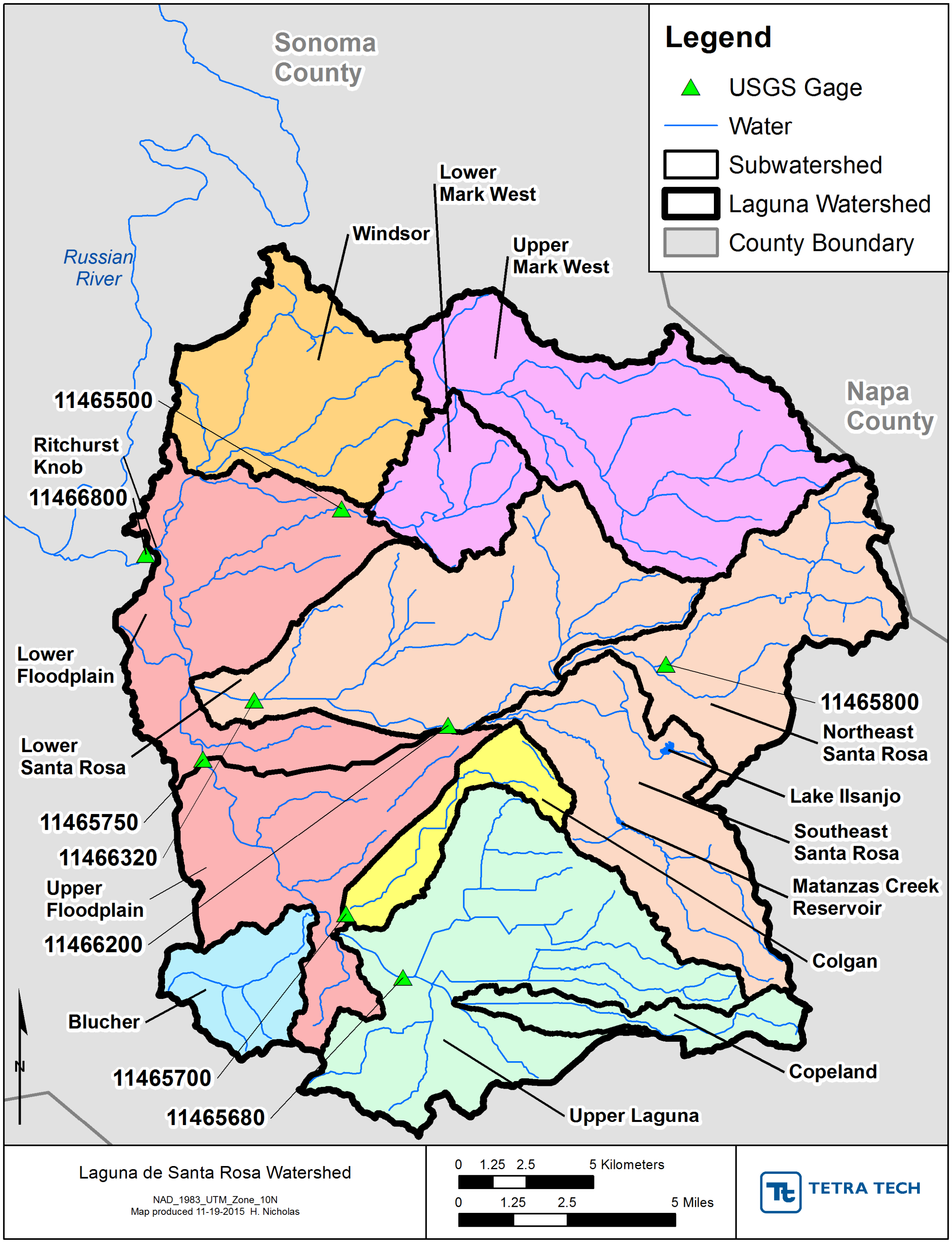

Figure 3-1. Delineation of Subwatersheds and Location of USGS Gages for the Laguna de Santa Rosa Watershed

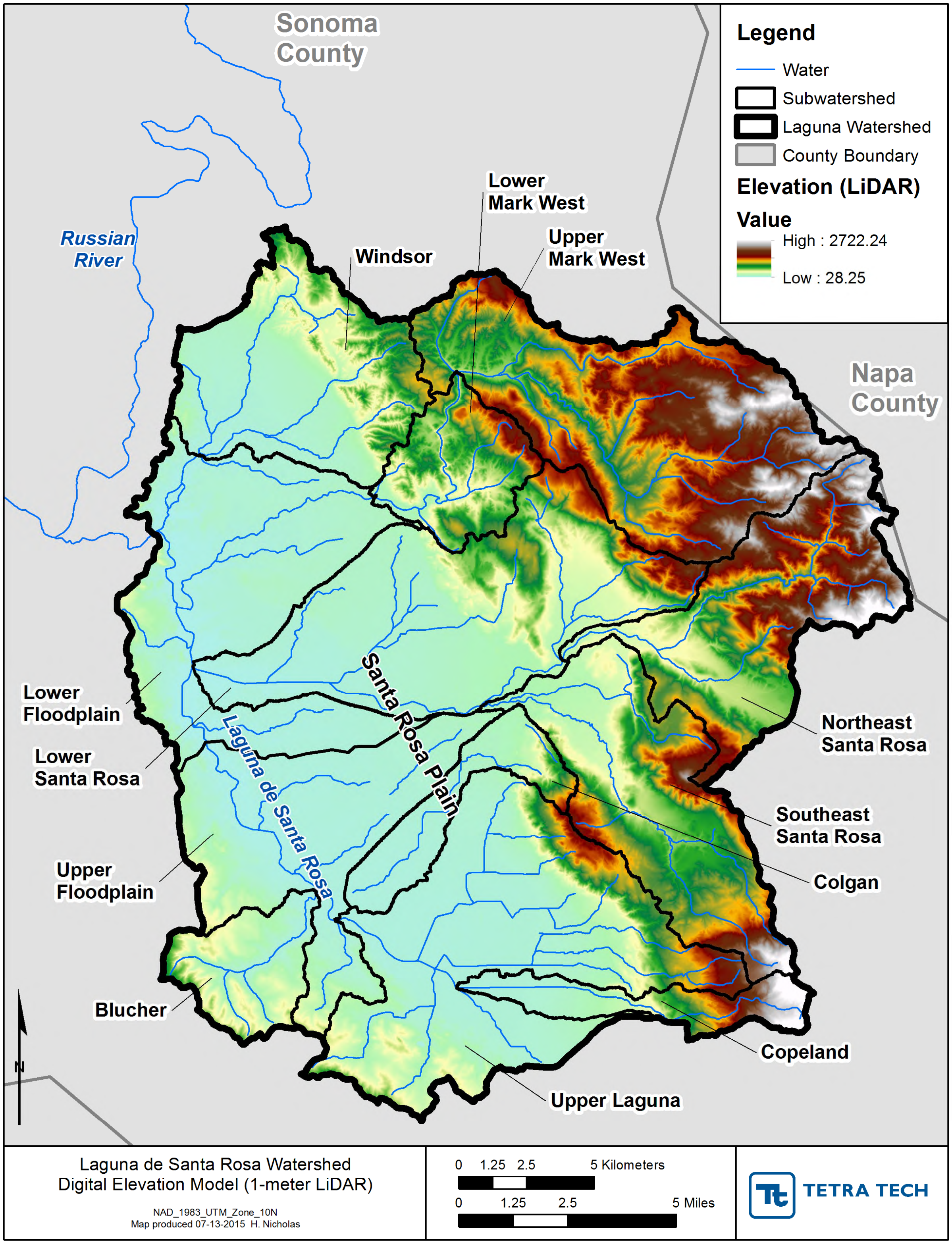

Figure 3-2. Topography of the Laguna de Santa Rosa Watershed

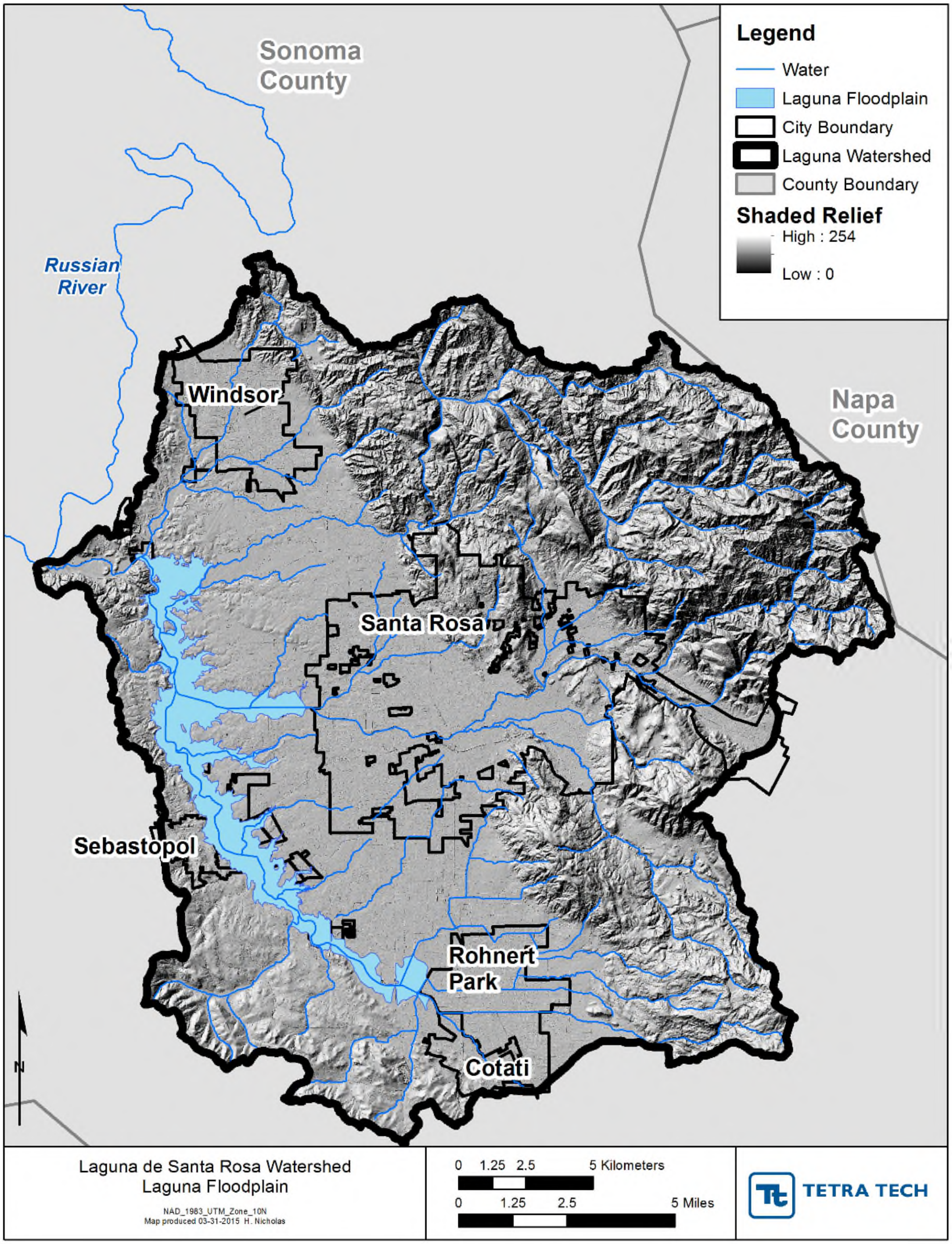

Figure 3-3. Laguna de Santa Rosa Floodplain based on FEMA 100-year Flood Delineation

A variety of other high resolution spatial data are part of the current analysis. Land cover data are primarily derived from U.S. Department of Agriculture (USDA) National Agricultural Statistics Service (NASS) Cropland Data Layer (CDL) mapping efforts (Table 3-1, Table 3-2, and Figure 3-4). The 2013 CDL data set uses the 2006 National Land Cover Database (NLCD) land use/land cover data for areas not under agricultural land cover, and 2013 aerial imagery and supplementary local information to delineate agricultural land covers into specific crop types. The 2006 NLCD provides an alternate interpretation of land use and land cover that is helpful in further resolving developed land areas (Table 3-3 and Figure 3-5). The LiDAR coverage was used to determine percent canopy cover and bare earth areas, as well as land slope characteristics. The USDA Soil Survey Geographic (SSURGO) database was used to determine appropriate Soil Erodibility Factor values (K-factor). Surficial geology in geospatial format was obtained from USGS.

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Table 3-1. Land Cover by Subbasin from 2013 Cropland Data Layer (acres)

Subbasin	Oats	Other Hay	Fallow	Grapes	Open Water	Developed Open	Developed Low Density	Developed Medium Density	Developed High Density	Barren	Deciduous Forest	Evergreen Forest	Mixed Forest	Shrubland	Grassland	Woody Wetland	Herbaceous Wetland	Sum
Lower Santa Rosa	6	0	0	1,133	104	4,669	4,148	4,171	542	1	46	976	693	1,228	3,746	40	8	21,511
Lower Mark West	0	0	0	23	1	845	194	50	1	0	88	1,428	1,102	1,273	861	7	0	5,873
Colgan	4	0	0	49	0	694	570	679	162	0	6	73	138	187	1,944	0	0	4,505
Blucher	1	0	0	244	4	414	111	14	1	0	28	122	254	649	3,053	40	2	4,936
Lower Floodplain	22	0	0	5,785	110	2,127	1,659	959	205	8	45	206	586	755	5,601	318	20	18,404
Upper Mark West	0	0	0	42	12	804	26	3	0	5	127	10,020	1,942	5,838	2,680	1	1	21,501
Southeast Santa Rosa	1	0	0	68	88	1,870	1,094	614	46	0	127	1,686	1,987	2,325	4,276	7	0	14,189
Northeast Santa Rosa	0	0	0	36	11	1,410	556	335	14	0	110	6,080	1,129	2,946	1,582	1	0	14,210
Upper Laguna	366	0	0	525	22	2,974	2,266	2,664	494	0	11	564	523	1,143	12,276	32	5	23,865
Windsor	4	0	0	1,511	58	1,618	1,358	1,461	179	0	50	709	1,378	2,090	3,308	8	5	13,738
Copeland	1	0	0	59	1	407	378	613	49	0	10	320	276	427	1,444	4	0	3,988
Upper Floodplain	25	0	1	762	64	2,666	1,790	1,218	215	13	29	52	232	566	6,571	135	16	14,353
Total	*429*	*1*	*2*	*10,238*	*474*	*20,497*	*14,150*	*12,780*	*1,907*	*28*	*678*	*22,235*	*10,239*	*19,427*	*47,341*	*593*	*57*	*161,075*

Note: Tabulation is for area upstream of Ritchurst Knob.

Table 3-2. Land Cover by Subbasin from 2013 Cropland Data Layer (percentage)

Subbasin	Oats	Other Hay	Fallow	Grapes	Open Water	Developed Open	Developed Low Density	Developed Medium Density	Developed High Density	Barren	Deciduous Forest	Evergreen Forest	Mixed Forest	Shrubland	Grassland	Woody Wetland	Herbaceous Wetland
Lower Santa Rosa	0.0%	0.0%	0.0%	5.3%	0.5%	21.7%	19.3%	19.4%	2.5%	0.0%	0.2%	4.5%	3.2%	5.7%	17.4%	0.2%	0.0%
Lower Mark West	0.0%	0.0%	0.0%	0.4%	0.0%	14.4%	3.3%	0.9%	0.0%	0.0%	1.5%	24.3%	18.8%	21.7%	14.7%	0.1%	0.0%
Colgan	0.1%	0.0%	0.0%	1.1%	0.0%	15.4%	12.7%	15.1%	3.6%	0.0%	0.1%	1.6%	3.1%	4.2%	43.1%	0.0%	0.0%
Blucher	0.0%	0.0%	0.0%	4.9%	0.1%	8.4%	2.2%	0.3%	0.0%	0.0%	0.6%	2.5%	5.1%	13.2%	61.8%	0.8%	0.0%
Lower Floodplain	0.1%	0.0%	0.0%	31.4%	0.6%	11.6%	9.0%	5.2%	1.1%	0.0%	0.2%	1.1%	3.2%	4.1%	30.4%	1.7%	0.1%
Upper Mark West	0.0%	0.0%	0.0%	0.2%	0.1%	3.7%	0.1%	0.0%	0.0%	0.0%	0.6%	46.6%	9.0%	27.2%	12.5%	0.0%	0.0%
Southeast Santa Rosa	0.0%	0.0%	0.0%	0.5%	0.6%	13.2%	7.7%	4.3%	0.3%	0.0%	0.9%	11.9%	14.0%	16.4%	30.1%	0.0%	0.0%
Northeast Santa Rosa	0.0%	0.0%	0.0%	0.3%	0.1%	9.9%	3.9%	2.4%	0.1%	0.0%	0.8%	42.8%	7.9%	20.7%	11.1%	0.0%	0.0%
Upper Laguna	1.5%	0.0%	0.0%	2.2%	0.1%	12.5%	9.5%	11.2%	2.1%	0.0%	0.0%	2.4%	2.2%	4.8%	51.4%	0.1%	0.0%
Windsor	0.0%	0.0%	0.0%	11.0%	0.4%	11.8%	9.9%	10.6%	1.3%	0.0%	0.4%	5.2%	10.0%	15.2%	24.1%	0.1%	0.0%
Copeland	0.0%	0.0%	0.0%	1.5%	0.0%	10.2%	9.5%	15.4%	1.2%	0.0%	0.2%	8.0%	6.9%	10.7%	36.2%	0.1%	0.0%
Upper Floodplain	0.2%	0.0%	0.0%	5.3%	0.4%	18.6%	12.5%	8.5%	1.5%	0.1%	0.2%	0.4%	1.6%	3.9%	45.8%	0.9%	0.1%
Total	*0.3%*	*0.0%*	*0.0%*	*6.4%*	*0.3%*	*12.7%*	*8.8%*	*7.9%*	*1.2%*	*0.0%*	*0.4%*	*13.8%*	*6.4%*	*12.1%*	*29.4%*	*0.4%*	*0.0%*

Note: Tabulation is for area upstream of Ritchurst Knob.

Table 3-3. Land Cover by Subbasin from 2006 National Land Cover Database (acres)

Subbasin	Open Water	Developed Open	Developed Low Density	Developed Medium Density	Developed High Density	Barren	Deciduous Forest	Evergreen Forest	Mixed Forest	Shrub/Scrub	Herbaceous	Hay/Pasture	Cultivated Crops	Woody Wetlands	Herbaceous Wetlands	Sum
Lower Santa Rosa	141	4,576	4,361	4,325	443	0	54	940	670	1,305	2,722	0	1,966	9	0	21,511
Lower Mark West	2	854	186	52	0	0	149	1,322	1,164	1,354	780	0	0	10	0	5,873
Colgan	1	689	555	739	128	0	8	68	179	170	1,878	0	90	0	0	4,505
Blucher	4	431	94	10	0	0	48	81	133	739	3,338	0	9	46	3	4,936
Lower Floodplain	87	2,278	1,841	982	166	4	70	130	302	805	3,618	104	7,781	229	6	18,404
Upper Mark West	11	807	24	1	0	8	162	9,391	2,308	6,160	2,614	0	5	10	0	21,501
Southeast Santa Rosa	94	1,852	1,139	590	41	2	321	1,685	1,594	2,513	4,043	0	260	50	4	14,189
Northeast Santa Rosa	12	1,383	586	340	10	0	141	5,719	1,401	3,071	1,451	0	95	2	0	14,210
Upper Laguna	12	2,917	2,256	2,800	437	4	47	512	534	1,237	11,381	0	1,663	58	6	23,865
Windsor	52	1,638	1,367	1,531	135	4	48	734	1,379	2,091	3,207	36	1,500	10	6	13,738
Copeland	0	394	368	642	39	0	60	305	228	413	1,439	0	93	7	0	3,988
Upper Floodplain	103	2,651	1,837	1,268	180	2	45	52	126	449	5,237	0	2,244	157	2	14,353
Total	*520*	*20,470*	*14,613*	*13,281*	*1,579*	*25*	*1,153*	*20,937*	*10,019*	*20,309*	*41,707*	*140*	*15,707*	*587*	*26*	*161,075*

Note: Tabulation is for area upstream of Ritchurst Knob.

