

Laguna de Santa Rosa – Linkage Analysis for Sediment Impairments (Revised)

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PREPARED FOR

North Coast Regional Water Quality Control Board

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ACRONYMS AND ABBREVIATIONS

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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1.0 INTRODUCTION

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

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 part or all of the cities of Santa Rosa, Rohnert Park, Cotati, Sebastopol, and Windsor (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 4.0, 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 mainstem segments of the Laguna de Santa Rosa have been identified as impaired for indicator bacteria, dissolved oxygen, phosphorus, water temperature, sediment, and mercury (among others) and has been listed on California’s Clean Water Act (CWA) Section 303(d) list of impaired waters requiring the development of a Total Maximum Daily Load (TMDL) since 1990.

In December 2015, Tetra Tech, Inc., under contract with U.S. EPA Region 9 in support of the North Coast Regional Water Quality Control Board (NCRWQCB), prepared the *Laguna de Santa Rosa Sediment Budget* (Tetra Tech, 2015). The 2015 Sediment Budget report was designed to provide information that could be used in developing a linkage analysis for a TMDL for sedimentation in the Laguna.

On May 10, 2019 Tetra Tech received a contract from the California State Water Resources Control Board to provide additional support to NCRWQCB in the development of a TMDL (or acceptable TMDL alternative) for the Laguna de Santa Rosa. Under Subtask 2.2 of that work assignment, Tetra Tech is updating the sediment analyses and developing a Linkage Analysis report for sediment impairment that could form the basis for a Staff Report to support a TMDL. The sediment analyses have been updated to incorporate new data and research available since 2015. Relevant portions of the earlier report (Tetra Tech, 2015) are also replicated here without modification for sediment budget components where new data are not available.

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).

In the following sections of this document we discuss the conceptual model of sediment impairment of the Laguna (2.0), the approach to creating the sediment budget and its modifications since 2015 (3.0), the currently available spatial and monitoring data and conclusions based on those data (4.0 and 5.0, model- and literature-based estimates of upland sediment loads (6.0), other sediment load sources (7.0), sediment sinks or loss term (0), all of which are combined to give an estimate of the current sediment budget for the Laguna (9.0). Section 10.0 contrasts these analyses to best estimates of the sediment mass balance prior to European settlement in the 1850s (10.0).

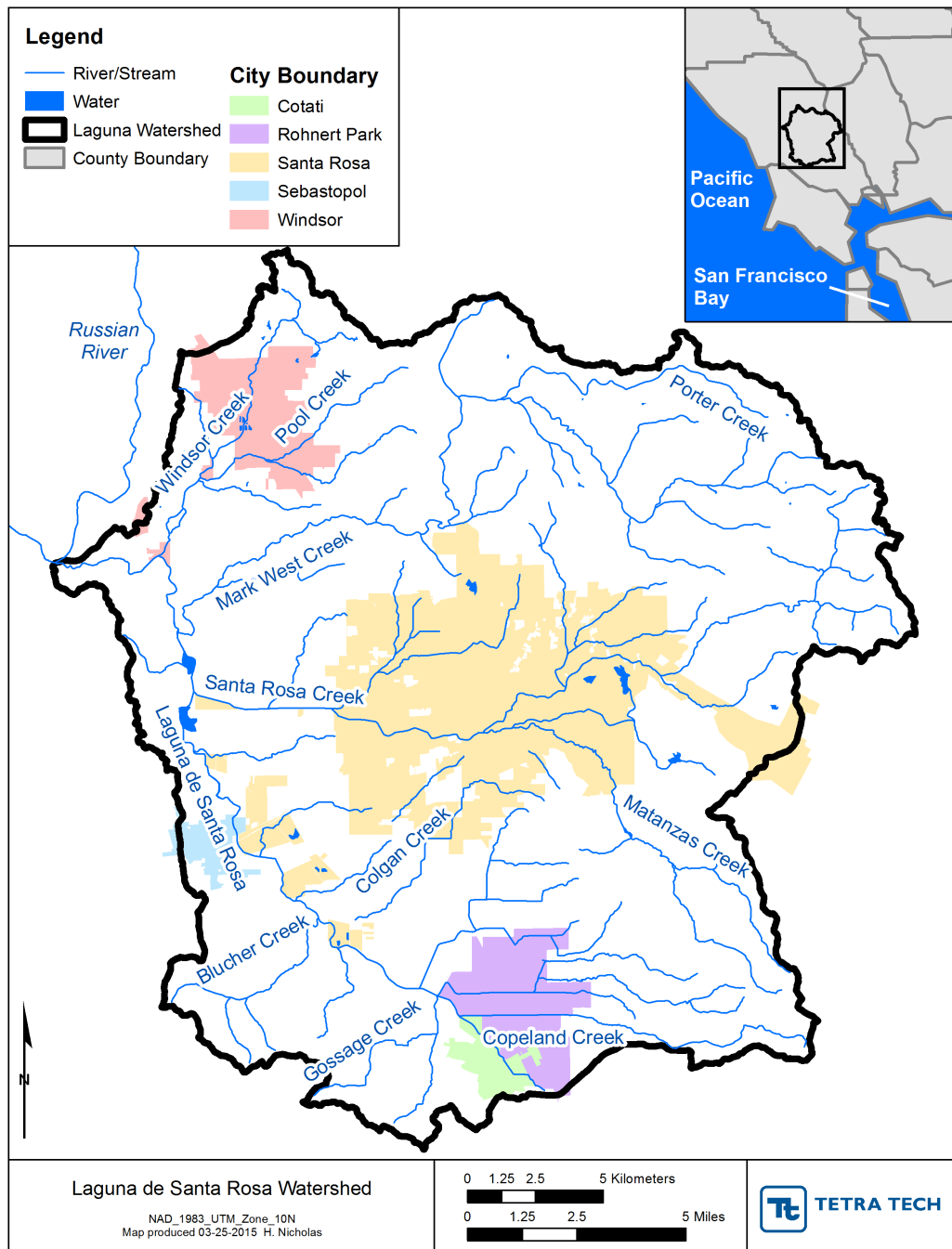


Figure 1-1. The Laguna de Santa Rosa Watershed

2.0 CONCEPTUAL MODEL OF SEDIMENT IMPAIRMENTS

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 watershed and widespread channelization of streams on the Santa Rosa Plain have resulted in greater sediment erosion and greater delivery and deposition of sediment in the Laguna de Santa Rosa.

Under historical conditions, natural 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.

European settlement began in the mid-1800s, and with it came altered land cover, removal of vegetation, and altered hydrology. Early ranching was followed by more intensive agriculture, with a later shift toward vineyards and the growth of Santa Rosa and other urban centers. 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 (see Section 10 for discussion of natural land cover). More recent development and urbanization in the watershed have dramatically affected watershed hydrology due to decreased infiltration, increased direct runoff, altered stream routing, alteration of wetlands, and other factors. 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.

A graphical conceptual model of changes in sedimentation processes in the watershed between historic and present day conditions was developed by PWA (2004a) and is reproduced in Figure 2-1.

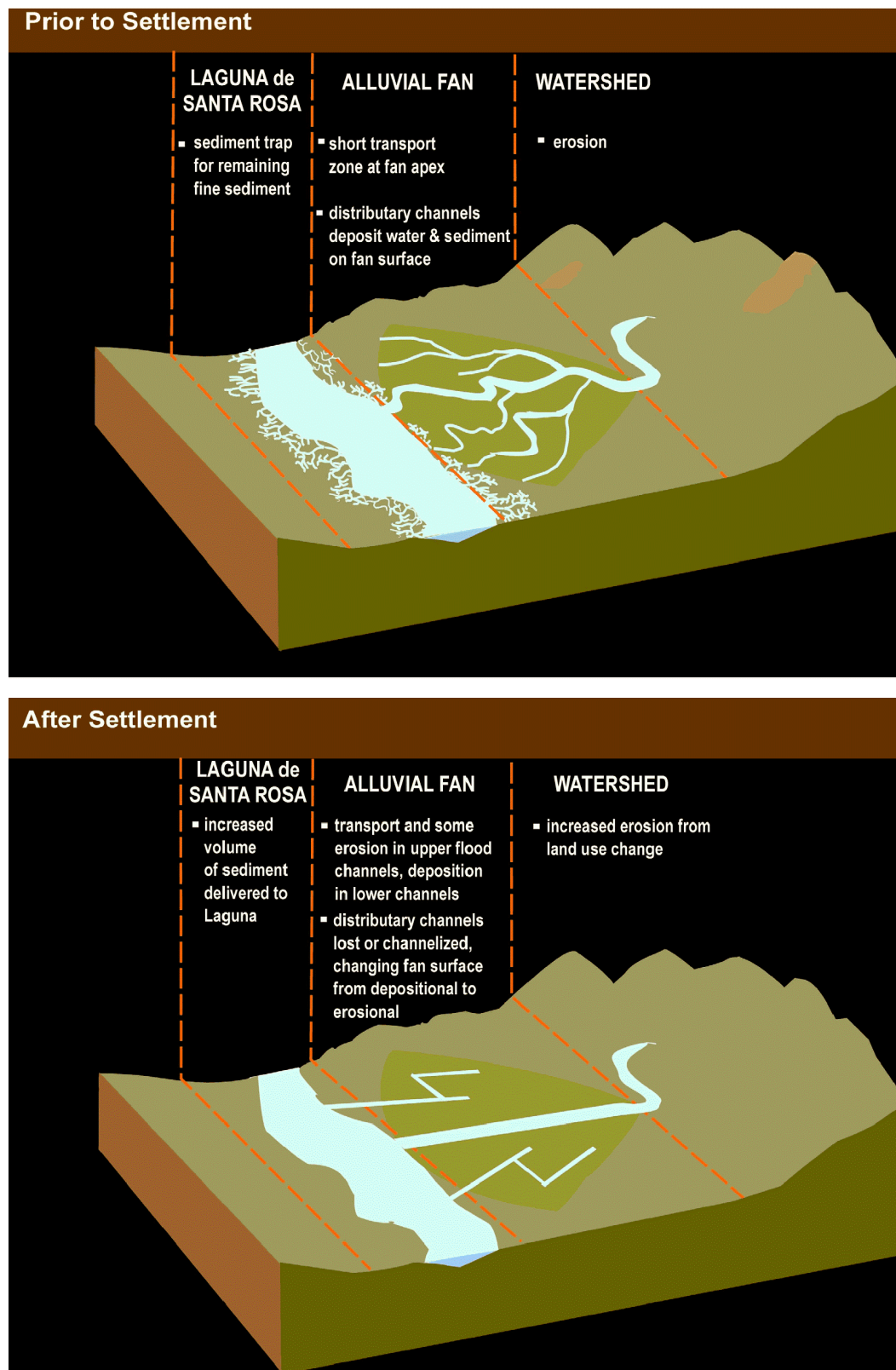


Figure 2-1. Graphical Representation of Sedimentation Processes in the Laguna de Santa Rosa Watershed before and after Settlement (from PWA, 2004a)

Support for beneficial uses in the Laguna is threatened by a variety of interacting historical and ongoing sources of impairment, including reduced water 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. The *Ludwigia* infestation in turn slows the flow of water and traps sediment, resulting in a feedback loop that further reduces the capacity of the Laguna. Quantifying the sources and status of sediment in the system is a key component for the successful resolution of multiple impairments of beneficial uses in the Laguna de Santa Rosa.

Some of the most important processes related to the sediment impairment of the Laguna de Santa Rosa are summarized in simplified form in Figure 2-2.

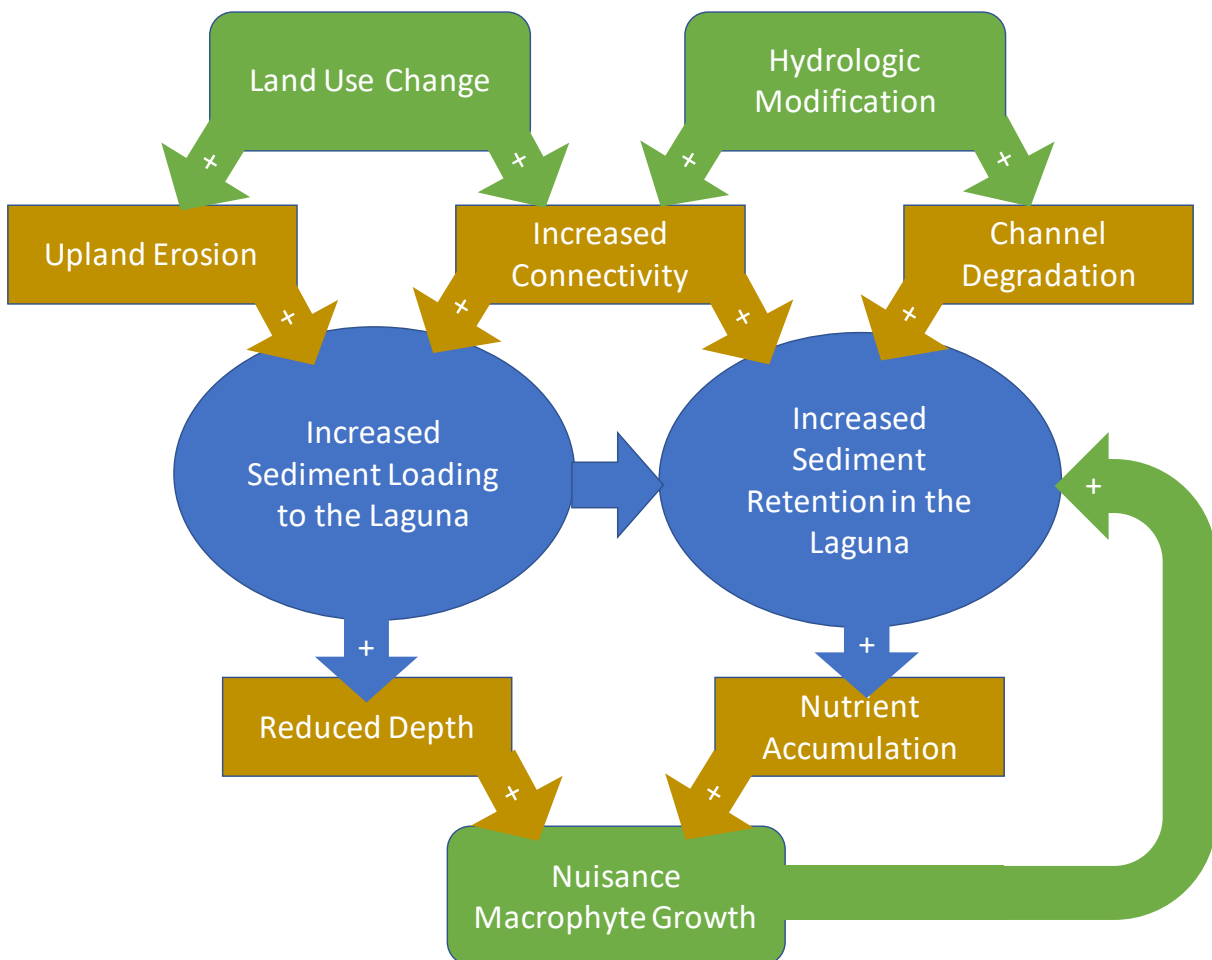


Figure 2-2. Simplified Conceptual Model for Sediment in the Laguna de Santa Rosa

3.0 APPROACH TO SEDIMENT BUDGET

Sediment budgets in the Laguna de Santa Rosa have been developed and refined through three major efforts beginning in the early 2000's. A brief background of these prior efforts is summarized in this section.

A sediment loading and budget analysis for the Laguna 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.

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; PSIAC, 1968) provided what appeared to be the most realistic estimates of sediment yield for the Laguna. The conceptual understanding of sediment transport processes in the watershed was expanded by Sloop et al. (2007), who concurred with this approach. 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 Tetra Tech (2015) sediment 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 were revisited based on current spatial data in Appendix A of that report. 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. A variety of additional

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.

lines of analysis discussed in Tetra Tech (2015) also suggested that the PSIAC estimates of delivered sediment load were too high. PSIAC also does not link tributary estimates of sediment load to specific sources. As a result, the PSIAC analyses have been rejected and are not discussed in detail in this report.

The modified approach to the sediment budget is described in the 2015 report and expanded in the current report to incorporate new data. 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 3-1.

Table 3-1. Sediment Source and Sink Categories Addressed in this Report

Category	Report Section	Notes
<i>Major Sediment Sources</i>		
Upland Sheet and Rill Erosion	6.0	RUSLE estimates of soil loss combined with landscape-based estimates of sediment delivery
Roads	7.1	Based on analyses conducted for Sonoma Creek TMDL
Soil Creep, Landslide, and/ Colluvial Bank Erosion	7.3	Expanded from analyses conducted for Sonoma Creek TMDL plus USGS studies of landslide and debris flow risk
Channel Incision and Gully Erosion	7.2	Expanded from analyses conducted for Sonoma Creek TMDL and PWA (2004a) plus new LiDAR analyses
<i>Major Sediment Sinks</i>		
Deposition in Reservoirs and Debris Basins	8.1	Data analysis
Deposition in the Laguna de Santa Rosa and Floodplain	8.1	USGS (Curtis et al., 2012)
Channel Maintenance Activities	8.2	Analysis of data from Sonoma County Water Agency (SCWA)
Export to Russian River	8.3	Data analysis

These components are assembled into a sediment budget for current conditions in Section 9.0. 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. A parallel analysis of the sediment budget under conditions prior to European settlement is provided in Section 10.0.

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4.0 WATERSHED DELINEATION AND SPATIAL DATA

This chapter provides an overview of the land uses, elevations, and floodplains across the watershed that are used to develop the sediment loading estimates in subsequent chapters. The Laguna de Santa Rosa watershed is defined as the area upstream of the pour point of Mark West Creek into the Russian River (Figure 4-1). 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 long-term 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 Tetra Tech (2015) study, for which 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 4-1). 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 4-2 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 (PWA, 2004a; Sloop et al., 2007).

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 10.0) 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.

