Laguna de Santa Rosa Sediment Budget APPENDICES

Prepared for

U.S. EPA Region 9 and

North Coast Regional Water Quality Control Board

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Appendix A Application of Modified PSIAC Method for Estimating Total Sediment Yield

The first analytical method used for developing the Laguna de Santa Rosa Sediment Budget (main report) is the Pacific Southwest Inter-Agency Committee or PSIAC method. The PSIAC method is an empirical approach to estimating total delivered sediment load (from all sources) in rivers of the Southwest. The original PSIAC (1968) method, which was applied by PWA (2004a), is somewhat hampered by the subjective nature of many of the constituent factors, which also renders a GIS-based analysis of specific source areas difficult. To address this issue, the U.S. Bureau of Land Management (BLM) developed and validated more quantitative procedures for estimating many of the PSIAC factors, including physical characteristics, Universal Soil Loss Equation (USLE) erodibility factors, precipitation and runoff volume characteristics, and bare ground and canopy cover percentages (Johnson and Gebhardt, 1982).

The original PSIAC (1968) method was intended to be used with qualitative field observations and assigns rating factors to nine different basin characteristics (see Table A-1). Additionally, a nomograph was provided to convert the overall rating to sediment volumetric yield in acre-feet per square mile per year. Refinements to the method reported by Johnson and Gebhardt (1982) estimate the sediment yield as:

$$Sy = 0.253\ e^{0.036(Y_1+Y_2+Y_3+Y_4+Y_5+Y_6+Y_7+Y_8+Y_9)}$$

Here, Sy is the sediment yield in metric tons per hectare, assuming a sediment bulk density of 1,360 kg/m^3, e is the base of natural logarithms, and the Y_n terms are the PSIAC rating factors. (PSIAC uses a slightly different bulk density than that adopted in the main report of 1,400 kg/m^3. The factor based on density of 1,360 kg/m^3 is retained for the PSIAC analyses because it was part of the fitting procedure used by Johnson and Gebhardt. The difference is about 3 percent.)

Final results from this method were converted from metric tons to English (short) tons, and from a hectare to an acre basis. The method is modified from the original PSIAC fit after shifting the range of Y_6 and Y_7 from -10 – 10 to 0 – 20 and converting to metric units.

Johnson and Gebhardt (1982) also derived methods to relate many of the PSIAC factors to more generally available measurable quantities. The PSIAC rating factors are listed in Table A-1 along with relevant data sources for this project.

Table A-1. PSIAC Factors and Data Sources

Factor	Name	Data Source
Y_1	Surface Geology Factor	USGS Surficial Geology
Y_2	Soils Factor	Soil Survey Geographic Database (USDA SSURGO) KFFACT
Y_3	Climate Factor	NOAA 2-year 6-hour Precipitation Grid
Y_4	Runoff Factor	USGS, PRISM, Gotvald et al. (2012), Johnson and Gebhardt (1982)
Y_5	Topography Factor	Sonoma County Vegetation Mapping and LiDAR Program
Y_6	Ground Cover Factor	Sonoma County Vegetation Mapping and LiDAR Program
Y_7	Land Use Factor	Sonoma County Vegetation Mapping and LiDAR Program
Y_8	Upland Erosion Factor	Bureau of Land Management (BLM) Erosion Condition Classification System (Clark, 1980) as interpreted by the PWA Report (2004a)
Y_9	Channel Erosion/ Sediment Transport Factor	BLM Erosion Condition Classification System (Clark, 1980) as interpreted by the PWA Report (2004a)

A.1 Surface Geology Factor (Y_1)

This factor is a geologic erosion index which is based on rock type, hardness, fracturing, and weathering potential of the surficial geology. This factor reflects a range from massive, hard formations (Y_1=0), to highly erodible mudstones and siltstones (Y_1=10). Using a combination of major and secondary rock types, Surface Geology Factors were assigned for relative erosivity (Figure A-1). For reference, PWA (2004a) reported Surface Geology Factors across subwatersheds as ranging between 5 and 10. Assignments of these factors based on rock types are seen in Table A-2.

Table A-2. PSIAC Surface Geology Factors Assigned by Rock Types

Major Rock Type	Secondary Rock Type	PSIAC Factor
Dacite	Rhyolite, Andesite	5
Rhyolite	Dacite	5
Sandstone	Conglomerate	7.5
Serpentinite	Peridotite	7.5
Greenstone	Basalt	7.5
Mudstone	Terrace	10
Melange	N/A	10
Alluvium	Terrace, Mudstone	10
Sandstone	Mudstone	10

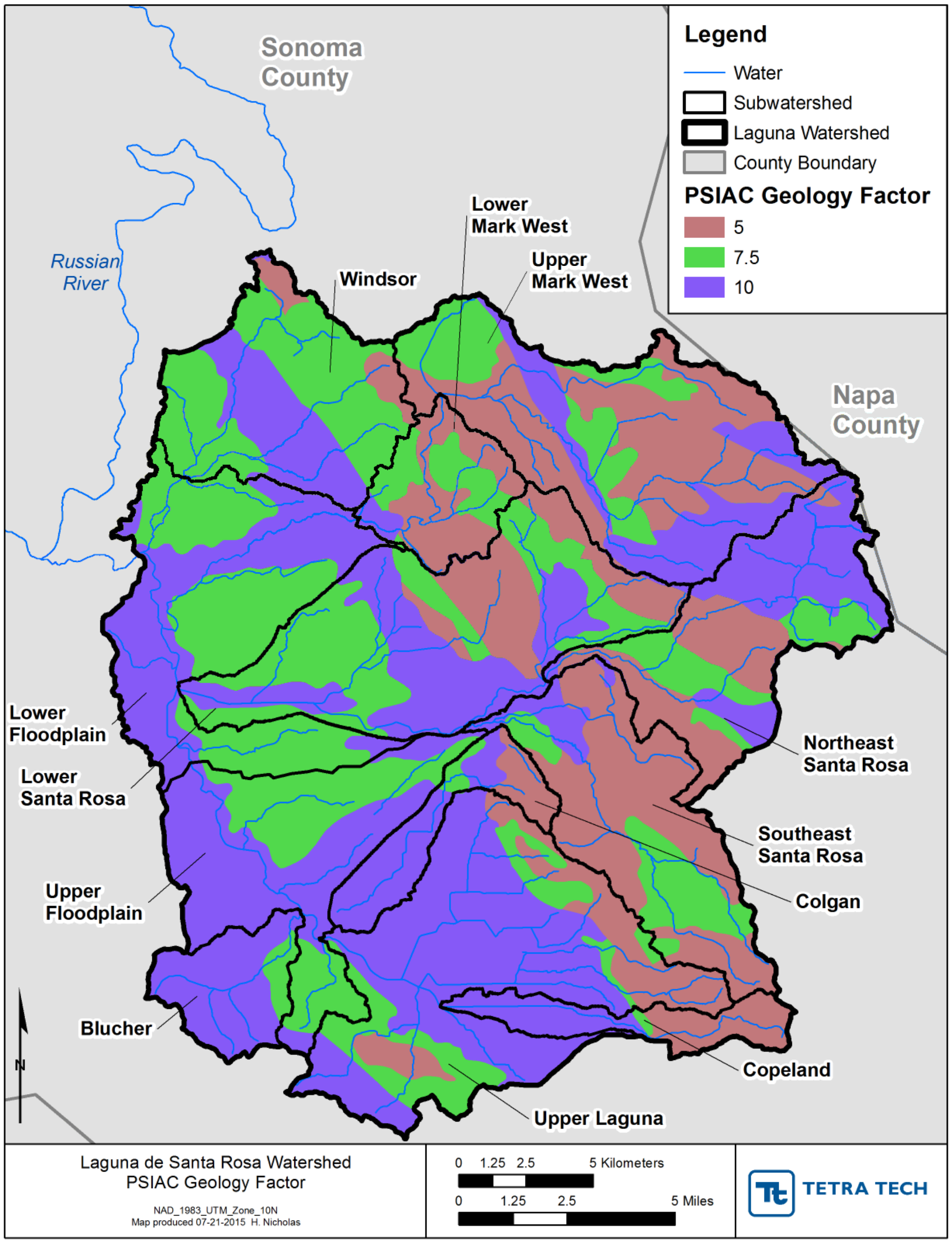

Figure A-1. PSIAC Surface Geology Factor for the Laguna de Santa Rosa Watershed

A.2 Soils Factor (Y_2)

The PSIAC Soils Factor is related by Johnson and Gebhardt to the USLE soil erodibility factor, also known as KFFACT (X_2):

$$Y_2 = (16.67)X_2$$

The soil erodibility factor (X_2) ranges from 0 to below 1, with larger values reflecting a higher susceptibility to erosion. KFFACT is available from the Soil Survey Geographic Database (SSURGO) and the resulting PSIAC Soils Factor can be seen in Figure A-2.

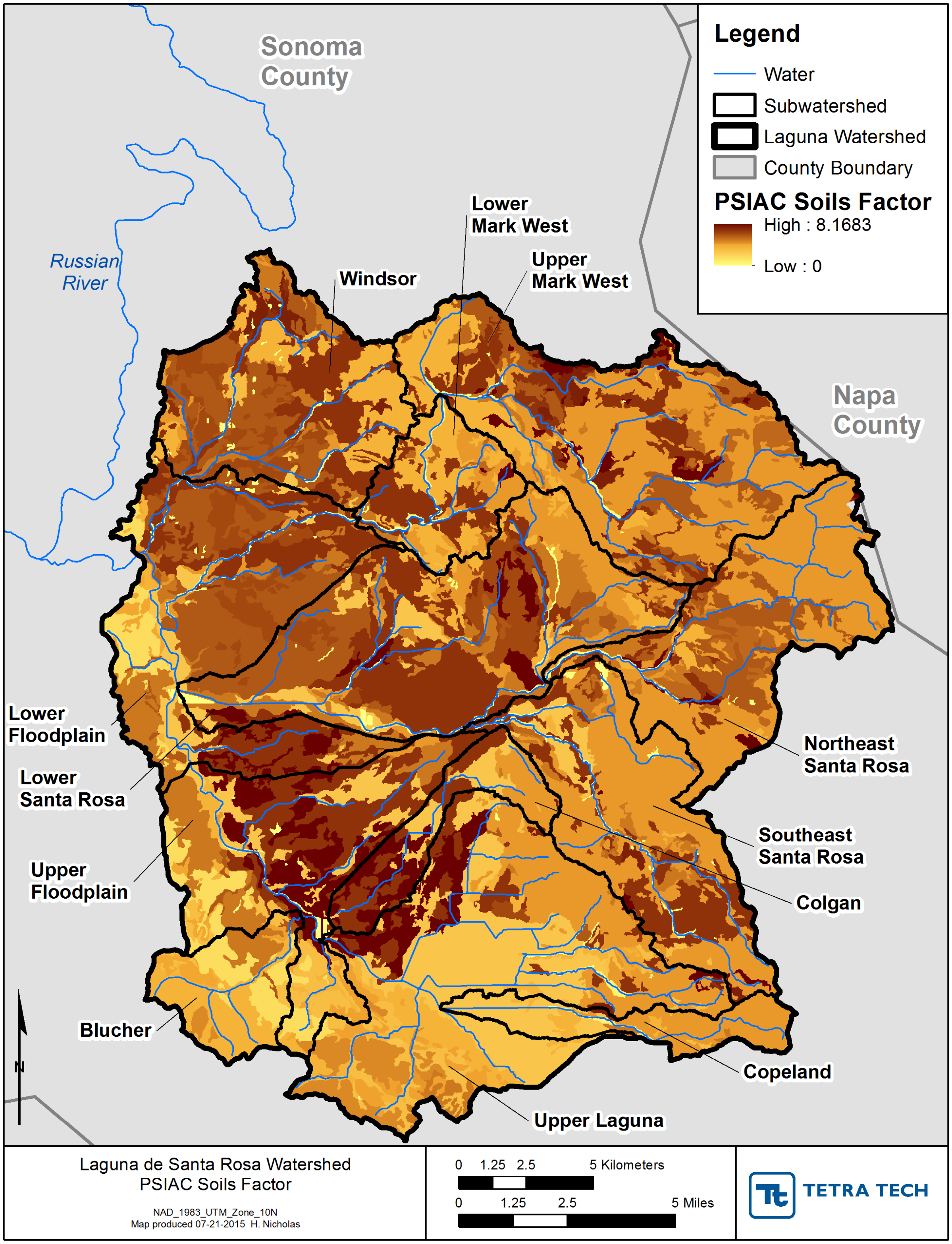

Figure A-2. PSIAC Soils Factor for the Laguna de Santa Rosa Watershed based on KFFACT (SSURGO)

A.3 Climate Factor (Y_3)

The Climate Factor is estimated by Johnson and Gebhardt from the 2-year recurrence 6-hour duration precipitation depth in mm (X_3) which represents rainfall intensity-duration-area-frequency regimes across the watershed:

$$Y_3 = (0.02)X_3$$

For this study, gridded X_3 values are obtained from the 2-year 6-hour precipitation grid on the National Oceanic and Atmospheric Administration (NOAA) precipitation frequency data server (http://hdsc.hws.noaa.gov/hdsc/pfds/index.html; Perica et al., 2011, rev. 2014). The calculated Climate Factor based on the 2-year 6-hour precipitation grid is shown in Figure A-3.