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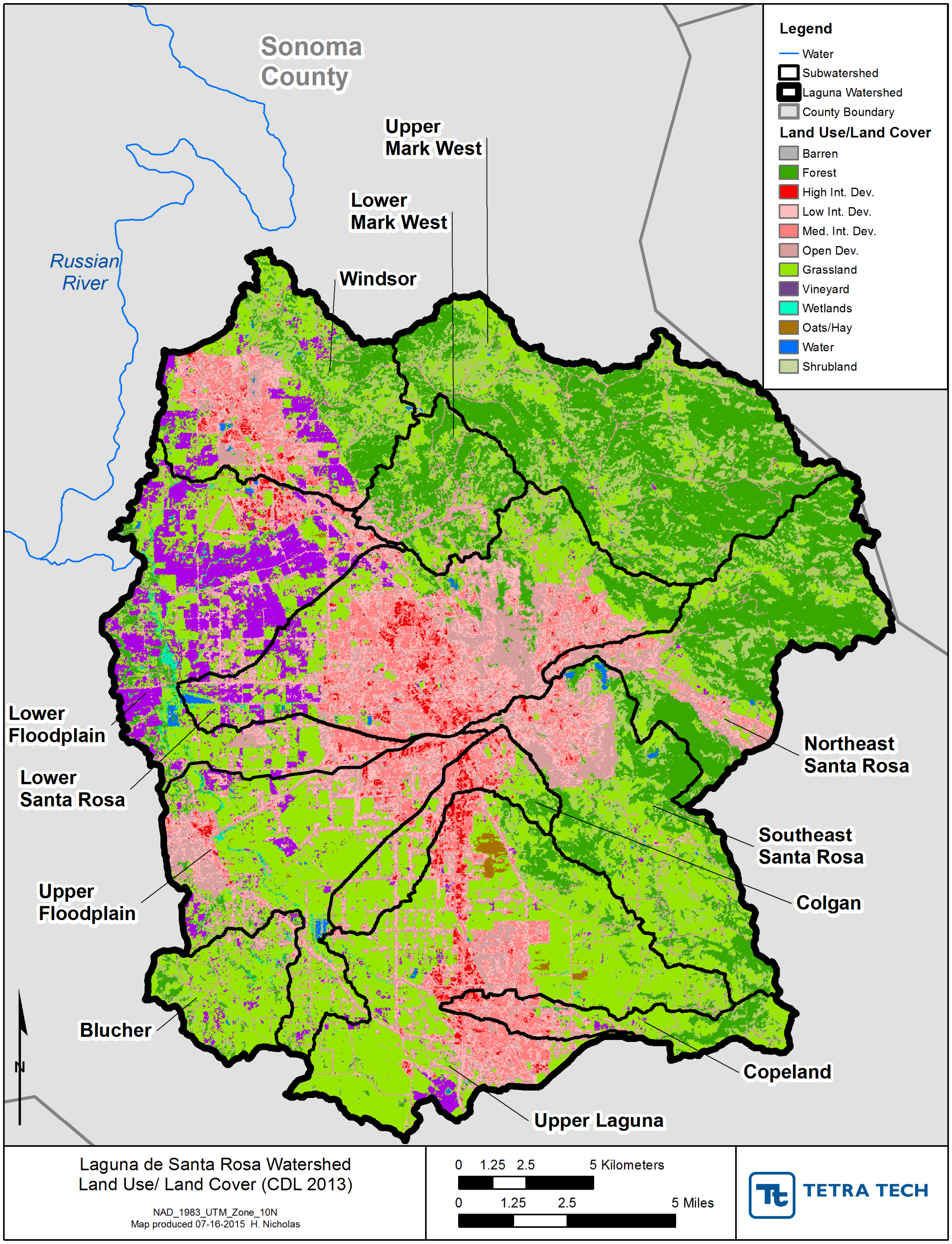

Figure 3-4. Current Land Use/Land Cover for the Laguna de Santa Rosa Watershed (USDA Cropland Data Layer, 2013)

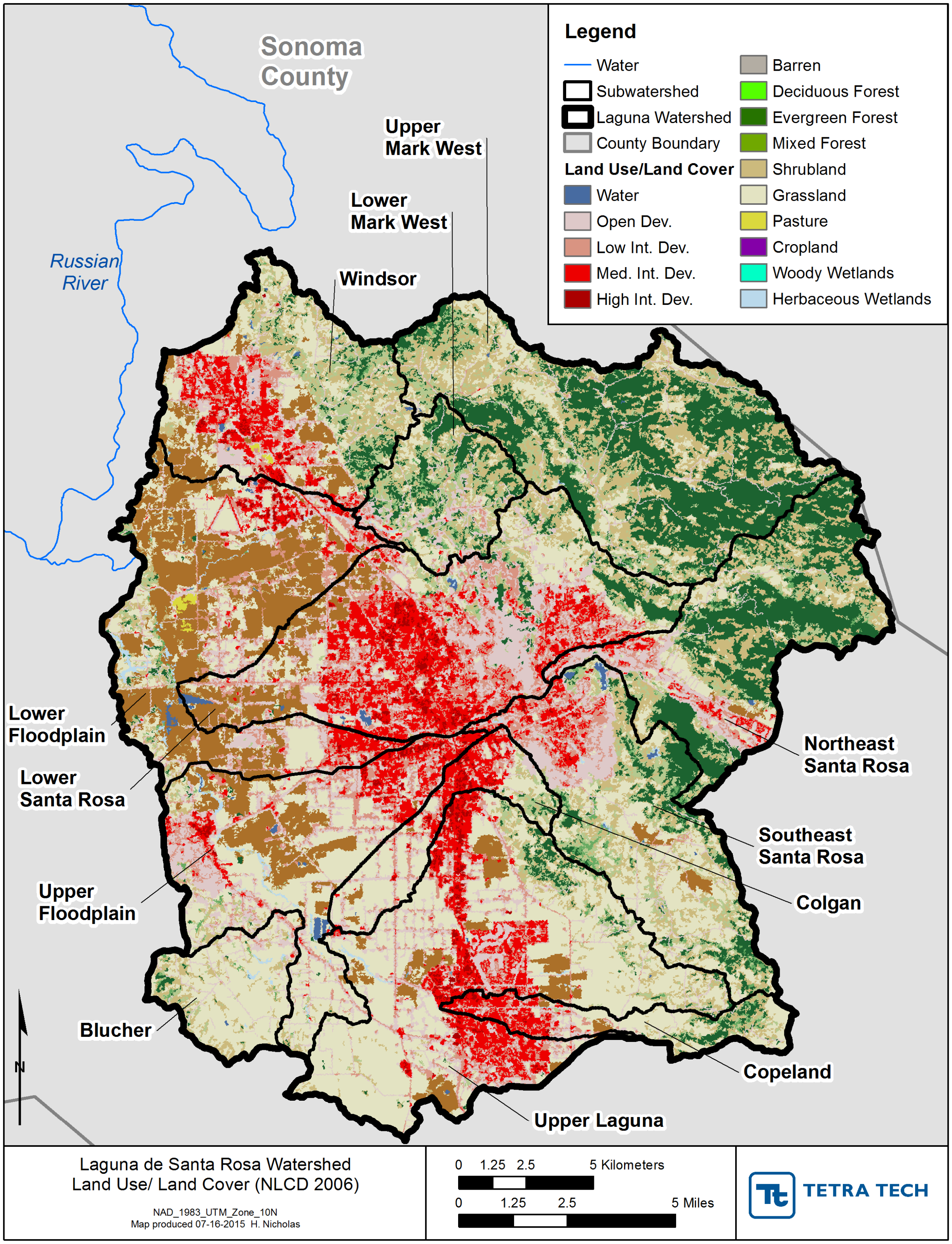

Figure 3-5. Land Use/Land Cover for the Laguna de Santa Rosa Watershed (National Land Cover Database, 2006)

4 Monitoring Data and Calculated Loads

As noted in Section 2, the PSIAC estimates of sediment loading to the Laguna de Santa Rosa and estimates based on USGS monitoring differ substantially. Ideally, modeled load estimates would be calibrated to and tested against loads inferred from monitoring and flow gaging. To date, the available monitoring of suspended sediment or surrogate measures is limited, and what does exist has been interpreted in contradictory ways. The available data and their interpretation are summarized below.

4.1 LOADS ESTIMATED FROM SSC MONITORING

USGS undertook direct monitoring of suspended sediment concentration (SSC) in the Laguna de Santa Rosa watershed in 2006-2008 and used these data together with gaged flows to estimate sediment loads, as reported by Curtis et al. (2012). The USGS work includes estimates of sediment output from the Laguna (Mark West Creek near Mirabel Heights [gage 11466800]) and inputs from three major gaged tributaries (Laguna de Santa Rosa near Sebastopol [11465750], Santa Rosa Creek at Willowside Road [11466320], and Mark West Creek near Windsor [11465500]; Flint, unpublished, reported in Curtis et al., 2012). A formal USGS report on this effort has not been issued; however, a detailed description of the sediment load estimation process was provided by the USGS investigator (personal communication from Lorraine Flint, March 8, 2014). The work included flow gaging and sediment sampling between October 2005 and September 2008 at three of four stations, while samples were collected only during the 2007 and 2008 water years at Mark West Creek near Windsor as that flow gage was not installed until 2007, unfortunately missing the large storm that occurred on New Year's Day 2006. Suspended sediment measurements were collected sparsely from May to November, periodically from November to May, and daily during high flow events. These data were used to calculate sediment rating curves (concentration as a function of flow) using the power function method and daily sediment loads were calculated using the rating curves and gaged streamflow. These results were then used to estimate the annual suspended sediment load at each of the four stations, including uncertain estimation of the load delivered by Mark West Creek during 2006, prior to installation of the flow gage and commencement of monitoring.

The USGS load estimates are notably lower than the estimates obtained using PSIAC and reported by PWA (2004a). Tetra Tech undertook a thorough re-evaluation of the PSIAC estimates using more recently available spatial coverages, which resulted in somewhat smaller estimates of sediment loading (see Appendix A and Appendix C), although still greater than obtained from the USGS monitoring. The USGS load estimates are compared to the long-term PSIAC load estimated by PWA (2004a) and the revised PSIAC estimates (from the appendices) at the corresponding gage locations in Table 4-1.

Table 4-1. Comparison of USGS Load Estimates for WY 2006-2008 to PSIAC Estimates at USGS Gage Stations (tons/yr)

Location	Drainage Area (mi^2)	USGS WY 2006–2008 Suspended Sediment Load (Curtis et al., 2012)	PSIAC Total Sediment Load (PWA, 2004a)	Revised PSIAC Total Sediment Load (this study)
11465750 Laguna de Santa Rosa nr Sebastopol	79.6	5,006 tons/yr 0.098 t/ac/yr	119,002 tons/yr 2.34 t/ac/yr	66,314 tons/yr 1.30 t/ac/yr
11466320 Santa Rosa Creek at Willowside Rd.	77.6	10,362 tons/yr 0.21 t/ac/yr	114,731 tons/yr 2.31 t/ac/yr	76,987 tons/yr 1.55 t/ac/yr
11465500 Mark West Creek nr Windsor	43.0	31,747 tons/yr[1] 1.15 t/ac/yr	50,530 tons/yr 1.84 t/ac/yr	47,572 tons/yr 1.73 t/ac/yr
11466800 Mark West Creek nr Mirabel Heights	251.7	14,440 tons/yr 0.090 t/ac/yr (outlet of Laguna)	ND	ND

Notes: tons/yr = English (short) tons per year; mi^2 = square miles; t/ac/yr = tons per acre per year; ND = no data; Results given in Curtis et al. (2012) have been converted from metric tons to short tons.

1. The flow gage on Mark West Creek near Windsor was not brought online until 10/1/2006. The load at this station reported in Curtis et al. (2012) incorporates an estimate of loads during the major flood event of 12/31/2005 (WY 2006) based on assumption that loads at this station were 3.5 times those estimated for Santa Rosa Creek at Willowside Drive for the same event.

Even with the revisions to the PSIAC analyses discussed in Appendix A, the PSIAC loads are from 149 percent to 1,310 percent of the USGS load estimates. The discrepancy is smallest for Mark West Creek near Windsor, which may reflect the fact that the other two locations are in watersheds that cross the lower gradient Santa Rosa Plain in floodways, whereas Mark West Creek at the Windsor gage is a relatively natural channel on a higher gradient and more representative of the types of streams for which PSIAC was designed.

The PSIAC loads are much larger than the USGS estimates; however, PSIAC provides long-term load estimates, while USGS results are based on only 2–3 years of data. Reanalysis of turbidity data reported below in Section 4.2.2 suggests that longer-term average annual loads are similar to those reported for 2006-2008, so this is not the major source of the inconsistency. Another potential factor that could contribute to the discrepancy on the USGS side is underestimation of bedload, which is often a major fraction of the total sediment load, especially in sand and gravel bed systems. However, USGS' samples were depth-integrated, which should reduce this source of discrepancy, although the samples still omit gravel and mobile sediment bedforms that are not suspended in the water column. Curtis et al. (2012) also compared measured sediment accumulation rates in the Laguna floodplain to mass balance computations based on the difference between computed suspended sediment inflow to and outflow from the Laguna and estimated that the monitoring data at the gages accounted for at most 20 percent of the sediment accumulation estimated from direct measurements (see Section 7.1.2). This could be due to several factors, including contribution of sand and gravel not captured in suspended sediment monitoring as well as channel erosion and other contributions from areas below the gages or in minor tributaries. PSIAC load estimates for Santa Rosa Creek and upstream of the Laguna de Santa Rosa gage near Sebastopol also need to be corrected for trapping in upstream impoundments and for the substantial amounts of sediment that are removed by the Sonoma County Water Agency (SCWA) in the maintenance of floodways; however, these mass estimates (Section 7) are still far less than needed to bring PSIAC into agreement with the loads estimated from monitoring.

Another source of discrepancy could be the sediment rating curves developed by USGS. The rating curves appear strong for Santa Rosa Creek at Willowside Road and Mark West Creek near Windsor, but are based on limited data, whereas the relationship looks weak for Laguna de Santa Rosa near Sebastopol. Ms. Flint provided R^2 and standard error statistics for the rating curve equations (R^2 ranged from 0.226 on Laguna de Santa Rosa to 0.836 on Santa Rosa Creek, while standard errors ranged from 23.6 to 45.3 milligrams per liter [mg/L]).

To further investigate the potential uncertainty in the sediment rating curves we undertook alternative analyses of the data using two software packages designed for estimating stream loads from concentration monitoring and flow gaging data: the USGS LOADEST program (Runkel et al., 2004) and the U.S. Army Corps of Engineers' FLUX program (Walker, 1986). The complete set of SSC monitoring data was not available on the National Water Information System (NWIS) website, but was supplied directly by Ms. Flint. Table 4-2 compares the loads calculated by these methods to loads calculated by reapplication of the rating curves to the available period of flow gage data, and suggests that the rating curve-based estimates in Curtis et al. (2012) are a reasonable interpretation of the data, albeit subject to uncertainty. The LOADEST program also provides a 95 percent upper confidence limit (UCL), which shows significant variability, especially for Mark West Creek near Windsor, but even the UCL is much less than the PSIAC load estimates in Table 4-1.

Table 4-2. Comparison of Suspended Sediment Load Estimates based on USGS Monitoring

Station	11465750 Laguna de Santa Rosa nr Sebastopol	11466320 Santa Rosa Cr at Willowside Rd.[1]	11465500 Mark West Cr nr Windsor	11466800 Mark West Cr nr Mirabel Heights
Gaged Period (Water Years)	2000-2013	1999-2013	2007-2008	2006-2013
Rating Curve (tons/yr)	3,845	6,239	2,040[2]	6,459
FLUX (tons/yr)	3,273	7,544	7,912	9,095
LOADEST (tons/yr)	3,862	9,784	7,401	4,800
LOADEST 95% Upper Confidence Limit (tons/yr)	4,428	13,081	26,378	5,400
LOADEST 95% Lower Confidence Limit (tons/yr)	3,240	6,696	1,360	4,252

Notes: Results are presented in English (short) tons.

1. The gage location for Santa Rosa Creek is not at the outlet of the subbasin. The estimated loads at the outlet based on the analyses in subsequent chapters suggest they should be greater than those at Willowside Road by a factor of 1.107.

2. Rating curve results for Mark West Creek near Windsor are significantly lower than the results from Curtis et al. (2012) shown above in Table 4-1 because those results incorporate estimated loads from the high flow event of 12/31/2005, prior to the start of operation of this gage.

Another source of corroboration is available for Santa Rosa Creek. SCWA has collected total suspended solids (TSS) and nutrient samples in Santa Rosa Creek at Fulton Road since 1997 in accordance with its municipal separate storm sewer system (MS4) stormwater permit. From 1997 to 2009 samples were collected on an annual basis during storm events. Since 2010, SCWA has collected samples on a monthly basis at a variety of flow conditions.

Unfortunately, flow is not monitored directly at Fulton Road. The USGS gage on Santa Rosa Creek is located a short distance downstream, at Willowside Road; however, Piner Creek, which drains a significant portion of the western part of the City of Santa Rosa, enters between these two locations. This limits the ability to evaluate loads from the SCWA monitoring. An approximate estimate was made by combining the monitoring with USGS gaging of flows in Santa Rosa Creek at Willowside Road, prorated for the difference in drainage area (factor of 0.9579), to develop estimates of suspended sediment loading using the FLUX tool.

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

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

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

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

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

The FLUX package implements all three of the general approaches described by Preston et al., including a number of variants on the regression approach, and allows flexible specification of stratification. FLUX also calculates error variances for the estimates. For Santa Rosa Creek at Fulton Road, the FLUX estimate of TSS load based on the Fulton Road data and using FLUX Method 6 (a bias-corrected regression of concentration on flow, implemented on a daily basis) for WY 1999-2013 flow gaging (corrected from Willowside Road to Fulton Road) is 4,104 tons/yr. This is less than half of the USGS estimate of suspended sediment load at Willowside Road. In part, the discrepancy may be explained by the additional drainage area between Fulton Road and Willowside Road, which includes Piner Creek, from which SCWA has periodically removed large volumes of sediment (see Section 7.2). In addition, the sampling at Fulton Road is based on TSS, rather than the more reliable suspended sediment concentration method, uses a sampling protocol that does not ensure weighting across all segments and depths of the stream, and includes a sparse representation of high flow events. Finally, the proration of flow based on drainage area is likely to underestimate the increase in flow between Fulton Road and Willowside Road because the intermediate drainage area includes large amounts of impervious surfaces. For these reasons, the MS4 sampling at Fulton Road is likely to be biased low relative to more complete estimates of sediment load – but does support the general order-of-magnitude estimates of sediment load delivered through Santa Rosa Creek.