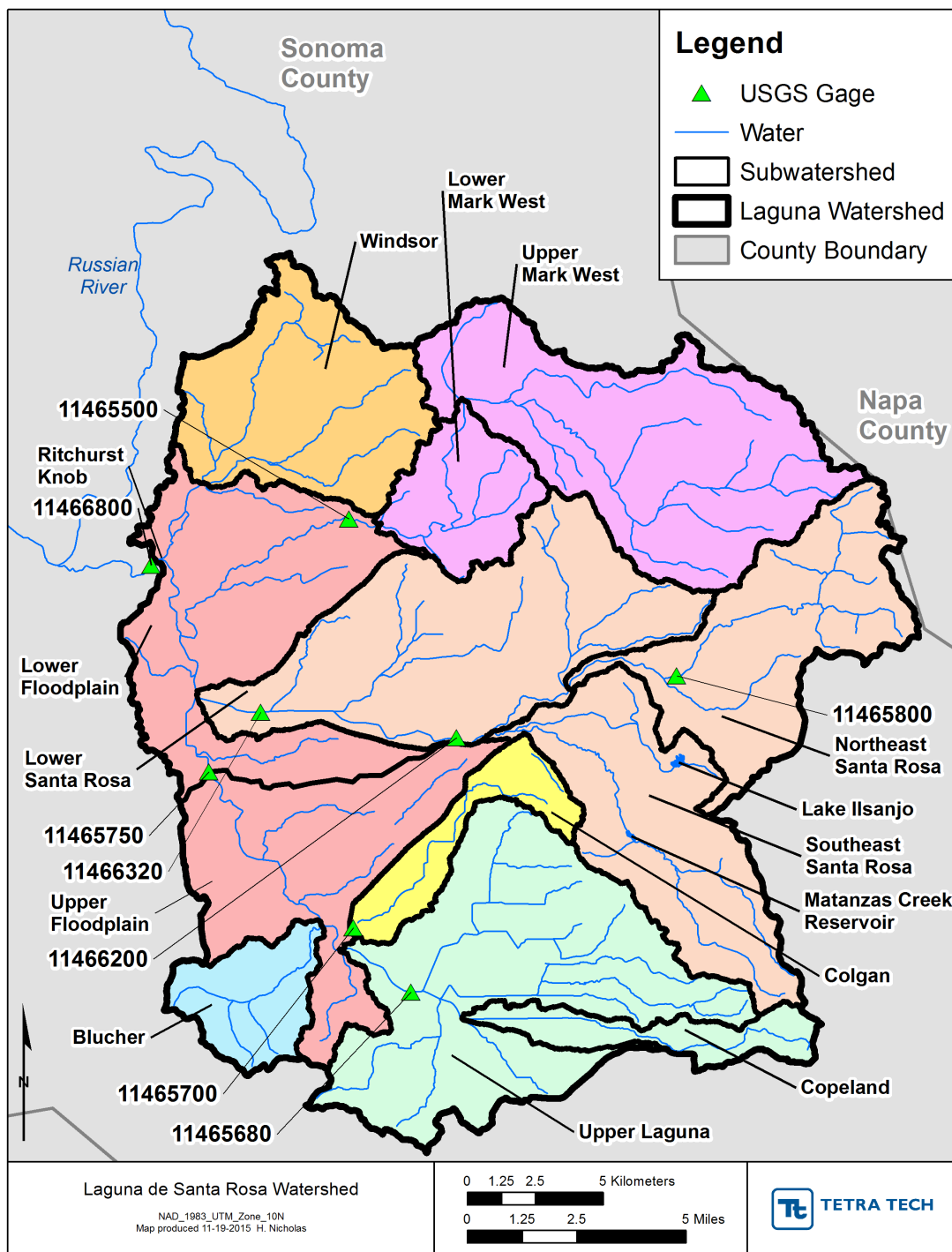


Figure 4-1. Delineation of Subwatersheds and Location of USGS Gages for the Laguna de Santa Rosa Watershed

USGS gages are: 11465500 Mark West Creek nr Windsor, 11465680 Laguna de Santa Rosa at Stony Point Rd., 11465700 Colgan Creek nr Sebastopol, 11465750 Laguna de Santa Rosa nr Sebastopol, 11465800 Santa Rosa Creek nr Santa Rosa, 11466200 Santa Rosa Creek at Santa Rosa, 11466320 Santa Rosa Creek at Willowside Rd., 11466800 Mark West Creek nr Mirabel Heights

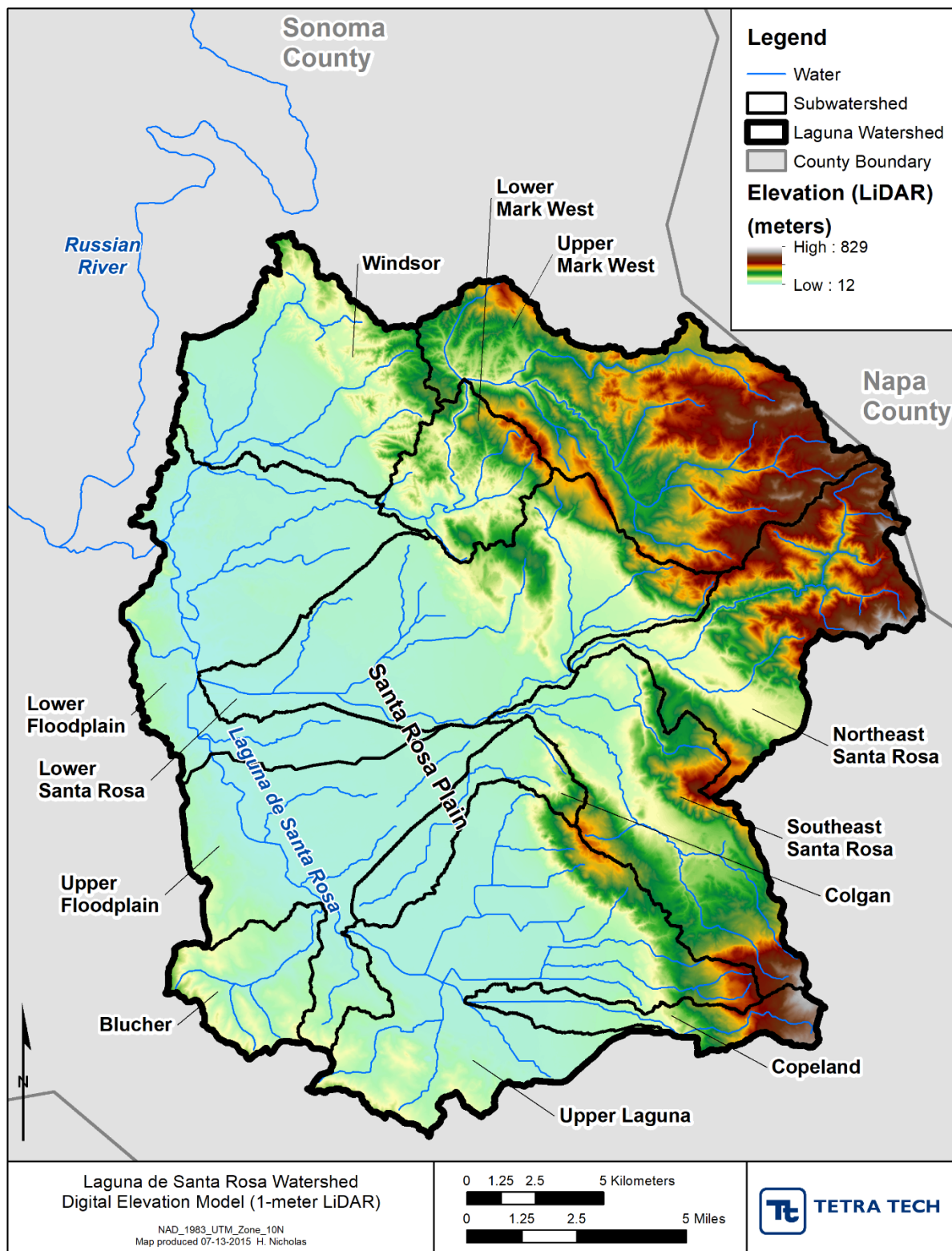


Figure 4-2. Topography of the Laguna de Santa Rosa Watershed

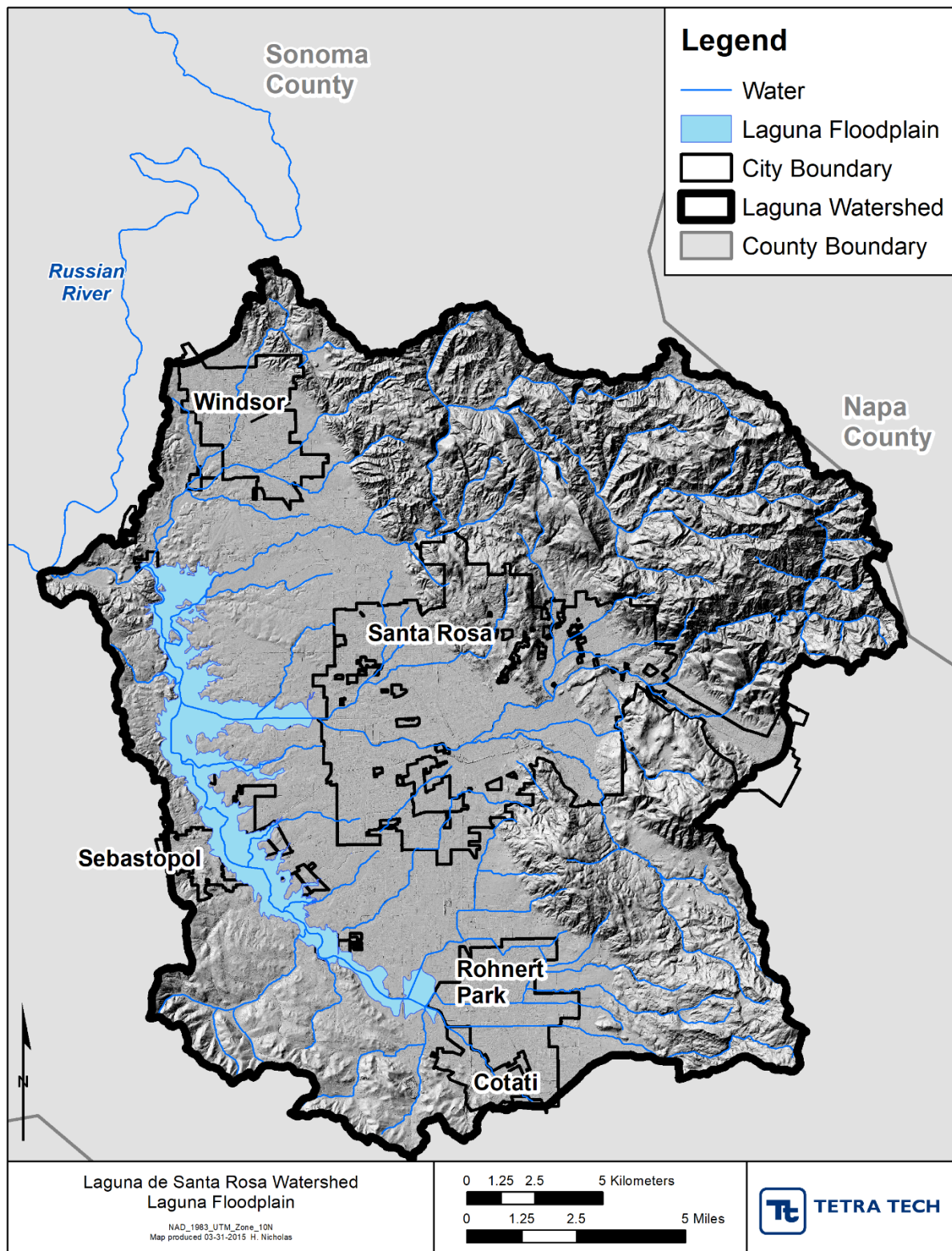


Figure 4-3. Laguna de Santa Rosa Floodplain based on FEMA 100-year Flood Delineation

A key source of spatial information for this project is provided by the Sonoma County Vegetation Mapping and LiDAR program (Sonoma VegMap, 2018). In addition to the LiDAR elevation data discussed above, which was available for the 2015 sediment budget analysis, the VegMap program has subsequently produced a wide range of vegetation, land use, and hydrologic products, all at a fine spatial scale. The land cover and land use information from this program provides the most comprehensive and reliable tabulations for the Laguna de Santa Rosa watershed and is used as the basis for many of the analyses in this report. The Lifeforms map provides general classification of cover types, with additional information on forest and agricultural lands in separate analyses, all combined into the Sonoma County Vegetation and Habitat Map, which delineates 23 unique lifeform classes

(<http://sonomaopenspace.maps.arcgis.com/home/item.html?id=2d7728a8aba44df5b154c80aa8588d79>).

There is also a separate Impervious Map, which provides fine scale delineations of impervious features, including identification of paved roads, unpaved roads, building footprints, and other impervious surfaces. One quirk of the Vegetation and Habitat Map is that it does not distinguish vegetation types within the city limits of Santa Rosa, Windsor, Sebastopol, Rohnert Park, and Cotati (see Figure 4-3), but instead classifies these areas as “Urban Window.” However, the Impervious Map does provide a full tabulation of impervious surfaces within the city limits, allowing identification of a general urban pervious classification for the remainder of the Urban Window area. A simplified representation of the Lifeforms Map (aggregated into 14 categories) is shown in Figure 4-4. Table 4-1 summarizes the percentage distribution of land use and land cover classes across the entire watershed. The watershed is 14.6 percent impervious. Over 29 percent of that impervious cover consists of public and private roads, but only 8.4 percent of the roads are classified as unpaved. A full tabulation of acreage by subbasin, using data from different sources, is described below.

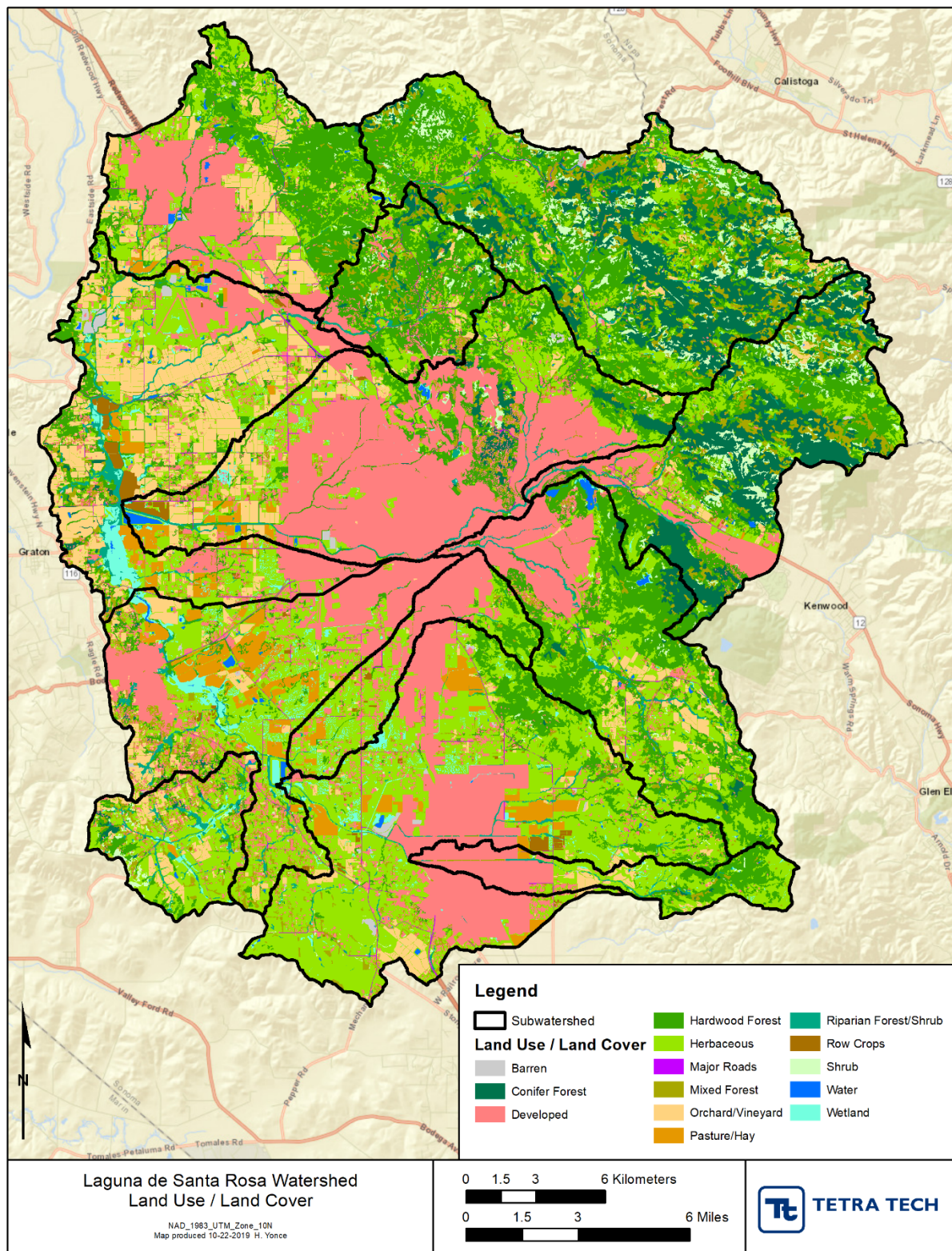


Figure 4-4. Simplified Lifeforms Distribution from Sonoma VegMap (2013 Data)

Table 4-1. 2013 Land Use and Land Cover Information for the Laguna de Santa Rosa Watershed from Sonoma VegMap Lifeforms and Impervious Coverages (Sonoma VegMap, 2018)

Land Use/Land Cover	Area (acres)	Percent of Watershed
<i>Pervious Land</i>		
Barren	585	0.4%
Conifer Forest	10,502	6.5%
Developed (pervious)	16,938	10.5%
Hardwood Forest	32,542	20.2%
Herbaceous	42,486	26.4%
Mixed Forest	7,288	4.5%
Orchards/Vineyards	12,652	7.9%
Pasture/Hay	3,837	2.4%
Row Crops	812	0.5%
Shrub	4,417	2.7%
Water/Wetland	3,209	2.0%
Woody Wetlands	2,322	1.4%
<i>Impervious Land</i>		
Paved Road	6,312	3.9%
Dirt Road	575	0.4%
Other Impervious	9,019	5.6%
Building	7,571	4.7%
<i>Total Area</i>	<i>161,067</i>	<i>100%</i>

Notes: The tabulations presented in this table combine information from the Sonoma VegMap life forms classification, the forest life forms classification, and the impervious cover classification. Impervious land classes are as defined in the impervious cover classification. After removing impervious land, the remaining pervious area classes were assembled and aggregated for use in later analyses as follows:

Barren: Barren and Sparsely Vegetated life forms

Conifer Forest: As defined in forest life form classification

Developed (pervious): Pervious portions of the Developed life form and the Urban Window area

Hardwood Forest: As defined in forest life form classification

Herbaceous: Herbaceous life form and the pervious part of the Major Roads life form

Mixed Forest: Forest Sliver, Mixed Conifer-Hardwood Forest, and Non-Native Forest life forms

Orchards/Vineyards: Orchard or Grove, Perennial Agriculture, Vineyard-Replant, and Vineyard life forms

Pasture/Hay: Intensively Managed Hayfield and Irrigated Pasture life forms

Row Crops: Annual Cropland life form

Shrub: Non-Native Shrub, Nursery or Ornamental Horticulture Area, Riparian Shrub, and Shrub life forms

Water/Wetland: Herbaceous Wetland, Aquatic Vegetation, and Water life forms

Woody Wetlands: Riparian Forest life form

Tetra Tech (2015) used two other land use coverages: the U.S. Department of Agriculture (USDA) National Agricultural Statistics Service (NASS) Cropland Data Layer (CDL) (Table 4-3 and Figure 4-5) and 2006 National Land Cover Database (NLCD) (Table 4-4 and Figure 4-6). Both are based on 30-m satellite imagery from 2006 and have a much coarser spatial resolution than the Sonoma VegMap coverages. (The coarser scale results in a slightly higher estimate of total watershed area). These older coverages provide somewhat different types of information than the VegMap lifeforms and impervious data (for instance, the CDL has more information on crop type, while the NLCD breaks out developed land into low, medium, and high density categories) and are repeated here for comparative purposes.