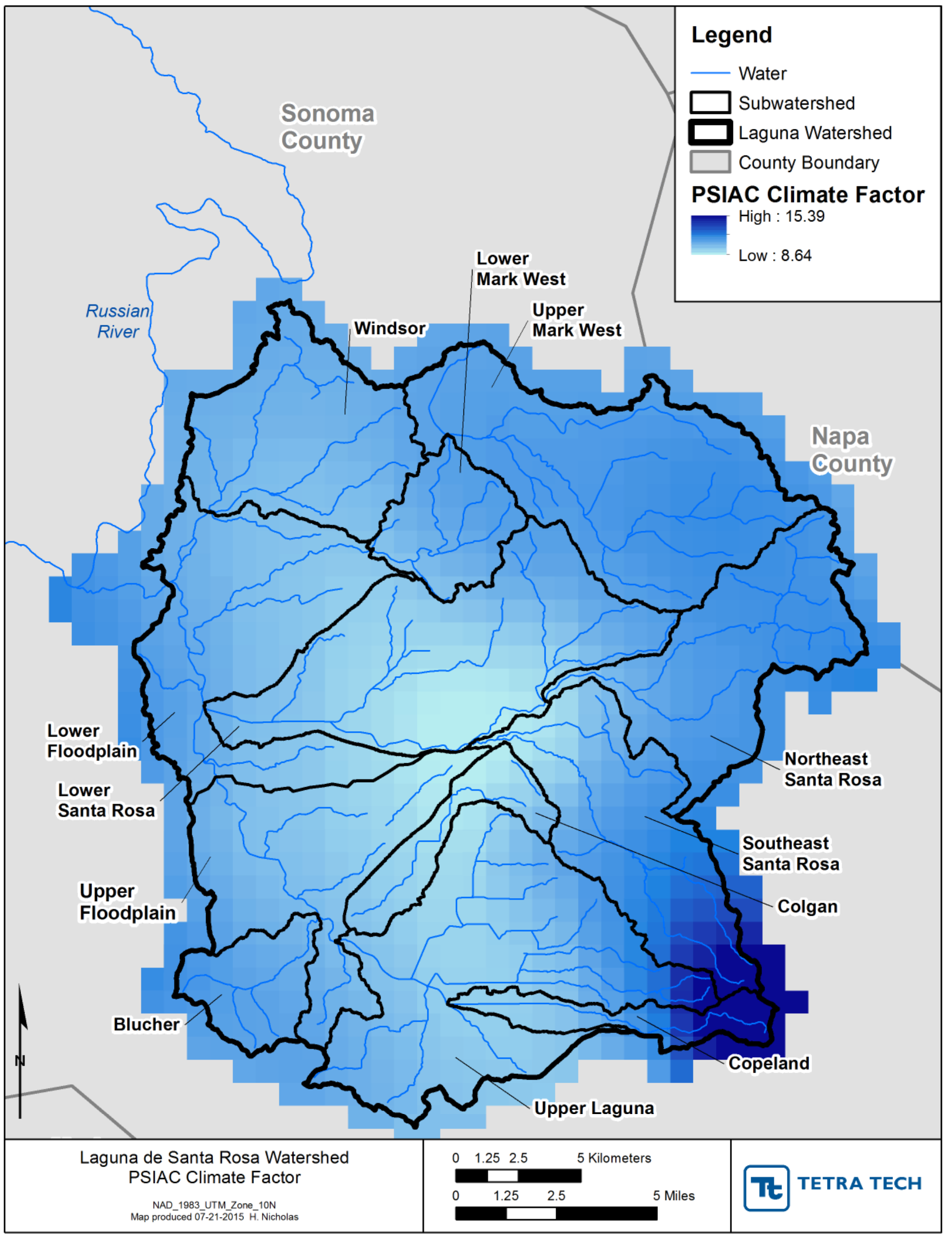

Figure A-3. PSIAC Climate Factor for the Laguna de Santa Rosa Watershed

A.4 Runoff Factor (Y_4)

The PSIAC Runoff Factor is a subbasin-scale parameter based on peak flows and runoff volume, as well as land use:

$$Y_4 = (0.2)X_4$$

In the method of Johnson and Gebhardt, the X_4 parameter is a function of both annual runoff volume in millimeters (V) and annual peak streamflow in cubic meters per second per square kilometer (P):

$$X_4 = (0.03)V + (50)P$$

Annual runoff volume (V) is calculated as a function of measured discharge recorded at five USGS gage stations in the Laguna de Santa Rosa watershed for the period of record (Table A-3). Because this is an approximate calculation based on a limited period of record, results are not discretized beyond the subbasin level.

The average area-weighted discharge for all of the USGS gages of 0.99 cfs/mi^2 is converted to the runoff depth estimate of 343.03 mm for a given year. The ratio of runoff depth to average annual precipitation for the watershed (937.01 mm) is 0.366. Runoff volume (in mm) for each subwatershed is estimated as the runoff ratio multiplied by the average precipitation for the subwatershed.

Annual peak streamflow (P, cfs) is estimated for each subwatershed using the regional regression equations for 2 through 100-year recurrence events presented in Gotvald et al. (2012) that estimate n-year recurrence flows as a function of drainage area in square miles (A), and average annual precipitation (PPT, inches) from the 30-year normal Precipitation-elevation Regressions on Independent Slopes Model (PRISM) dataset that interpolates rainfall based on topography (PRISM Climate Group, Oregon State University, http://prism.oregonstate.edu; accessed 2/5/2013). For example, the two-year recurrence event is estimated as:

$$P = (1.82)A^{0.904} * PPT^{0.983}$$

PSIAC requires the annual (one-year) event. The Gotvald equations are approximately log-linear versus recurrence interval (Figure A-4) and are extrapolated to the one-year event to obtain the 1-year to 2-year ratio which can be applied to the two-year estimate to obtain the annual peak streamflow required for the PSIAC Runoff Factor.

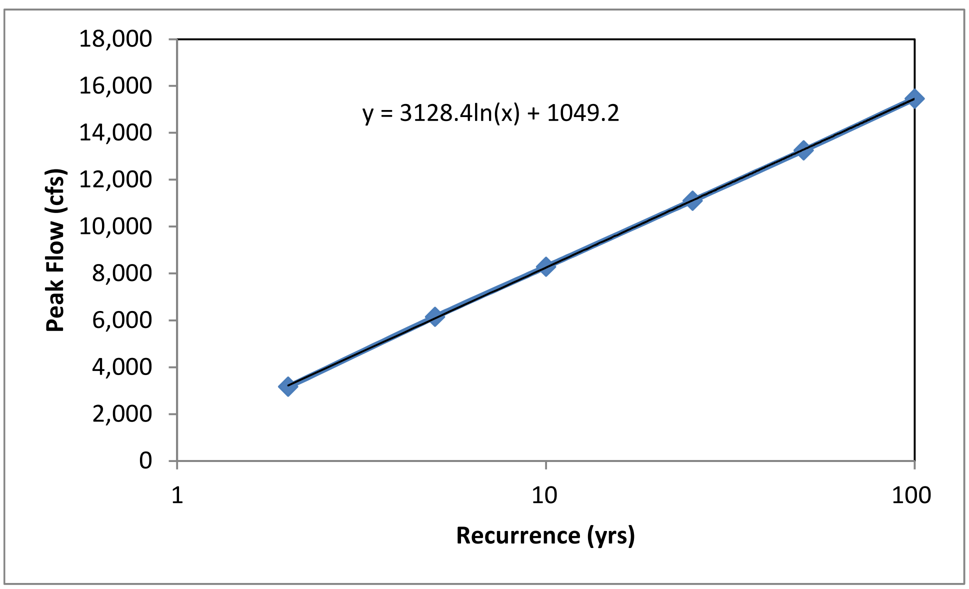

Figure A-4. Example Relationship of Peak Flow to Recurrence Interval, Lower Santa Rosa Basin

Table A-3. Average Annual Discharge for USGS Stream Gages in Laguna de Santa Rosa Watershed

Average Annual Discharge (cfs)					
Year	**11465680 Laguna de Santa Rosa at Stony Point Rd**	**11465700 Colgan Cr nr Sebastopol**	**11465750 Laguna de Santa Rosa nr Sebastopol**	**11466200 Santa Rosa Cr at Santa Rosa**	**11466320 Santa Rosa Cr at Willowside Rd**
Drainage Area (mi²)	**40.80**	**6.78**	**79.60**	**57.00**	**77.60**
1999	30.54	7.24	83.95	No Data	91.31
2000	33.24	8.35	84.55	No Data	81.11
2001	36.99	12.62	77.06	Incomplete	106.75
2002	37.14	11.02	78.93	73.32	123.08
2003	22.99	5.63	89.26	58.87	87.09
2004	31.05	9.34	72.41	40.92	94.12
2005	58.88	15.61	126.63	45.89	137.74
2006	50.16	10.52	109.49	103.65	137.40
2007	13.95	2.47	36.92	26.20	43.03
2008	25.58	5.02	95.10	43.17	65.53
2009	15.10	3.97	16.02	28.07	48.19
2010	45.11	11.95	101.32	83.21	121.13
2011	33.44	6.06	73.81	61.40	91.13
2012	21.30	8.59	81.76	65.44	107.30
2013	5.40	1.31	11.81	6.03	11.72
Average Annual Discharge (cfs)	30.73	7.98	75.93	64.55	89.78
Area-Weighted Average Discharge (cfs/mi²)	0.75	1.18	0.95	0.93	1.16
Average Area-Weighted Annual Discharge (cfs/mi²)	0.99				

The Gotvald equations were created for undeveloped lands, so in our analyses the annual peak streamflow estimate is scaled using the Rational Method to account for the influence of impervious surfaces on the peak. Runoff Factors for urban lands are assigned based on percent imperviousness, while Runoff

Factors for rural lands are calculated as unity minus the sum of factors for land use, soil, and slope. Area-weighted rational method runoff coefficients (Novotny and Olem, 1994) were first calculated based on all existing land uses to yield parameter *C*, and then re-calculated under the assumption that developed land uses consisted entirely of pervious lawns to create parameter $C*$. The Gotvald estimate of peak flow for undeveloped land is adjusted by multiplying by the ratio C/C* to account for the effect impervious surface on peak streamflow. The key difference between C and C* calculations are that for C*, all runoff coefficients for rural areas remain the same, and all runoff coefficients for urban areas are set to 0.2.

An example calculation of the Runoff Factor (Y_4) is shown below for the Blucher subbasin:

1. Spatially averaged precipitation: 42.91 inches = 1089.84 mm
2. Total drainage area: 7.68 square miles = 19.89 square kilometers
3. Runoff Volume:

$$V[mm] = \left(\frac{V_{norm}}{PPT_{avg}}\right) * (PPT)$$

$$V[mm] = \left(\frac{343.03\ mm}{937.02\ mm}\right) * (1089.84\ mm) = 398.97\ mm$$

4. Runoff Coefficients (C and C*):

   Slope Raster, Land Use Raster, and Soils Raster were reclassified by the bins identified in Table A-4. The three rasters were added together and subtracted from 1, and the various possible combinations of slope/land use/soil were assigned C values (Table A-4).

   The runoff coefficient, spatially-averaged for the entire subwatershed is the C parameter, which for Blucher is 0.42. The C* parameter is the spatially-averaged runoff coefficient with urban area runoff coefficients set to 0.2, which is appropriate for urban lawns on tight soils with average slopes (10.9% of the Blucher subwatershed), therefore the C* parameter is 0.41.

5. 2-year Peak Streamflow:

$$P[cfs] = (1.82)A^{0.904} * PPT^{0.983}$$

$$P[cfs] = (1.82)(7.68\ mi^2)^{0.904} * (42.91\ in)^{0.983} = 462.70\ cfs$$

$$P\left[\frac{cms}{km^2}\right] = 462.70\ cfs * \frac{1\ m^3}{35.315\ ft^3} * \frac{1}{19.89\ km^2} = 0.659\ cms/km^2$$

6. Annual Peak Streamflow (adjusted for 1-year recurrence and for imperviousness):

$$P_{adj} = 0.659\frac{cms}{km^2} * (0.313) * \left(\frac{0.42}{0.41}\right) = 0.218\frac{cms}{km^2}$$

7. Final Equation:

$$Y_4 = (0.2)[(0.03)V + (50)P]$$

$$Y_4 = (0.2)\left[(0.03)(398.97\ mm) + (50)\left(0.218\frac{cms}{km^2}\right)\right] = 4.58$$

The Runoff Factor for each subwatershed was estimated using total upstream drainage areas, except for the Lower Floodplain which used C, C*, precipitation, and drainage areas associated only with the floodplain area to represent minor direct tributaries to the Laguna. The resulting estimates are shown in Figure A-5 and vary across a small range due mostly to differences in precipitation and impervious cover.

Table A-4. Example Calculation of Runoff Coefficients for Blucher Subbasin

Raster Value	Land Use/Land Cover Note	Runoff Coefficient Subfactor			Total Runoff Coefficient	Area in Blucher Subbasin (m^2)
		Land Use	Soil	Slope		
1101	Cropland	0.1	0.1	0.3	0.5	0
1102		0.1	0.1	0.2	0.6	0
1103		0.1	0.1	0.1	0.7	0
1201		0.1	0.2	0.3	0.4	208,800
1202		0.1	0.2	0.2	0.5	338,400
1203		0.1	0.2	0.1	0.6	4,886,100
1301		0.1	0.4	0.3	0.2	555,300
1302		0.1	0.4	0.2	0.3	2,295,900
1303		0.1	0.4	0.1	0.4	5,032,800
2101	Forest	0.2	0.1	0.3	0.4	0
2102		0.2	0.1	0.2	0.5	0
2103		0.2	0.1	0.1	0.6	0
2201		0.2	0.2	0.3	0.3	27,900
2202		0.2	0.2	0.2	0.4	61,200
2203		0.2	0.2	0.1	0.5	2,307,600
2301		0.2	0.4	0.3	0.1	72,000
2302		0.2	0.4	0.2	0.2	387,900
2303		0.2	0.4	0.1	0.3	1,427,400
3000-3999	Water/Wetland	0.0	n/a	n/a	0.0	180,000
4000-4999	High Dev.	0.83	n/a	n/a	0.785	3,600
5000-5999	Low Dev.	0.33	n/a	n/a	0.4275	433,800
6000-6999	Open Dev.	0.17	n/a	n/a	0.265	1,686,600
7000-7999	Medium Dev.	0.60	n/a	n/a	0.6225	55,800