Based on these multiple lines of evidence, it is clear that the PSIAC method over-estimates loads based on measured suspended sediment concentration, at least for Laguna de Santa Rosa near Sebastopol and Santa Rosa Creek at Willowside Road. This is likely because the PSIAC estimates are biased high; however, the discrepancy could in part be due to transport of unsuspended bedload that is not represented in the suspended sediment concentration monitoring.

4.2 SEDIMENT LOAD ESTIMATED FROM TURBIDITY

4.2.1 Prior Estimates

PWA (2004a) supported the use of PSIAC for determining sediment loads to the Laguna based on a comparison of PSIAC loads and loads inferred from continuous turbidity monitoring conducted from Dec. 19, 2002 – June 28, 2003 coincident with three USGS gages (Laguna de Santa Rosa at Stony Point Road, Santa Rosa Creek at Willowside Road, and Laguna de Santa Rosa at Occidental Road). Section 4.5.9 of the PWA report states the following:

> *The turbidity data gives us a measure of suspended sediment yield from Santa Rosa Creek and from the upper Laguna that can be compared with the modeled sediment yield and estimated sediment trapped. For Santa Rosa Creek at Willowside the estimated suspended sediment load for the 2002-2003 season (excluding the first major storm) was 96,993 tons. For Laguna de Santa Rosa at Stony Point Road (including the first major storm) the load was estimated at 34,241 tons, while for Laguna de Santa Rosa at Occidental Road the load (excluding the first storm) was estimated at 385,297 tons. The value associated with Santa Rosa Creek is more reliable than the values associated with the Laguna, owing to the better sediment rating curve at this site.*

PWA Section 4.7 then compares the turbidity-based estimates to PSIAC:

> *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 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 (all storms) the measured suspended sediment load was 385,2297* [sic] *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'.*

Based on the turbidity analysis, PWA (2004a) suggested that the loads generated by PSIAC are consistent with the monitoring data. PWA provided a copy of the spreadsheet used to estimate SSC loads from the raw turbidity data. One key step in the spreadsheet is the conversion from raw turbidity data (in nephelometric turbidity units [NTU]) to suspended concentrations (in mg/L). The following equations were used (the equation for Occidental Road is not in the spreadsheet, just pasted results, but the relationship can be inferred from those results):

Laguna de Santa Rosa at Stony Point Rd.	$\text{SSC} = 9.42 \cdot \text{Turbidity} - 48.9$
Laguna de Santa Rosa nr Sebastopol[1]	$\text{SSC} = 41.88 \cdot \text{Turbidity} - 82.5$
Santa Rosa Creek at Willowside Rd.	$\text{SSC} = 38.10 \cdot \text{Turbidity} - 25.8$

Following conversion to SSC, rating curves with polynomial or linear relationships were developed to relate sediment load to discharge. An example of the polynomial fit for Santa Rosa Creek at Willowside Road is shown in Figure 4-1.

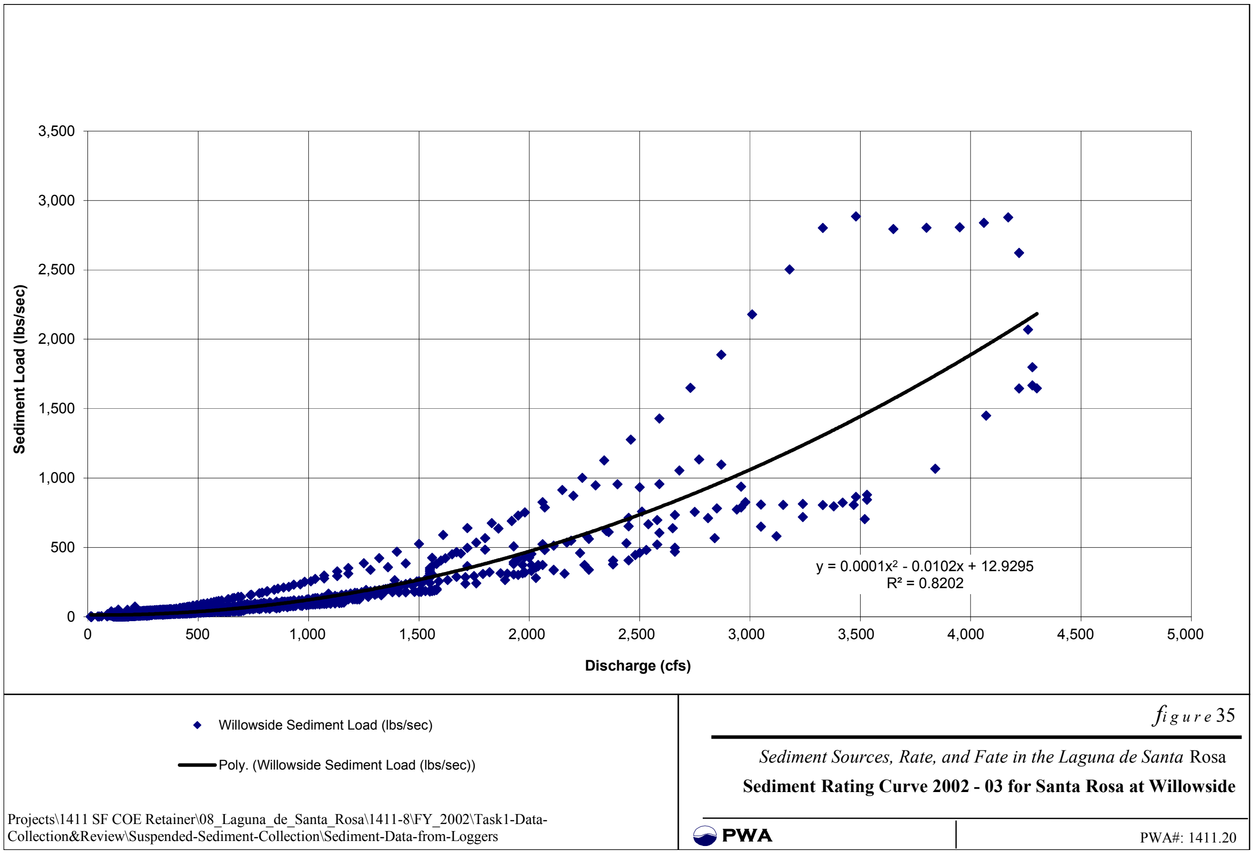

Figure 4-1. Example Rating Curve from PWA (2004a)

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[1] This station is referred to by PWA as Laguna de Santa Rosa at Occidental

The rating curve equations used by PWA to predict sediment load y in pounds per second (lb/sec) from discharge x in cubic feet per second (cfs) are as follows:

Laguna de Santa Rosa at Stony Point Rd.	$y = 6.1698 \cdot 10^{-5} \cdot x^2 + 5.9185 \cdot 10^{-2} \cdot x - 0.06355$
Laguna de Santa Rosa nr Sebastopol	$y = 0.26252 \cdot x$
Santa Rosa Creek at Willowside Rd.	$y = 1.1975 \cdot 10^{-4} \cdot x^2 - 1.01680 \cdot 10^{-2} \cdot x + 12.9294$

Two of the rating equations include an intercept term, which does not make physical sense (e.g., load is predicted to be non-zero when flow is zero). In the example for Santa Rosa Creek at Willowside Road the PWA rating curve predicts a load of over 12.9 lb/sec when discharge is zero; however, for the Laguna de Santa Rosa at Stony Point Road the intercept is negative, -0.0635 lb/sec.

We examined the rating curve at Willowside Road and found that a fit with a nearly equivalent R^2 of 0.819 can be obtained with a zero intercept term ($y = 1.1232 \cdot 10^{-4} \cdot x^2 + 1.6750 \cdot 10^{-2} \cdot x$). Use of the fit through the intercept has a considerable impact on load predictions at Willowside Road, as flow is often near zero in summer. We applied both versions of the rating equation to the available discharge records from 12/9/1998-7/1/2014 at this station. The original PWA rating curve yields a load estimate of 352,000 tons/yr over these years, whereas the revised rating curve estimates only 176,000 tons/yr – but this is still much greater than the load estimate obtained by USGS (9,400 tons/yr). Applying the same methods to available records at the Laguna de Santa Rosa at Stony Point Road, regression through the origin would result in an increase in predicted loads.

The PWA turbidity-based sediment load estimates depend on the accuracy of the regression relating SSC to turbidity. Section 4.5.4 of the PWA report implies that there were split samples collected for turbidity and SSC: “suspended sediment grab samples were collected to help verify calibration between turbidity and suspended sediment.” We contacted PWA staff, but they were not able to locate any such SSC/turbidity split samples. Instead, it appears that PWA developed the relation to turbidity by using a bench calibration procedure, described in Section 4.5.6 of the PWA report:

> *To determine suspended sediment concentration from the collected turbidity data, site-specific calibrations were performed for each instrument platform with sediment collected at each of the three monitoring locations. Each instrument platform was calibrated with the following procedure:*
>
> *1. Sediment samples were collected from the creek bed at the monitoring location, and the samples were thoroughly dried.*
>
> *2. The specific instruments (OBS 3, PT 1230, and CR 510) used at each location were mounted in a test bucket with 12 liters of filtered water. The data logger was started to collect a clear water turbidity readings.*
>
> *3. Sediment from the specific monitoring location was filtered through a sieve to remove coarse material and ground with a mortar and pestal* [sic] *to break up aggregates.*
>
> *4. Two to five grams of the fine grained soil particles collected at the specific monitoring location was weighed on a digital scale and added to the 12 liters of water. The resulting suspended sediment mixture was thoroughly mixed with a paint mixer mounted to a hand drill. The data logger collected a turbidity reading of the suspended sediment mixture.*
>
> *5. Step 4 was repeated to develop a calibration curve with six to eight suspended sediment vs. turbidity points.*

According to former PWA employees involved in the analysis, this procedure was recommended by the turbidity meter supplier (personal communication from Mark Lindley, PE, Environmental Science Associates, via Elizabeth Andrews, PE, Environmental Science Associates, to Jonathan Butcher, Tetra Tech, October 3, 2014) and has been suggested as a quick and cost-efficient approach to turbidity calibration (Earhart, 1984). The method essentially determines the equivalent amount of bed sediment that would need to be suspended to yield an observed turbidity measurement. A potential problem with this approach is that it assumes that the suspended sediment and bed sediment particle size distributions are essentially equivalent. This is unlikely to be true in an active stream where much of the suspended sediment may consist of fine particles that generally do not settle to the bed. Thus, the suspension obtained by mixing bed sediments is likely to have a smaller fraction of fine clay than suspended sediment in the water column. PWA (2004a) reports for most locations in the tributary streams that bed material was greater than 50 percent gravel and around 40 percent sand, with fines constituting less than 5 percent except in specific depositional locations. In contrast, the SSC samples collected by USGS in 2006-2008 were predominantly (> 90 percent) silt and clay, suggesting that the bed sediment and suspended sediment have different particle size distributions.

Fine clay sediment has much greater light scattering power per unit mass than does coarser sediment. Thus, calibration to bed sediment mass is likely to bias the relationship of SSC mass to turbidity upward, as is discussed by Thackston and Palermo (2000): “any samples used to produce a correlation curve between TSS and turbidity must be suspension-specific, not just site-specific. The sample must approximate the suspension to be represented in the size, number, shape, and type of particles.”

In sum, there is considerable uncertainty in the turbidity-based estimates of sediment load provided by PWA (2004a) and theoretical reasons to suspect that these estimates may significantly over-estimate actual loads. It should be noted, however, that the turbidity data collected by PWA, as well as any turbidity data collected in future, might be of considerable use in evaluating sediment loads if better correlations are developed based on split sample analyses of water column samples for SSC and turbidity.

4.2.2 Recalculated Turbidity-based Estimates

The prior analysis of sediment load based on turbidity monitoring appears to be flawed by lack of an accurate relationship between turbidity and suspended sediment concentrations based on ambient samples. As part of the Sonoma Creek Sediment Source Analysis (Appendix D in Sonoma Ecology Center, 2006), work was undertaken to derive a relationship between suspended sediment concentration (SSC, mg/L) and turbidity (in NTU) based on a relatively strong relationship found in 127 samples taken at the Sonoma Creek continuous monitoring station in Eldridge, CA (Figure 4-2).

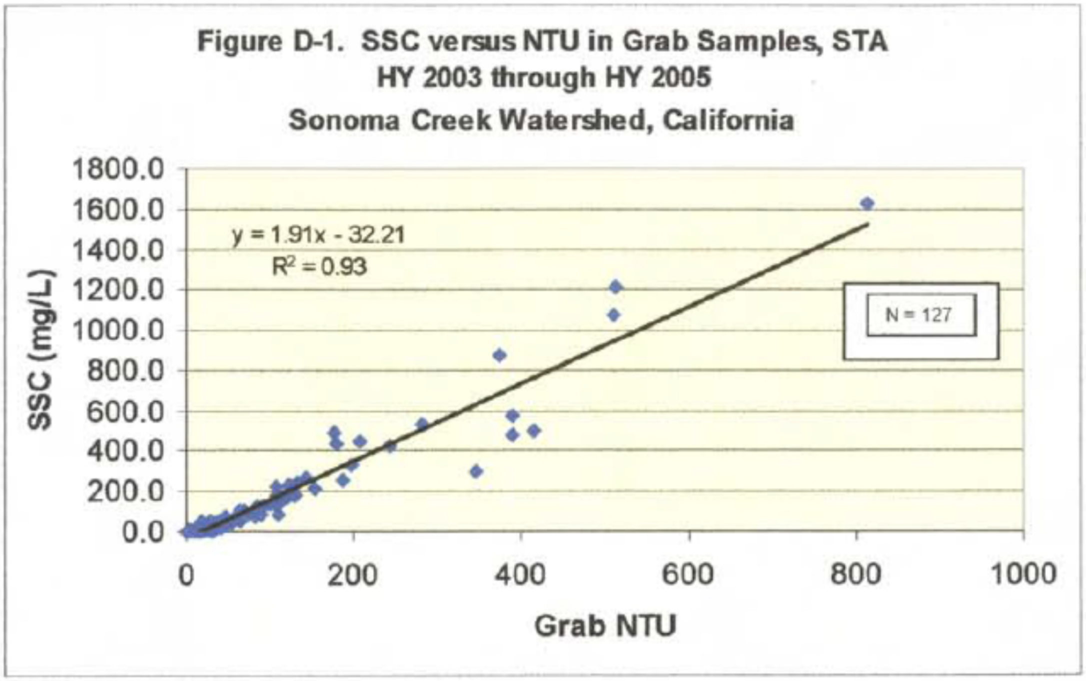


Figure 4-2. Relationship of SSC to Turbidity (NTU) in Sonoma Creek (from Appendix D to Sonoma Ecology Center, 2006)

The resulting equation is:

$$\mathrm{SSC} = 1.91 \cdot \mathrm{Turbidity} - 32.21 \text{ (for Turbidity } \geq 16.9 \text{ NTU);}$$

$$\mathrm{SSC} = 0, \text{(for Turbidity} < 16.9 \text{ NTU)}$$

As the Sonoma Creek watershed is immediately adjacent to the Laguna de Santa Rosa watershed and shares similar geology this relationship may be relevant and applicable to the Laguna de Santa Rosa observations. One caution is that the PWA turbidity sampling for the Laguna de Santa Rosa watershed used a D & A Instruments – OBS 3 turbidity meter, while the Sonoma Creek work used a HACH 2100p turbidity meter. It is well known that different meters can yield rather different results for turbidity. Experiments undertaken by the Forest Service (Lewis et al., 2007) suggest that results from the 2100p turbidity meter tend to be biased high relative to those obtained with OBS 3. Nonetheless, the SSC-turbidity relationship reported for Sonoma Creek is much lower than that used by PWA (2004a).

The PWA analysis was redeveloped with the Sonoma Creek SSC-turbidity relationship and used to recreate a relationship between SSC and discharge. The new relationship gives much lower loading estimates than those provided by PWA (2004a). For example, PWA estimated a load of 96,993 tons for Santa Rosa Creek at Willowside Road for the 2002-2003 season, but this is reduced to 3,684 tons using the revised turbidity-SSC relationship.

The revised rating curve equations to predict sediment load y in lb/sec from discharge x in cfs are as follows:

Laguna de Santa Rosa at Stony Point Rd.	$y = 1.3345 \cdot 10^{-5} \cdot x^2 + 8.8313 \cdot 10^{-3} \cdot x$; $R^2 = 0.466$
Laguna de Santa Rosa nr Sebastopol	$y = 0.01066 \cdot x$; $R^2 = 0.450$
Santa Rosa Creek at Willowside Rd.	$y = 5.6335 \cdot 10^{-6} \cdot x^2 - 1.0988 \cdot 10^{-3} \cdot x$; $R^2 = 0.785$

Average annual sediment loads calculated with these equations are presented in Table 4-3 and compared to the estimates of load reported by USGS at two stations.

Table 4-3. Sediment Loads Calculated from Revised Turbidity – SSC Relationships

Station	Revised Regression, 11/98 – 2/15 (tons/yr)	Revised Regression, WY 2006-2008 (tons/yr)	USGS Analysis, WY 2006-2008 (tons/yr)
11465680 Laguna de Santa Rosa at Stony Point Rd.	8,212	12,231	NA
11465750 Laguna de Santa Rosa nr Sebastopol	11,000	14,333	5,006
11466320, Santa Rosa Creek at Willowside Rd	8,066	7,063	10,362

Note: NA = not applicable; tons/yr = English (short) tons per year. Results for USGS analysis taken from Curtis et al. (2012) but have been converted from metric tons to short tons.

It is evident from Table 4-3 that the revised turbidity-SSC relationship is in much closer agreement with the USGS results than the PWA (2004a) analysis, with a better agreement for the station with the best rating-curve regression fit (Santa Rosa Creek at Willowside Road). Although there are many uncertainties in the approach (such as the applicability of the Sonoma Creek relationship and the likely bias between different turbidity meters) this analysis supports the use of loading rate estimates derived from the USGS monitoring. It also suggests that continuous turbidity monitoring may be a useful method of estimating sediment loads in the Laguna de Santa Rosa watershed if an effort is made to develop local turbidity-SSC relationships specific to the watershed and the turbidity meter used.

4.3 SEDIMENTATION IN MATANZAS RESERVOIR

Matanzas Reservoir is a small flood control impoundment on Matanzas Creek, constructed in the early 1960s as part of the Central Sonoma Watershed Project. This reservoir is an effective sediment trap and has a drainage area of 11.5 mi^2 in the steeper headwaters of the larger Santa Rosa Creek watershed. As summarized by PWA (2004a), the Soil Conservation Service surveyed storage capacity in this reservoir in June 1964, March 1972, and August 1982, over which time capacity decreased from 1,500 to 1,324 acre-feet (AF). This is equivalent to a sedimentation rate of 0.85 acre-feet per square mile per year ($AF/mi^2/yr$), or about 2.53 tons per acre per year (t/ac/yr), assuming a density of 1,400 kilograms per cubic meter (kg/m^3). The loading rate estimated from measured sedimentation in Matanzas Reservoir closely matched PWA's PSIAC-based estimate of a net yield of 0.85 $AF/mi^2/yr$ from the entire Santa Rosa Creek basin, yet we would expect the total sediment yield rate to be much higher in the steep headwaters area draining to Matanzas Reservoir than in the Santa Rosa Creek watershed as a whole. The revised PSIAC results presented in Appendix C are lower, equivalent to a sedimentation rate of 0.53 $AF/mi^2/yr$ for the Santa Rosa Creek watershed as a whole and 0.64 $AF/mi^2/yr$ for the Southeast Santa Rosa subbasin that contains Matanzas Reservoir, again assuming a density of 1,400 kg/m^3, which is equivalent to 100 pounds per cubic foot (lb/ft^3). (Note that PWA (2004a) calculates mass from volumes predicted by PSIAC using a density of 81.8 lb/ft^3 in their Table 12, not 90 lb/ft^3 as stated.)