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.

Table 4-2. 2013 Land Use and Land Cover Acreage by Subbasin for the Laguna de Santa Rosa Watershed from Sonoma VegMap Lifeforms and Impervious Coverages (Sonoma VegMap, 2018)

Subbasin	Pervious Area (acres)												Impervious Area (acres)				Total Area
	Barren	Conifer Forest	Developed (pervious)	Hardwood Forest	Herbaceous	Mixed Forest	Orchards/Vineyards	Pasture/Hay	Row Crops	Shrub	Water/Wetland	Woody Wetlands	Paved Road	Dirt Road	Other Impervious	Building	
Blucher	2	69	271	450	2,216	380	573	27	6	181	141	290	98	22	108	103	4,936
Colgan	4	0	747	432	1,937	78	25	110	35	14	131	7	238	5	406	336	4,505
Copeland	3	17	539	767	1,409	96	217	34	0	52	43	59	196	4	303	248	3,988
Lower Floodplain	183	91	1,587	1,497	4,391	512	5,428	625	344	250	812	491	606	79	870	636	18,403
Lower Mark West	0	330	393	2,968	817	401	119	0	1	171	9	101	208	10	183	162	5,873
Lower Santa Rosa	73	546	4,684	3,022	3,433	575	1,376	374	155	224	303	246	1,666	48	2,566	2,219	21,510
Northeast Santa Rosa	26	3,838	760	3,929	1,885	1,314	202	14	13	1,049	39	166	277	45	326	327	14,209
Southeast Santa Rosa	6	415	1,195	5,014	4,047	344	795	0	0	160	193	250	501	49	659	562	14,188
Upper Floodplain	73	38	2,117	737	4,841	592	902	1,441	69	226	753	162	598	25	944	835	14,353
Upper Laguna	146	4	2,863	1,816	11,429	541	820	1,081	184	141	571	236	1,076	51	1,605	1,299	23,865
Upper Mark West	37	5,129	141	7,697	3,261	2,188	373	14	2	1,827	72	214	198	175	101	71	21,500
Windsor	32	24	1,642	4,213	2,821	267	1,821	117	3	122	142	100	651	62	947	773	13,737
Total	585	10,502	16,938	32,542	42,486	7,288	12,652	3,837	812	4,417	3,209	2,322	6,312	575	9,019	7,571	161,067

Note: Tabulation is for area upstream of Ritchurst Knob.

Table 4-3. 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 Wetlands	Sum
Blucher	1	0	0	244	4	414	111	14	1	0	28	122	254	649	3,053	40	2	4,936
Colgan	4	0	0	49	0	694	570	679	162	0	6	73	138	187	1,944	0	0	4,505
Copeland	1	0	0	59	1	407	378	613	49	0	10	320	276	427	1,444	4	0	3,988
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
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
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
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
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
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
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
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
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
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 4-4. 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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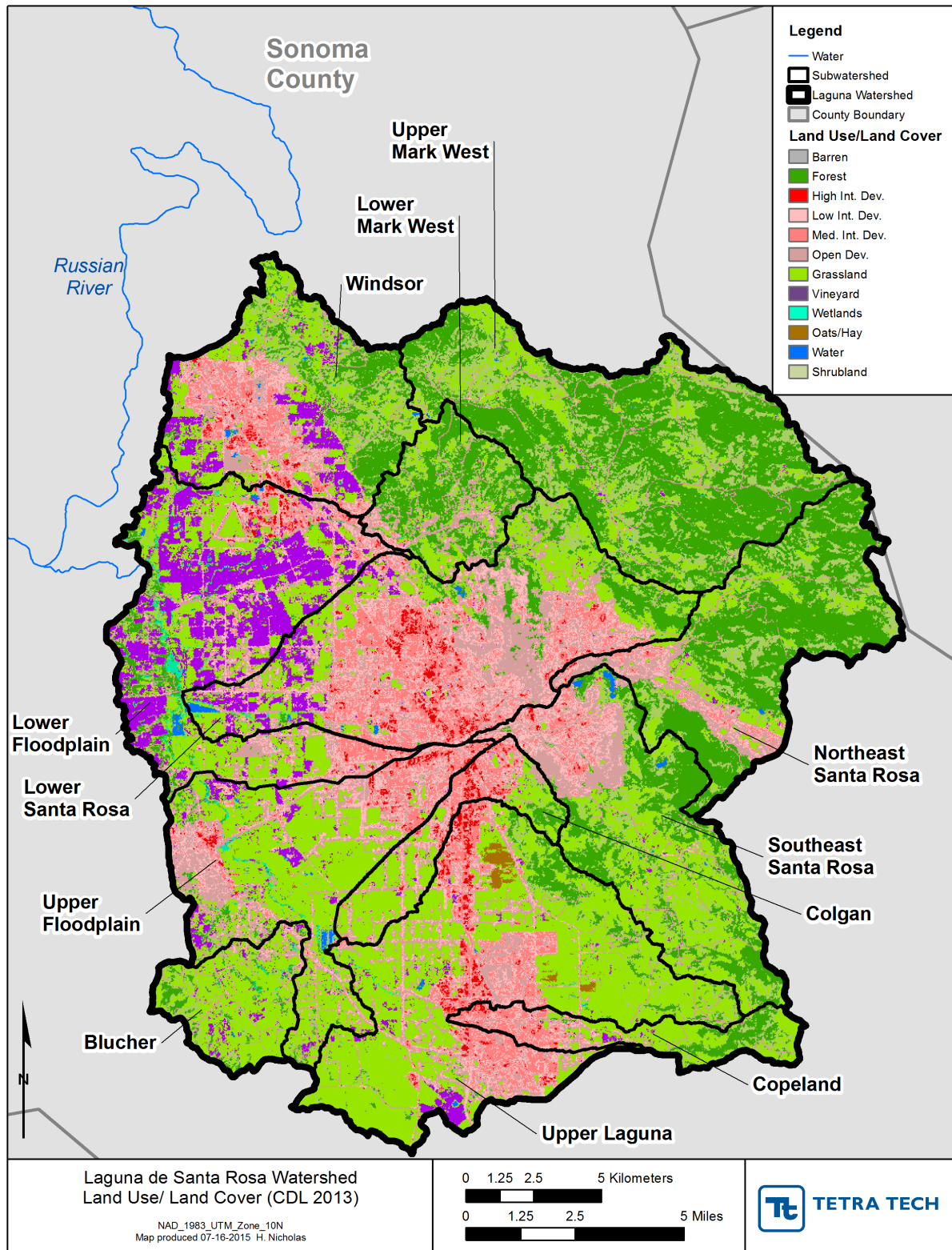


Figure 4-5. Current Land Use/Land Cover for the Laguna de Santa Rosa Watershed (USDA Cropland Data Layer, 2013)

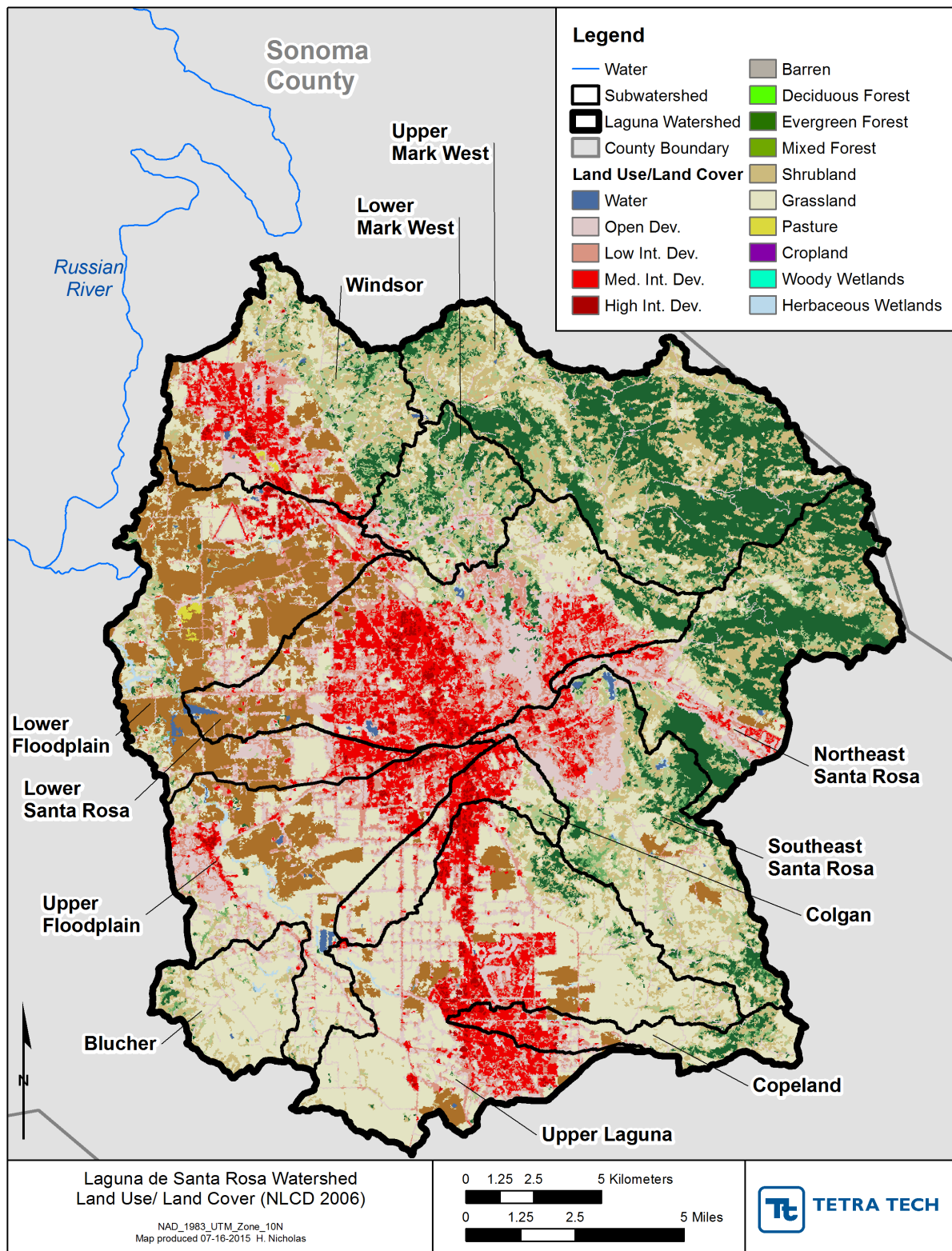


Figure 4-6. Land Use/Land Cover for the Laguna de Santa Rosa Watershed (National Land Cover Database, 2006)

5.0 MONITORING DATA AND CALCULATED LOADS

This chapter describes estimates of sediment loads at monitored locations at key locations across the Laguna watershed. Ideally, sediment load estimates would be calibrated to and tested against loads inferred from long-term monitoring and flow gaging. However, the available monitoring of suspended sediment or surrogate measures is limited. The available data and their interpretation are summarized below.

5.1 LOADS ESTIMATED FROM SSC AND TSS 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, USGS, to Jon Butcher, Tetra Tech, 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.

Table 5-1. Summary of USGS Suspended Sediment Concentration (SSC) Data (mg/L), 2006-2008

Station	11465750 Laguna de Santa Rosa nr Sebastopol	11466320 Santa Rosa Creek at Willowside Rd.	11465500 Mark West Creek nr Windsor	11466800 Mark West Creek nr Mirabel Heights
Count	150	40	36	393
Average	47	40	21	45
Median	39	8.5	3	39
Maximum	210	457	237	190

Curtis et al. used the SSC and flow data 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 summarized in Table 5-2.

Table 5-2. USGS Suspended Sediment Load Estimates for WY 2006-2008 (Curtis et al., 2012)

Location	Drainage Area (mi ²)	WY 2006–2008 Suspended Sediment Load (tons/yr)
11465750 Laguna de Santa Rosa nr Sebastopol	79.6	5,006 tons/yr 0.098 t/ac/yr
11466320 Santa Rosa Creek at Willowside Rd.	77.6	10,362 tons/yr 0.21 t/ac/yr
11465500 Mark West Creek nr Windsor	43.0	31,747 tons/yr ¹ 1.15 t/ac/yr
11466800 Mark West Creek nr Mirabel Heights	251.7	14,440 tons/yr 0.090 t/ac/yr (outlet of Laguna)

Notes: tons/yr = English (short) tons per year; mi² = 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.

The load estimates in Table 5-2 are based on sediment rating curves developed by USGS, which could be a significant source of uncertainty. 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 appears weak for Laguna de Santa Rosa near Sebastopol. Dr. Flint provided R² and standard error statistics for the rating curve equations (R² 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 refine the sediment load estimates 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 USGS SSC monitoring data was not available on the National Water Information System (NWIS) website, but was supplied directly by Dr. Flint. A search of CEDEN revealed a limited number of additional SSC samples at these stations beyond those reported by Flint, including 8 samples from 2008 and 2014 from Mark West Creek at Trenton-Healdsburg Road (approximately collocated with Mark West near Mirabel Heights gage (11466800), one 2014 quantified sample from Santa Rosa Creek at Willowside Road (plus four non-detects at a detection limit of 2 mg/L from 2008), and three September 2008 samples from Laguna de Santa Rosa near Sebastopol. (The latter three samples ranged from 26 to 40 mg/L SSC, but the USGS gage reported zero flow during this period so they are not usable in FLUX, but can be incorporated in LOADEST). While only very limited additional SSC sampling is available, additional flow records extending through 2019 are available for three of the four gages and were incorporated into the analysis.

Table 5-3 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 when compared to FLUX, albeit subject to uncertainty. The LOADEST program outputs 95 percent confidence limits, which show significant uncertainty in the estimates.

Table 5-3. 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 ²	11466800 Mark West Cr nr Mirabel Heights
Gaged Period (Water Years)	2000-2019	1999-2019	2007-2008	2006-2019
Rating Curve (tons/yr)	3,902	6,810	2,040 ²	9,136
FLUX (tons/yr)	3,122	8,235	7,912	12,533
LOADEST Model	6	7	8	7
LOADEST 95% Confidence Interval (tons/yr)	3,521 -5,480	2,173 - 78,311	1,360 - 26,378	5,053 - 11,763

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 sections suggest they should be greater than those at Willowside Road by about 10%.

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 5-2 because those results incorporate estimated loads from the high flow event of 12/31/2005, prior to the start of operation of this gage.

3. FLUX estimates use model 6.

Another source of sediment concentration observations is available for Santa Rosa Creek. Sonoma County Water Agency (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. Data were provided through January 16, 2019.

TSS samples are collected at the center of the stream cross-section within 1 m of the water surface. The samples are then analyzed by using a pipette to extract a fixed volume subsample. In contrast, suspended sediment concentration (SSC) samples are collected using width- and depth-integrated methods and the entire sample is analyzed (see discussion in Ellison et al., 2014). It has been established that TSS measurements are often a poor indicator of SSC, and that TSS is likely to be biased low relative to SSC when a significant sand fraction is present (Gray et al., 2000).

Unfortunately, flow, which is needed to convert concentration to load, 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 our 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. For Santa Rosa Creek at Fulton Road, the FLUX estimate of TSS load based on TSS data and using FLUX Method 6 (a bias-corrected regression of concentration on flow, implemented on a daily basis) for WY 1999-2019 flow gaging (corrected from Willowside Road to Fulton Road) is 9,232 tons/y. which is within 15% of the FLUX estimate of suspended sediment load at Willowside Road.