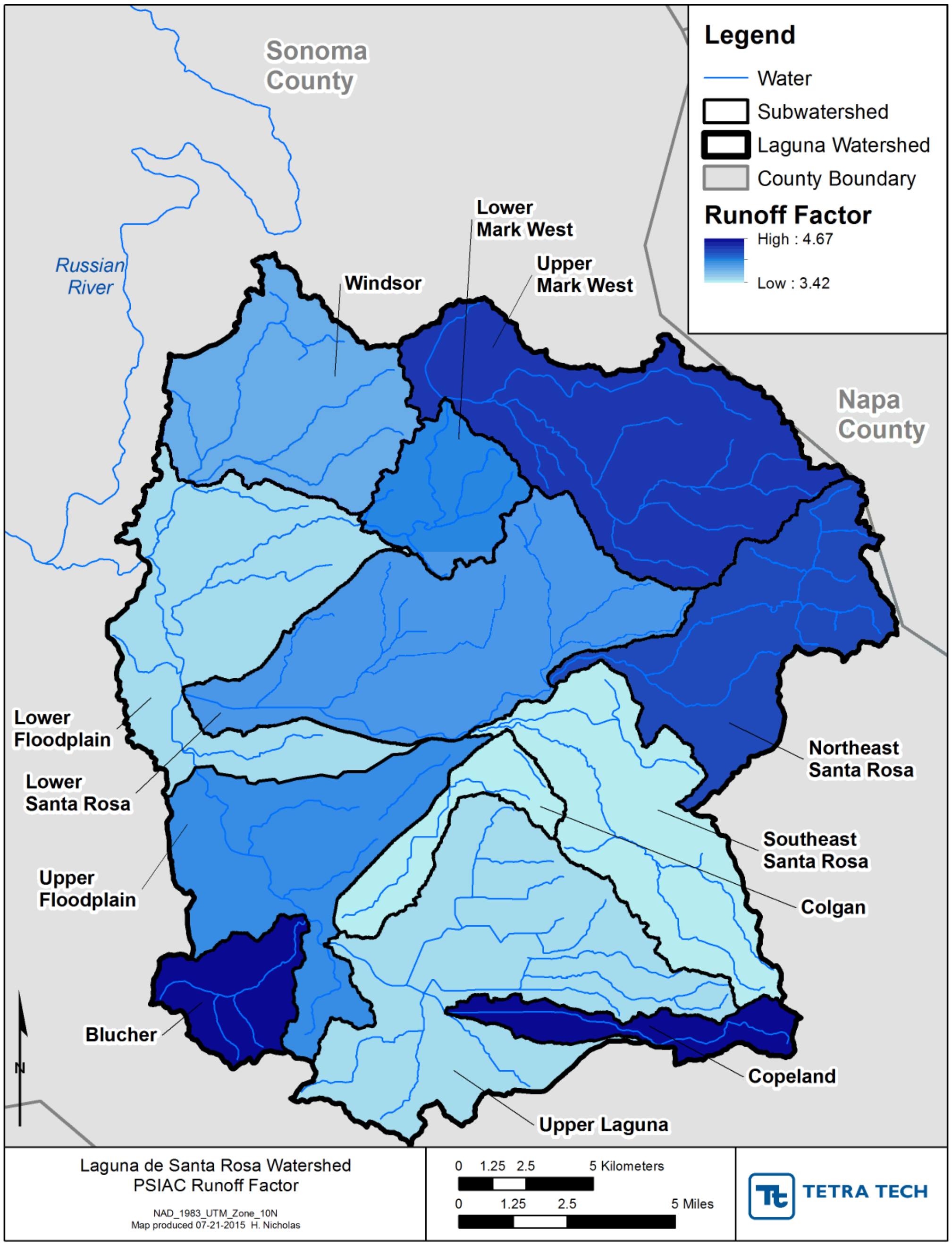

Figure A-5. PSIAC Runoff Factor for the Laguna de Santa Rosa Watershed

A.5 Topography Factor (Y_5)

The Topography Factor is based on slope in percent (X_5), which is calculated from 1-meter resolution LiDAR data from the Sonoma County Vegetation Mapping and LiDAR Program flown in 2013. In the Johnson and Gebhardt (1982 method), Y_5 is calculated as:

$$Y_5 = (0.33)X_5$$

This can occasionally result in very large numbers on the steepest slopes, which typically have little erodible soil. In our application, the Topography Factor was capped at a maximum of 20 to be consistent with the original PSIAC method. Results are shown in Figure A-6.

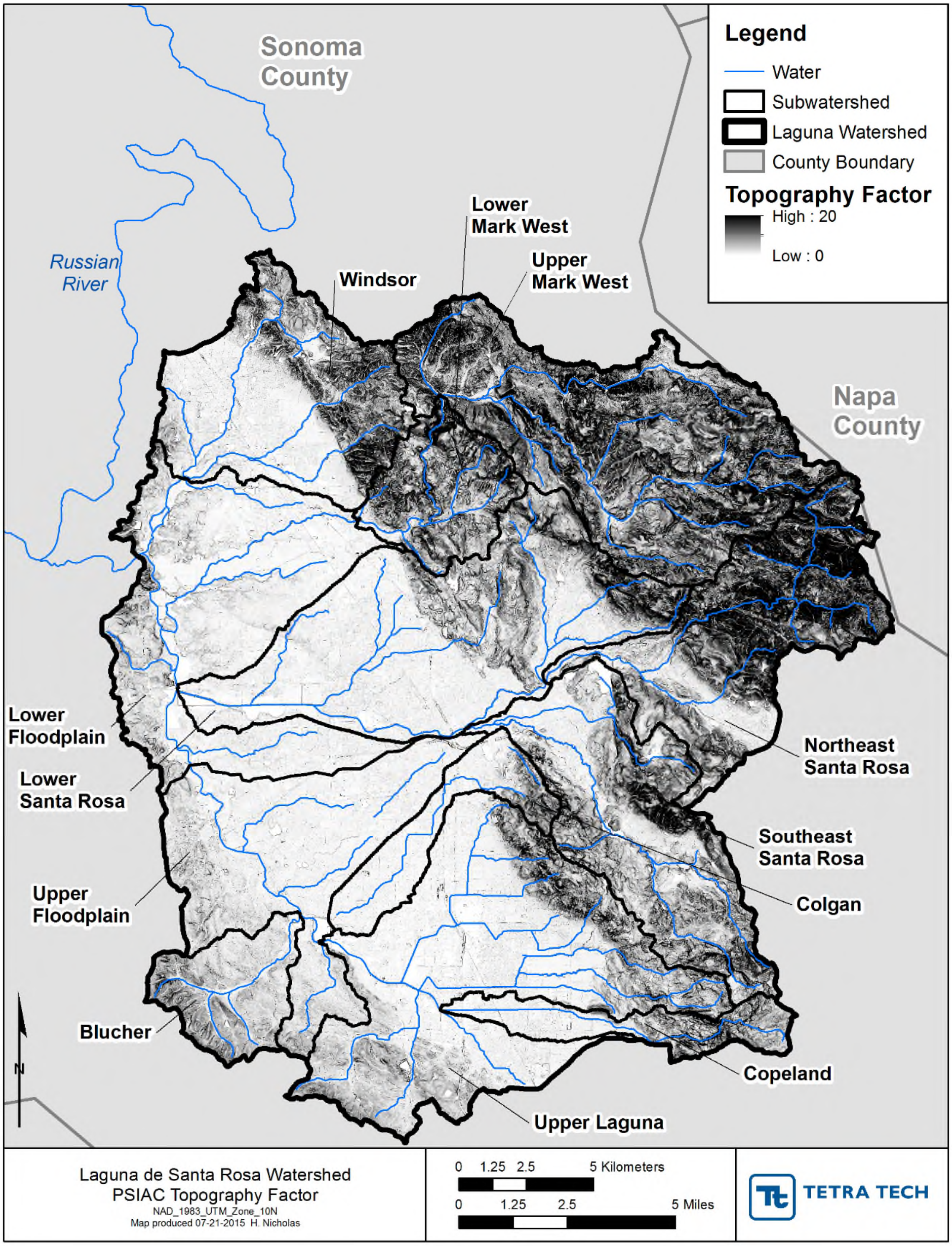

Figure A-6. PSIAC Topography Factor for the Laguna de Santa Rosa Watershed

A.6 GROUND COVER FACTOR (Y_6)

The Ground Cover Factor in the original PSIAC method represented the extent of ground cover through a factor that ranged from -10 to 10. Johnson and Gebhardt (1982) redefined this on a 0 – 20 range as a function of percent bare ground (X_6):

$$Y_6 = (0.2)X_6$$

The final interpreted bare earth percentage LiDAR from the Sonoma County Vegetation Mapping and LiDAR Program is not yet available, therefore a series of GIS processes were used to estimate this percentage from available raw 1-m LiDAR data. Because of the fine (1-m) scale of the analysis, each individual pixel was defined as either bare ground or not bare ground.

The process began by removing building footprints and cells for which tree canopy is identified as present. We then analyzed LiDAR return signatures for the remaining areas, in which low-range values <100 represent high reflectivity associated with roads and buildings and high-range values >200 represent low reflectivity associated with grass and vegetation. Return values of approximately 145-200 appear to best represent bare ground based on examination of orthophotography from the day of the LiDAR acquisition. Finally, the resulting 1-m raster of bare ground was used to tabulate the Ground Cover Factor across the watershed (Figure A-7).

A.7 LAND USE FACTOR (Y_7)

The PSIAC Land Use Factor is based on the fraction of area cultivated, logged, burned, or intensively grazed. Johnson and Gebhardt (1982) redefined the Land Use Factor on a 0 – 20 range and estimated it from percent canopy cover (X_7). The percent canopy cover is based on 1-meter resolution LiDAR data for the watershed flown in 2013. The calculation for the Land Use Factor is:

$$Y_7 = 20 - (0.2)X_7.$$

The Land Use Factor grid based on the fraction of canopy cover is shown in Figure A-8.