The PSIAC method may thus under-estimate sediment loading rates to Matanzas Reservoir, while over-estimating the total delivered load from Santa Rosa Creek to the Laguna de Santa Rosa. These observations suggest there may be additional load sources not fully accounted for by PSIAC in the steeper headwater regions of the watershed, but also likely further sediment sinks between these headwater areas and the Laguna de Santa Rosa. Sources and sinks of sediment in the watershed are discussed further in the following sections.

5 Upland Sediment Loads

5.1 SHEET AND RILL EROSION

Established techniques from USDA, specifically the RUSLE (Revised Universal Soil Loss Equation; Renard et al., 1997) approach can be used to estimate rates of soil *loss* due to sheet and rill erosion on upland areas. RUSLE includes inputs that tune the method to local conditions; including sub-factors based on canopy cover and ground cover, and has been applied successfully in the nearby Sonoma Creek watershed (Sonoma Ecology Center, 2006). However, it is also strictly an upland field loss method that does not account for channel processes and delivery, for which reason PWA (2004a) did not apply it. This problem is addressed by using the method of Vigiak et al. (2012) to estimate delivered sediment loads from RUSLE soil loss, as described in the next section. Because it is grounded in a detailed grid-based analysis, the RUSLE approach also provides a firm basis for evaluating individual upland sediment source areas. RUSLE analysis does not, however, account for load derived from channel and gully enlargement, for which further field data and other analytical techniques are needed.

The details of the application of the RUSLE analysis are provided in Appendix B. Appendix C compares the RUSLE results with those obtained from PSIAC and shows that the delivered RUSLE loads, representing only one among multiple sources of sediment, are less than and thus compatible with the total sediment loads estimated from monitoring and discussed in Section 4. Average annual RUSLE soil loss rates by subbasin are shown in Table 5-1.

Table 5-1. RUSLE Average Annual Field-Scale Soil Loss Rates by Subbasin

Subbasin	Subbasin Area (acres)	RUSLE Field-Scale Soil Loss (t/ac/yr)
Lower Santa Rosa	21,511	4.99
Lower Mark West	5,873	6.91
Colgan	4,505	1.60
Blucher	4,936	1.29
Upper Mark West	21,501	6.91
Southeast Santa Rosa	14,189	4.46
Northeast Santa Rosa	14,210	6.50
Upper Laguna	23,865	1.71
Windsor	13,738	5.98
Copeland	3,988	2.03
Upper Floodplain	14,353	1.58
Lower Floodplain*	18,404	5.61
Total Watershed	*161,075*	*4.49*

* Excluding drainage area below Ritchurst Knob.

5.2 LANDSCAPE CONNECTIVITY AND UPLAND SEDIMENT DELIVERY

RUSLE estimates rates of upland soil loss due to sheet and rill erosion at the field or site scale; it does not directly estimate downstream delivery of this sediment, much of which may be trapped near the source. It is common practice to apply a sediment delivery ratio (SDR) to adjust RUSLE soil loss to basin sediment yield at the outlet; however, uncertainty in this calculation is typically high.

Bicknell et al. (2001) present an equation derived from the curve presented in the Soil Conservation Service National Engineering Handbook (USDA, 1983) to estimate SDR as a function of watershed area:

$$\mathrm{SDR} = 0.417762 \cdot (\mathrm{A}^{-0.134958}) - 0.127097$$

where A is the upstream area in square miles. The area-based method is subject to large errors as it does not take into account either the topography of the watershed or the connectivity between source areas and ultimate sinks. Further, the empirical comparisons between basin outlet data and field-scale soil loss estimates on which the relationship is based do not account for additional sediment sources such as channel incision, gully formation, or soil creep. This results in a potential high bias in which the empirical fit to observed data used to develop the area-based SDR over-estimates the fraction of upland sheet and rill erosion that is delivered to the basin mouth to compensate for the omission of other sources of sediment loading.

Recently a group of researchers led by Lorenzo Borselli has developed advanced geographical information system (GIS) techniques for determining sediment and flow connectivity on landscapes (Borselli et al., 2008) and has extended the method to provide parametric landscape-based estimates of sediment delivery ratios that can be used with grid-based applications of RUSLE (e.g., Vigiak et al., 2012). This approach is in the process of being incorporated into the InVEST ecosystem valuation software tools of the Natural Capital Project supported by Stanford University, The Nature Conservancy, World Wildlife Fund, and the University of Minnesota (http://www.naturalcapitalproject.org). This provides an effective means of converting the RUSLE analysis to an estimate of delivered sediment yield from upland sources.

To provide a site-specific estimate of SDR for each grid cell we first use the methods of Borselli et al. (2008) to establish flow path connectivity. This method calculates an Index of Connectivity (IC) that, for each point, depends on both upslope and downslope components (D_{up}, D_{dn}) relative to a receiving point of interest. The receiving point is, somewhat confusingly, termed a "sink" in the literature, although it actually can represent a location beyond which full connection is maintained.

IC is defined for a cell k as the common logarithm of the ratio of upstream and downstream characteristics:

$$IC_k = \log_{10}\left(\frac{D_{up,k}}{D_{dn,k}}\right) = \log_{10}\left(\frac{\overline{W_k}\,\overline{S_k}\,\sqrt{A_k}}{\sum_{i=k,n_k} d_i \big/ (W_i\,S_i)}\right)$$

where W_i is the dimensionless weighting factor for the ith cell, $\overline{W_k}$ is the average weighting factor for the upslope contributing area, S_i is the slope of the ith cell, $\overline{S_k}$ is the average slope of the contributing area, A_k is the upstream contributing area, and d_i is the length of the ith cell along the downslope path ending at cell n_k. The dimensionless weighting factors are typically computed from RUSLE C factors or surface roughness measures, but the result is shown to be relatively insensitive as to the choice of this metric (Vigiak et al., 2012).

Borselli and colleagues define IC in two ways, either as connectivity to the nearest perennial stream or other sink ($IC_{channels}$) or as connectivity to the watershed outlet (IC_{out}; see D'Haen et al., 2013). In our application we calculate $IC_{channels}$ and define perennial streams, floodways, and roads as "sinks" as recommended by Borselli et al. (2008). Roads are included because they typically have enhanced conveyances in areas where they are downstream along flow accumulation pathways. $IC_{channels}$ is used under the assumption that the stream channels transmit all the incoming sediment downstream, consistent with the approach used by Vigiak et al. (2012) and with observations that most upland stream channels in the watershed are either enlarging or at least not aggrading, while transport across the upper Santa Rosa Plain in larger streams is enhanced by the maintenance of floodways. To control for the likelihood that smaller, ephemeral channels may store rather than transmit sediment, the stream sinks used in the analysis are defined from the 1-m digital elevation model (DEM), after smoothing to a 2-m grid to meet computer memory limitations, as corresponding to areas of flow accumulation that have a 5 square kilometer (km^2) or greater upstream drainage area. Roads represented as sinks are those defined in the 2010 Tiger roads coverage (U.S. Census Bureau, 2010), which includes most public and private roads and some, but not all private vineyard alleys and farm roads. Private road segments that are not simulated as flow accumulation pathways likely do not have drainage ditches that would define them as a sink. Streams and roads not represented as sinks nonetheless generally receive higher estimates of connectivity based on the definition of IC, which accounts for the ratio of the square root of upstream area to distance to a downstream sink. An example is shown in Figure 5-1.

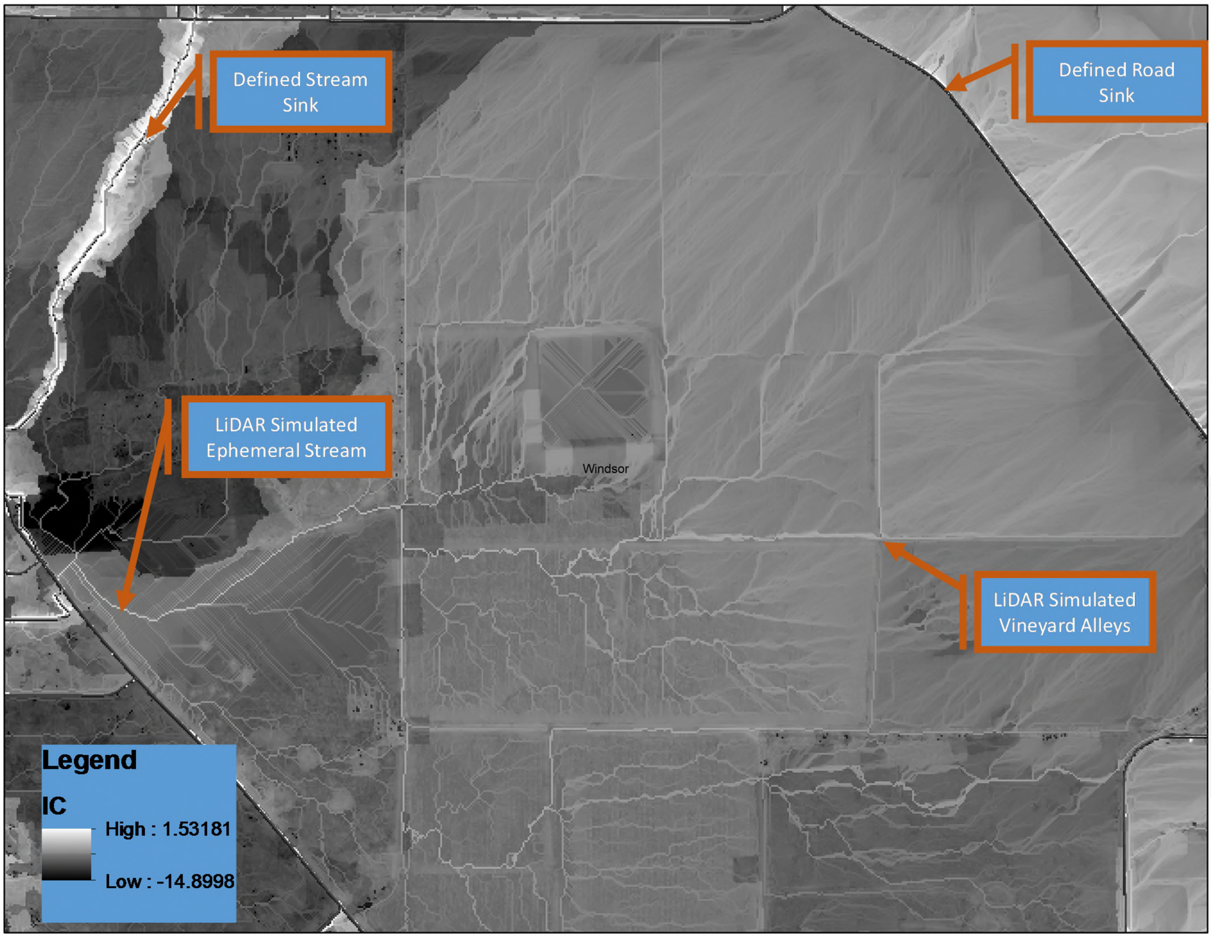


Figure 5-1. Example Connectivity Estimates for Vineyard Area in Windsor Creek Watershed

The Connectivity Index ToolBox in ArcGIS (Cavalli et al., 2013, 2014) uses inputs of high-resolution elevation data to estimate an IC grid. For the Laguna watershed, the elevation data is obtained from the 1-m bare earth LiDAR and the surface roughness weighting is based on the C-factor from the SSURGO soils database, as recommended by Borselli et al. (2008). Resulting IC estimates, shown in Figure 5-2, are strongly affected by the presence of roads.

Vigiak et al. (2012) conducted a study of methods to convert a variety of landscape metrics, including IC, to sediment delivery ratios, using a case study on the Avon-Richardson catchment in southeast Australia (with a climate not dissimilar to California) and found that IC-based methods provided the best results. SDR for a cell *i* is estimated using a sigmoid model of delivery that takes the following form:

$$SDR_i = SDR_{\max,i}\left[1+\exp\left(\frac{IC_0 - IC_i}{k}\right)\right]^{-1}$$

In this equation, IC_0 and k are calibration parameters, IC_i is the Index of Connectivity for the *i*th cell, and $SDR_{\max,i}$ is the maximum possible delivery ratio for the *i*th cell, usually defined on the basis of particle size. Vigiak et al. (2012) defined this as the fraction of topsoil particles finer than coarse sand (< 1,000 micrometers [μm]).

Vigiak et al. calibrated the approach to sediment data at the mouth of the Avon-Richardson catchment. The best fit was obtained with IC_0 set to 0.5, which is the same value found in previous studies in Italy (Borselli et al., 2008), and Vigiak suggests that this factor may be landscape-independent. This leaves k as the primary calibration factor, for which Vigiak et al. obtained a best fit with $k = 2$. The SDR is applicable to sediment derived both from upland erosion and from disconnected gullies (i.e., gullies that are not directly connected to the stream network) and Vigiak's work included estimation of sediment yield from both sources (Whitford et al., 2010).

For application to the Laguna we assumed $IC_0 = 0.5$ based on Vigiak et al. (2012). We assumed SDR_{max} was equal to 0.99 for clay and 0 for coarse sand and calculated a value for each grid cell based on average soil particle diameter (d, μm):

$$SDR_{max} = 0.92 - 0.00093 \cdot d; \quad 2 < d < 989.25 \text{ μm}$$

The average soil particle diameter for each cell in the watershed was estimated from the top 30 centimeters (cm) soil texture data (clay, silt, and sand percentages) from the SSURGO database, yielding SDR_{max} values ranging from 0.68 to 0.88. The fitting parameter in the equation for SDR_i, k, was left at 2, the value optimized for the Avon-Richardson watershed by Vigiak et al., due to lack of rigorous calibration data for delivered loads in the Laguna watershed. Sensitivity analyses showed that the response to varying k between 1 and 3 was nearly linear, with higher SDR corresponding to greater values of k. The results (Figure 5-3) could thus readily be scaled as additional data are collected in the future.

Table 5-2 compares the resulting IC-based composite SDRs for each subbasin to those based on the simple area-based method and reports the estimated average annual upland sediment delivery using the IC-based method. For the Southeast Santa Rosa watershed, results are reported separately for the areas downstream and upstream of Matanzas Reservoir and Lake Ilsanjo under the assumption that these two waterbodies are effective traps for sediment that preclude most transport downstream. For the IC-based method, the composite SDR is calculated as the sum of the RUSLE delivered sediment yield estimates for each cell divided by the total field-scale soil loss for the subbasin. The IC-based SDRs are lower than the area-based SDRs for this watershed by a factor of 2 to 5 times. This reflects the fact that much of the sediment delivered downstream does not derive from upland erosion but rather arises from other sources, as described in Section 6.