5.2 SEDIMENT LOAD ESTIMATED FROM TURBIDITY

PWA (2004a) estimated sediment loads based on continuous turbidity monitoring conducted from Dec. 19, 2002 – June 28, 2003 at 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). PWA developed a regression equation to convert turbidity (NTU) to SSC (mg/L), and then used this relationship to estimate rating curves to predict sediment load from discharge. As discussed in Section 4.2.1 of Tetra Tech (2015), the relationship between SSC and turbidity used in this work is suspect as it was derived from bench tests and not from paired field samples. As a result, the sediment loads estimated by this method were judged to have a severe high bias and are not usable.

No field data with paired SSC and turbidity measurements are available for the Laguna watershed. Therefore, we continue to use an alternate method as was done in Tetra Tech (2015): 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 5-1).

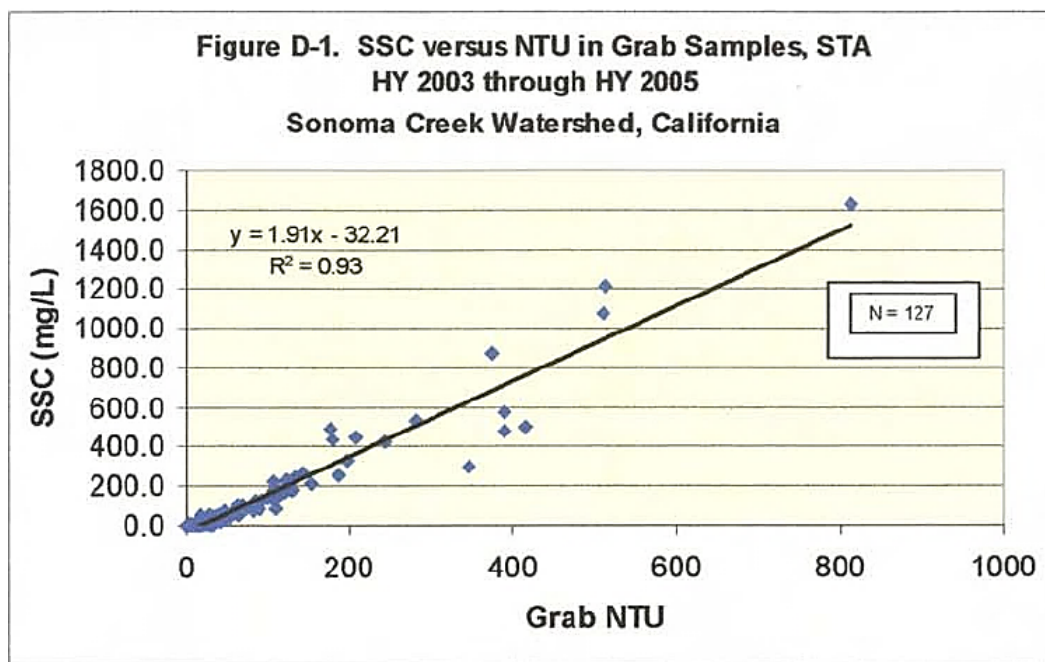


Figure 5-1. Relationship of SSC to Turbidity (NTU) in Sonoma Creek (from Appendix D to Sonoma Ecology Center, 2006)

The resulting relationship is:

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

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

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 Regional Water Quality Control Board conducted a special monitoring program after the disastrous Tubbs Fire of 2017 and data from 2017 through 2/1/2019 (personal communication from Rich Fadness, SWAMP Regional Coordinator, North Coast Regional Water Quality Control Board to Jonathan Butcher, Tetra Tech, 7/3/2019). This contains nine paired SSC and turbidity samples in 2019 from Mark West Creek, Piner Creek, Paulin Creek, and Santa Rosa Creek.) These limited results (Figure 5-2) suggest that the Sonoma Creek equation provides a good approximation for the Laguna watershed as well. (They also suggest that there may be site-specific variations in the relationship as the samples from Paulin Creek fall well below the line.)

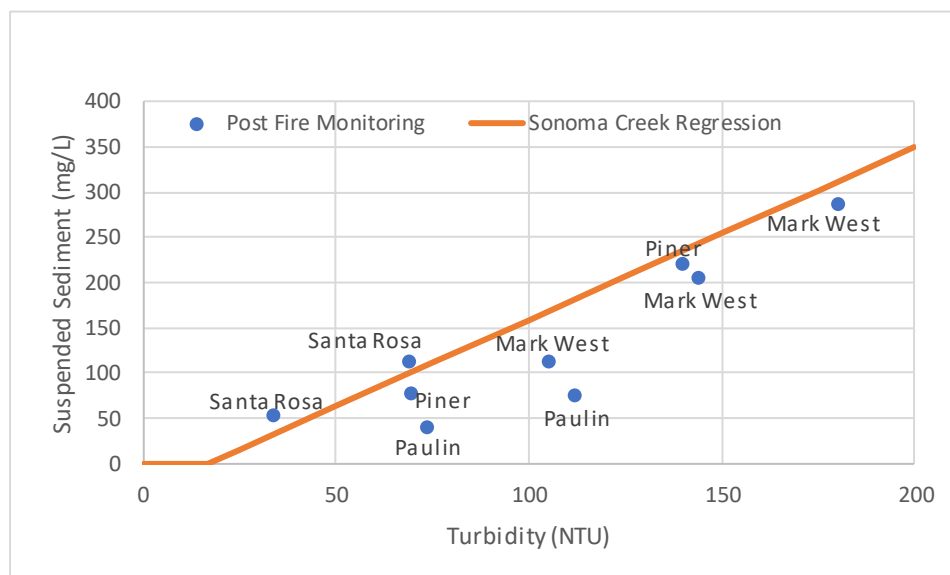


Figure 5-2. Suspended Sediment Concentration and Turbidity Results from Laguna de Santa Rosa Watershed Post-Fire Monitoring

We redeveloped the PWA turbidity – SSC analysis with the Sonoma Creek SSC-turbidity equation and used it 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:

$$\text{Laguna de Santa Rosa at Stony Point Rd.} \quad y = 1.3345 \cdot 10^{-5} \cdot x^2 + 8.8313 \cdot 10^{-3} \cdot x; R^2 = 0.466$$

$$\text{Laguna de Santa Rosa nr Sebastopol} \quad y = 0.01066 \cdot x; R^2 = 0.450$$

$$\text{Santa Rosa Creek at Willowside Rd.} \quad y = 5.6335 \cdot 10^{-6} \cdot x^2 - 1.0988 \cdot 10^{-3} \cdot x; R^2 = 0.785$$

Average annual sediment loads calculated with these equations are presented in Table 5-4 and compared to the estimates of load from the rating curve and FLUX methods reported in Table 5-3.

Table 5-4. Sediment Loads Calculated from Revised Turbidity – SSC Relationships

Station	Turbidity Regression, 11/98 – 9/19 (tons/yr)	Rating Curve (tons/yr)	FLUX (tons/yr)
11465680 Laguna de Santa Rosa at Stony Point Rd.	8,212	NA	NA
11465750 Laguna de Santa Rosa nr Sebastopol	11,000	3,902	3,122
11466320, Santa Rosa Creek at Willowside Rd	8,066	6,810	8,235

Note: NA = not applicable; tons/yr = English (short) tons per year. Rating curve and FLUX results are from Table 5-3.

Estimates using the revised turbidity-SSC relationship are in much closer agreement with the rating curve and FLUX estimates for Santa Rosa Creek at Willowside Road than for Laguna de Santa Rosa near Sebastopol, where the turbidity-based regression appears to be biased high. This might be because there is a more significant non-SSC component to turbidity within the Laguna due to planktonic algae and organic detritus.

One other continuous turbidity record in the watershed is available from USGS. This is for Mark West Creek near Mirabel Heights (gage 11466800) and runs from 11/27/2017 to 5/1/2018 at 15 minute intervals (with gaps; Figure 5-3). This reports turbidity as formazin nephelometric units (FNU) rather than NTU and shows a maximum value of 155 FNU. A scatterplot of turbidity versus flow (Figure 5-4) shows the correlation between turbidity and flow is not very strong at this site. As the location is at the downstream exit of the Laguna, turbidity here may also be affected by elevated algae and organic detritus concentrations. There are no SSC or TSS measurements paired with this set of turbidity measurements.

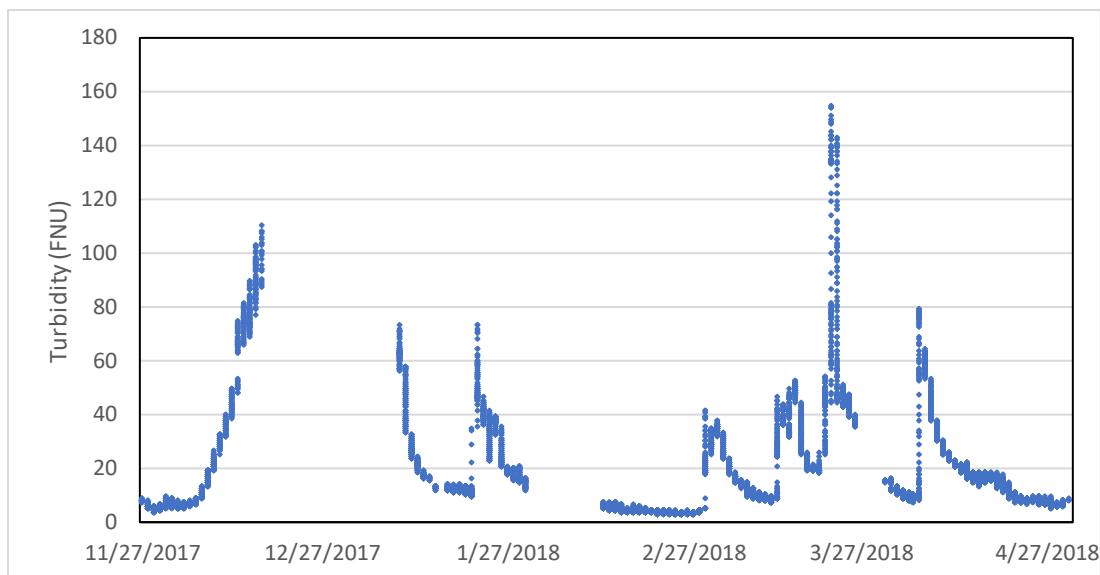


Figure 5-3. Continuous Turbidity Measurements, Mark West Creek near Mirabel Heights, 2017-2018

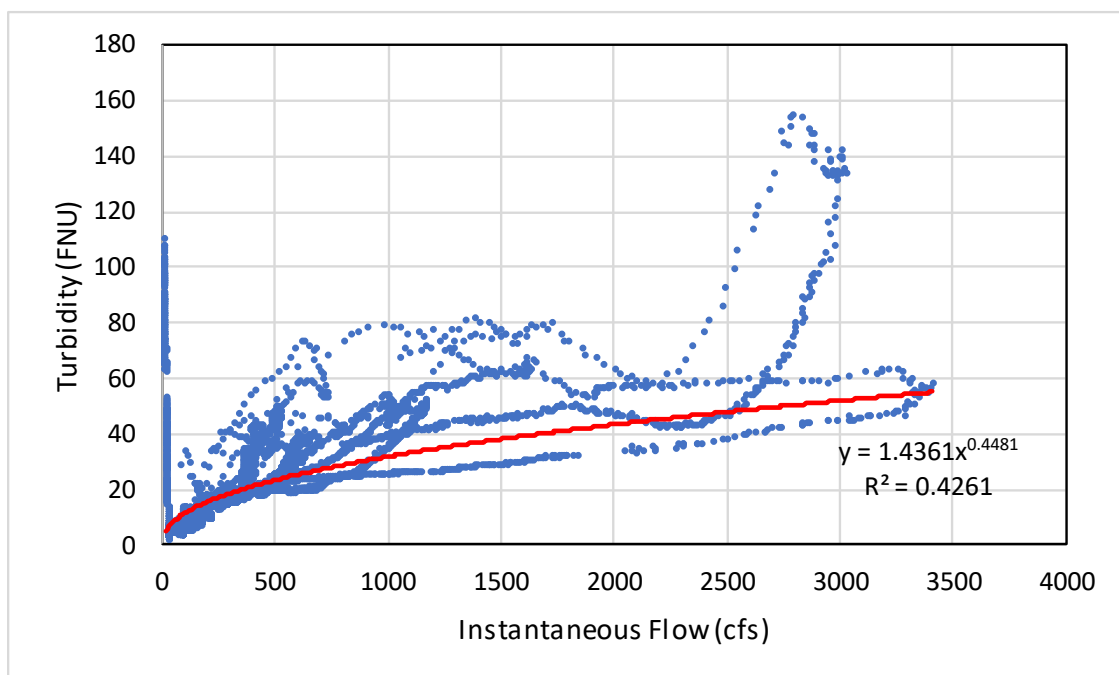


Figure 5-4. Relationship between Turbidity and Flow, Mark West Creek near Mirabel Heights, 2017-2018

A search of CEDEN revealed 197 additional turbidity samples from the Laguna watershed at 22 stations. Most individual stations had less than 20 samples, with the largest count (39) from Santa Rosa Creek above Rincon Creek. None of these samples appear to be paired with SSC or TSS observations.

In the future, continuous turbidity monitoring may be a useful method of estimating sediment loads in the Laguna de Santa Rosa watershed during TMDL implementation if an effort is made to develop local turbidity-SSC relationships specific to the watershed and the turbidity meter used.

5.3 SEDIMENTATION IN MATANZAS RESERVOIR

[No new data on this topic are available since Tetra Tech (2015).]

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 mi² 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/mi²/yr), or about 2.53 tons per acre per year (t/ac/yr), assuming a density of 1,400 kilograms per cubic meter (kg/m³). The total sediment yield rate is likely higher in the steep headwaters area draining to Matanzas Reservoir than in the Laguna de Santa Rosa watershed as a whole.

Further information on sedimentation in reservoirs is provided in Section 8.1.

6.0 UPLAND SEDIMENT LOADS

Upland loads refer to the sediment loads that are generated across the watershed and then transported through streams to the Laguna. Typically, these loads cannot be measured directly, but are estimated through different approaches as described below.

6.1 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 1. Average annual RUSLE soil loss rates by subbasin are shown in Table 6-1, both in terms of total acreage and pervious acres. RUSLE only estimates load from pervious acres, and the major load from impervious areas is associated with roads, which are tabulated separately in Section 7.1.

Table 6-1. RUSLE Average Annual Field-Scale Soil Loss Rates by Subbasin

Subbasin	Total Area (acres)	Pervious Area (acres)	Soil Loss (tons per total acreage)	Soil Loss (tons per pervious acre)
Lower Santa Rosa	21,510	15,011	6.20	8.87
Lower Mark West	5,873	5,310	9.78	10.69
Colgan	4,505	3,520	2.29	2.95
Blucher	4,937	4,606	4.48	4.81
Upper Mark West	21,500	20,955	11.54	11.84
Southeast Santa Rosa	14,190	12,419	7.83	8.88
Northeast Santa Rosa	14,210	13,235	9.42	10.10
Upper Laguna	23,863	19,832	3.05	3.68
Windsor	13,737	11,304	11.41	13.76
Copeland	3,987	3,236	3.86	4.80
Upper Floodplain	14,353	11,951	2.41	2.92
Lower Floodplain*	18,402	16,211	9.28	10.62
<i>Total Watershed</i>	<i>161,067</i>	<i>137,590</i>	<i>7.24</i>	<i>8.48</i>

* Excluding drainage area below Ritchurst Knob.

6.2 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:

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

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 has been 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:

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

where W_i is the dimensionless weighting factor for the i th cell, $\overline{W_k}$ is the average weighting factor for the upslope contributing area, S_i is the slope of the i th 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 i th 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 6-1.

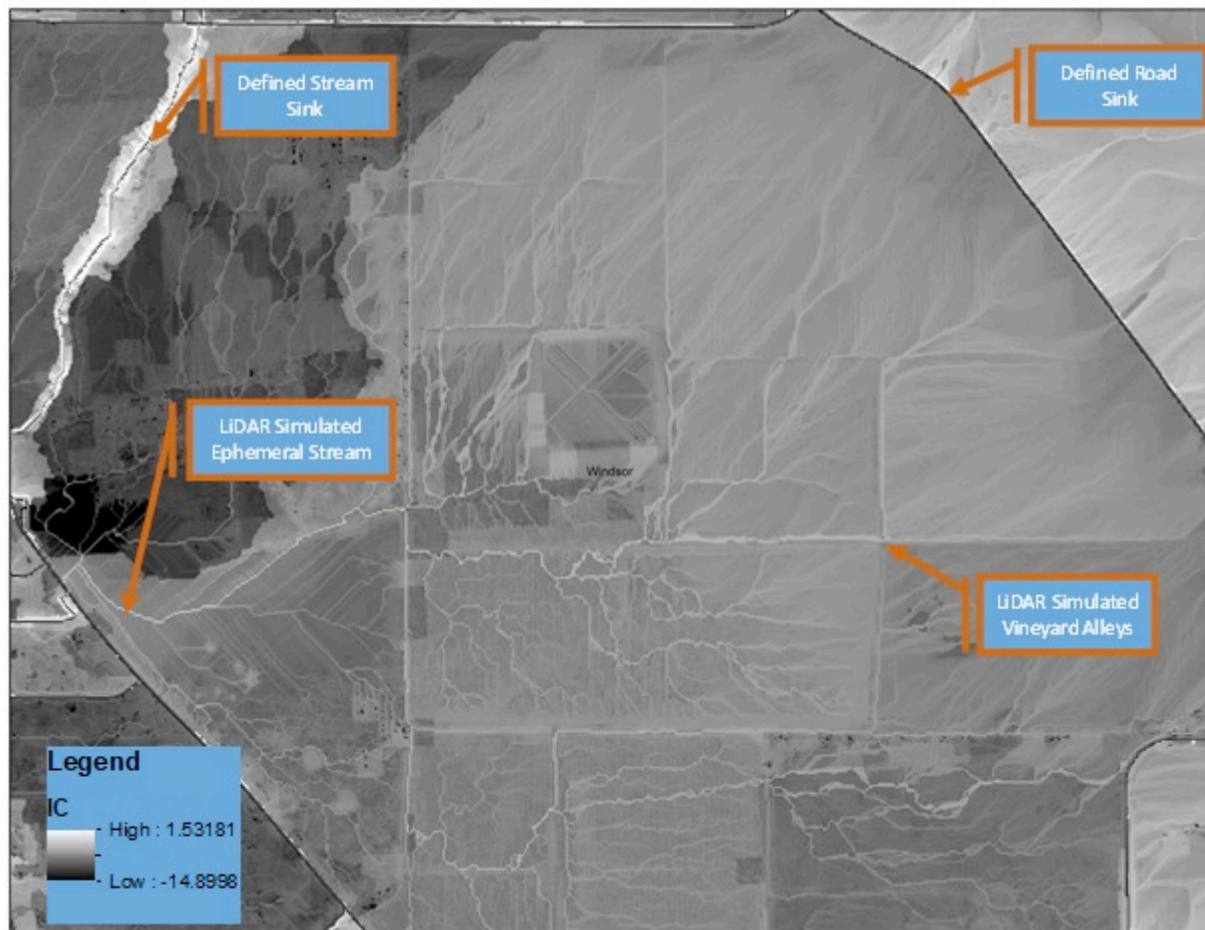


Figure 6-1. Example Connectivity Estimates for Vineyard Area in Windsor Creek Watershed

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 6-2, 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):

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

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 6-3) could thus readily be scaled as additional data are collected in the future.