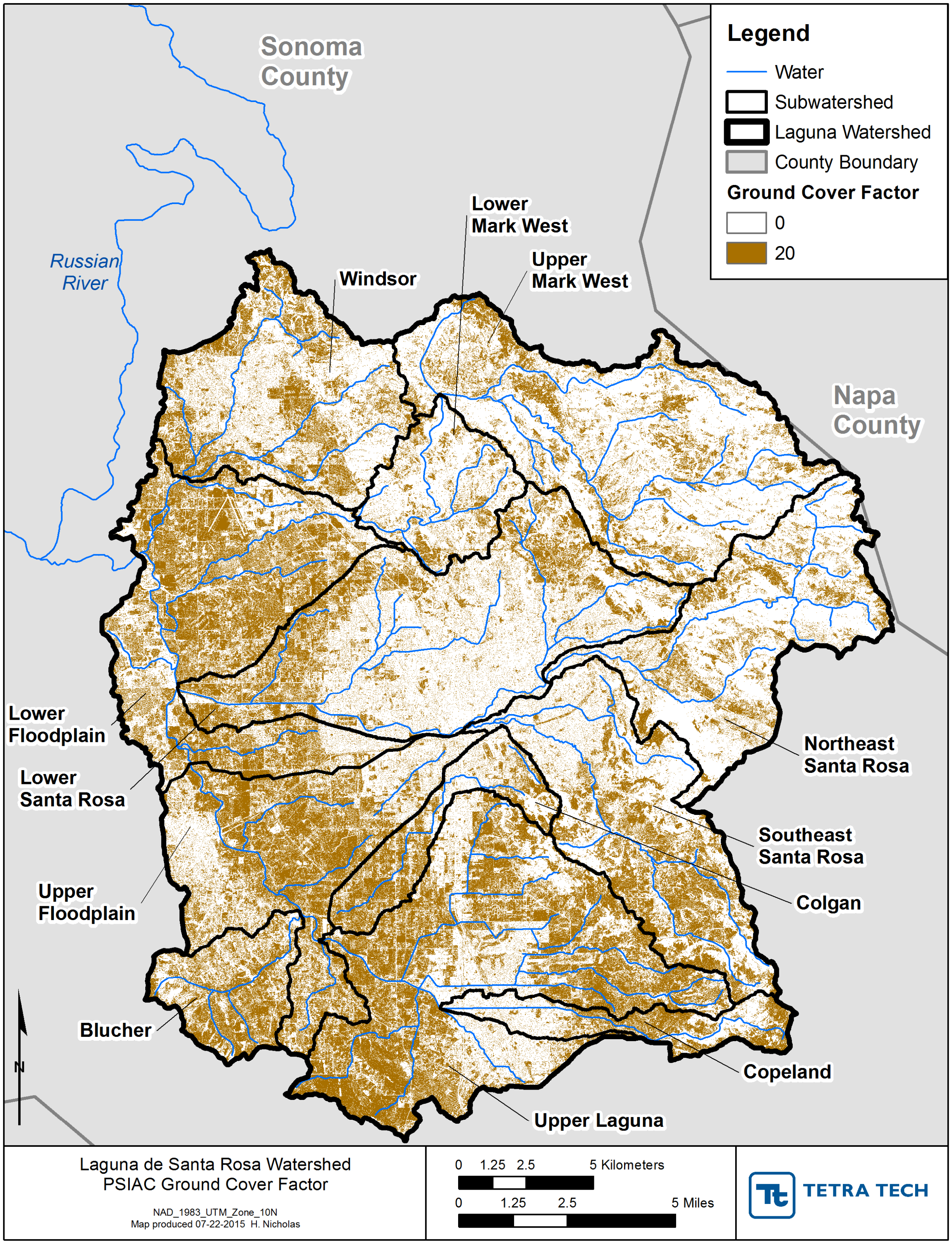

Figure A-7. PSIAC Ground Cover Factor for the Laguna de Santa Rosa Watershed

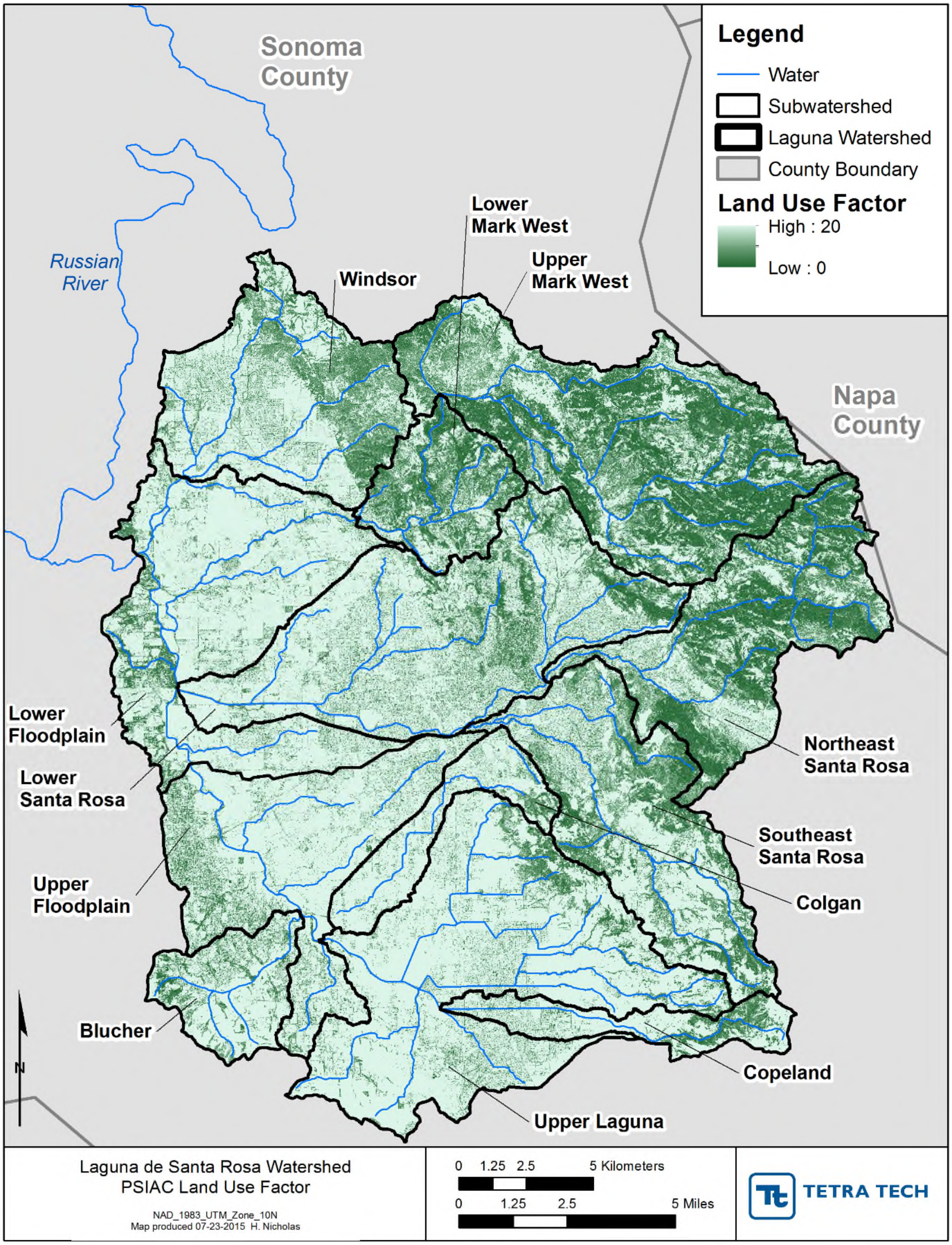

Figure A-8. PSIAC Land Use Factor for the Laguna de Santa Rosa Watershed

A.8 Upland Erosion Factor (Y_8)

Johnson and Gebhardt (1982) provide a relationship between the Upland Erosion Factor and the BLM soil surface factor, or SSF (Clark, 1980). However, the SSF is based on examination of fine-scale soil surface characteristics, such as the presence of pedestalling. Therefore, we retain the original PSIAC estimates for this factor, which are based on percent of the area characterized by the extent of evident rill, gully, and landslide erosion. Assignments from PWA (2004a) are applied by subwatershed as the average value reported, with the exception of Lower Santa Rosa which was assigned a lower Upland Erosion Factor of 4 due to its high percentage of urban area (Figure A-9).

A.9 Channel Erosion/Sediment Transport Factor (Y_9)

For rangelands, Johnson and Gebhardt (1982) relate this factor to the BLM SSF gully rating (Clark, 1980); however, the original PSIAC methodology is based on the extent of eroding banks in stream channels. PWA (2004a) provided a detailed analysis of stream channel condition and their ratings are largely retained for this factor. Stream conditions described in the Sonoma County Water Agency Stream Maintenance Program Manual (SCWA, 2009) were checked for consistency with the PWA descriptions of channel erosion. Assignments from PWA (2004a) are applied by their subwatersheds as the average value reported (Figure A-10). Main deviations from the PWA assignments are decreasing the Channel Erosion Factor for Lower Santa Rosa, Upper Laguna, and Copeland subbasins to 5 in order to capture the mix of erosive channels in the headwaters and backwater depositional areas on the Santa Rosa plain (see Laurel Marcus and Associates, 2004, for a detailed discussion of Copeland). Also, the Upper and Lower Floodplains were assigned a factor of 0 to represent their predominantly depositional character.

A.10 Results

Results of the revised PSIAC analysis are included in Appendix C (refer to Figure C-1 and Table C-3).

A.11 Additional References

(See also Section 10 in main report)

Clark, R. 1980. Erosion Condition Classification System. Technical Note 346. U.S. Department of the Interior- Bureau of Land Management.

Gotvald, A.J., N.A. Barth, A.G. Veilleux, and C. Parrett. 2012. Methods for Determining Magnitude and Frequency of Floods in California Based on Data through Water Year 2006. Scientific Investigations Report 2012-5113. U.S. Geological Survey, Reston, VA.

Johnson, C.W., and K. A. Gebhardt. 1982. Predicting sediment yields from sagebrush rangelands. Pages 145-156 *in* Proceedings of the Workshop on Estimating Erosion and Sediment Yield on Rangelands, Tucson, Arizona: March 7-9, 1981. Agricultural Reviews and Manuals ARM-W-26. U.S. Dept. of Agriculture, Agricultural Research Service.

Novotny, V. and H. Olem. 1994. Water Quality; Prevention, Identification, and Management of Diffuse Pollution. Van Nostrand Reinhold, New York.

Perica, S., S. Deitz, S. Heim, et al. 2011 (rev. 2014). NOAA Atlas 14, Precipitation-Frequency Atlas of the United States, Volume 6 Version 2.3: California. National Oceanic and Atmospheric Administration, Silver Spring, MD.

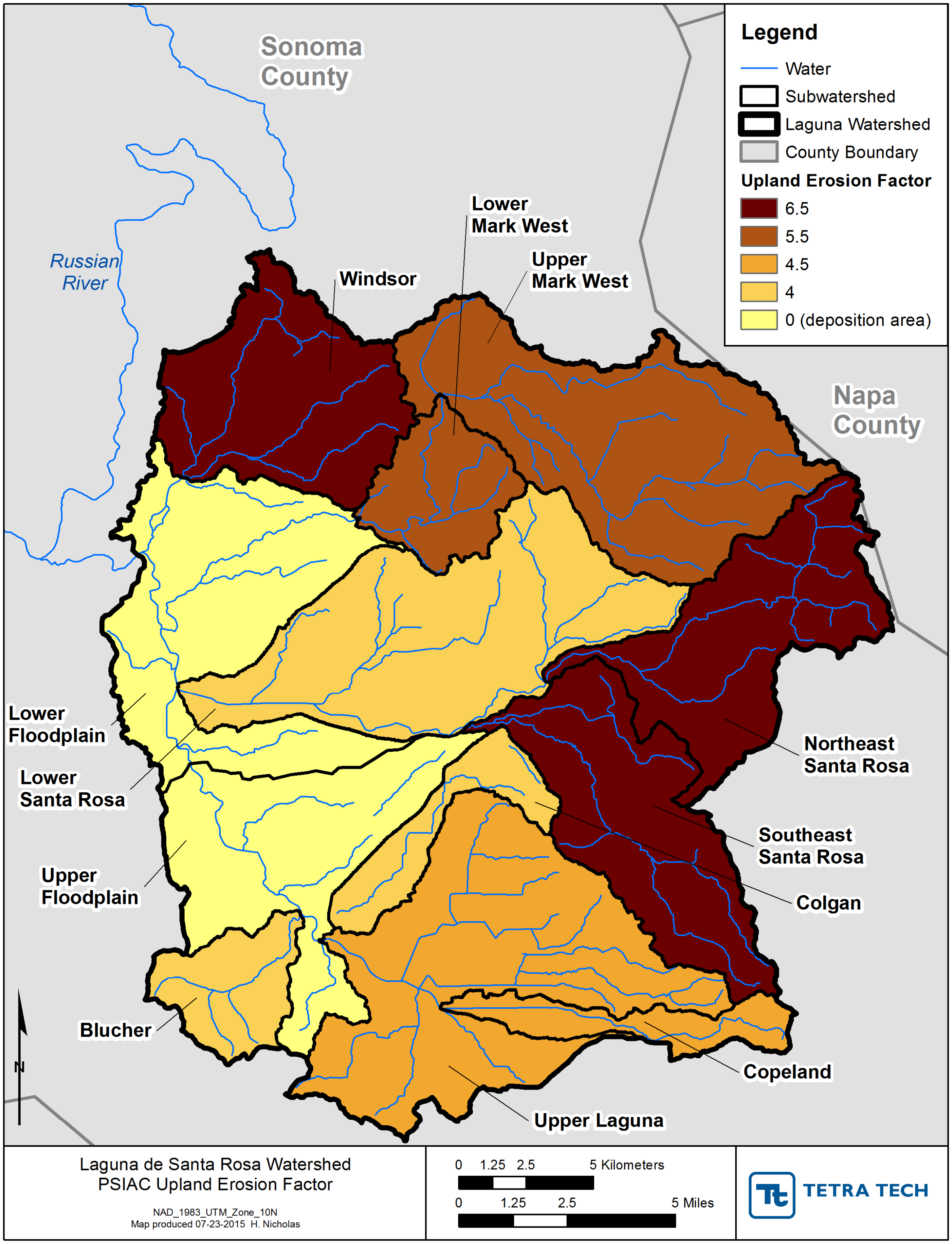

Figure A-9. PSIAC Upland Erosion Factor (PWA, 2004a) for the Laguna de Santa Rosa Watershed

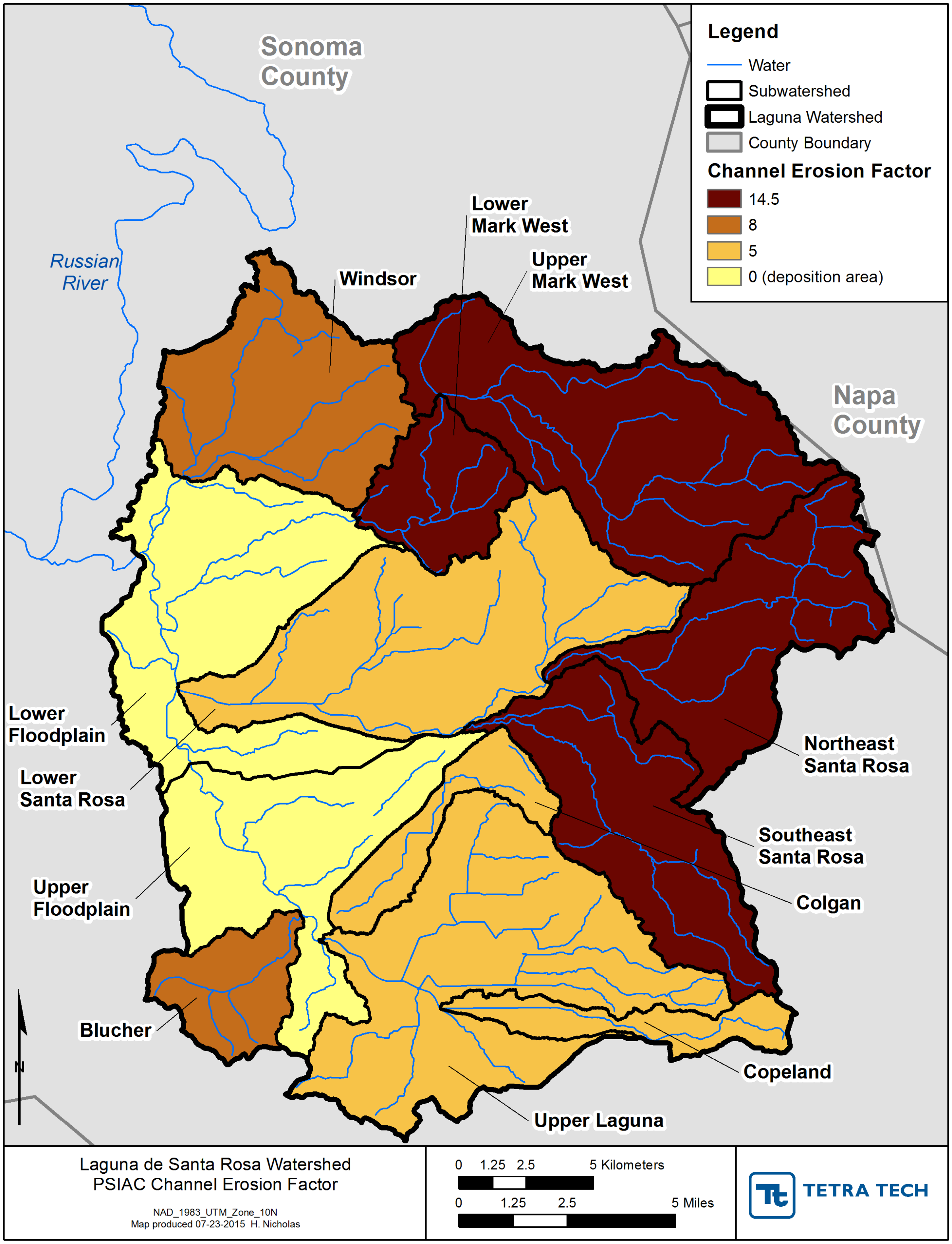

Figure A-10. PSIAC Channel Erosion Factor (PWA, 2004a) for the Laguna de Santa Rosa Watershed

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Appendix B Application of RUSLE Method for Estimating Upland Sediment Loss

The second analytical method used for developing the Laguna de Santa Rosa Sediment Budget (main report) employs the Revised Universal Soil Loss Equation (RUSLE; Renard et al., 1997) within a GIS to estimate sediment yield. The approach uses spatially explicit (grid-based) parameter inputs building on equations and recommendations found in the RUSLE user's guide to estimate upland soil loss. Most of this soil is re-deposited near the source and only slowly reaches flowing streams. Converting field-scale soil loss to sediment delivery at the subbasin scale has been a major obstacle to the use of RUSLE and similar methods in watershed sediment budget studies.