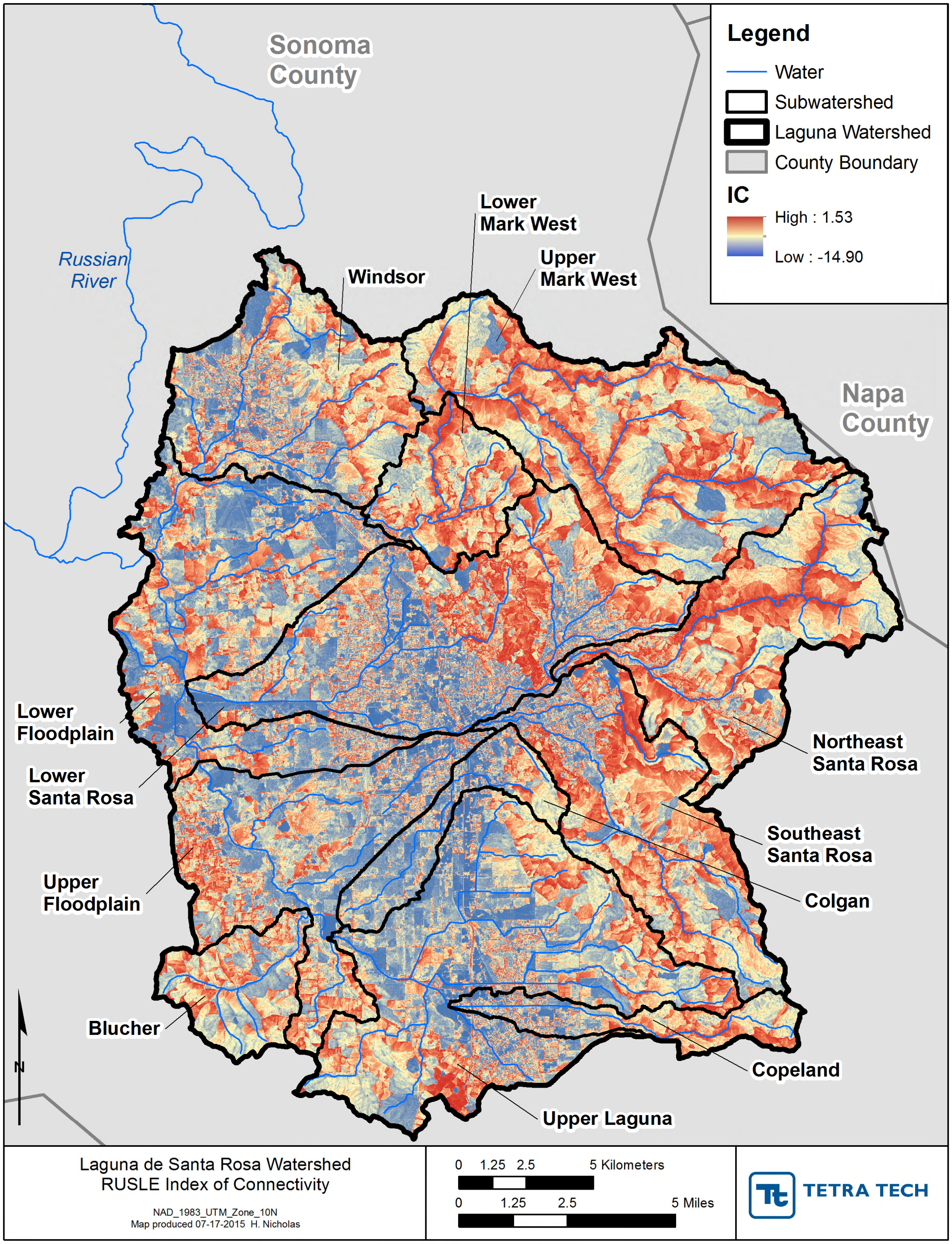


Figure 5-2. Index of Connectivity (IC) for the Laguna de Santa Rosa Watershed

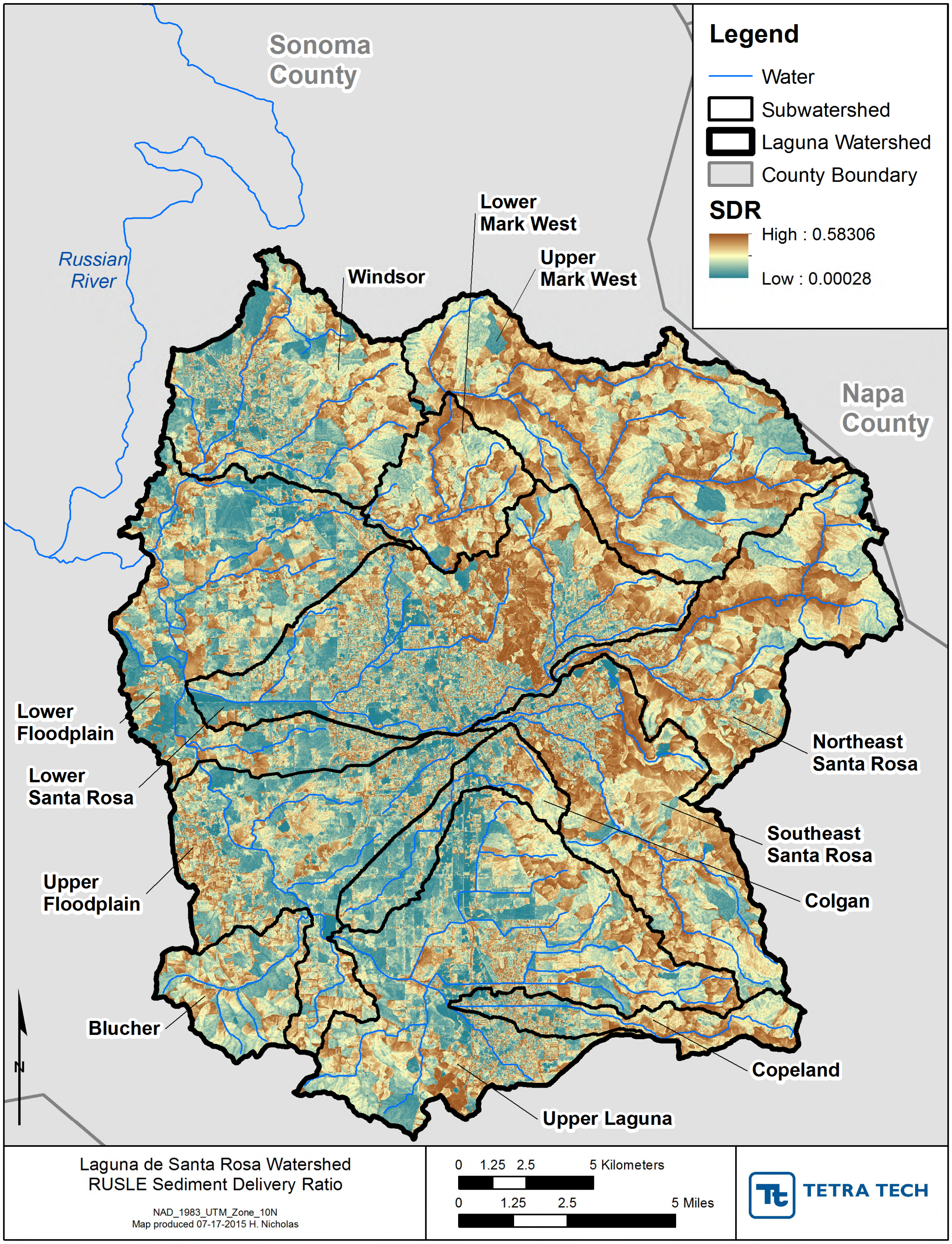


Figure 5-3. IC-based Sediment Delivery Ratio (SDR) for the Laguna de Santa Rosa Watershed

Table 5-2. IC-Based vs. Area-Based Composite Sediment Delivery Ratio Estimates and RUSLE Delivered Upland Sediment Yield by Subbasin

Subbasin	Subbasin Area (acres)	SDR (IC-based)	SDR (Drainage Area-based)	RUSLE Delivered Sediment Yield (tons/yr)
Lower Santa Rosa	21,511	0.031	0.13	3,377
Lower Mark West	5,873	0.024	0.18	988
Colgan	4,505	0.021	0.19	152
Blucher	4,936	0.017	0.19	108
Upper Mark West	21,501	0.023	0.13	3,490
Southeast Santa Rosa (excluding Matanzas and Ilsanjo drainages)	6,037	0.033	0.18	923
Southeast Santa Rosa (trapped by Matanzas and Ilsanjo)	8,152	0.021	0.17	739
Northeast Santa Rosa	14,210	0.025	0.15	2,277
Upper Laguna	23,865	0.024	0.13	969
Windsor	13,738	0.020	0.15	1,618
Copeland	3,988	0.023	0.20	187
Upper Floodplain	14,353	0.021	0.15	469
Lower Floodplain*	18,404	0.019	0.14	1,973
Total Watershed	*161,073*			*17,270*

* Excluding drainage area below Ritchurst Knob.

5.3 UPLAND LOADS BY SOURCE

As described in the previous section, it is likely that upland sediment yield is significant, but not the major source of sediment loading to the Laguna de Santa Rosa under current conditions. Controlling loss of capacity in the Laguna will likely need to focus on stabilizing and controlling loads derived from incising channels and enlarging gullies. However, the upland portion of the total load, which includes runoff from agriculture and urban pervious areas, is of particular interest in terms of delivery of nutrients and organic matter to the Laguna.

Even with the SDR, the RUSLE application does not provide a fully tested and calibrated estimate of upland sediment loading, simply because the available monitoring data are not sufficient to provide a firm basis for calibrating the SDR parameters at this time. Instead, the RUSLE application is best viewed as an estimator of relative risk of upland sediment delivery to the Laguna from different components of the landscape. The spatially averaged delivered sediment loads are tabulated by land use class in Table 5-3. The range of loading rates between land uses is somewhat compressed and relatively high for forest. This may seem counter-intuitive at first, but reflects the fact that forest cover is predominantly on steeper slopes and in the higher elevation, higher rainfall portions of the watershed, whereas the majority of agriculture is in the flatter lowlands.

Table 5-3. RUSLE Upland Delivered Sediment Yield Estimates by Land Use Group

Land Use	Area (acres)*	RUSLE Sediment Delivery Rate (t/ac/yr)	RUSLE Sediment Yield (tons/yr)	Percentage
Cropland	10,669	0.138	1,475	8.5%
Water/Wetland	1,123	0.025	28	0.2%
Developed	49,334	0.119	5,872	34.0%
Barren	28	0.107	3	0.0%
Forest	33,152	0.112	3,709	21.5%
Shrubland	19,427	0.135	2,625	15.2%
Grass/Pasture	47,341	0.075	3,558	20.6%
Total	*161,075*	*0.107*	*17,271*	*100%*

* Excluding drainage area below Ritchurst Knob.

Figure 5-4 shows the location of the upland sediment yields by land use type across the watershed with bins for higher (> 0.2 t/ac/yr) and lower (< 0.2 t/ac/yr) delivered sediment load highlighted in different color ramps. The RUSLE sediment yield raster is developed at the 1-meter (m) scale of the LiDAR but is summarized at a 30-m grid scale (the resolution of the land use coverage). The summary maps provide an indicator of areas of potentially higher risk of upland sediment loading (see example close-up view from the predicted high erosion risk area on the north side of Santa Rosa in Figure 5-5). As these estimates are derived from spatial data at varying resolutions and do not take into account site-specific details of land use and stormwater management, results should be treated as qualitative measures of potential sediment loading risk that need to be further confirmed through field inspection.

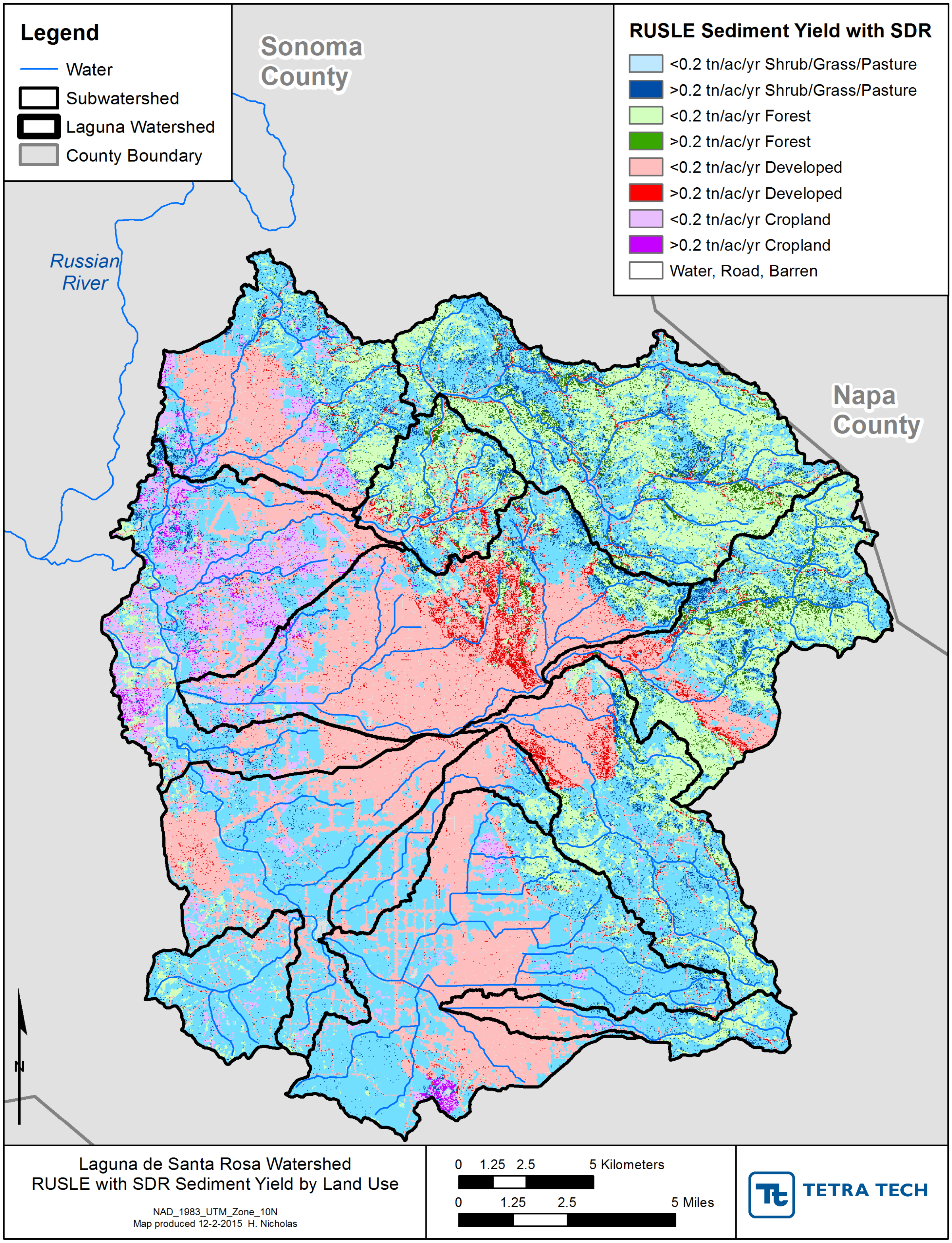


Figure 5-4. RUSLE Sediment Yield Estimates (with IC-based SDR) for the Laguna de Santa Rosa Watershed by Land Use

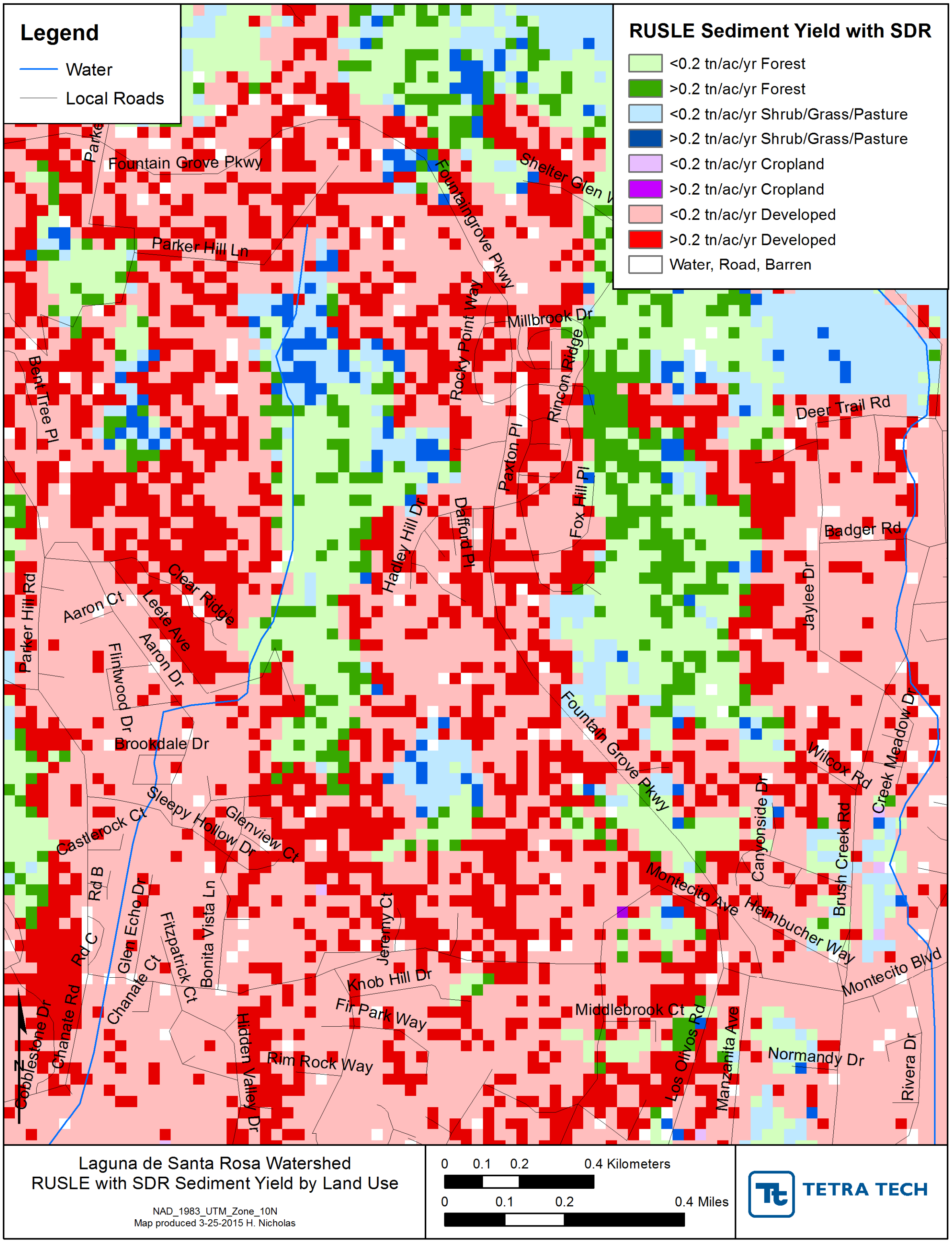


Figure 5-5. Detail from RUSLE Sediment Yield Map, North Side of Santa Rosa, CA

Note: RUSLE results are aggregated to the 30-m scale of the land use coverage

6 Other Sediment Load Sources

6.1 ROADS

Roads are an important source of sediment load generation in the California landscape and were estimated to contribute nearly 10 percent of the total sediment load in the Sonoma Creek TMDL (Low and Napolitano, 2008). Roads contribute sediment loads through a number of processes, including erosion of the road tread, erosion of road cut slopes, washoff of sediment deposited on roads by soil creep from adjacent hillsides, and fluvial effects at stream crossings.

No detailed inventory or analysis of road conditions and sediment yield has been conducted for the Laguna de Santa Rosa watershed. Therefore we rely on an approximate analysis based on the detailed work conducted for the Sonoma Creek Sediment Source Analysis (Sonoma Ecology Center, 2006), especially Appendix B to that document (*Road Erosion/Delivery Assessment for Sonoma Creek Watershed* prepared by Martin Trso, P.G.). The Sonoma Creek watershed is immediately adjacent to the Laguna de Santa Rosa watershed (on the eastern side) and shares similar geology and land use.

Trso worked with a detailed inventory of roads produced by the Sonoma Ecology Center combined with field work to verify road conditions and applied the SEDMODL2 GIS-based road erosion model (Boise Cascade and NCASI, 2005). The analysis addressed paved roads (47 percent of total miles in the Sonoma Creek watershed), dirt roads (24 percent), and vineyard roads/avenues (29 percent) and also evaluated geomorphic terrain units according to erodibility. Roads within 100 feet of streams were considered to be fully connected, those between 100 and 200 feet of streams were considered partially connected, and those more than 200 feet from streams were considered disconnected, with sediment loads directed to adjacent pervious areas. Trso's general conclusion was that roads within the Sonoma Creek watershed delivered approximately 5 tons of sediment per year per mile of road, and that each stream crossing contributed approximately 0.2 tons/yr of sediment due to fluvial erosion. The results of the SEDMODL2 application were generally confirmed by measurements and observations at 43 sites.

Unfortunately, detailed results by road type and subbasin are not included in the Trso report. In addition there are a number of differences in the information used by Trso and that available for the Laguna de Santa Rosa watershed, including the following:

- Trso worked with a detailed road inventory prepared from aerial photography and updated by field work, including determination of road surface type. This level of information is not currently available for the Laguna de Santa Rosa watershed.
- The primary difference between road coverages appears to be that the database used by Trso had a near complete tabulation of vineyard avenues, whereas the Tiger roads coverage includes only a fraction of these private roads. However, Trso reported that vineyard roads exhibited largely non-erosive conditions due to straw mulch ground cover or grassed road surfaces. It is therefore likely sufficient to treat any vineyard roads omitted from the roads coverage as part of the general loading rate from vineyard land uses.
- Trso worked with a 10-m DEM, which likely limited the accuracy of the analysis relative to the LiDAR coverages now available.
- The stream channel network used by Trso is derived from 1:24,000 USGS blue lines and 1:24,000 aerial photography. This appears reasonable for defining streams that provide 100 percent conveyance of road-derived sediment; however, the optimal resolution for definition is unclear.

Detailed road coverages identified for the Laguna de Santa Rosa include the Sonoma County Streets coverage (ftp://gisftp.sonoma-county.org/Vector/TRA_STREETS.zip) and the Tiger roads coverage (U.S. Census Bureau, 2010). We used the Tiger coverage because it includes the vast majority of public roads plus many of the larger private roads. The Trso estimates of 5 tons per mile per year (t/mi/yr) and 0.2 tons/yr per stream crossing were then applied. These estimates are uncertain and could be refined in future with more detailed analysis and information on the characteristics of roads in the Laguna de Santa Rosa watershed.

It should also be noted that the final staff report for the Sonoma Creek TMDL (Low and Napolitano, 2008) argued for modification of Trso's estimates. This report argues that the definition of streams be extended to smaller ephemeral channels not captured at the 1:24,000 scale, increasing both the fraction of roads actively delivering sediment and the number of stream crossings, resulting in an approximately two-fold increase in the estimate of road-derived sediment. This adjustment appears unsupported because very small headwater streams may not generate sufficient power to move 100 percent of the road-derived load and the estimates for fluvial erosion at road crossings are based on measurements from larger streams.