Table 6-2 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 (except when the emergency overflow is active). For the IC-based method, the composite SDR is back-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 (see Appendix 1). 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 7.0.

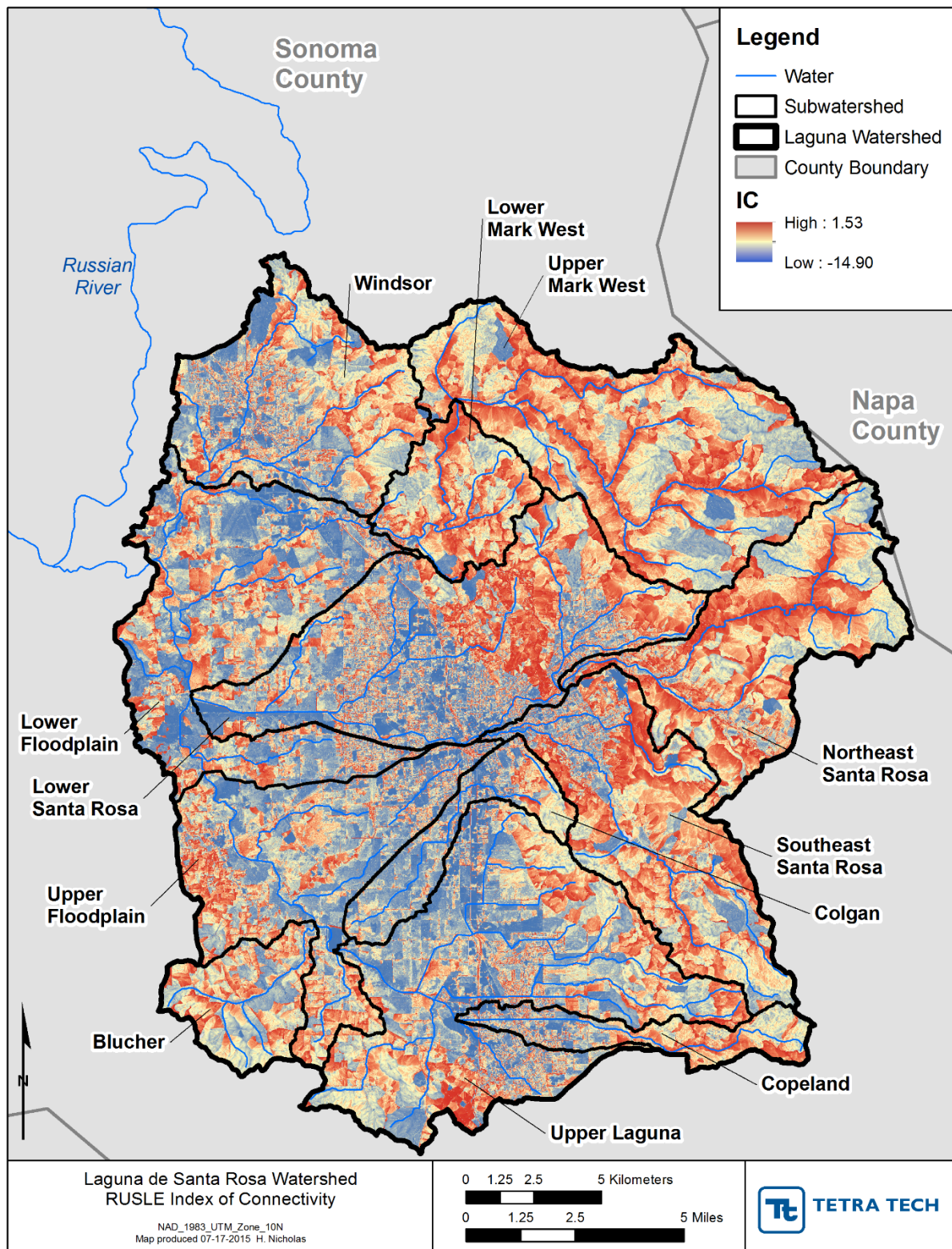


Figure 6-2. Index of Connectivity (IC) for the Laguna de Santa Rosa Watershed

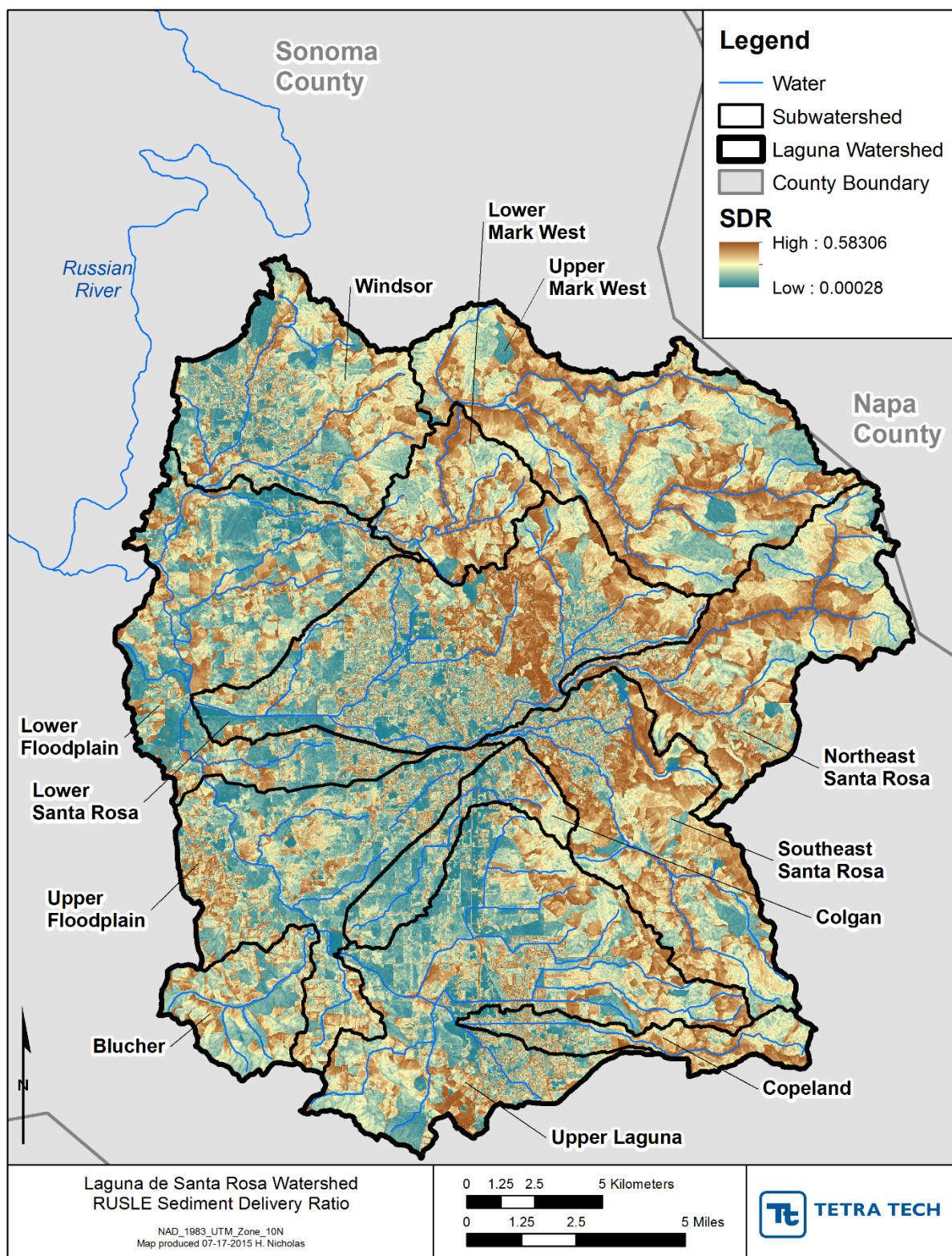


Figure 6-3. IC-based Sediment Delivery Ratio (SDR) for the Laguna de Santa Rosa Watershed

Table 6-2. IC-Based vs. Area-Based Composite Sediment Delivery Ratio Estimates and RUSLE Delivered Upland Sediment Yield by Subbasin

Subbasin	Subbasin Pervious Area (acres)	SDR (IC-based) ³	SDR (Drainage Area-based)	RUSLE Delivered Sediment Yield (tons/yr)
Lower Santa Rosa	21,510	0.024	0.13	3,151
Lower Mark West	5,873	0.020	0.18	1,148
Colgan	4,505	0.017	0.19	182
Blucher	4,937	0.015	0.19	323
Upper Mark West	21,500	0.021	0.13	5,098
Southeast Santa Rosa (excluding Matanzas and Ilsanjo drainages)	6,037	0.037	0.19	[741]
Southeast Santa Rosa (trapped by Matanzas and Ilsanjo)	8,152	0.019	0.17	1,568
Northeast Santa Rosa	14,210	0.021	0.15	2,869
Upper Laguna	23,863	0.021	0.13	1,531
Windsor	13,737	0.016	0.15	2,463
Copeland	3,987	0.021	0.20	319
Upper Floodplain	14,353	0.015	0.15	533
Lower Floodplain ¹	18,402	0.016	0.14	2,748
<i>Total Watershed²</i>	<i>161,067</i>	<i>0.019</i>	<i>0.07</i>	<i>21,106</i>

Notes: 1. Lower Floodplain excludes drainage area below Ritchurst Knob.
 2. Sum for Total Watershed excludes sediment trapped by Matanzas and Ilsanjo Reservoirs.
 3. For the IC-based method, the composite SDR is back-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.

6.3 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 IC-based 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 6-3. 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 6-3. RUSLE Upland Delivered Sediment Yield Estimates by Land Use Group

Aggregated Land Use	Pervious Area (acres)*	RUSLE Sediment Delivery Rate (t/ac/yr)	RUSLE Sediment Yield (tons/yr)	Percentage
Cropland (Row Crops, Orchard/Vineyard)	12,696	0.521	6,623	31.38%
Water/Wetland	5,433	0.006	32	0.15%
Developed	16,819	0.103	1,742	8.26%
Barren	580	2.147	1,246	5.90%
Forest (Hardwood, Conifer, Mixed)	46,676	0.130	6,098	28.89%
Shrub	4,321	0.263	1,138	5.39%
Pasture/Hay	3,698	0.062	229	1.08%
Herbaceous	39,503	0.101	3,998	18.94%
<i>Total</i>	129,725	0.163	21,106	100.00%

* Excluding drainage area below Ritchurst Knob and portions of Southeast Santa Rosa subbasin trapped by Ilsanjo and Matanzas reservoirs.

Figure 6-4 shows the location of the upland sediment yields by aggregated 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 summary maps provide an indicator of areas of potentially higher risk of upland sediment loading (see example close-up view from the predicted higher erosion risk area on the north side of Santa Rosa in Figure 6-5). 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.

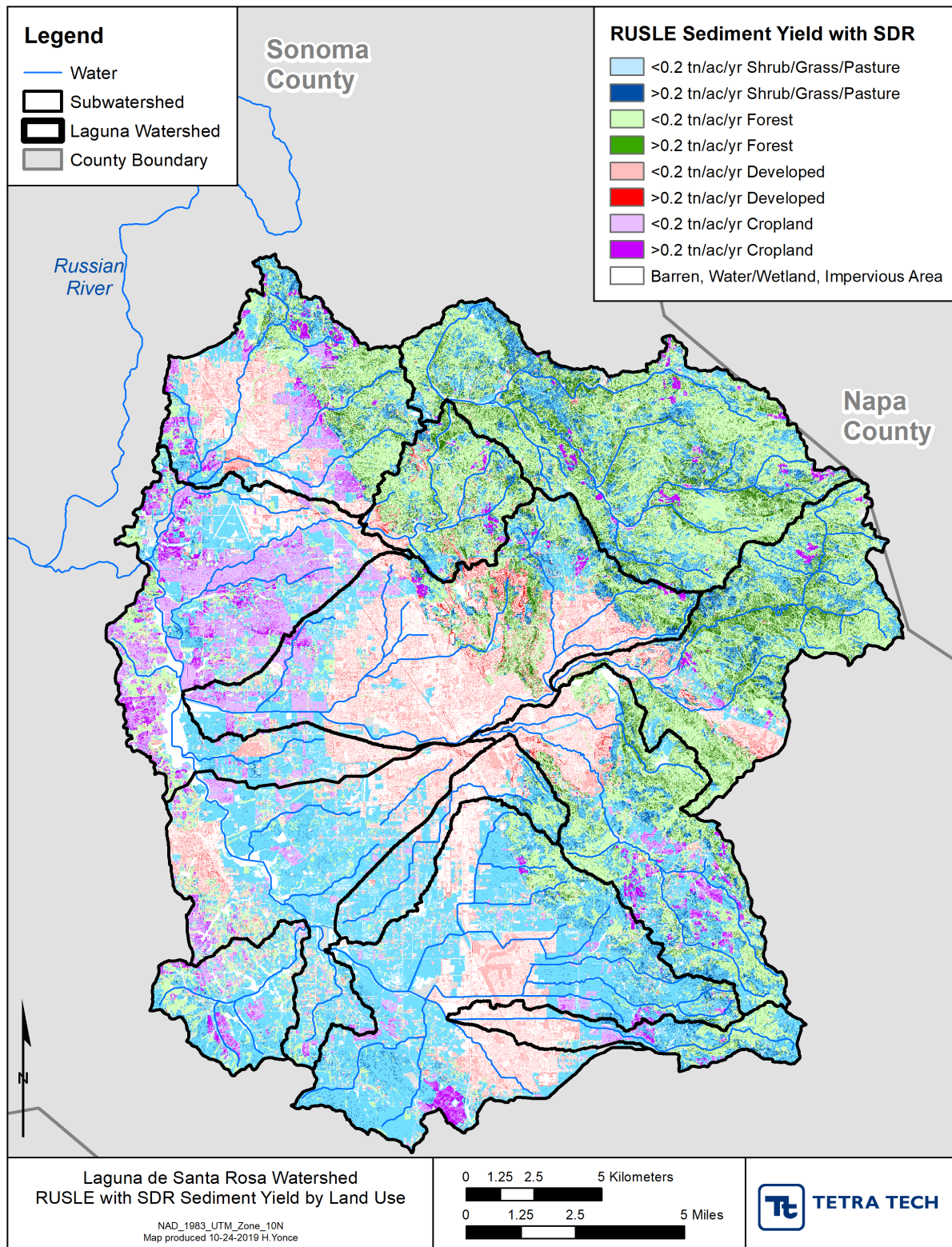


Figure 6-4. RUSLE Sediment Yield Estimates (with IC-based SDR) for the Laguna de Santa Rosa Watershed by Aggregated Land Use

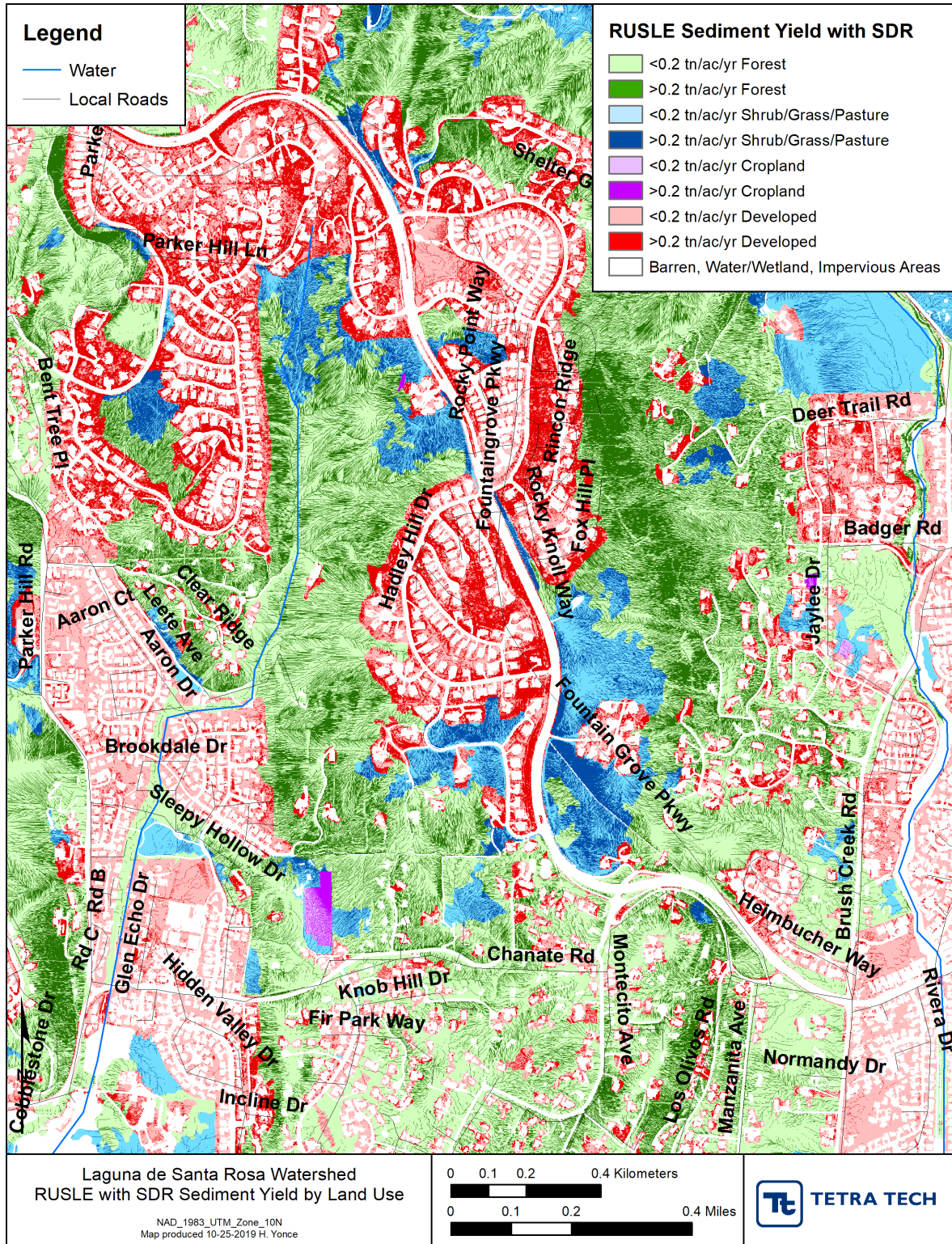


Figure 6-5. Detail from RUSLE Sediment Yield Map, North Side of Santa Rosa, CA

6.4 POTENTIAL IMPACTS OF FIRE

In October of 2017 the Tubbs Fire burned substantial portions of the Mark West Creek and Santa Rosa Creek watersheds. Intense fires destroy vegetative cover and can also seal soils, reducing infiltration and promoting runoff. These increased flows can deliver high concentrations of suspended sediment (e.g., Burke et al., 2013). As discussed in Section 5.2, a post-fire monitoring program was instituted in 2017 and included sampling from five stations downstream of burn areas in the Laguna watershed. The 2017-2018 monitoring included TSS, with SSC measurements obtained in 2019 (Table 6-4).