The RUSLE method estimates sheet and rill erosion caused by rainfall and its associated runoff through five multiplicative factors:

$$A = R * K * LS * C * P$$

where A is the average annual soil loss from sheet and rill erosion caused by rainfall and its associated overland flow (short tons/ac/yr). The input factors are summarized in Table B-1.

Table B-1. RUSLE Factors and Data Sources

Factor Variable	RUSLE Factor	Input Data Sources
R	Rainfall-Runoff Erosivity Factor	California Isoerodent Map (California Water Boards)
K	Soil Erodibility Factor	USDA SSURGO Database
LS	Slope Length and Steepness Factor	Sonoma County Vegetation Mapping and LiDAR Program
C	Cover-Management Factor	Sonoma Ecology Center (2006) and Sonoma County Agricultural Commissioner (2013)
P	Support Practice Factor	Set to 1 everywhere

A quasi-steady-state, grid-based approach is employed to estimate average annual soil loss with RUSLE. The remainder of this section contains detailed descriptions of how each factor is derived. It is important to note that RUSLE does not estimate sediment load from channel and gully enlargement or mass wasting processes. Therefore, delivered load estimates from RUSLE are anticipated to be less than those from PSIAC.

B.1 Rainfall-Runoff Erosivity Factor (R)

As was done in the Sonoma Creek RUSLE study, the California Water Boards' isoerodent map (ftp://swrcb2a.waterboards.ca.gov/pub/swrcb/dwq/cgp/Risk/RUSEL/RUSLE_R_Factor; see USEPA, 2012) was used to create the Rainfall-Runoff Erosivity Factor. The annual average isoerodent map of California is provided as polylines in GIS which were used for spatial interpolation to estimate a grid of R factors across the watershed (Figure B-1).

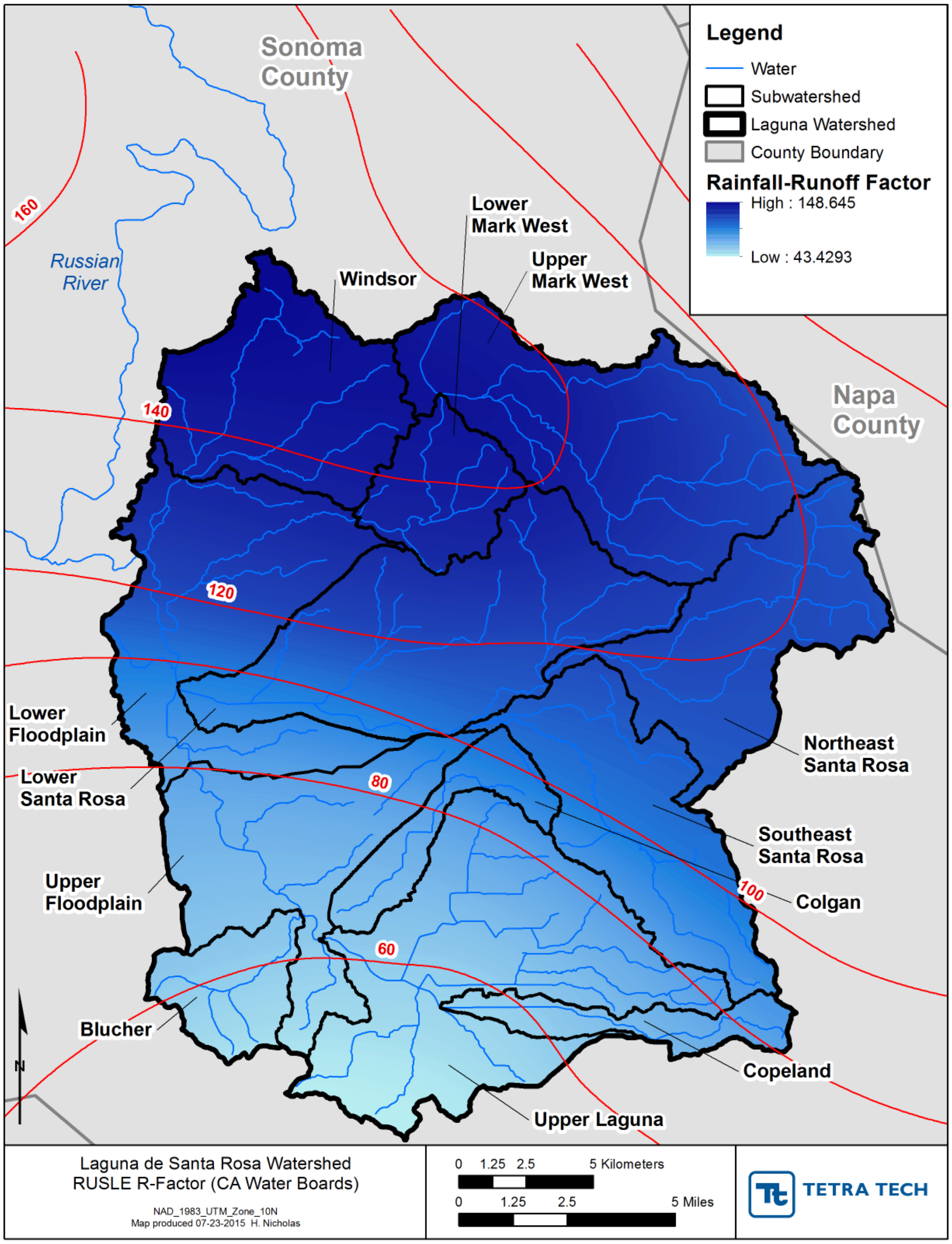

Figure B-1. RUSLE Rainfall-Runoff Erosivity Factor (R; hundreds of foot-tonf-inch/acre-hour-year)

B.2 Soil Erodibility Factor (K)

The Soil Erodibility Factor from SSURGO (KFFACT) as developed for the PSIAC Method (Appendix A) is the same as the K factor used for the RUSLE approach, which represents the susceptibility of soil to erode because of precipitation events. The distribution of K factors across the watershed is shown in Figure B-2.

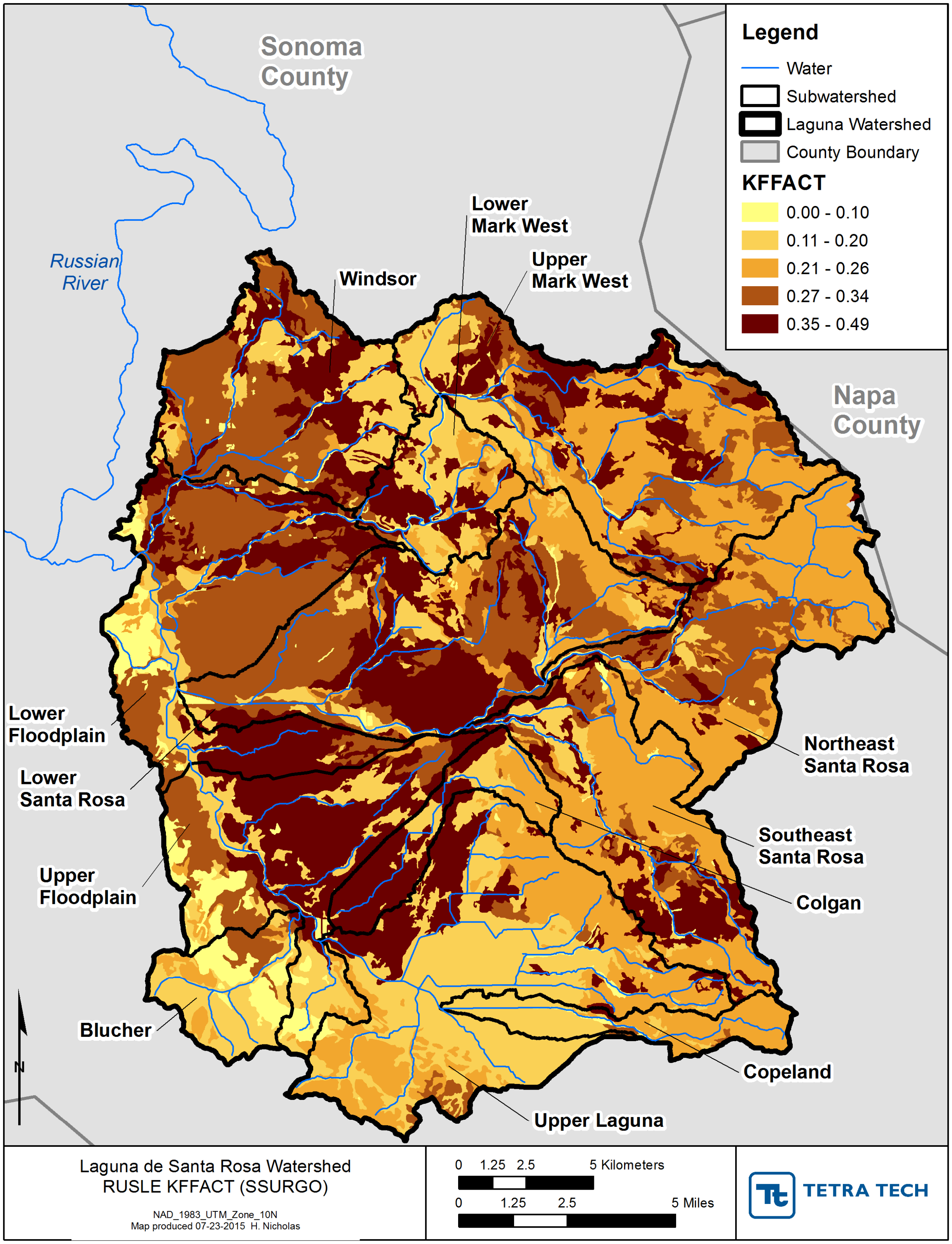

Figure B-2. RUSLE Soil Erodibility Factor (K; ton-acre-hour/hundreds of acre-foot-tonf-inch)

B.3 Slope Length and Steepness Factor (LS)

Slope Length and Steepness Factors are estimated using 1-meter resolution LiDAR. Mitasova et al. (1996) developed a GIS-based approach incorporating impacts of flow convergences by replacing hillslope length with upslope contributing area. Mitasova et al. acknowledge that direct application of USLE/RUSLE methods can be relatively restrictive in GIS but results can be considered an extreme case where the maximum spatial extent of soil erosion possible is estimated. The equation from Mitasova was refined by Fernandez et al. (2003) to calculate the slope factor (S) separately for high and low slopes to allow for variable types of erosion which occur on different slopes. The length factor (L) is calculated as:

$$L = (m + 1) * \left(\frac{A}{a_0}\right)^m$$

The value m is set to 0.6, as determined by Moore and Wilson (1992) to provide RUSLE results consistent with theoretical sediment transport equations for slope lengths less than 100 m and slope angles less than 14 degrees. The parameter a_0 is the standard USLE plot length (22.13 m), and A is the upslope contributing area in square-meters per unit width in meters. As refined by Fernandez et al. (2003), the slope factor can be calculated for slopes (b) above and below 5.14 degrees as follows:

$$S(b < 5.14°) = 10.8 * \sin(b) + 0.03$$

$$S(b \geq 5.14°) = 16.8 * \sin(b) - 0.5$$

To calculate the upslope contributing area (A) and slope (b), the following GIS analyses were completed:

1. “Mosaic” Tool was run on the 1-meter bare-earth LiDAR DEM to create a single raster, and project it to NAD 1983 UTM Zone 10N.
2. “Extract by Mask” Tool was run on the new raster to clip it to the Laguna watershed.
3. “Fill” Tool was run on the new raster to remove small imperfections or “pits” in the data.
4. “Slope” Tool was run on the pit-filled DEM to create the slope raster needed for the b-parameter. Note that slope is transformed from degrees to radians in order to run the sine function in Raster Calculator. These two are referred to as Slope_Raster_Degrees and Slope_Raster_Radians.
5. “Flow Direction” Tool was run on the pit-filled DEM.
6. “Flow Accumulation” Tool was run on the flow direction raster.
7. “Reclassify” Tool was run on the flow direction raster to group the directions by unit width (N, E, S, W directions were given a width of 0.914 meters; NW, NE, SE, SW directions were given a width of 1.293 meters). Note that “reclassify” requires integer inputs so 914 and 1293 were used as the width *1000.0 which was later corrected.
8. “Raster Calculator” was run to create the A-parameter as the flow accumulation raster divided by the reclassified flow direction raster.
9. “Raster Calculator” was run to create the L-Factor by applying the aforementioned equation (0.6+1)*((A_Raster / 22.13)^(0.6)). A maximum limit on slope length of 150 m was imposed based on Fernandez et al. (2003).
10. “Raster Calculator” was run to create the S-Factor using a high and low slope-conditional statement: Con(Slope_Raster_Degrees < 5.14, 10.8*sin(Slope_Raster_Radians)+0.03, 16.8*sin(Slope_Raster_Radians)-0.5). The S-Factor raster ranges from 0.3 to 16.23.

11. "Raster Calculator" was run to create the combined LS Factor by multiplying the L Factor by the S Factor. Calculated LS factors are limited to a maximum of 72.15 consistent with the RUSLE User's Manual.

The resulting LS Factor raster is displayed in Figure B-3.