Road lengths and stream crossing counts by subbasin for the Laguna de Santa Rosa watershed are summarized in Table 6-1, amounting to 9,312 tons/yr. Of this total, 265 tons/yr in the Southeast Santa Rosa subbasin are upstream of Matanzas Creek Reservoir or Lake Ilsanjo and can be considered to be largely cut off from downstream transport. Despite the differences in data availability, the total sediment load estimated from roads appears to be about 10 percent of the total load delivered to Laguna de Santa Rosa (see below, Section 8), consistent with the relative importance of road sources in the Sonoma Creek TMDL.

Table 6-1. Road Sediment Source Analysis for Laguna de Santa Rosa Watershed

Subbasin	Road Length (miles)	Stream Crossings (count)	Estimated Road-related Sediment Load (tons/yr)
Blucher	36.76	7	185
Colgan	64.77	19	328
Copeland	53.41	13	270
Lower Floodplain*	170.35	20	856
Lower Mark West	49.42	10	249
Lower Santa Rosa	430.75	114	2,177
Northeast Santa Rosa	105.25	26	531
Southeast Santa Rosa (excluding Matanzas and Ilsanjo)	112.61	35	570
Southeast Santa Rosa (trapped by Matanzas and Ilsanjo)	52.57	10	265
Upper Floodplain	198.21	46	1,000
Upper Laguna	285.10	132	1,452
Upper Mark West	105.04	39	533
Windsor	164.23	51	831
Total	*1,828.47*	*522*	*9,247*

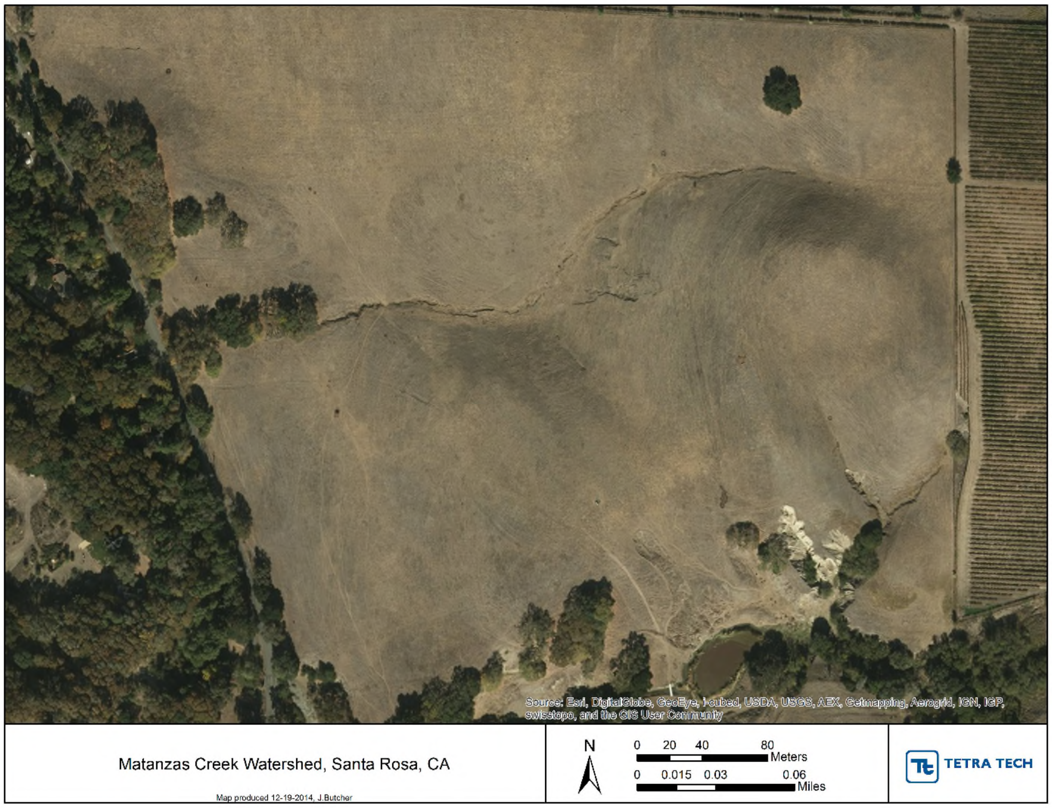
* Excluding drainage area below Ritchurst Knob.

6.2 CHANNEL INCISION, GULLY EROSION, AND LANDSLIDES

The Sonoma Creek TMDL evaluates other sources of sediment loading that arise within or are directly related to stream channels, including bed incision, streamside landslides, and gullies connected to the channel corridor. Channel incision was identified as a significant sediment delivery process along mainstem Sonoma Creek and in alluvial reaches of its tributaries where they traverse the valley floor. Gully erosion and landslides also were identified as significant sources of sediment delivery along tributaries in upland reaches (Low and Napolitano, 2008).

With the exception of some limited areas at higher elevations, the density and risk of large landslides is relatively low within the Laguna de Santa Rosa watershed (Wentworth et al., 1998) and the annual rate of volumetric soil delivery from landslides is not known. Channel surveys by PWA (2004a) show, however, that smaller debris flows are frequent in the upper elevation portions of the watershed, especially along upper Mark West Creek, its tributary Porter Creek, and some of the upper tributaries of Santa Rosa Creek. The risk of debris flows corresponds to the area in which larger amounts of soil creep are also expected to occur. The soil creep / colluvial bank erosion estimates are therefore increased to approximate the long-term average rate of sediment contribution from streamside debris flows and occasional landslides in Section 6.3.

The analysis in Section 4 suggests that the sediment loading rate to Matanzas Reservoir is higher than the loading rate for the Santa Rosa Creek watershed in general. The additional load in this area is likely associated with channel incision and gully processes. Examination of aerial photography of the Matanzas Reservoir watershed shows clear instances of recent gully development. For example, Figure 6-1 shows several active gullies in a grazed area downstream of a vineyard in this watershed. Such gullies are likely major sources of sediment load, and are not accounted for in a RUSLE-based analysis.



Source: Esri, DigitalGlobe, GeoEye, i-cubed, USDA, USGS, AEX, Getmapping, Aerogrid, IGN, IGP, swisstopo, and the GIS User Community

Figure 6-1. Example of Enlarging Gullies upstream of Matanzas Reservoir

PWA (2004a, 2004b) undertook both aerial photograph analysis and geomorphic surveys to identify sediment sources in the watershed. The aerial photograph analysis covered the entire watershed, but surveys of stream segments were limited to areas where access was not precluded by private land. The aerial photograph analysis reported "very few visible signs of erosion," including "no evident large landslide scars, actively eroding gullies or active logging"; however, these conclusions are not fully supported by subsequent ground investigations that detected gully formation in a number of areas. For instance, the contributing area north of Mark West Creek along Loch Haven Road "mostly consists of grasslands and are scattered with highly incised and widened gullies" (see photograph on p. 21 of PWA, 2004a). This likely indicates the difficulty of identifying gullies on aerial photography. The summary of sources in Section 4.2.3 of PWA (2004a) states the following:

> *Based on our ground investigations and understanding of the watershed, we believe the main sources of coarse sediment (cobble and gravel) are steep, currently vegetated gullies in the headwaters of Mark West Creek in the north and Copeland Creek in the south, along with channel erosion and debris flows on the same systems. The main source of medium (sand size) sediment appears to be bank erosion in the mid portions of most streams on the east side of the watershed. The main sources of fine sediment are likely to be from urbanization/ suburbanization (notably north of Santa Rosa, East Windsor and east of Rohnert Park), gully expansion and road runoff associated with housing development (notably in the headwaters of Mark West Creek and Santa Rosa Creek), roadside ditches, channel incision and erosion (notably Santa Rosa Creek and Porter Creek, tributary to Mark West Creek), and channel dredging and maintenance (Upper Laguna tributaries near Cotati and through Rohnert Park).*

Channel incision is clearly an important process contributing sediment in some reaches, especially on former alluvial fans at the edge of the Santa Rosa Plain, and likely reflects channel response to increased runoff that accompanies urbanization. For instance, regarding Santa Rosa Creek PWA (2004a, p. 17) notes:

> *In Doyle Park, the channel has incised at least 6 feet into its bed. The scars from mass bank failure in this reach appear well established and this may indicate that incision has since ceased, or that it continues at a slow rate. It is possible that tectonic movement is a contributory cause. The same incision trend is evident in Matanzas Creek above the Spring Creek confluence and continues to Yulupa Road where the bridge apron apparently stops approximately 3 feet of incision from working upstream (1961 bridge).*

Areas of stream incision and gullies are also noted by PWA for portions of Mark West Creek, Copeland Creek, and other tributaries (see also Laurel Marcus and Associates, 2004). Gullying and stream incision are also noted as important sources of sediment load in the Sonoma Creek and Petaluma watersheds (Sonoma Ecology Center, 2006; Southern Sonoma RCD, 1999). In contrast, areas where streams are confined to maintained floodways have little incision. Unfortunately, there are no quantitative estimates available of the rate of sediment production by gullies or stream incision in the Laguna de Santa Rosa watershed.

The exact demarcation between gullies and ephemeral stream channels is somewhat arbitrary. Poesen et al. (2003) define a gully as a relatively deep, recently-formed eroding channel existing on valley sides and on valley floors where no well-defined channel previously occurred. Given the impacts of a cycle of development that included logging, ranching, and urban development with flood control, many of what are now considered ephemeral headwater stream reaches may meet the definition of a "recently-formed eroding channel" from a historical perspective. In any case, many of the same sediment generating processes should apply.

Whitford et al. (2010) provide a useful summary of recent research on gully erosion, drawing largely on Poesen et al. (2003), among others, but note that, while gully erosion is a major source of sediment load in many watersheds, "there is a general paucity of erosion rates reported in the literature", due largely to difficulties in measurement. Gully erosion evolves via a cycle of initiation, stabilization, and accretion that may occur over decades to centuries. Initiation can occur rapidly during large flow events as a result of factors including removal of vegetative cover and concentrated flow induced by cattle trails. This phase produces the largest yields, but lasts only a short time during which the maximum linear extent is quickly reached. This is followed by a long stabilization phase characterized by the progressive erosion of gully sidewalls at a rate that tends to decrease exponentially until a more stable form is reached (Whitford et al., 2010; Sidorchuk, 1999). Eventually, revegetation of gully sidewalls and floors enables the trapping of sediment in an accretion phase. In the Laguna de Santa Rosa watershed it is likely that there is a population of older partially stabilized gullies that originated during the ranching period accompanied by a newer population of enlarging gullies initiated by land use changes such as residential development, road drainage, and vineyard expansion.

Gullies may be classified either as connected to the stream network or disconnected (i.e., discharging to alluvial fans). Loads from connected gullies are rapidly transported downstream, while loads emerging from disconnected gullies are subject to the same processes as upland loads and may be described with an IC-based SDR (Vigiak et al., 2012).

Whitford et al. (2010) propose a method for simplified assessment of gully erosion rates based on a constant production during the initiation phase followed by exponentially declining rates. While simplified, this approach still requires detailed survey information on location and extent (cross-section, length) of gullies. Whitford et al., working in the Avon-Richardson catchment, found that a combination of aerial photography and local knowledge was needed to correctly identify gully location and type. Identification of active versus inactive gullies from LiDAR can be difficult and is still an area of continuing development (Perroy et al., 2010). Combining LiDAR with a stream power index has shown promise for identifying gullies (e.g., Galzki et al., 2011) and the IC metric discussed in Section 5.2 has similar characteristics and would likely serve the same function.

In sum, sediment load generated by channel and gully enlargement is likely a major part of the sediment budget of Laguna de Santa Rosa; however, quantification of this load would likely require a combination of LiDAR topographic analysis and field investigations. For the present analysis, an estimate of gully erosion is included within the estimated rate of soil creep / colluvial bank erosion in Section 6.3, as both phenomena are most likely to occur in steeper headwater areas. In contrast, channel incision is likely to be a dominant process where streams cut into alluvial fans on the Santa Rosa Plain and is treated as a potential additional load source in the sediment balance. Essentially, it is assigned as the remainder necessary to make the balance occur, but could be better constrained by field surveys in the future.

6.3 SOIL CREEP AND COLLUVIAL BANK EROSION

According to USGS, colluvium is "a general term applied to any loose, heterogeneous, and incoherent mass of soil material and/or rock fragments deposited by rainwash, sheetwash, or slow, continuous downslope creep, usually collecting at the base of gentle slopes or hillsides" (http://mrdata.usgs.gov/geology/state/sgmc-lith.php?text=colluvium; accessed 3/24/2015). Where channel banks are hillslopes colluvium can be directly mobilized by streams, termed colluvial bank erosion.

Colluvial erosion associated with overland flow is already addressed in the RUSLE/IC analysis and should not be double-counted. However, downslope soil creep can also be an important process separate from wash processes. In the Sonoma Creek TMDL (Low and Napolitano, 2008), "rates of [additional] sediment delivery from colluvial bank erosion are assumed to be equal to rates of soil creep." This is not quite correct as the load associated with soil creep should not include colluvium due to rainwash and sheetwash, but does point out the importance of the process. While the TMDL staff report cites Sonoma Ecology Center (2006) as the source of estimates for soil creep, the method is actually described in Collins (2007):

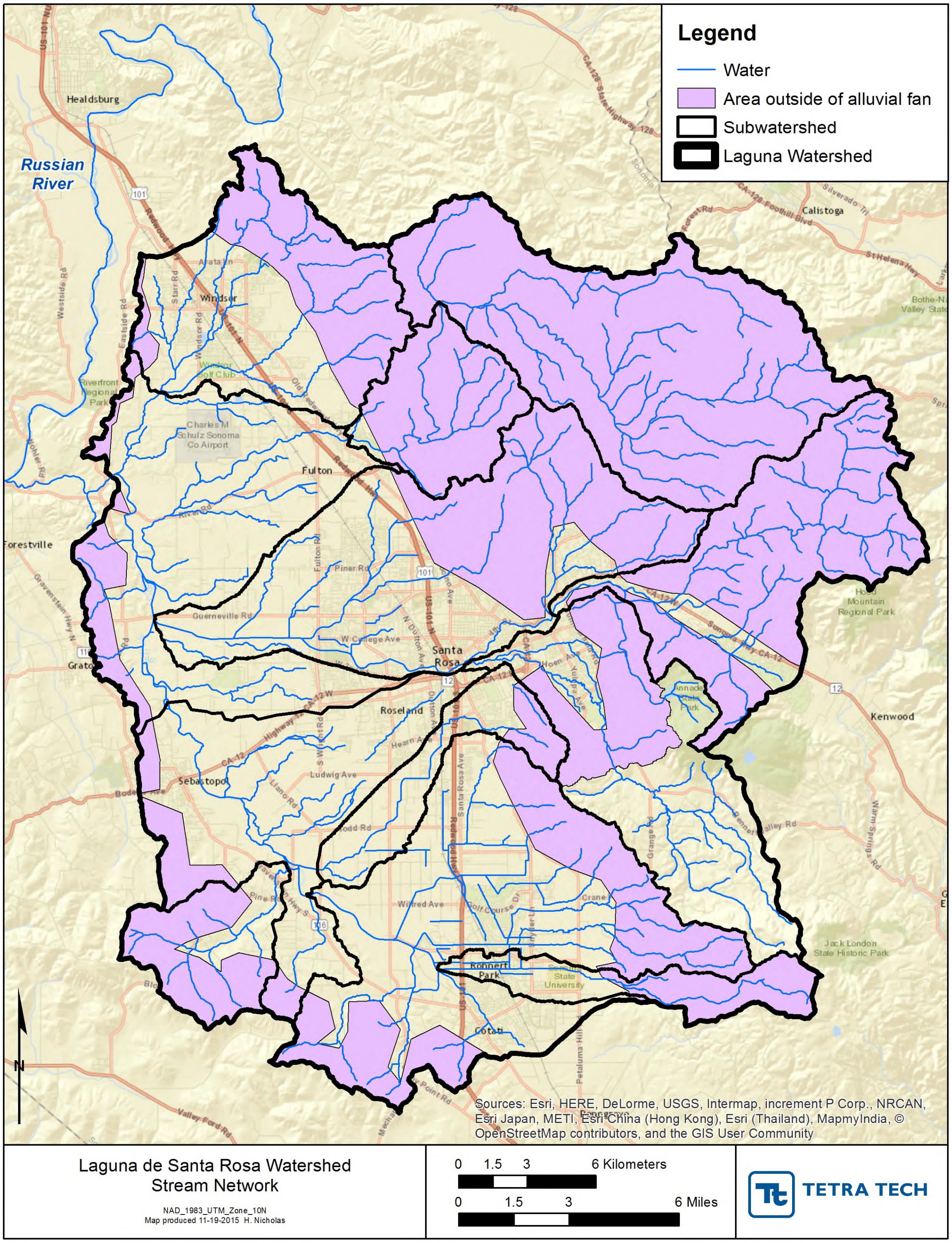
> *Sediment supply from soil creep was only determined for upland channels in the hillsides, not for alluvial channels, those on alluvial fans, or channels along the Sonoma Valley floor Morphologic Units. We referred to literature, published reports, and had discussions with Dr. William Dietrich (UC Berkeley Department of Planetary Sciences), to develop a reasonable average creep rate. Soil creep rates for upland channels were assumed to average about three mm/yr for the upper 3 ft of soil profile. The rate of soil creep and depth of soil was multiplied by the combined length of both banks for the upland geomorphic units.*

In the Sonoma Creek TMDL this approach was applied to stream channels based on the blue-line stream network and extended into any headwater channels visible on aerial photographs. At a stated bulk density of 1.6 tons per cubic yard (tons/yd^3), the estimated rate of sediment delivery from colluvial bank erosion via soil creep in the Sonoma Creek watershed is 115 tons per square mile per year (t/mi^2/yr), or 0.180 tons per acre per year (t/ac/yr). The density assumed for sediment in the Sonoma Creek TMDL seems high, however, as 1.6 tons/yd^3 is a typical value used for wet sand. This report assumes a density of 1,400 kilograms per cubic meter (kg/m^3), equal to 1.18 tons/yd^3, which would reduce the estimated loading rate to 0.133 t/ac/yr.

Buffleben (2009) provides a useful overview of soil creep estimation. The rate of loading due to soil creep is dependent on the linear creep rates and the assumed depth over which creep applies. While there is much literature on the subject, it is in some cases difficult to separate estimates of true creep from other diffusive hillslope processes associated with rainfall and already addressed in RUSLE. Total diffusive sediment flux on hillslopes is clearly and non-linearly dependent on slope (e.g., Roering et al., 1999), but a useful treatment of the creep component alone as a function of slope has not been located. Saunders and Young (1983) summarize many experimental estimates of soil creep rates from around the world and found the linear creep rates to be generally in the 0.5 to 2 millimeters per year (mm/yr) range. Lehre (1987) measured subsurface soil creep rates for the Lone Tree watershed near Mount Tamalpais in Marin County and reported inorganic creep rates on the order of 1.5 mm/yr, but suggested a much more significant source of creep was attributable to animal burrowing. The key uncertainty in estimating mass loading seems to be the depth over which creep is calculated. Saunders and Young suggested that a typical depth for soil creep is 25 millimeter (mm) in temperate climates, while Lehre estimated soil creep over a depth of 0.5 m. The calculation over a depth of 3 feet (ft) (0.914 m) recommended by Dietrich (as cited in Collins, 2007) seems large relative to published depths from other studies, but this may reflect the drier inland climate of the Sonoma Creek watershed.

Given the uncertainty and the lack of site-specific information for the Laguna de Santa Rosa watershed this analysis relies on the rate calculations derived from Dr. Dietrich and documented in Collins (2007). In addition to its use in the Sonoma Creek TMDL, this rate of soil creep loading yields estimates of colluvial bank erosion that are consistent with load estimates derived from instream concentration measurements in the Laguna de Santa Rosa watershed (Section 4).