Table 6-4. Summary of Post-Fire Monitoring Results in the Laguna de Santa Rosa Watershed

	SSC (mg/L)	TSS (mg/L)
Dates	2019	2017-2018
Count	9	12
Average	131	124
Median	111	28
Maximum	286	740

Note: Samples area from Mark West Creek (Fulton Road), Mark West Creek (Leslie Road), Piner Creek, Paulin Creek, and Santa Rosa Creek.

The sample size is too small to draw firm conclusions; however, the average concentrations are more than twice those reported (at different stations) in the 2006 – 2008 USGS SSC sampling. It is thus possible that the 2017 fire resulted in a temporary increase in sediment loads from the burned areas; however, further evidence on this topic is needed. Effects of fire should dissipate over time as vegetation returns.

7.0 OTHER SEDIMENT LOAD SOURCES

7.1 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 comprehensive inventory or analysis of road conditions and sediment yield has been conducted for the Laguna de Santa Rosa watershed. Sonoma VegMap impervious coverage identifies roads as polygons and distinguishes paved from unpaved roads – showing that only about 8 percent of roads in the Laguna watershed are unpaved. For roads maintained by the county there is a coverage that identifies pavement type and rates pavement condition (personal communication from Maxine Istin-Flores, Sonoma County Department of Transportation and Public Works, to Kelsey Cody, NCRWQCB, August 5, 2019). The county maintained roads coverage (which does not include municipal or private roads) shows that only 1.1 percent of these roads are dirt or gravel. Various asphalt roads have poor pavement condition ratings, but are still unlikely to provide large loads from the road tread. The Sonoma County Department of Transportation and Public Works is also building a coverage of road drainage characteristics (“NPDES lines”) that distinguishes between open gutters or channels and closed pipes – although the coverage is available only for certain limited areas at this time. Anecdotally, most urban streets have curb and gutter with closed pipe drainages, while many roads in more rural areas have open channels. Open channels are likely to provide greater sediment yields – all other things being equal – but the state of most road drainage channels is not well documented.

Given the lack of detailed information on road condition and sediment yields from roads in the Laguna watershed, 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 upper two thirds of the Sonoma Creek watershed is immediately adjacent to the Laguna de Santa Rosa watershed (on the eastern side, adjacent to the Copeland, Southeast Santa Rosa, and Northeast Santa Rosa subbasins in the Laguna watershed) 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, generally unpaved but low traffic and mulched) 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 with limited sediment delivery, 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. Highest sediment loading rates were estimated for roads at the apex of alluvial fans at the transition from upland volcanics to lowland sedimentary geology, largely because of higher road cutslopes in these areas. Vineyard roads were

found to be largely non-erosive due to mulch cover or grassed road surfaces. Dirt roads in the Sonoma Creek watershed are mostly located within state and regional parks (largely in Jack London State Park on the east side of Sonoma Mountain) and were noted as largely non-erosive. The results of the SEDMODL2 application were generally confirmed by measurements and observations at 43 sites.

Detailed results by individual road type 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 condition inventory prepared from aerial photography and updated by field work. This level of information is not currently available for roads in the Laguna de Santa Rosa watershed.
- 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.

Despite these differences, the Trso report does appear to provide a reasonable basis for approximating road-related sediment loads. To accomplish this, we converted SEDMODL2 sediment delivery estimates presented in Trso's appendices to loading rates per mile of road. We selected subbasins from Sonoma Creek that are adjacent to or near the Laguna watershed boundary in classes representing upland volcanic geology and lowland sedimentary geology to apply to roads in subbasins with similar characteristics in the Laguna de Santa Rosa watershed. The Sonoma Creek subbasins incorporating the Jack London State Park with an excess number of unpaved roads were not included. Table 7-1 shows the selected Sonoma Creek subbasins and their application to analysis of road loads in the Laguna de Santa Rosa watershed. There is not a very clean match, as many of the subbasins defined for the Laguna de Santa Rosa watershed combine areas in upland volcanics and sedimentary geology. Fortunately, the road tread and cutbank load estimates are very similar for the two groups (Table 7-2).

Table 7-1. Selected Sonoma Creek Subbasins for Extrapolation of Road Sediment Loads to Laguna de Santa Rosa Watershed

Sonoma Creek Subbasin	Dominant Land Uses	Applied to Laguna de Santa Rosa Subbasins
<i>Upland Volcanic Geology</i>		
Frey	Forest, Residential	Northeast Santa Rosa, Copeland, Upper Mark West, Lower Mark West
Yulupa	Forest, Residential	
Zen	Forest, Vineyard	
Snag	Forest, Vineyard	
Carriger	Forest, Residential	
<i>Sedimentary Geology</i>		
Serres	Residential, Vineyard	Windsor, Lower Floodplain, Upper Floodplain, Lower Santa Rosa, Southeast Santa Rosa, Colgan, Upper Laguna, Blucher
Sobre Vista	Residential, Vineyard, Forest	
Fetters Hot Springs	Residential	
Dowdall	Residential, Forest, Vineyard	
Fryer	Residential	
Lewis Felder	Vineyard, Forest	
Leveroni	Vineyard	
City West	Vineyard, Residential	
Fowler	Vineyard, Hay/Pasture	
Upper Schell	Residential, Vineyard	
Lower Schell	Hay/Pasture	

Table 7-2. Estimated Road Tread and Cutbank Sediment Loading Rates from Sonoma Creek TMDL

	Whole Basin	Selected Upland Volcanic Subbasins	Selected Sedimentary Subbasins
Area-weighted Average (tons/mile/yr)	5.41	4.70	4.23
Standard Deviation	3.81	3.07	2.83

Detailed road coverages identified for the Laguna de Santa Rosa include the Sonoma VegMap Impervious coverage and the Tiger roads coverage (U.S. Census Bureau, 2010). The VegMap data is difficult to use because roads are represented as polygons and do not have a readily retrievable length attribute. We therefore used the Tiger road coverage to estimate road miles, which includes the vast majority of public roads plus many of the larger private roads. The Trso estimates of tons per mile per year from Table 7-2 plus 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.

Road lengths and stream crossing counts by subbasin for the Laguna de Santa Rosa watershed are summarized in Table 7-3, amounting to 7,986 tons/yr. Of this total, 224 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 9.0), consistent with the relative importance of road sources in the Sonoma Creek TMDL.

Table 7-3. 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	157
Colgan	64.77	19	278
Copeland	53.41	13	254
Lower Floodplain*	170.35	20	725
Lower Mark West	49.42	10	234
Lower Santa Rosa	430.75	114	1845
Northeast Santa Rosa	105.25	26	500
Southeast Santa Rosa (excluding Matanzas and Ilsanjo)	112.61	35	483
Southeast Santa Rosa (trapped by Matanzas and Ilsanjo)	52.57	10	224
Upper Floodplain	198.21	46	848
Upper Laguna	285.10	132	1232
Upper Mark West	105.04	39	501
Windsor	164.23	51	705
<i>Total</i>	<i>1,828.47</i>	<i>522</i>	<i>7,986</i>

* Excluding drainage area below Ritchurst Knob.

7.2 CHANNEL DEGRADATION AND GULLY EROSION

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).

The analysis in Section 5.3 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 7-1 shows several active gullies in a grazed area downstream of a vineyard in this watershed. Such gullies are potential sources of sediment load that are not accounted for in a RUSLE-based analysis.



Figure 7-1. 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 near the apex of alluvial fans at the edge of the Santa Rosa Plain. This likely reflects channel response to changes in the relationship between runoff rates and sediment supply over time. 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.

A detailed analysis of rates of sediment generation from channel degradation would require site-specific measurements over time. Evidence of the extent of the problem is, however, available from high resolution LiDAR, which is able to resolve channel cross sections. (Because most upland streams were dry or nearly dry during the LiDAR flights, there does not appear to be significant interference by water surfaces). As described in the conceptual model (Section 2.0), the watershed has undergone a cycle of anthropogenic disturbances that have likely resulted in continuous change in channel morphology. LiDAR profiles provide a snapshot of channel form as of the LiDAR flights of 2013, but cannot provide information on rates of change.

A basis for comparison for the LiDAR cross sections is provided by Collins and Leventhal (2013), who developed regional curves of hydraulic geometry for wadeable streams with what was considered to be stable geometry in Marin and Sonoma counties. These are generally not natural or undisturbed streams, but are considered to be in equilibrium with their water and sediment supply. None of the sites are from the Laguna de Santa Rosa watershed, and results have not been stratified by general valley type;

nonetheless, they do provide some indication of the expected dimensions of stable stream channels in the area. Of interest are strong relationships developed for bankfull cross-sectional area (ft²) and bankfull width (ft) versus drainage area (DA, mi²):

$$\text{Bankfull Cross-Sectional Area} = 13.292 \text{ DA}^{0.8335}; R^2 = 0.95793$$

$$\text{Bankfull Width} = 12.893 \text{ DA}^{0.4662}; R^2 = 0.89833$$

A key challenge for applying these equations to LiDAR cross sections is identifying bankfull depth. In the main, channels were found to be incised (e.g., Figure 7-2). Assuming that bankfull depth is equivalent to the visible floodplain elevation (orange line in the figure) is very likely incorrect as this is most probably an abandoned terrace. Incised alluvial channels have a tendency to form a new inner bench floodplain within their terrace banks; however, if present, this was generally not resolvable from the LiDAR. In such cases, the total dimensions of the channel (up to the terrace) are likely to approximate degradation from a relatively stable pre-settlement condition, so the comparison to the regional curves may provide some information on long-term channel changes.

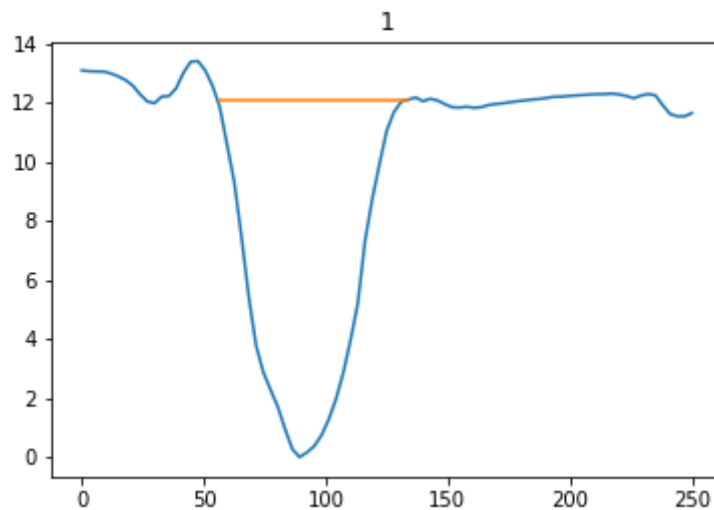


Figure 7-2. Typical LiDAR cross section, Rincon Creek (also known as Brush Creek), tributary to Santa Rosa Creek

Proper identification of bankfull elevation is best done in the field and typically is based on the top elevation of point bars and the lowest elevation of woody vegetation, in addition to breaks in slope (Rosgen, 1996). In a few cases, point bars were visible in the LiDAR cross sections (e.g., Figure 7-3)

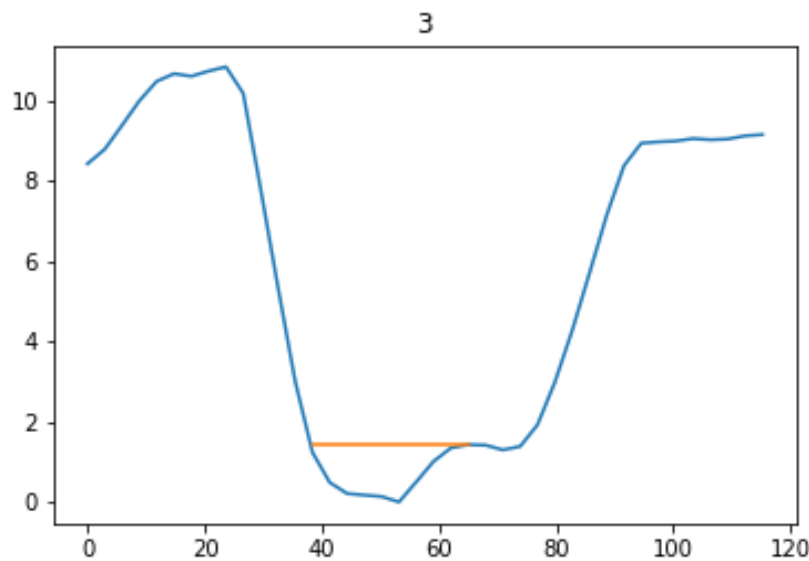


Figure 7-3. LiDAR cross section with visible point bars, Mark West Creek

Cross sectional area when measured to the surrounding terrace was predominantly greater, and often much greater than the bankfull area predicted from the regional hydraulic geometry curves. The width was also greater than expected for stable streams; however, in the few cases where point bars could be clearly identified, both area and width were generally less than predicted from the curves. A summary of the results is presented in Table 7-4. The various cross sections vary in the degree to which even the terrace elevation is clearly visible. Results for cross-sectional area for the more readily interpretable cross sections (Figure 7-4) emphasizes the extent of incision.

Table 7-4. Comparison of Cross-sectional Area and Width to Regional Hydraulic Curves

Stream	Cross-sectional Area Exceeds Regional Curve	Width Exceeds Regional Curve
<i>Measurements Relative to Terrace</i>		
Blucher	87.50%	87.50%
Gossage	100.00%	100.00%
Mark West	100.00%	71.43%
Rincon	83.33%	83.33%
Santa Rosa	100.00%	100.00%
Washoe	75.00%	87.50%
Windsor	87.50%	50.00%
<i>Measurements Relative to Point Bar Tops</i>		
Mark West	25.00%	12.50%

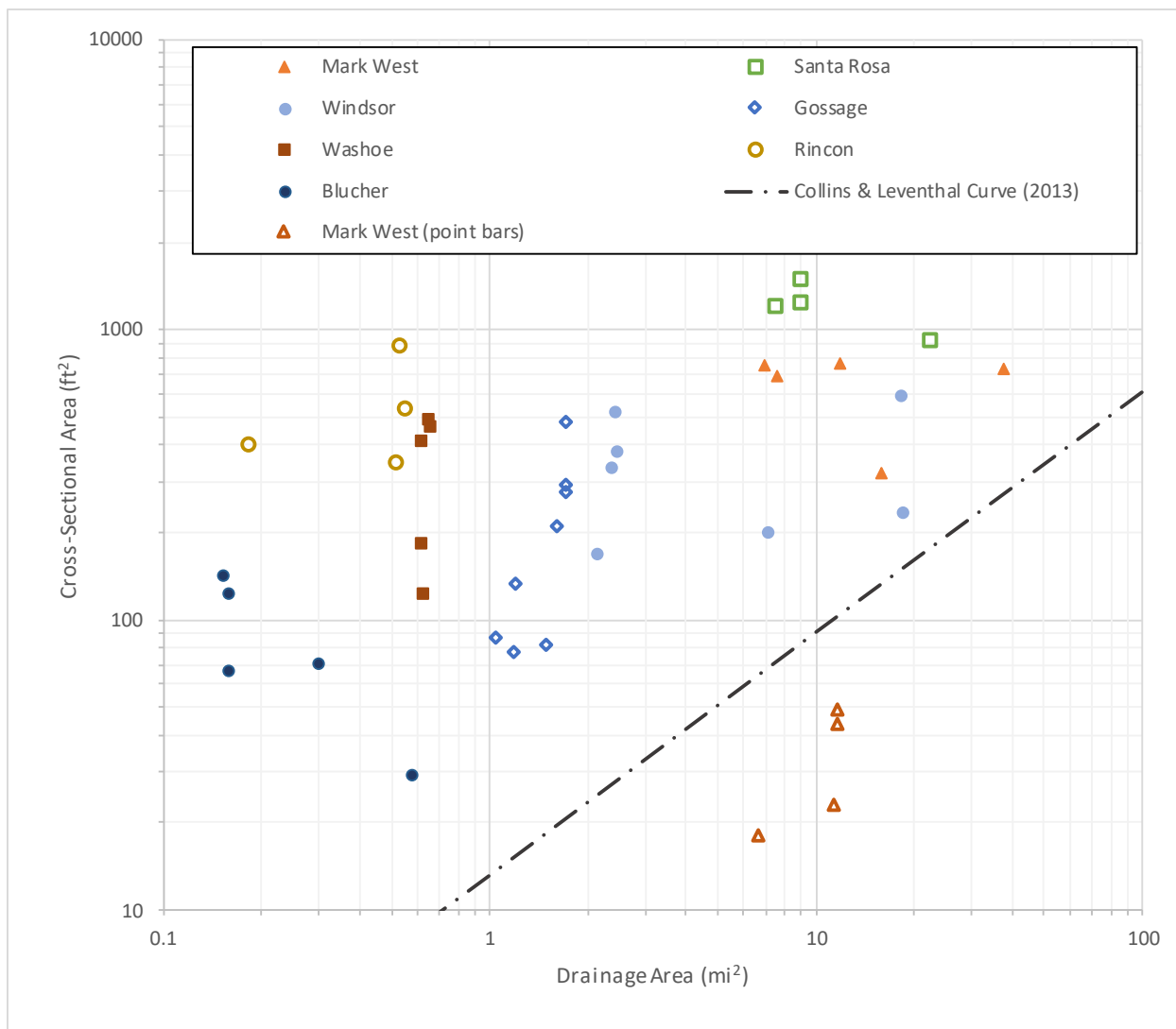


Figure 7-4. Comparison of Selected Sites to Regional Hydraulic Curves for Cross-sectional Area

Further conclusions regarding stream geomorphology will need to be informed by field work. It does appear clear that many channels have enlarged and adjusted to changes in the flow/sediment ratio over the past 150 years. The LiDAR evidence appears to be consistent with a history of disturbance that resulted in channel incision, followed by a readjustment that has started to create a new channel form at the bottom of the incised profile that suggests a Rosgen adjustment progression from a type C to type G stream that may now be progressing to widening into type F. The LiDAR, however, does not tell us much about the rate at which sediment mobilization from the channel has occurred.