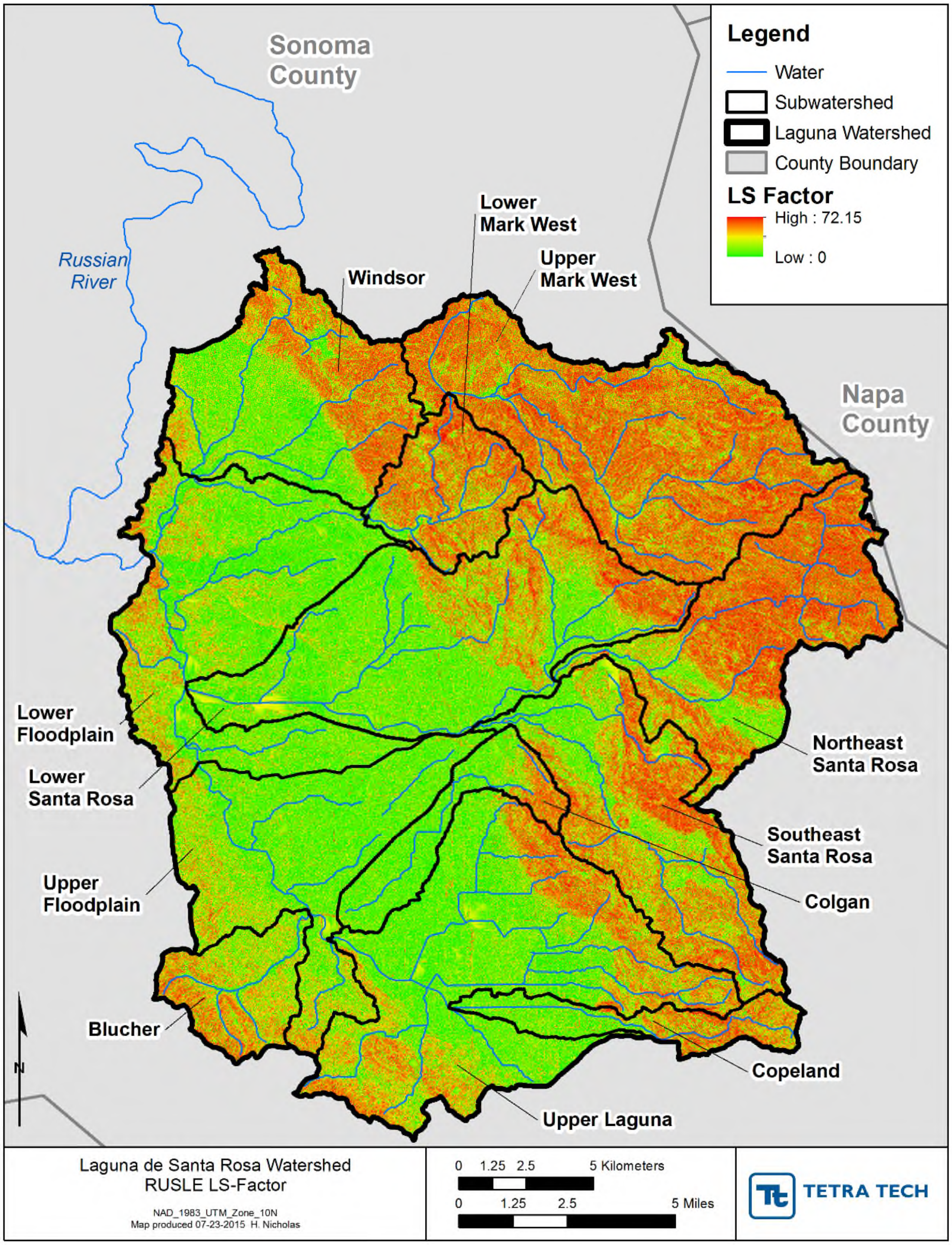

Figure B-3. RUSLE Slope Length and Steepness Factor (LS; unitless)

B.4 COVER - MANAGEMENT FACTOR (C)

The Cover-Management Factor (C) is generally used to represent the effect of agricultural cropping and management practices employed to reduce erosion, with lower values representing less cover and greater erosion potential. The mix of vegetative canopy, soil surface cover, soil surface roughness, and impacts of low soil moisture on the reduction of runoff from lower intensity rainfall events impact the C factor (Renard, et al., 1997). The C factor can be developed as a weighted average of the soil loss rate (SLR) over the year, with weighting by the erosivity index for each time period. However, because most of the watershed land cover does not rapidly change, it is suggested by Renard et al. that a single annual factor can be used, in which case C is simply equal to SLR. For the California climate erosive storm events occur primarily in the winter to early spring rainy season, when canopy development is low. Therefore, when a single C factor is used it should reflect winter-spring cover and leaf development conditions.

SLR can be determined as the product of five subfactors:

$$C = SLR = PLU * CC * SC * SR * SM$$

where the subfactors are: Prior Land Use subfactor (PLU), Canopy Cover subfactor (CC), Surface Cover subfactor (SC), Surface Roughness subfactor (SR), and Soil Moisture subfactor (SM).

The Regional Board investigated, but was not able to obtain detailed information on site-specific C factors or sub-factors for the Laguna watershed. Therefore, the central tendency of C factors for each land use are adjusted to match the annual average values presented in Table 3 of Appendix A (*Surface Erosion Study*) developed for RUSLE modeling in the Sonoma Creek watershed analysis (Sonoma Ecology Center, 2006)[1]. These values are modified on a cell-by-cell basis by incorporating LiDAR analysis of canopy cover.

Assuming that all subfactors other than CC are constant, the equation for SLR can be rewritten as:

$$SLR = \alpha * CC, \text{ with}$$

$$\alpha = PLU * SC * SR * SM = SLR / CC$$

The CC subfactor expresses the effectiveness of vegetative cover in reducing the energy of rain drops as they fall on the soil surface:

$$CC = 1 - F_c * \exp(-0.1 * H)$$

where F_c is the fraction of the land surface covered by vegetative canopy, and H is the distance in feet that a raindrop falls after striking the canopy. H is considered an average property of the land cover class.

As noted above, the expected value of SLR, written as E(SLR), is assumed to be that given by the Sonoma Creek study. We can write:

$$E(SLR) = \alpha * E(CC) = \alpha * [1 - E(F_c) * \exp(-0.1 * H)$$

where $E(F_c)$ is the expected value or average of canopy cover fraction for the land use class. For an individual grid cell with canopy cover F_i this equation is rewritten as:

$$SLR = \alpha * [1 - F_i * \exp(-0.1 * H)]$$

As α may be defined as E(SLR) / E(CC), we can estimate it as

$$\alpha = E(SLR) / [1 - E(F_c) * \exp(-0.1 * H)]$$

[1] Note that we use the average values in Table 3 rather than the site-specific C values estimated in the pilot study for Jack London State Historical Park and discussed in the text, which are somewhat larger.

The component factors that are combined with F_i to obtain the gridded SLR estimates are shown in Table B-2. The resulting spatial distribution of C factors is shown in Figure B-4. Canopy density was obtained from the LiDAR coverage, while vegetation height was based on weighted averages of height classes contained in the LANDFIRE vegetation coverage from the U.S. Forest Service (http://www.landfire.gov/). Results were tabulated by National Land Cover Database (NLCD) classifications rather than the Cropland Data Layer (CDL) classifications (discussed in Section 3 of the main report) to better distinguish between different developed land categories.

Table B-2. C Factor Components by NLCD Land Cover for the Laguna de Santa Rosa Watershed

NLCD Categories	Sonoma Watershed Land Use Categories	E(SLR)	Canopy Density E(Fc)	Vegetation Height H (ft)	Alpha Factor
Open Water	Water	0.00	0.06	0.00	0
Developed Open	Average of Residential and Grassland	0.083	0.27	21.19	0.0857
Developed Low	Residential	0.14	0.18	0.10	0.1694
Developed Medium	Urban Low	0.03	0.13	0.10	0.0345
Developed High	Urban High	0.00	0.07	0.10	0
Barren	NA	1.00	0.07	0.00	1.0699
Deciduous Forest	Forest	0.013	0.70	54.33	0.0130
Evergreen Forest	Forest	0.013	0.73	87.34	0.0130
Mixed Forest	Forest	0.013	0.58	39.53	0.0131
Shrub/Scrub	Chaparral	0.031	0.37	17.59	0.0331
Herbaceous	Chaparral	0.031	0.08	8.30	0.0322
Hay/Pasture	Average: Pasture and Oats	0.0945	0.03	1.51	0.0970
Cultivated Crops	Vineyard	0.365	0.06	5.18	0.3790
Woody Wetlands	Wetland	0.003	0.45	26.54	0.0031
Herbaceous Wetlands	Wetlands	0.003	0.13	5.77	0.0032

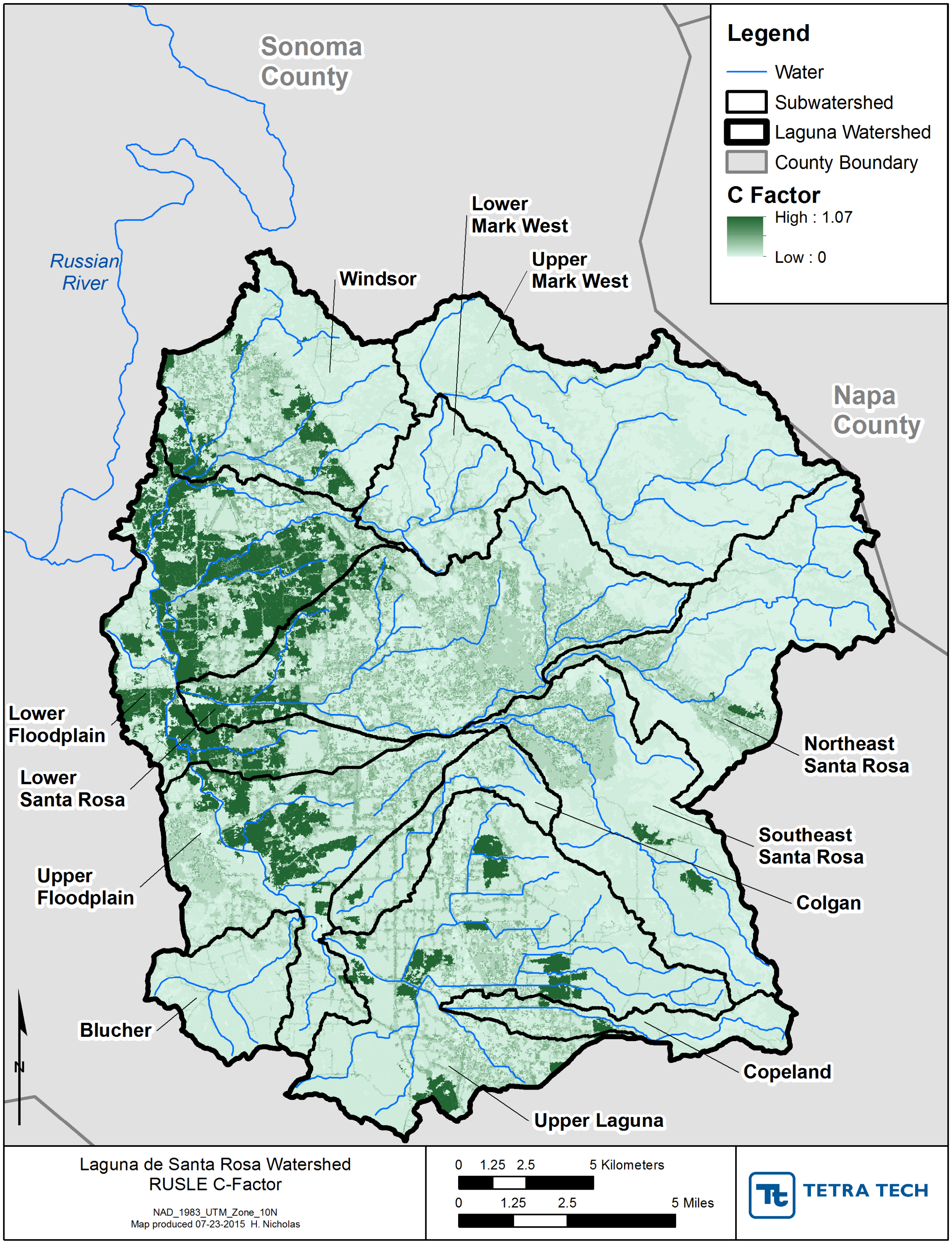

Figure B-4. RUSLE Cover-Management Factor (C; unitless)

B.5 SUPPORT PRACTICE FACTOR (P)

This factor reflects the impact of support practices associated with cropland (contouring, strip-cropping, row-farming, terracing, etc.). For non-agricultural land uses it is typically assumed that the land surface is not subject to such practices, thus a P factor of 1 is appropriate. For agricultural land uses (predominately vineyards in this watershed), Sonoma County has adopted codes and manuals to address drainage and erosion and a P factor less than 1 may be appropriate. The Sonoma County Agricultural Commissioner's report on Best Management Practices for Agricultural Erosion and Sediment Control (2013) provides P Factor estimates based on vineyard land slopes, drainage, and tillage processes which range from 0.05 to 1. Most tillage practices do not apply to long-lived grape vineyards, and in this watershed nearly all vineyards are located in the very low-sloped floodplain. Due to the low slopes and lack of much obvious terracing or contouring of rows from aerial imagery inspection, a P factor of 1 is applied to agricultural lands for this analysis. This may result in over-estimation of sediment yield from some agricultural lands. Similarly, the analysis does not address sediment trapping by stormwater detention or other practices on urban lands.

B.6 RESULTS

The predicted field-scale soil losses produced by the RUSLE method are shown in Figure B-5. Much of the soil eroded at the field-scale is re-deposited downslope and not actually delivered to water courses. Calculation of delivered sediment based on the Index of Connectivity (IC) approach is discussed in the main report (Section 5.2). Resulting RUSLE-based estimates of delivered sediment load are compared to PSIAC results in Appendix C.