Beyond creep rates and applicable depths, a third source of uncertainty is the definition of the stream network to which colluvial erosion applies. The Sonoma Creek TMDL extended the blue-line network to the extent that channels were visible on aerial photographs. This may be too aggressive, as the intent should be to use only the channel length that encompasses streams with sufficient power to be able to readily transport the colluvial bank material. Montgomery and Dietrich (1988) recommend using channels up to the farthest upslope location of a channel with well-defined banks. As a compromise we used the NHD high-resolution stream lines coverage to define streams where colluvial bank erosion is considered. Such erosion does not occur in the flood plain or alluvial deposits, so the selection is further restricted to those streams that lie in higher relief areas (see the purple shaded area in Figure 6-2). For these streams, the rate of colluvial bank erosion via soil creep was estimated as twice the length (two sides) times the loading rate recommended by Dr. Dietrich, which amounts to 13.62 short tons per stream-mile per year, assuming a sediment bulk density of 1,400 kilograms per cubic meter (kg/m^3).



Sources: Esri, HERE, DeLorme, USGS, Intermap, increment P Corp., NRCAN, Esri Japan, METI, Esri China (Hong Kong), Esri (Thailand), MapmyIndia, © OpenStreetMap contributors, and the GIS User Community

Figure 6-2. Streams Evaluated for Colluvial Bank Erosion in the Laguna de Santa Rosa Watershed

As noted in Section 6.2, gully formation and small landslides are likely to be important sources of sediment load in steeper areas of the watershed, but are unquantified. The load associated with these sources is therefore taken as a calibration term and adjusted to provide consistency with the total loading estimates that are available at the various gages in the stream network. A term to approximate these sources is added to the colluvial bank erosion estimate, also as a function of stream mile within the steeper areas of the watershed. A total loading rate (sum of colluvial bank erosion, gully formation, and small landslides) of 63.4 tons per stream mile per year is applied within the steeper portions of the watershed identified in Figure 6-2, implying that the loading due to gully formation and small landslides in these areas is 49.78 tons per stream mile per year. (The combined rate of 63.4 tons per stream mile per year is equivalent to a load of roughly 53.9 tons per square mile per year (t/mi^2/yr) spread over the whole Laguna de Santa Rosa watershed.) The resulting load estimates by subbasin are given in Table 6-2.

Table 6-2. Sum of Colluvial Bank Erosion, Gully Erosion, and Landslide Loading Estimates for the Laguna de Santa Rosa Watershed

Subbasin	Applicable Stream Length (miles)	Sediment Load (tons/yr)
Blucher	6.93	439
Colgan	2.00	127
Copeland	6.75	428
Lower Floodplain *	3.03	192
Lower Mark West	15.79	1,001
Lower Santa Rosa	18.80	1,192
Northeast Santa Rosa	38.95	2,469
Southeast Santa Rosa (excluding Matanzas and Ilsanjo)	7.37	467
Southeast Santa Rosa (trapped by Matanzas and Ilsanjo)	22.25	1,411
Upper Floodplain	0.30	19
Upper Laguna	18.15	1,151
Upper Mark West	55.99	3,550
Windsor	17.63	1,118
Total	*213.94*	*13,564*

* Excluding drainage area below Ritchurst Knob.

6.4 BACKWATER FROM THE RUSSIAN RIVER

During flood events on the Russian River, sediment laden water may back up into the Laguna de Santa Rosa. This constitutes another potential source of sediment load. PWA (2004a) discusses this issue and noted that deposition from Russian River water may help to contribute to shallowing at the downstream end of the Laguna de Santa Rosa. They concluded, however, that such sedimentation is “unlikely to be significant compared to the frequent deliveries of sediment from the Laguna-Mark West itself.”

7 Sediment Sinks

The sediment generated from the sources described in Sections 5 and 6 are either trapped within the watershed (including within the Laguna de Santa Rosa itself) or passed through to the Russian River.

7.1 SEDIMENTATION LOSSES

7.1.1 Reservoirs and Debris Basins

Several flood control reservoirs and debris basins capture and retain sediment within the watershed upstream of the Laguna de Santa Rosa. The largest of these is Matanzas Creek Reservoir, with a drainage area of 11.83 mi^2 in the Southeast Santa Rosa subbasin. Loss of storage volume to sedimentation in Matanzas Creek Reservoir between 1964 and 1982 was discussed above in Section 4.3. In more recent years the Sonoma County Water Agency (SCWA) has operated Matanzas Creek Reservoir for sediment control and regularly cleans out the sedimentation forebay. Lake Ilsanjo, also in the Southeast Santa Rosa subbasin, is also believed to be an effective sediment trap. Sediment loading in the watersheds of both Matanzas Creek Reservoir and Lake Ilsanjo are thus eliminated from the sediment budget analysis.

SCWA operates several other flood control sedimentation facilities, which are described in the Stream Maintenance Program Manual (SCWA, 2009). These provide partial trapping of upstream sediment, so their watershed areas are not removed from the sediment budget analysis. Spring Lake is operated for flood and sediment control and receives water diverted from Santa Rosa Creek. There is another flood control reservoir on Brush Creek Middle Fork and one on Paulin Creek that is referred to as the Piner Creek Reservoir, as well as sedimentation basins on Cook Creek (tributary to Coleman Creek) and Adobe Creek. In contrast to Matanzas Creek Reservoir, these facilities have relatively small drainage areas and capture varying amounts of influent sediment. Therefore, their rates of sediment trapping are estimated based on records from periodic cleanout of sediment reported by SCWA.

7.1.2 Sedimentation in the Laguna de Santa Rosa and Floodplain

The preceding sections discuss sediment loading into the Laguna. A complete mass balance also requires consideration of storage in the Laguna and floodplain along with purging and transport out of the system. The difference between these two rates represents the change in storage, with a positive change in storage equivalent to aggradation and filling of the Laguna. Morphological evidence on aggradation in the Laguna also provides an additional constraint on sediment loading estimates.

The hydrology of the Laguna itself is complex and a rigorous modeling basis is not available for estimating rates of retention in the system; however, various sources of information are available. PWA (2004a) discusses changes to the morphology of the Laguna over time, noting that portions have been straightened and channelized. The channelization increases sediment transport capacity, but only locally, and flow and sediment transport through the Laguna is controlled by a bedrock outcrop approximately 1,500 feet north of the Trenton Road crossing as well as being affected by backwater from the Russian River. As a result, the Laguna continues to trap and retain sediment.

Sediment accumulation during flooding may be particularly important. During large floods the Laguna expands onto the adjacent floodplain. PWA analysis of the flood of April 14, 1999 and other information such as the 1956 surveys estimated that sediment deposition of 1.5 to 2 feet (about 10-12 mm/yr) had occurred since the 1950s in three areas: near the Mark West Creek confluence, north of Guerneville Road, and between the Santa Rosa Creek Flood Channel and Occidental Road. PWA (2004a, Section 4.4.5) estimated from the survey and cross-section data that the net sedimentation rate within the Laguna amounts to 54 acre-feet per year (AF/yr), or 102,792 short tons/yr at an assumed density of 1,400 kilograms per cubic meter (kg/m^3). PWA further concluded that roughly 50 percent of the sediment load generated within the watershed does not reach the Laguna itself, due to storage in the uplands and channels, and that about 50 percent of the sediment reaching the Laguna is trapped therein.

Another significant flood event occurred on December 31, 2005 – January 1, 2006, during the period in which the USGS was studying sediment transport in the Laguna (but unfortunately prior to the installation of the flow gage on Mark West Creek near Windsor). Curtis et al. (2012) reported sediment deposition from this event in most areas of the floodplain as a thin veneer of less than 2 mm thicknesses, but there were also regions of extreme sedimentation that aggraded by up to 1.5 m where steep western tributaries flow out of the uplands and on to the floodplain resulting in alluvial fan development.

Curtis et al. also measured short term deposition rates in the Laguna floodplain using clay pads (for 2007 to 2008, a relatively dry period) and long term deposition rates using dendrochronologic analysis of buried tree trunks. The final estimate of Curtis et al. is that deposition amounts to 3.6 mm/yr over an area of 11 km^2, or 39,600 cubic meters per year (m^3/yr). This is equivalent to 61,112 English (short) tons/yr assuming a unit weight of 1,400 kilograms per cubic meter (kg/m^3), which equates to a retained loading rate from the watershed of 0.38 t/ac/yr based on a drainage area of 161,075 acres. This estimate of accumulation rate is lower than that cited above from PWA (2004a), which is equivalent to 0.64 t/ac/yr.

The USGS study (Curtis et al., 2012) also made use of flow and suspended sediment monitoring at the outlet of Laguna (USGS gage 11466800, Mark West Creek near Mirabel Heights) and estimated an average annual outflow of sediment of 13,100 tons/yr for 2006-2007. The total inflow from the Laguna de Santa Rosa, Santa Rosa Creek, and Mark West Creek for this period was estimated by Curtis et al. as 42,741 tons/yr, for a difference of 29,641 tons/yr. Our reanalysis with LOADEST (Table 4-2) suggests the actual outflow rate may have been smaller.

It is also possible that significant amounts of additional trapping and retention of sediment may be occurring in the flat areas of the Santa Rosa Plain, but *outside* the Laguna flood boundaries evaluated in the PWA (2004a) and Curtis et al. (2012) studies. This is especially true for historical conditions, under which high sediment loads from the uplifting hills to the north and west are believed to have been largely retained on the Santa Rosa Plain in alluvial fans fed by distributaries from the upland creeks (PWA, 2004a; Sloop et al., 2007). These streams likely delivered little sediment directly to the Laguna. Human modifications to mitigate flooding included consolidating, straightening, and deepening channels and establishing dikes, the net effect of which was to connect the upland channels more directly to the Laguna and move more sediment into the Laguna. The lower reaches of the engineered channels can, however, still overflow during large storm events, exporting sediment onto the plain. PWA (2004a) describes this portion of the watershed as follows:

> *…the region is characterized by flood control channels. The sediment dynamics of these reaches can be conceptually sub-divided into two zones. In the middle reach areas, fine sediment deposition occurs periodically due to local conditions in the flood control channels, varying according to stream power as increases in discharge and slope promote greater sediment transporting capacity are more or less offset by increase in channel width that reduce sediment transporting capacity for a given flow. Fine sediment storage in these zones is likely to be temporary in general, and mobilized in high flows. Further downstream, the channels are more directly under the backwater influence of the Laguna de Santa Rosa and, in conjunction with summer irrigation return flows, create a store of sediment in conjunction with aquatic vegetation growth across the entire channel bed. It is assumed that these flood control channel[s] create a near-permanent store of sediment and represent the headwater extent of the Laguna system, as much as the individual creeks. Vegetation and sediment are periodically cleared from these channels to increase their flood conveyance capacity.*

A detailed account of these processes is available for the Copeland subwatershed near Rohnert Park (Laurel Marcus and Associates, 2004). This study shows how the original system of distributaries has been replaced by incision into the alluvial fan and the shifting of sediment downstream. The lowest reaches of Copeland Creek have a very low gradient, and the flood control channel has been subject to rapid filling, requiring frequent and extensive dredging.

There is a possibly significant export of sediment from the stream channels onto agricultural lands in the Santa Rosa Plain during major flood events. One possible source of evidence for this would be comparison of USGS topographic maps from the 1950s to recent LiDAR. The Regional Board has attempted some analyses of this type, but the results may be confounded by significant amounts of import of fill for construction in the Santa Rosa area. After correcting for change in vertical datum for the older maps from NGVD29 to NAVD88 it appears there may be a net elevation gain of around 2 feet since the 1940s adjacent to many of the creeks and flood channels that cross the plain, likely as a result of both flooding and disposal of dredge material from the channels.

7.2 CHANNEL MAINTENANCE ACTIVITIES

The *Stream Maintenance Program Manual* (SCWA, 2009) notes that the flatter portion of stream channels on the Santa Rosa Plain are prone to deposition, and a number of these channels, as well as sedimentation basins, are regularly dredged to improve conveyance. County-wide, it is stated that the Maintenance Program removes 10,000 – 25,000 cubic yards per year (yd^3/yr) from fluvial channels in the county, some of which has been placed on adjacent lands.

Detailed records for individual water courses are not available prior to 2008. Since that time, specific removal activities have been included in the annual reports, and SCWA kindly provided a summary of these activities for 2008 through 2014 (personal communication from Keenan Foster, SCWA, to David Kuszmar, NCRWQCB, 3/6/2015). Results are shown in Table 7-1, assuming a dry density of 1,400 kilograms per cubic meter (kg/m^3). Note that the average annual removal is of the same order of magnitude as the total load at USGS gages estimated in Section 4. Sediment removal is based on need and the amounts and locations of removal activities vary considerably from year to year, as is evident from the standard deviation shown in Table 7-1. Nonetheless, this seven-year average provides the best estimate available of typical sediment removal rates by the SCWA Stream Maintenance Program.

7.3 EXPORT TO THE RUSSIAN RIVER

Sediment export to the Russian River is discussed in Section 4.1. The LOADEST reanalysis reported in Table 4-2 suggests a best estimate of 4,800 tons/yr for load passing the USGS gage on Mark West Creek near Mirabel Heights, slightly downstream of the bedrock ledge and constriction at Ritchurst Knob that controls water elevations in the Laguna de Santa Rosa. Because Windsor Creek enters Mark West Creek just upstream of Ritchurst Knob it is likely that much of the sediment load observed at the Mirabel Heights gage is derived from Windsor Creek, implying greater trapping of loads derived from other tributaries to the Laguna de Santa Rosa.

Table 7-1. Sediment Removal for the SCWA Stream Maintenance Program

Subbasin	Total Volume, 2008-2014 (yd^3)	Average Mass (tons/yr)	Median Mass (tons/yr)	Standard Deviation on Annual Mass
Lower Floodplain	0	0	0	0
Windsor	800	135	0	357
Lower Mark West	0	0	0	0
Upper Mark West	0	0	0	0
Lower Santa Rosa	26,939	2,953	1,138	3,669
Northeast Santa Rosa	4,054	683	517	700
Southeast Santa Rosa (excluding Matanzas and Ilsanjo)	175	30	0	78
Southeast Santa Rosa (trapped by Matanzas and Ilsanjo)	2,838	478	522	464
Upper Floodplain	1,264	213	0	493
Colgan	14,001	2,360	236	5,518
Blucher	0	0	0	0
Upper Laguna	75,298	14,282	14,915	7,805
Copeland	14,948	2,520	812	3,463
Total	*140,317*	*23,653*	*22,555*	*11,337*

Note: yd^3 = cubic yards. Mass is expressed in English (short) tons.

8 Sediment Budget for Current Conditions

The preceding sections summarize the available data and provide estimates of the magnitude of all major sources and sinks of sediment in the Laguna de Santa Rosa watershed. All of these estimates have associated uncertainty, and some are more uncertain than others. Nonetheless, they are sufficient to develop an estimate of the overall sediment budget for the watershed. The estimated sediment budget for current conditions is summarized in Table 8-1.

Table 8-1 begins with the proposition that the RUSLE soil loss analysis augmented by the IC-based sediment delivery analysis provides a reasonable representation of upland sediment load generation and transport to the Laguna de Santa Rosa. Therefore, the subbasin estimates of upland load are taken directly from Section 5. Sediment sources associated with roads, colluvial bank erosion, gullies, and landslides are as described in Section 6, although these are believed to have higher uncertainty than the upland sediment loads. For sediment sinks, removal via SCWA channel maintenance activities is taken from Section 7.2, while Matanzas Creek Reservoir and Lake Ilsanjo are assumed to trap the majority of the upstream sediment load and their watersheds (totaling 8,152 acres) are thus omitted from all source and sink categories in the analysis for the Southeast Santa Rosa watershed. Downstream outflows have been estimated from data at five locations (four from suspended sediment concentration data and one from turbidity measurements). Downstream loads at the four stations with suspended sediment-based load analyses were initially set to the LOADEST best estimate and varied slightly to achieve balance, but constrained to be within the confidence limits for the LOADEST analyses. Trapping within the Laguna de Santa Rosa is set at a rate that equals the findings of Curtis et al. (2012) summarized in Section 7.1.2.

To complete a full balance consistent with the estimates of trapping within the Laguna it would appear that there is an additional source of sediment within the Santa Rosa Plain. This “Other” source category is believed to primarily represent channel incision into the alluvial fans on the Santa Rosa Plain, likely a result of increased impervious surface area and resulting higher peak storm flows. These loads are assigned to the Colgan, Copeland, Windsor, Upper Laguna, Upper Floodplain, and Lower Floodplain watersheds based on requirements to achieve mass balance closure at the gage locations where loading rates have been estimated. Similar loads may occur in other subbasins, but were not needed to achieve the sediment mass balance.

Estimates of channel incision loads to the Upper Laguna and Upper Floodplain are constrained by total sediment load estimates for Laguna de Santa Rosa near Sebastopol and Laguna de Santa Rosa at Stony Point Road and likely derive from the various small tributaries that cross the Santa Rosa Plain in this region. The channel incision loads to the downstream subbasins (Upper Laguna, Upper Floodplain, and Lower Floodplain) are set to balance the estimated deposition rate within the Laguna de Santa Rosa provided by Curtis et al. (2012), which are said to focus deposition in the Lower Floodplain.

The observed evidence on condition of individual channels at least partially agrees with the estimated channel incision loads developed in the mass-balance analysis. The channel incision estimate for Copeland is consistent with the study of that watershed (Laurel Marcus and Associates, 2004) that reports that “nearly 50,000 yd^3” of sediment had been generated from incision and widening of the channel on the alluvial fan over the last 40 – 50 years. For the Lower Floodplain, these loads in large part are believed to represent incision on Mark West Creek downstream of the gage near Windsor. PWA (2004a) notes channel incision occurring on several segments of lower Mark West Creek below the stream gage on the Santa Rosa Plain, including strong incision near Slusser Road, which is suggested to be a result of conversion from pasture to vineyards coupled with additional development. Windsor Creek is also noted as incised and widening throughout most of its length. The total inferred channel incision load required to balance estimates in the Lower Floodplain subbasin is assigned one third to Windsor Creek and two thirds to the lower portion of Mark West Creek that lies within the Lower Floodplain subbasin based on relative upstream drainage area. An additional channel incision load is not assigned to Lower Santa Rosa Creek because most of the channel is confined to maintained floodways.

The sediment balance analysis assigns a relatively large channel incision load to the direct drainages to the Upper Laguna subbasin and a relatively small load to the Upper Floodplain subbasin. The balance between these two subbasins may be an artifact of attempting to honor the estimate of sediment loading passing the Stony Point Road gage, which is based only on the turbidity regression and is thus highly uncertain. SCWA (2009) notes that the lowest reaches of Roseland and Colgan Creeks pass through agricultural land and there are problems with cattle crossings and grazing in the channel in lower Roseland Creek, which drains into the Upper Floodplain subbasin. For the Upper Laguna, PWA (2004a) notes channel incision problems in Gossage Creek. In addition, the Bellevue-Wilfred watershed, Hinebaugh Creek, lower Copeland Creek, and the ‘headwaters’ of Laguna de Santa Rosa in Cotati are all noted as having limited zones of sediment production near the edge of the Sonoma Mountains, as well as some locations of channel incision. Much of this sediment deposits in the floodways and is periodically removed by SCWA; however, some of the sediment production is likely transported into the Laguna de Santa Rosa, and channel deposits may also be remobilized during high flow events.