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; López-Vicente et al., 2013).

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 6.2 has similar characteristics and could 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 require a combination of LiDAR topographic analysis and field investigations. Channel degradation is likely to be a dominant process where streams cut into the upstream edge of the 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.

7.3 SOIL CREEP, LANDSLIDES, AND COLLUVIAL BANK EROSION

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., 1997) and the annual rate of volumetric soil delivery from landslides is not known. Wentworth et al.’s mapping of landslides in the San Francisco Bay Region (Figure 7-5) show that the largest areas with historic slides are in Upper Mark West Creek and along the eastern edge of the watershed. Channel surveys by PWA (2004a) also indicate 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 (Figure 7-6) also corresponds to the higher elevation portions of the watershed area in which larger amounts of soil creep are also expected to occur (Ellen et al., 1997).

In a tectonically active landscape, uplift, as is occurring on the northeastern portion of the watershed, results in downslope movement of soils by gravitational forces, a process referred to in general as soil creep. Landslides are essentially an extreme form of soil creep. These processes result in the accumulation of colluvium at the base of hill slopes.

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 or dry ravel can also be an important process separate from wash processes, especially for steep slopes in arid or semiarid landscapes, where particles may be mobilized by animal or human activity and small landslides. Fire can enhance this process by mobilizing sediment wedges trapped behind vegetation (Gabet, 2003).

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.

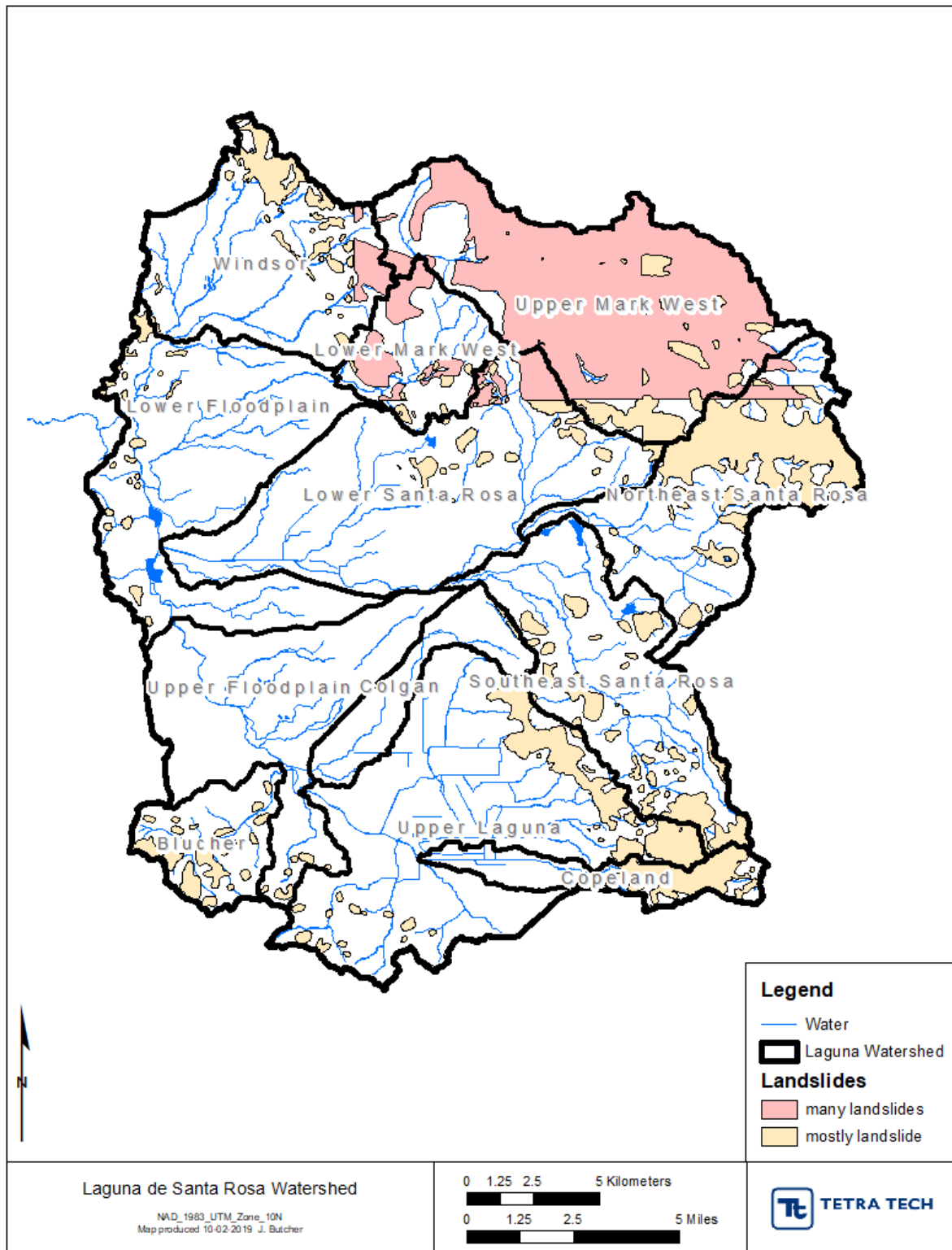


Figure 7-5. Landslide Prevalence in the Laguna de Santa Rosa Watershed (Wentworth et al., 1997)

Note: The Wentworth et al. map was produced from multiple sources collected by varying methods and at different resolutions, which results in some “straight line” discontinuities between the many and mostly landslide areas.

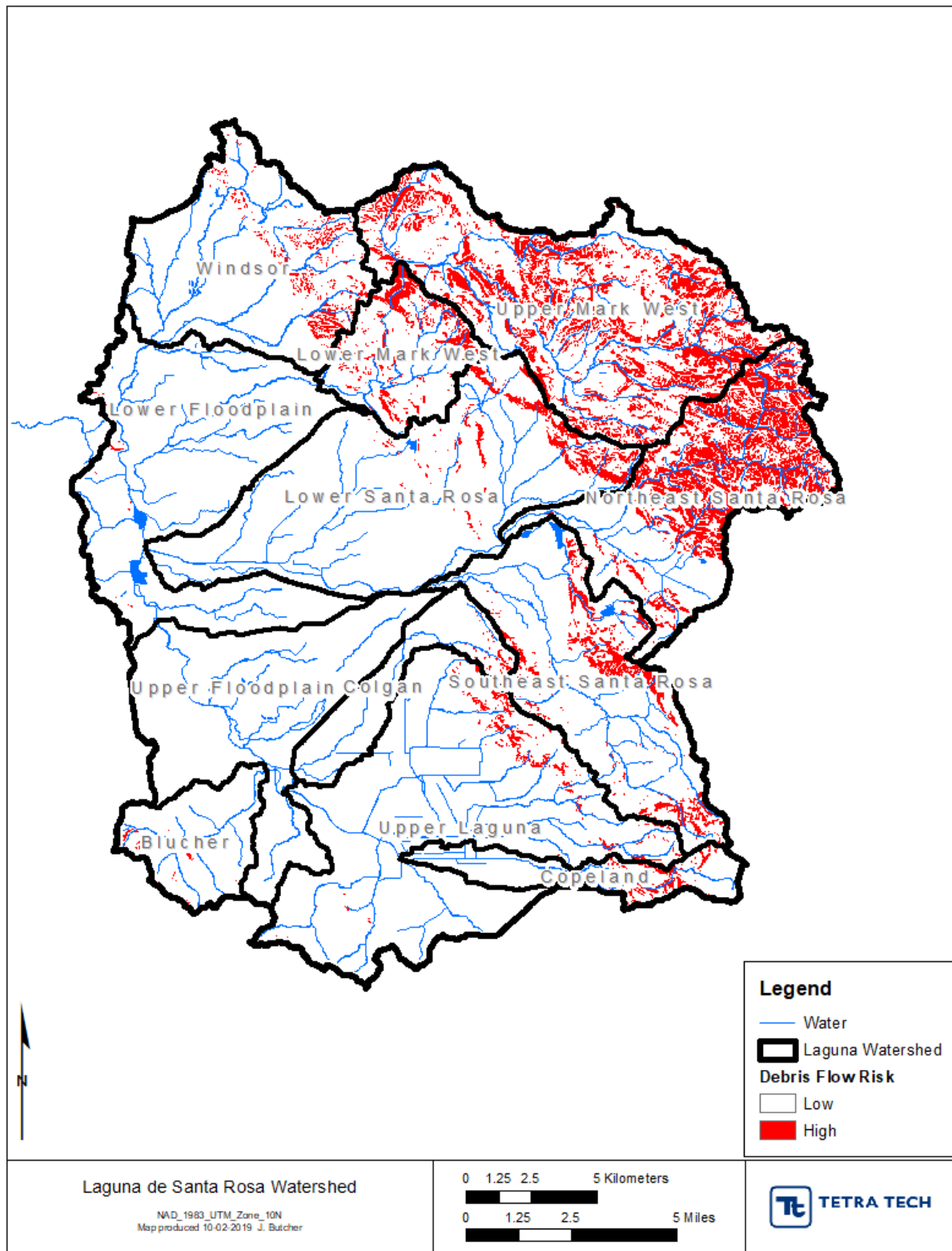


Figure 7-6. Debris Flow Risk in the Laguna de Santa Rosa Watershed (Ellen et al., 1997)

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 ($\text{t/mi}^2/\text{yr}$), 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.

A 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) is large relative to published depths from these studies, but is believed to reflect the geological conditions of the mountainous portion of the Sonoma Creek and adjacent watersheds.

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 5.0).

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 7-7). 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).

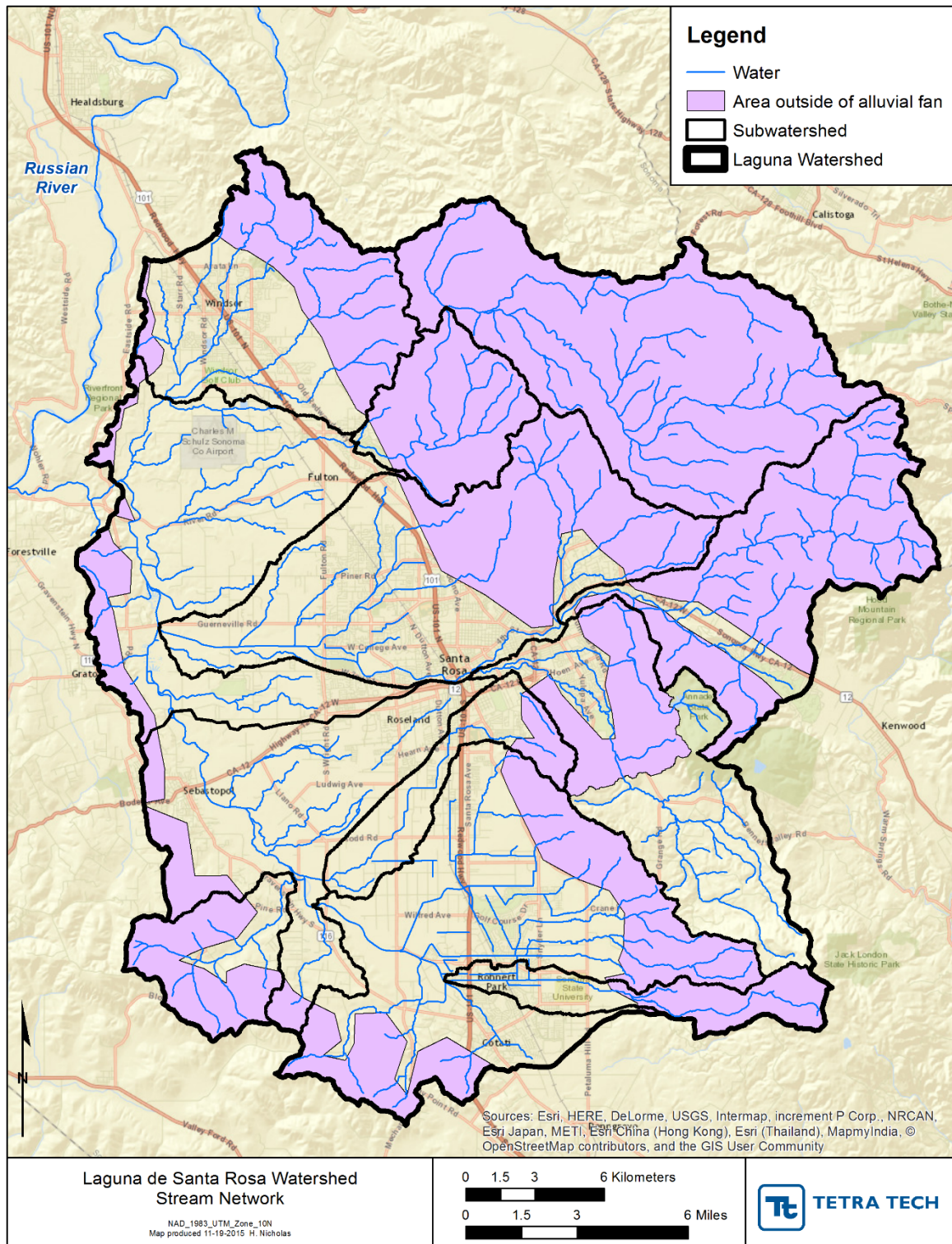


Figure 7-7. Streams Outside Alluvial Fans Evaluated for Colluvial Bank Erosion in the Laguna de Santa Rosa Watershed

As noted in Section 7.2, 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 7-7, 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 7-5.

Table 7-5. 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
<i>Total</i>	<i>213.94</i>	<i>13,564</i>

* Excluding drainage area below Ritchurst Knob.

7.4 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.”

Although probably not a major source, it is possible that backwater sediment loads from the Russian River have changed over time due to logging and other land use disturbances in the Russian River watershed. Another possible factor is sea level rise, which may decrease the flushing capacity of the Russian River. Over the past hundred years, relative sea levels along this part of the coast south of Point Reyes have increased at a rate of about 2 mm/yr (Griggs et al., 2017), whereas the relative sea level rise north of Cape Mendocino is negative due to high tectonic uplift rates.

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8.0 SEDIMENT SINKS

8.1 SEDIMENTATION LOSSES

The sediment generated from the sources described in Sections 6.0 and 7.0 are either trapped within the watershed (including within the Laguna de Santa Rosa itself) or passed through to the Russian River.

8.1.1 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 mi² 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 5.3. 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 primarily receives water diverted from Santa Rosa Creek¹. 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. Other small waterbodies in the watershed include Fountaingrove Lake on Piner creek, Lake Ralphine, Roberts Lake, and Santa Rosa Creek Reservoir (on a tributary to Santa Rosa 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.

8.1.2 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,

¹ Spring Lake also receives water from Lake Ilsanjo via Spring Creek when the Ilsanjo emergency overflow is reached or when it is undergoing controlled draw down. Spring Creek only flows into its natural course when flooding and through a controlled diversion during lower flows; otherwise it flows into Spring Lake. These complex details are not incorporated into the sediment budget.

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 (Table 5-3) 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. Regional Board staff have 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 two 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.

8.2 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 (yd³/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 provided a summary of these activities for 2008 through 2019 (personal communication from Chase Takajo, SCWA, to Kelsey Cody, NCRWQCB, 6/24/2019). Results are shown in Table 8-1, assuming a dry density of 1,400 kilograms per cubic meter (kg/m³). Note that the average annual removal is of the same order of magnitude as the sum of the load at USGS gages upstream of the main body of the Laguna estimated in Section 5.1 (e.g., Table 5-3 sum for Laguna de Santa Rosa near Sebastopol, Santa Rosa Creek at Willowside Rd., and Mark West Creek near Windsor FLUX sum of 19,369 tons/yr compared to Table 8-1 average annual sediment removal of 22,309 tons/yr)..