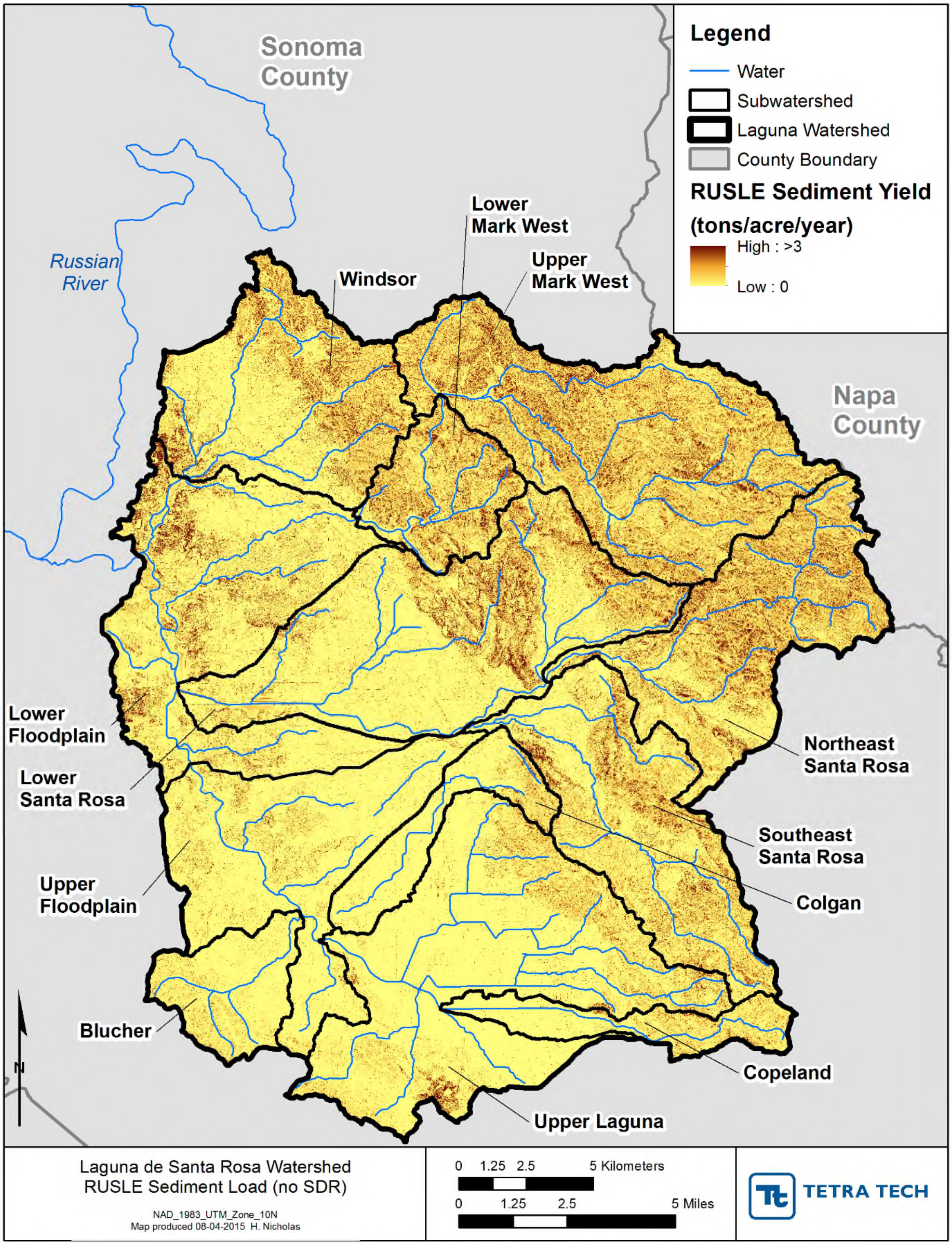

Figure B-5. Field-scale Soil Loss Predicted by RUSLE for the Laguna de Santa Rosa Watershed

B.7 ADDITIONAL REFERENCES

(see also Section 10 in main report)

Fernandez, C., J.Q. Wu, D.K. McCool, and C.O. Stockle. 2003. Estimating water erosion and sediment yield with GIS, RUSLE, and SEDD. *Journal of Soil and Water Conservation*, 58(3): 128-136.

Mitasova, H., J. Hofierka, M. Zlocha, and L.R. Iverson. 1996. Modeling topographic potential for erosion and deposition using GIS. *International Journal of Geographical Information Science*, 10(5): 629-641 (reply to a comment on this paper appears in 1997 in *Int. Journal of Geographical Information Science*, Vol. 11, No. 6). http://skagit.meas.ncsu.edu/~helena/gmslab/papers/erijgis.html.

Moore, I.D., and J.P. Wilson. 1992. Length-slope factors for the Revised Universal Soil Loss Equation: Simplified method of estimation. *J. Soil and Water Cons*., 47:423-428.

Sonoma County Agricultural Commissioner (SCAC). 2013. Best Management Practices for Agricultural Erosion and Sediment Control. Sonoma County Grading, Drainage, &Vineyard & Orchard Site Development Ordinance (VESCO).

USEPA (U.S. Environmental Protection Agency). 2012. Stormwater Phase II Final Rule, Construction Rainfall Erosivity Waiver. EPA 833-F-00-014, Fact Sheet 31. Office of Water, U.S. Environmental Protection Agency, Washington, DC.

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Appendix C Comparison of PSIAC and RUSLE Results

Annual sediment loads were estimated by the PSIAC method (Appendix A) and RUSLE method (Appendix B) using their respective additive and multiplicative rating factors. PSIAC provides estimates of sediment yield or delivered loads, while RUSLE predicts soil erosion at the field scale. As described in Section 5.2 of the main report, RUSLE soil loss was multiplied by the IC-based sediment delivery ratio (SDR) grid to estimate total sediment delivery to the Laguna de Santa Rosa. The resulting sediment yield estimates are presented in Table C-1. The RUSLE predictions of delivered loads are less than those from PSIAC, but do not include any contributions from gully erosion and channel incision. The relatively high loading rates estimated by RUSLE for the Lower Floodplain stand out. These are due to the inclusion in this unit of several minor tributaries outside the floodplain proper toward the Mark West Creek drainage that are characterized by vineyards with low cover (Figure B-4) and relatively high erosivity (Figure B-1). Sediment yield across the Laguna watershed is shown for both the PSIAC and RUSLE analyses in Figure C-1 and Figure C-2.

Table C-1. Sediment Yield Estimates, Delivered Load to the Laguna by Individual Subbasin

Subbasin	Subbasin Area (acres)	PSIAC Delivered Sediment Yield (short tons/ac/yr)	RUSLE Field-Scale Soil Loss (short tons/ac/yr)	RUSLE Delivered Sediment Yield with IC-based SDR (short tons/ac/yr)
Lower Santa Rosa	21,511	1.12	4.99	0.157
Lower Mark West	5,873	1.60	6.91	0.168
Colgan	4,505	1.31	1.60	0.034
Blucher	4,936	1.67	1.29	0.022
Upper Mark West	21,501	1.76	6.91	0.162
Southeast Santa Rosa	14,189	1.87	4.46	0.117
Northeast Santa Rosa	14,210	1.89	6.50	0.160
Upper Laguna	23,865	1.41	1.71	0.041
Windsor	13,738	1.52	5.98	0.118
Copeland	3,988	1.38	2.03	0.047
Upper Floodplain	14,353	0.97	1.58	0.033
Lower Floodplain *	18,404	0.98	5.61	0.107
Total Watershed	*161,075*	*1.43*	*4.49*	*0.107*

* Excluding drainage area below Ritchurst Knob.

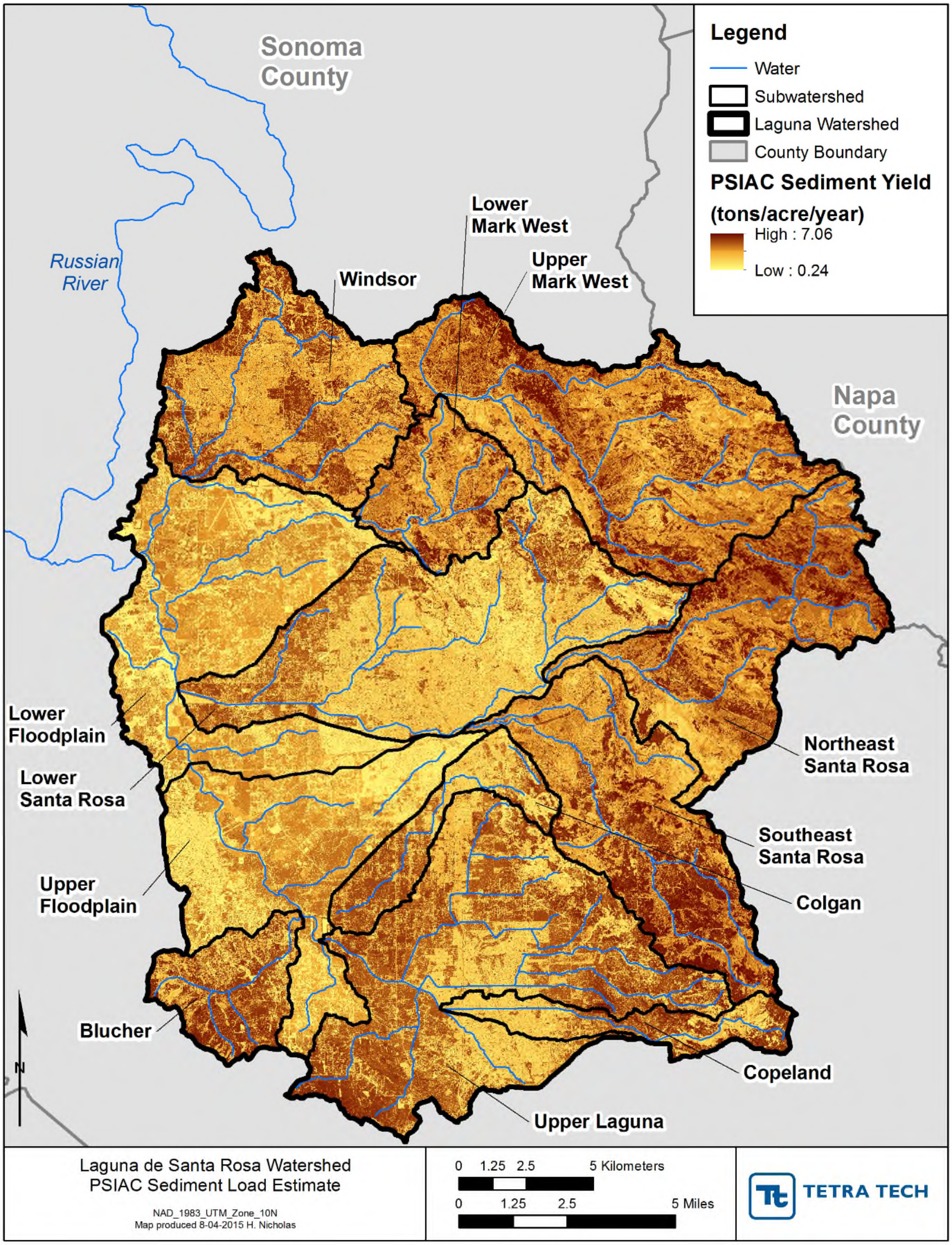


Figure C-1. PSIAC Sediment Yield Estimates for the Laguna de Santa Rosa Watershed

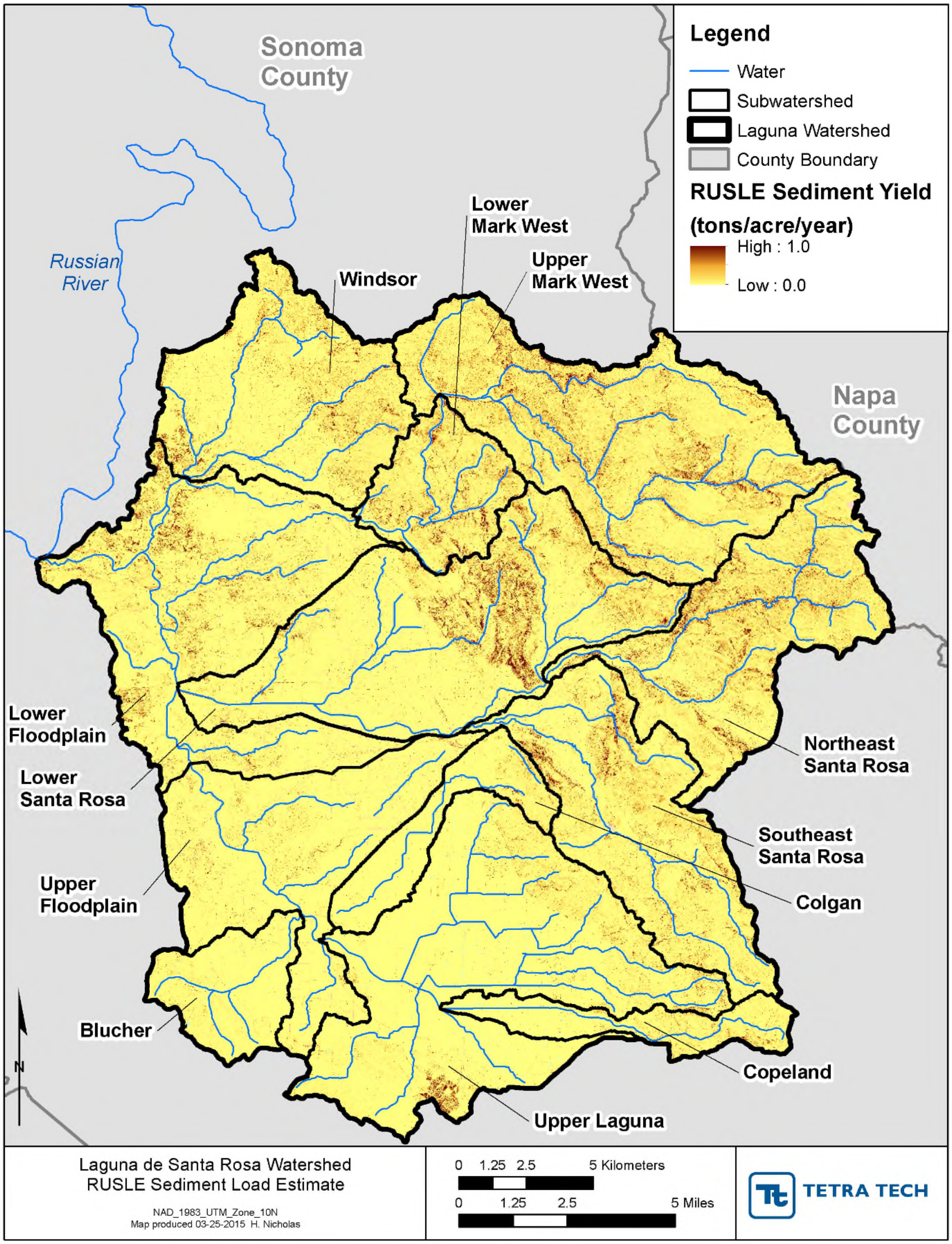


Figure C-2. RUSLE Delivered Upland Sediment Yield for the Laguna de Santa Rosa Watershed

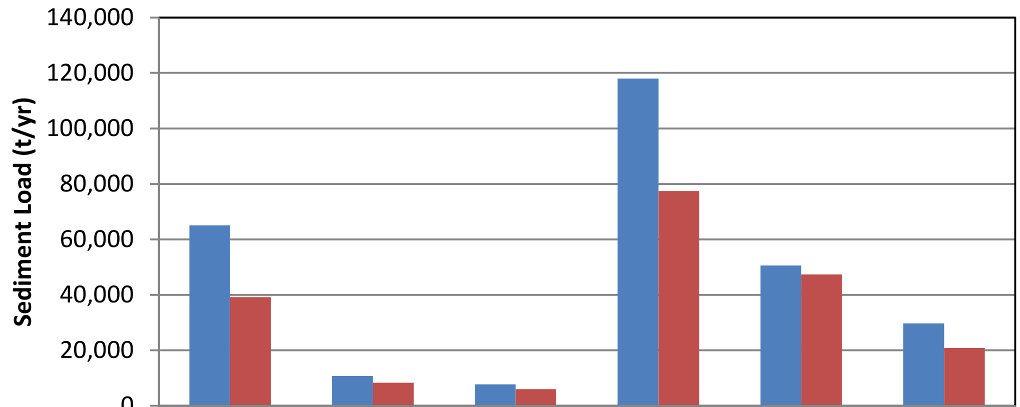
Note: Delivered yield calculated using IC-based Sediment Delivery Ratios.