Currently available data are not sufficient to constrain the sediment budget to a unique solution; however, the results presented in Table 8-1 are a plausible and internally consistent representation of long-term sediment dynamics for the Laguna de Santa Rosa watershed. Additional field work would be necessary to confirm and potentially refine these estimates of sediment loading rates apparently associated with channel incision on the Santa Rosa Plain.

Table 8-1. Sediment Balance for Current Conditions in the Laguna de Santa Rosa Watershed by Subbasin (short tons/yr)

	Northeast Santa Rosa	Southeast Santa Rosa[1]	Lower Santa Rosa	Windsor	Upper Mark West	Lower Mark West	Blucher	Colgan	Copeland	Upper Laguna	Upper Floodplain	Lower Floodplain[2]	Sum
SOURCES													
Upland	2,277	923	3,377	1,618	3,490	988	108	152	187	969	469	1,973	16,532
Upstream	0	0	6,525	0	0	7,573	0	0	0	1,784	9,334	35,913	
Road Crossings	5	7	23	10	8	2	1	4	3	26	9	4	102
Road Tread	526	563	2,154	821	525	247	184	324	267	1,426	991	852	8,880
Soil Creep, Gullies	2,469	467	1,192	1,118	3,550	1,001	439	127	428	1,151	19	192	12,153
Other (Channel)	0	0	0	8,489	0	0	0	19	1,711	17,138	3,253	16,978	47,589
Total In	*5,278*	*1,960*	*13,271*	*12,056*	*7,573*	*9,811*	*733*	*625*	*2,596*	*22,494*	*14,075*	*55,912*	*85,255*
SINKS													
Sediment Removal	683	30	2,953	135	0	0	0	236	812	14,282	213	0	19,343
Downstream	4,595	1,931	10,319	11,921	7,573	9,811	733	389	1,784	8,212	3,862	4,800	4,800
Deposition	0	0	0	0	0	0	0	0	0	0	10,000	51,112	61,112
Total Out	*5,278*	*1,960*	*13,271*	*12,056*	*7,573*	*9,811*	*733*	*625*	*2,596*	*22,494*	*14,075*	*55,912*	*85,255*

[1] Excluding drainage areas above Matanzas Creek Reservoir and Lake Ilsanjo (8,152 acres).

[2] Excluding drainage area below Ritchurst Knob (2,453 acres). As delineated, the Lower Floodplain includes a substantial amount of the lower portion of Mark West Creek downstream of the USGS stream gage, as well as several smaller tributaries that flow into the Laguna de Santa Rosa.

Sources:

Upland: Estimated delivered sheet and rill erosion from RUSLE analysis with IC-based sediment delivery (Section 5).

Upstream: Sum of downstream output of all upstream subbasins.

Road Crossing: Based on Sonoma Creek analysis of load per stream crossing (Section 6.1).

Road Tread: Based on Sonoma Creek analysis of load per mile of road (Section 6.1).

Soil Creep, Gullies: Analysis of colluvial bank erosion via soil creep (Section 6.2), adjusted upward to account for gully erosion and landslides (Section 6.3).

Other: Remainder, believed to represent loads from degradation and incision of channels in former alluvial fans on the Santa Rosa Plain.

Sinks:

Sediment Removal: Average (or median) rate of sediment removal from SCWA channel maintenance activities, 2008-2014 (Section 7.2). Areas of sediment removal change significantly from year to year, depending on need. The median is used for Colgan and Copeland because the averages appear to be biased high by a single year in which large amounts of sediment were removed.

Downstream: Outflow downstream; constrained to 95 percent confidence interval range of LOADEST reanalyses (Table 4-2) for Lower Santa Rosa (gage at Willowside Rd., inflated by a factor of 1.107 to yield an average of 10,828 tons/yr, range 7,409 -14,476), Lower Mark West (gage near Windsor, average 7,401 tons/yr, range 1,360-26,378), Upper Floodplain (gage near Sebastopol, average 3,862 tons/yr, range 3,240-4,428), and Lower Floodplain (gage near Mirabel Heights, average 4,800 tons/yr, range 4,252-5,400). Upper Laguna set to estimated load based on turbidity reanalysis for Laguna de Santa Rosa at Stony Point Rd. (Table 4-3).

Deposition: Sediment deposition within the Laguna based on best estimate of accumulation rate from Curtis et al. (2012), yielding a rate of 61,112 short tons/yr (Section 7.1.2).

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Despite the acknowledged uncertainties, Table 8-1 provides an internally consistent and reasonable estimate of the current sediment budget in the Laguna de Santa Rosa watershed. The budget components over the whole watershed are summarized on a percentage basis in Figure 8-1. On the source side, the largest contributor to the sediment load to the Laguna de Santa Rosa is estimated to be channel incision, mostly within the Santa Rosa Plain. On the sink side, it is notable that SCWA's current channel maintenance activities currently appear to remove about one-quarter of the potential load that would otherwise reach the Laguna de Santa Rosa.

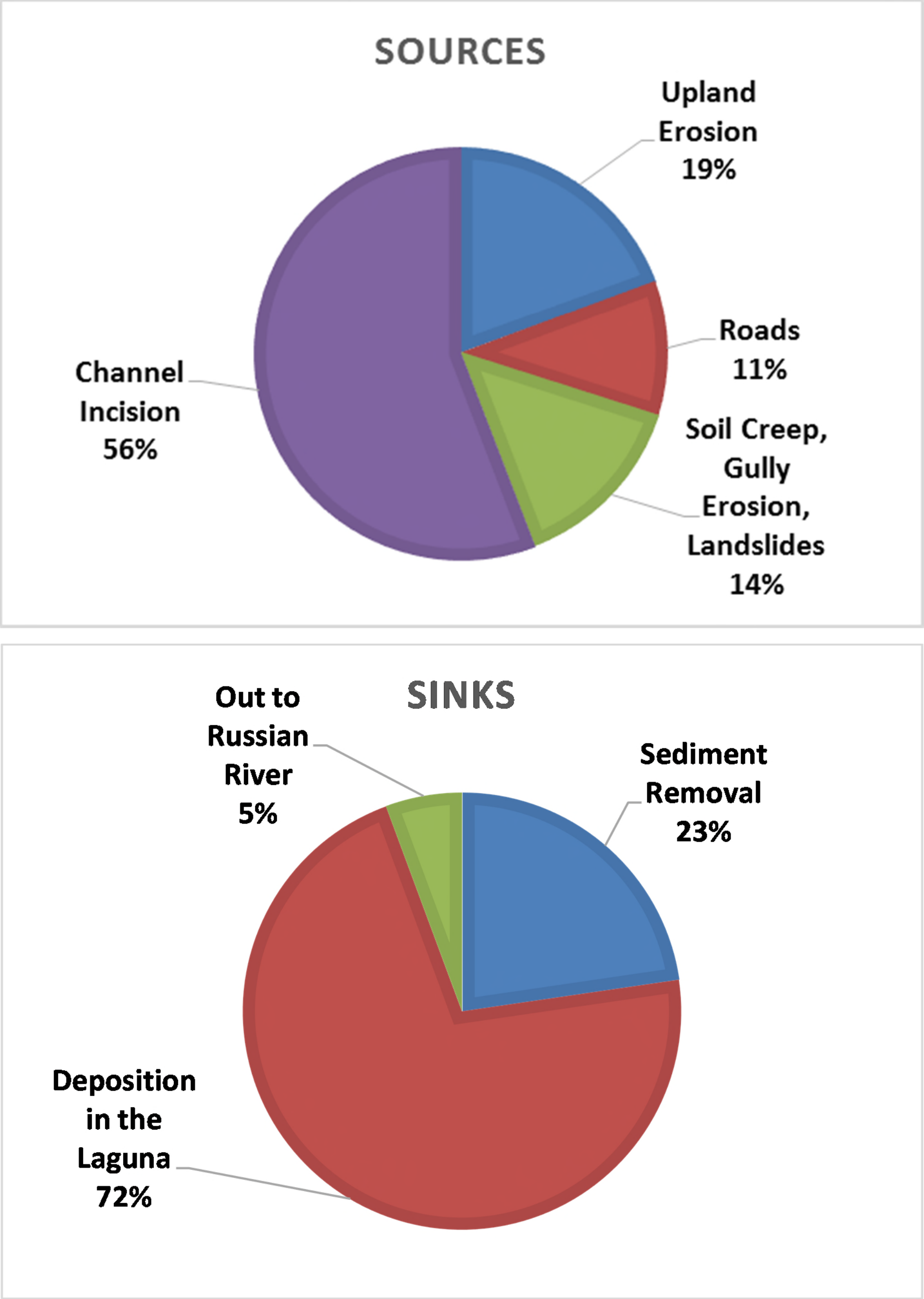

Figure 8-1. Summary of the Laguna de Santa Rosa Sediment Budget for Current Conditions

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9 Sediment Budget Prior to European Settlement

To evaluate the impact of watershed development and land use change on sedimentation in the watershed, a baseline sediment budget was estimated for pre-settlement conditions (Appendix D). European settlement began in the mid-1800s, and with it came altered land cover, removal of vegetation, and altered hydrology. The pre-settlement land cover of the Laguna de Santa Rosa watershed was a mix of rangeland, oak savanna, and forests, and a mosaic of open channels, wetlands, and lake-like features. More recent development and urbanization in the watershed have dramatically impacted watershed hydrology due to decreased infiltration, increased direct runoff, altered stream routing, alteration of wetlands, and other factors.

The land cover map used for this pre-settlement scenario was developed by the North Coast Regional Water Quality Control Board and is documented by Butkus (2011; see also Price et al., 2006). The land cover area breakdown and map are depicted below in Table 9-1 and Figure 9-1.

Table 9-1. Land Cover prior to European Settlement

	Open Water	Perennial Wetland	Riverine Wetland	Rangeland	Oak Savanna	Forest	Sum
Area (acres)	2,963	16,964	5,058	24,182	28,832	83,076	161,075
Area (percentage)	1.8%	10.5%	3.1%	15.0%	17.9%	51.6%	100%

Note: Coverage from Butkus (2011). Tabulation excludes area downstream of Ritchurst Knob. Water and wetland extent is based on a wet climate year.

Sources and sinks in the sediment budget were modified for these conditions as follows:

Sources:

- ***Upland Erosion***: Estimated as the delivered sheet and rill erosion from RUSLE analysis with IC-based sediment delivery under pre-settlement land use (Appendix D).
- ***Roads***: Roads were not present in the watershed prior to settlement, so this source is removed.
- ***Soil Creep, Gully Erosion, Landslides***: Because the Laguna de Santa Rosa watershed is tectonically active, soil creep, some gully erosion, and occasional landslides would have been present even under pre-settlement conditions, although better vegetative cover, less soil compaction, and less impervious surface would have mitigated these sources to some extent. These sources were set to 33 percent of the current loading rate; however, the areas upstream of dams on Matanzas Creek Reservoir and Lake Ilsanjo are now included in the loading estimates for all pre-settlement source categories.
- ***Channel Incision***: As noted in Section 8, under current conditions it is likely that more than half of the sediment load is derived from channel incision processes. Much of this load was likely absent prior to European settlement and extensive ranching. However, some loads of this type would still be present due to the continual tilting and uplift of the Santa Rosa and Sebastopol blocks (Sloop et al., 2007), climate cycles, and periodic understory burning by the native Pomo Indian populations (PWA, 2004a). For a conservative estimate assuming quasi-steady state conditions it is assumed there is no net incision into the alluvial fans themselves, but some incision in upland channels on the rising part of the Santa Rosa block is accounted for by multiplying stream length times an assumed channel bed width of 3-m times an estimated typical uplift rate along the northern San Andreas Fault of 0.02 centimeters per year (cm/yr; Brown,

1990) or 0.79 inches per century, although Richardson (2000) reports a higher rate of 0.077 cm/yr at the mouth of the Russian River on the Gualala block.

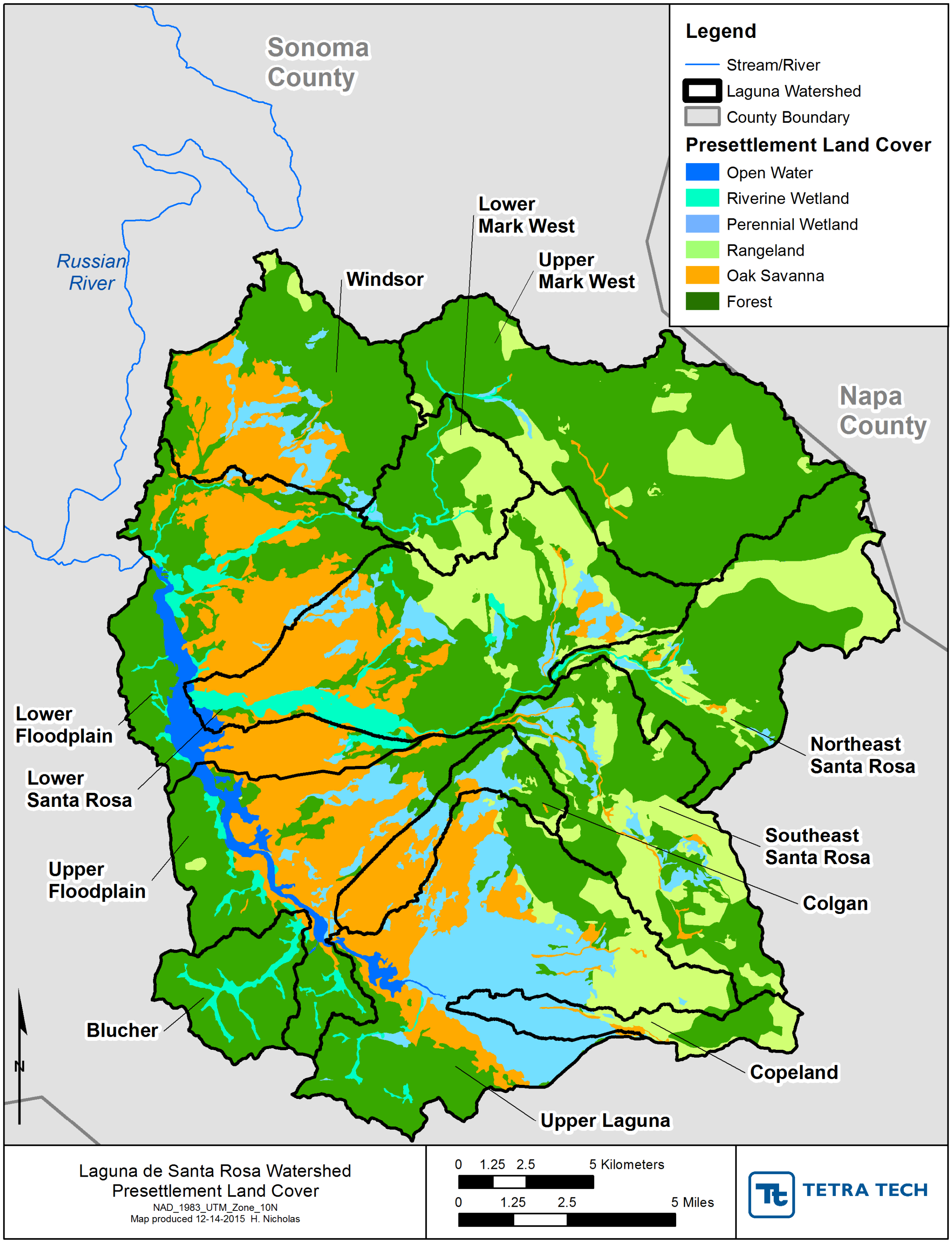

Figure 9-1. Land Cover prior to European Settlement of the Laguna de Santa Rosa Watershed (Butkus, 2011)

Sinks:

- ***Sediment Removal vs. Deposition outside the Laguna de Santa Rosa***: Prior to European settlement, there were no managed floodways and no removal of sediment in maintenance activities for those floodways. It is likely, however, that much of the sediment that currently collects within the floodways and is removed by the Sonoma County Water Agency (SCWA) was previously deposited on alluvial fans in the upper portion of the Santa Rosa Plain. Not all alluvial fan deposition during typical flow years is permanent, however, as major flow events cause channel realignment and incision, with remobilization and delivery of sediment deposited during prior years. No quantitative evidence was identified to estimate rates of net sediment accumulation on the alluvial fans prior to European settlement. For the purposes of completing a pre-settlement sediment budget it is assumed that 25 percent of the total sediment load generated from all sources in the watershed was lost to sediment deposition on the alluvial fans. The resulting loss rate approximates the fraction of total watershed load that is currently removed by SCWA channel maintenance activities, but reduces the total mass removed from about 19,000 to less than 2,000 tons/yr.
- ***Trapping in and Transport out of the Laguna de Santa Rosa***: Outflow from the Laguna de Santa Rosa is controlled by a bedrock ledge. As such, the dynamics of sediment trapping in the Laguna and transport out of the system under pre-settlement conditions were likely similar to those that apply today. We therefore assumed that the trapping efficiency of the Laguna de Santa Rosa under pre-settlement conditions was the same as under current conditions, calculated as 92.27 percent of the sediment load reaching the Laguna (the “Total In” estimate shown in the mass balance calculations in Table 8-1 minus the mass removed by SCWA channel maintenance activities).

The estimated components of the sediment budget prior to European settlement are presented and compared to current conditions estimates in Table 9-2. Total loads under current conditions are estimated to be about 10 times more than those that existed under conditions prior to European settlement. Similarly, the current rate of sediment accumulation in the Laguna de Santa Rosa is estimated to be 10 times more than the pre-settlement rate.

It is believed that the estimates of trapping within the Laguna prior to European settlement represent a conservative upper bound. Historical evidence indicates that the confluence of the Laguna de Santa Rosa and Mark West Creek throughout the 19th century was located further north, not far from the current confluence with Windsor Creek (Baumgarten et al., 2014). The current alignment of Mark West Creek is a result of ditching in the early 1900s to create additional farmland, resulting in a lower gradient channel that discharges more directly into the main body of the Laguna de Santa Rosa. As a result, the rate of trapping and deposition of sediment from upper Mark West Creek within the Laguna de Santa Rosa was also likely lower, but has not been quantified. Therefore, the total rate of sediment load accumulation within the Laguna de Santa Rosa prior to European settlement may be even smaller than the rate shown in Table 9-2.

Table 9-2. Comparison of Estimated Sediment Budgets for the Laguna de Santa Rosa Watershed for pre-European Settlement and Current Conditions

	Pre-European Settlement Sediment Load (short tons/yr)[2]	Current Conditions Sediment Load (short tons/yr)[1,2]	Percent Increase
SOURCES			
Upland	2,817	16,532	487%
Roads	0	8,982	NA
Soil Creep, Gullies, Landslides	4,476	12,153	172%
Other (Channel)	365	47,589	12947%
Total In	*7,658*	*85,255*	*1010%*
SINKS			
Sediment Removal (*Current Conditions*) or Net Deposition on Alluvial Fans (*Pre-settlement*)	1,914	19,343	910%
Deposition in Laguna de Santa Rosa	5,325	61,112	1048%
Downstream to Russian River	418	4,800	1047%
Total Out	*7,658*	*85,255*	*1014%*

[1] Excluding drainage area above Matanzas Creek Reservoir and Lake Ilsanjo (8,152 acres).

[2] Excluding drainage area below Ritchurst Knob.

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