Sediment removal is based on need and the amounts and locations of removal activities varies from year to year, as is evident from the standard deviation shown in Table 8-1. Nonetheless, this twelve-year average provides the best estimate available of typical sediment removal rates by the SCWA Stream Maintenance Program.

Table 8-1. Sediment Removal for the SCWA Stream Maintenance Program

Subbasin	Total Volume, 2008-2018 (yd ³)	Average Mass (tons/yr)	Median Mass (tons/yr)	Standard Deviation on Annual Mass
Lower Floodplain	0	0	0	0
Windsor	944	101	0	284
Lower Mark West	0	0	0	0
Upper Mark West	0	0	0	0
Lower Santa Rosa	30,547	3,277	3,682	3,201
Northeast Santa Rosa	11,965	1,284	743	1,636
Southeast Santa Rosa (excluding Matanzas and Ilsanjo)	583	63	0	152
Southeast Santa Rosa (trapped by Matanzas and Ilsanjo)	17,098	1,834	642	2,739
Upper Floodplain	1,264	136	0	397
Colgan	14,093	1,512	0	4,433
Blucher	0	0	0	0
Upper Laguna	100,327	10,762	9,119	8,004
Copeland	31,146	3,341	1,192	3,725
<i>Total</i>	<i>207,967</i>	<i>22,309</i>	<i>22,555</i>	<i>9,737</i>

Note: yd³ = cubic yards. Mass is expressed in English (short) tons. The entry for Total in the Median column represents the median of annual mass removal from the entire watershed.

8.3 EXPORT TO THE RUSSIAN RIVER

Sediment export to the Russian River is discussed in Section 5.1. The FLUX analysis reported in Table 5-3 suggests a best estimate of 12,533 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.

9.0 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 a credible estimate of the overall sediment budget for the watershed. The estimated sediment budget for current conditions is summarized in Table 9-1.

Table 9-1 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 6.0. Sediment sources associated with roads, colluvial bank erosion, gullies, and landslides are as described in Section 7.0, 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 0, 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 corresponding to the four stations with suspended sediment-based load analyses were set to the FLUX estimates (for Santa Rosa Creek at Willowside [exit of Lower Santa Rosa subbasin], Mark West Creek near Windsor [Lower Mark West], and Mark West Creek near Mirabel Heights [Lower Floodplain] and to the turbidity-based estimate for Laguna de Santa Rosa near Sebastopol [Upper Laguna] from Section 5.0. Trapping within the Laguna de Santa Rosa is set at a rate that equals the findings of Curtis et al. (2012) summarized in Section 8.1.2.

The major remaining component in the sediment balance is the *net* of channel scour and deposition processes. Channel degradation is believed to be a significant component of the overall sediment load source, but has not been quantified (Section 7.2). The net contribution can be estimated as the remainder in the sediment balance equation when the downstream load estimates and rate of deposition in the Laguna are constrained as described above. It is important to emphasize that this gives an estimate of the net of scour and deposition that is conditional on the estimates of the other components and that the differencing procedure cannot resolve scour and deposition components individually. For example, a net load contribution of channel processes of zero could mean there is no significant scour or deposition, or that there is a large amount of scour but balanced by an equal amount of deposition (and sediment removal). Further, the approach does not guarantee a unique solution where there are not constraints imposed by load estimates based on monitoring data. For instance, the balance for an individual subbasin could be completed by assigning the difference between other sources and sinks either to net channel processes or to downstream transport.

Net positive loads from channel processes are assigned to the Northeast Santa Rosa, Southeast Santa Rosa, Windsor, Colgan, Copeland, 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 net channel loads to the Upper Laguna and Upper Floodplain subbasins are constrained by total sediment load estimates for Laguna de Santa Rosa near Sebastopol and Laguna de Santa Rosa at Stony Point Road – and are conditional on the accuracy of those estimates. The net channel 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 the condition of individual channels at least partially agrees with the estimated net channel loads developed in the mass-balance analysis. The net channel load estimate for Copeland is consistent with the study of that watershed (Laurel Marcus and Associates, 2004) that reports that “nearly 50,000 yd³” 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, the channel loads may 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 degradation 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.

While currently available data are not sufficient to constrain the sediment budget to a unique solution, the results presented in Table 8-1 provide a credible 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, especially the net channel load component.

Table 9-1. 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 ³	Windsor	Upper Mark West	Lower Mark West ³	Blucher	Colgan	Copeland	Upper Laguna ³	Upper Floodplain	Lower Floodplain ^{2,3}	Sum
SOURCES													
Upland	2,869	741	3,151	2,463	5,098	1,148	323	182	319	1,531	533	2,748	21,106
Upstream	0	0	7,408	0	0	9,149	0	0	0	0	9,132	34,026	
Road Crossings	5	7	23	10	8	2	1	4	3	26	9	4	102
Road Tread	495	476	1,822	695	494	232	155	274	251	1,206	838	721	7,659
Soil Creep, Gullies	2,469	467	1,192	1,118	3,550	1,001	439	127	428	1,151	19	192	12,153
Net Channel	835	389	0	8,489	0	0	0	926	2,340	15,060	5,331	16,978	50,348
Total In	6,673	2,081	13,595	12,775	9,149	11,533	920	1,512	3,341	18,974	15,863	54,669	91,370
SINKS													
Sediment Removal	1,284	63	3,277	101	0	0	0	1,512	3,341	10,762	136	0	20,475
Downstream Flux	5,390	2,018	10,319	12,673	9,149	7,912	920	0	0	8,212	3,122	12,533	12,533
Deposition	0	0	0	0	0	3,621	0	0	0	0	12,605	42,136	58,362
Total Out	6,673	2,081	13,595	12,775	9,149	11,533	920	1,512	3,341	18,974	15,863	54,669	91,370

¹ Excluding drainage areas above Matanzas Creek Reservoir and Lake Ilсанjo (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 near Windsor, as well as several smaller tributaries that flow into the Laguna de Santa Rosa.

³Point of calibration to FLUX-estimated loads

Sources:

Upland: Estimated delivered sheet and rill erosion from RUSLE analysis with IC-based sediment delivery (Section 6.1).

Upstream: Sum of downstream output of all upstream subbasins. For example, upstream total for Lower Santa Rosa is equal to the downstream amounts of Northeast and Southeast Santa Rosa.

Road Crossing: Based on Sonoma Creek analysis of load per stream crossing (Section 7.1).

Road Tread: Based on Sonoma Creek analysis of load per mile of road (Section 7.1).

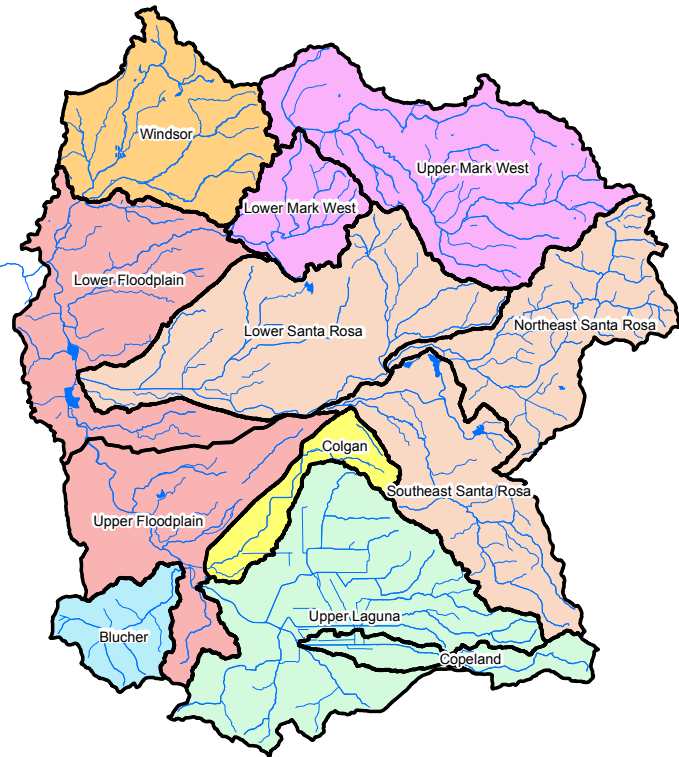
Soil Creep, Landslides: Analysis of colluvial bank erosion via soil creep (Section 7.3).

Sinks:

Sediment Removal: Average (or median) rate of sediment removal from SCWA channel maintenance activities, 2008-2014 (Section 8.2). Areas of sediment removal change significantly from year to year, depending on need.

Downstream: Outflow downstream; constrained to FLUX and turbidity-based load estimates (Table 5-3 and Table 5-4) for Lower Santa Rosa (inflated by a factor of 1.107 to account for area downstream of age), Lower Mark West, Upper Laguna, Upper Floodplain, and Lower Floodplain subbasins.

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 (8.1.2).



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Despite the acknowledged uncertainties, Table 9-1 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 9-1. On the source side, the largest contributor to the sediment load to the Laguna de Santa Rosa is estimated to be channel degradation (incision and widening). On the sink side, it is notable that SCWA's current channel maintenance activities currently appear to remove nearly one-quarter of the potential load that would otherwise reach the Laguna de Santa Rosa. These results are similar to, but differ somewhat from those presented in Tetra Tech (2015). Upland erosion is estimated to be somewhat more important as a source in the new analyses (23% versus 19%), while transport out to the Russian River increased from 5% to 14%. These differences are due primarily to the addition of newer flow and sediment data, along with revisions to the cover factor used in the upland RUSLE sediment load analysis.

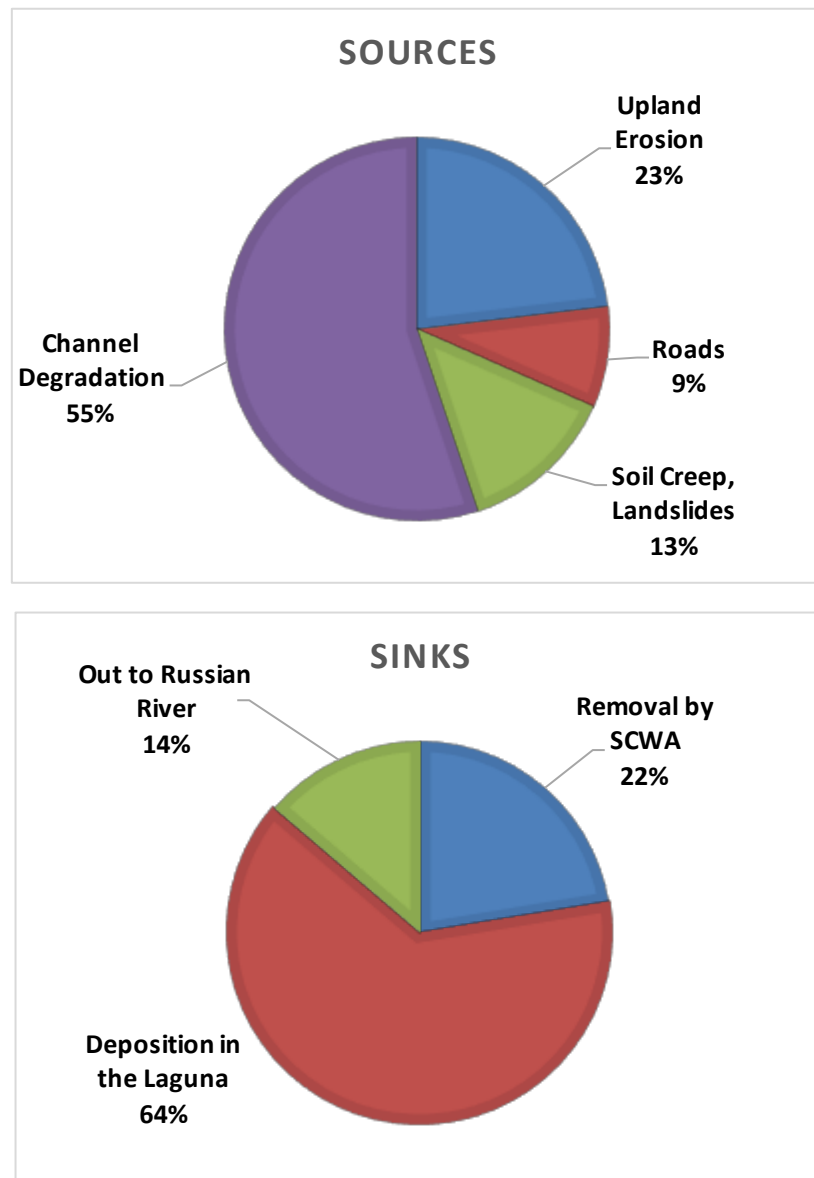


Figure 9-1. Summary of the Laguna de Santa Rosa Sediment Budget for Current Conditions

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10.0 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 2). 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 10-1 and Figure 10-1.

Table 10-1. 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 sink estimates 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 2).
- **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 Degradation:** As noted in Section 9.0, under current conditions it is likely that more than half of the sediment load is derived from channel degradation 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. Estimates of uplift based on cosmogenic isotopes for the upper South Fork Eel River range from 0.02 to 0.05 cm/yr (Fuller et al., 2009; Willenbring et al., 2013), but are likely higher than in the Laguna de Santa Rosa watershed due to closer proximity to the uplift maximum associated with the Mendocino triple junction (Roering et al., 2015).

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 82.3 percent of the sediment load reaching the Laguna in **Table 9-1**.

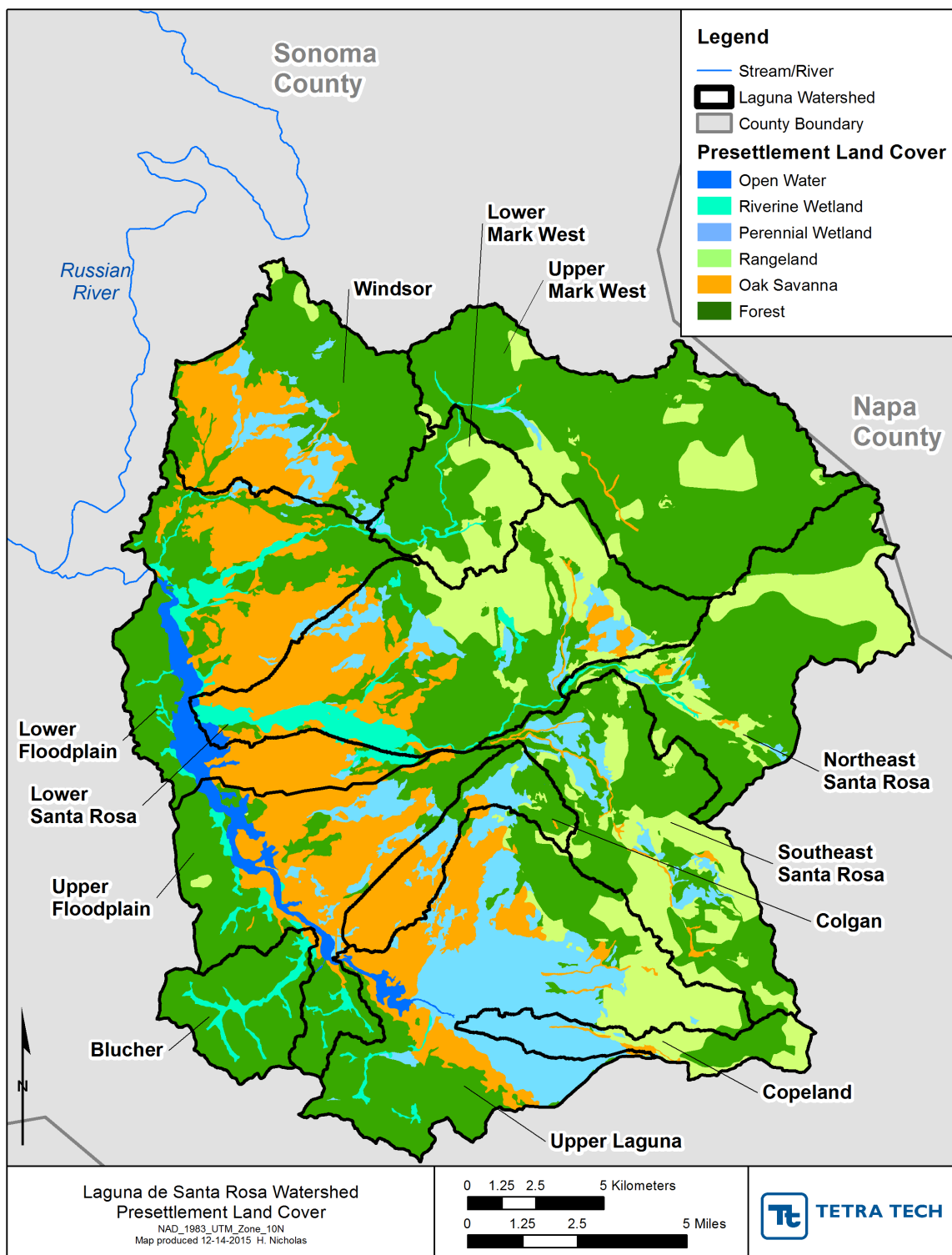


Figure 10-1. Land Cover prior to European Settlement of the Laguna de Santa Rosa Watershed (Butkus, 2011)

The estimated components of the sediment budget prior to European settlement are presented and compared to current conditions estimates in Table 10-2. 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 10-2.

Table 10-2. 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	21,106	649%
Roads	0	7,762	NA
Soil Creep, Gullies, Landslides	4,476	12,153	172%
Net Channel	365	50,348	13703%
<i>Total In</i>	<i>7,658</i>	<i>91,370</i>	<i>1093%</i>
SINKS			
Sediment Removal (<i>Current Conditions</i>) or Net Deposition on Alluvial Fans (<i>Pre-settlement</i>)	1,914	20,475	969%
Deposition in Laguna de Santa Rosa	5,325	58,362	1134%
Downstream to Russian River	418	12,533	1134%
<i>Total Out</i>	<i>7,658</i>	<i>91,370</i>	<i>1093%</i>

¹ Excluding drainage area above Matanzas Creek Reservoir and Lake Ilseño (8,152 acres).² Excluding drainage area below Ritchurst Knob.

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