The PWA (2004a) study also calculated sediment budgets using a version of the PSIAC method. These results are compared to the revised PSIAC and new RUSLE results from this study in Table C-2. The PWA (2004a) study subbasins are generally larger areas than the subbasins identified for this study, so note the "corresponding subbasin" column for reference.

Table C-2. Sediment Yield Estimates by Major Subbasin Compared to the PWA Study (2004a)

PWA (2004a) Subbasin	Corresponding Subbasins (This Study)	PSIAC Method (PWA, 2004a)	PSIAC Method (This Study)	RUSLE Method Soil Loss (This Study)	RUSLE Method with IC-based SDR (This Study)
		Sediment Yield (short tons/ac/yr)			
Laguna	Upper Laguna and Copeland	2.34	1.41	1.76	0.04
Blucher	Blucher	2.17	1.68	1.29	0.02
Colgan	Colgan	1.70	1.32	1.60	0.03
Santa Rosa	Lower Santa Rosa, Northeast Santa Rosa, and Southeast Santa Rosa	2.36	1.55	5.27	0.15
Mark West	Upper Mark West and Lower Mark West	1.85	1.73	6.91	0.16
Windsor	Windsor	2.16	1.52	5.98	0.12

The revised PSIAC estimates, although lower, compare reasonably well with the PSIAC results previously developed by PWA (2004a), indicating that the grid-based analysis methods of Johnson and Gebhardt (1982) perform appropriately (Figure C-3). The RUSLE method with IC-based SDR results in considerably lower delivered sediment yield estimates.



	Laguna	Blucher	Colgan	Santa Rosa	Mark West	Windsor
PSIAC (PWA, 2004)	65,064	10,706	7,666	117,990	50,557	29,729
PSIAC (This Study)	39,179	8,254	5,924	77,368	47,321	20,846

Figure C-3. Comparison of PWA and Revised PSIAC Method Sediment Load Estimates for the Laguna de Santa Rosa Watershed (PWA Subbasins)

Table C-3. Comparison of PSIAC and RUSLE (with SDR) Sediment Load Estimates

Subbasin	Revised PSIAC Total Load (short tons/yr)	RUSLE with IC-based SDR Upland Load (short tons/yr)
Lower Santa Rosa	24,042	3,377
Lower Mark West	9,393	988
Colgan	5,924	152
Blucher	8,254	108
Upper Mark West	37,932	3,490
Southeast Santa Rosa	26,516	1,661
Northeast Santa Rosa	26,873	2,277
Upper Laguna	33,674	969
Windsor	20,846	1,618
Copeland	5,504	187
Upper Floodplain	13,899	469
Lower Floodplain	18,019	1,973
Total	*230,876*	*17,271*

* Excluding drainage area below Ritchurst Knob.

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Appendix D RUSLE Application for Conditions 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. 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, altered routing, alteration of wetlands, etc.

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). The land cover area breakdown and map are depicted below in Table D-1 and Figure D-1. This section describes how RUSLE factors are altered to model the pre-settlement conditions within the watershed. This is followed by an evaluation of pre-settlement upland loads together with potential changes in the locations where this sediment was deposited.

Table D-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.

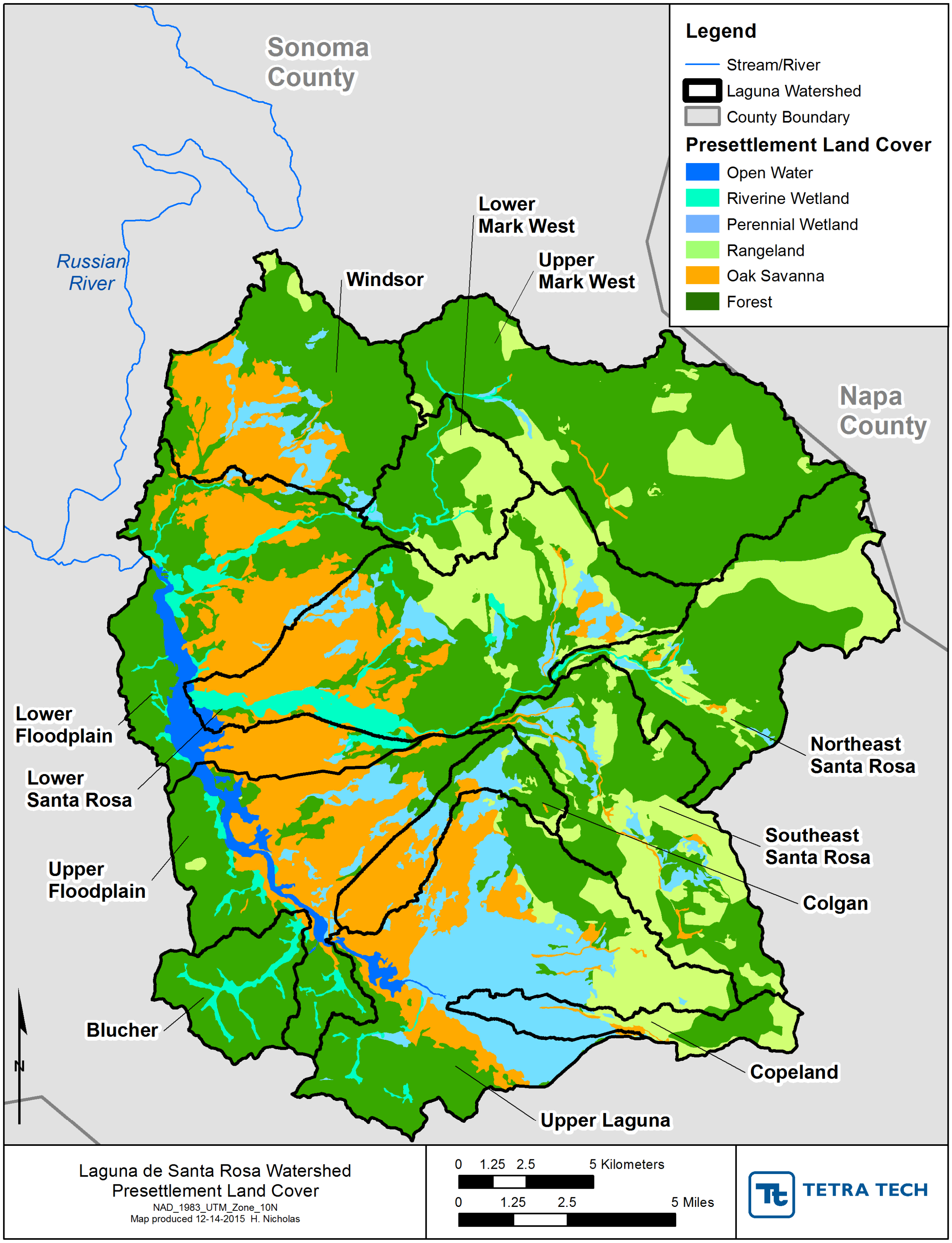

Figure D-1. Land Cover prior to European Settlement for the Laguna de Santa Rosa Watershed (based on Butkus, 2011)

The RUSLE method with IC-based SDR (as described in Section 5.2 of the main report) was applied to estimate upland sediment delivery associated with land cover prior to European settlement. Certain RUSLE input factors associated with land cover and topography are altered to represent conditions prior to settlement. The Rainfall-Runoff Erosivity Factor (R) and the Soil Erodibility Factor (K) do not change, and the Support Practice Factor (P) is left at 1.

The Slope Length and Steepness Factor (LS) is modified to eliminate most effects of road beds and development-associated grading. This was done by using the coarser 10-meter DEM, rather than the 1-meter LiDAR as the elevation basis to provide a smoothed estimate of the landscape without anthropogenic artificial slopes and breaks.

The Cover-Management factor (C) changes primarily because the land cover is different. In addition, adjustments for bare ground from LiDAR were removed and C factors are assigned to land cover types directly from the values assigned in Sonoma Creek Watershed Report (Sonoma Ecology Center, 2006), resulting in the factors shown in Figure D-2.

The SDR is also expected to be different under pre-settlement conditions. The 10-m DEM was also used for the pre-settlement IC analysis and the roads and urban areas were no longer defined as sinks for sediment delivery, significantly decreasing the "connectedness" of the landscape. The stream network was left unchanged due to lack of precise data. In fact, the stream network was sparser under pre-development conditions and many of the streams dispersed onto alluvial fans on the Santa Rosa Plain; thus, their sediment load was often not carried all the way to the Laguna. The resulting SDR map (Figure D-3) and associated estimated upland sediment yield (see Table 9-2 in main report) thus likely represent upper bound estimates on sediment delivery to the Laguna itself. Even with these caveats, the estimated pre-settlement sediment yield from upland sources is only about one-sixth of the current yield.

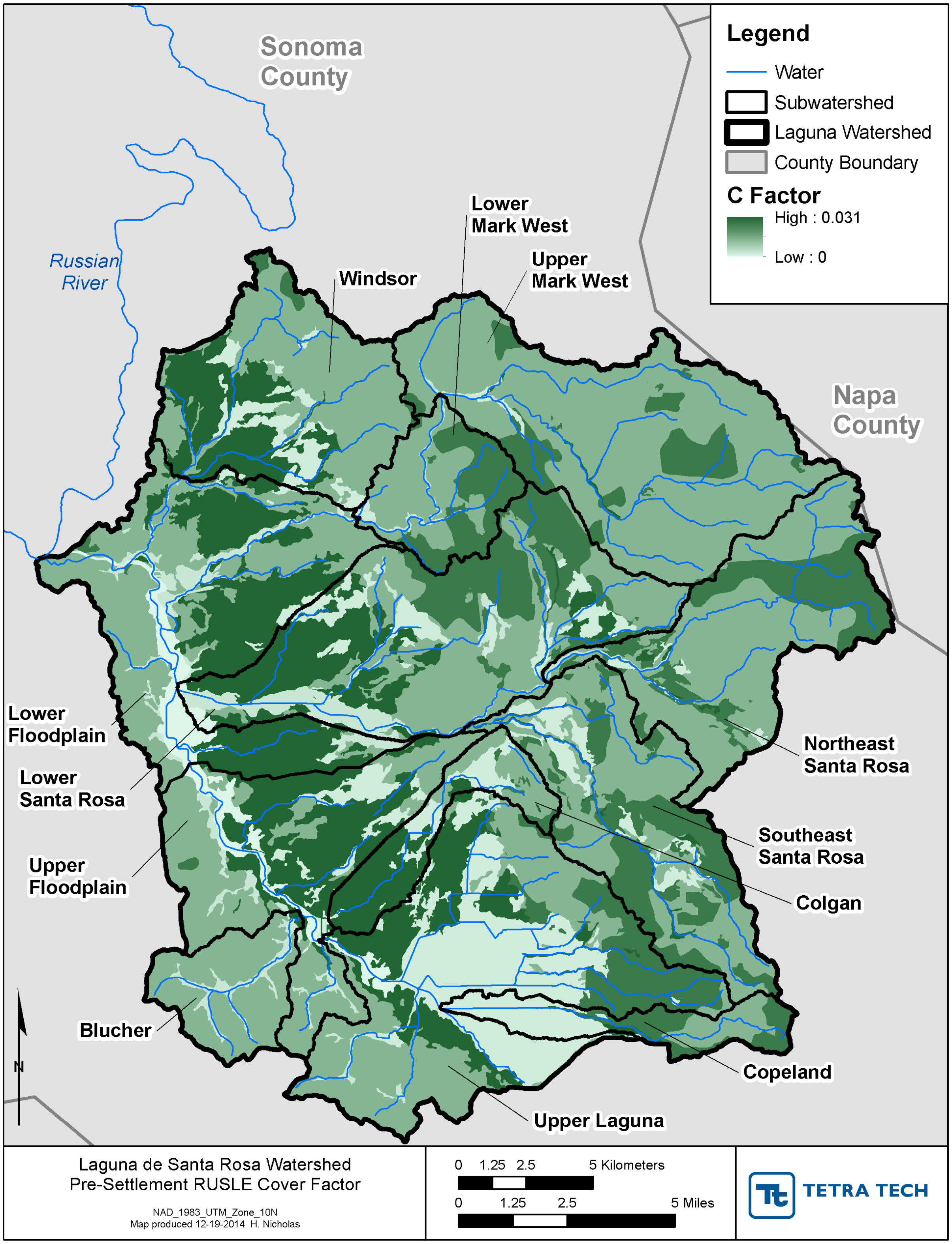

Figure D-2. Pre-Settlement RUSLE C Factor for Laguna de Santa Rosa Watershed

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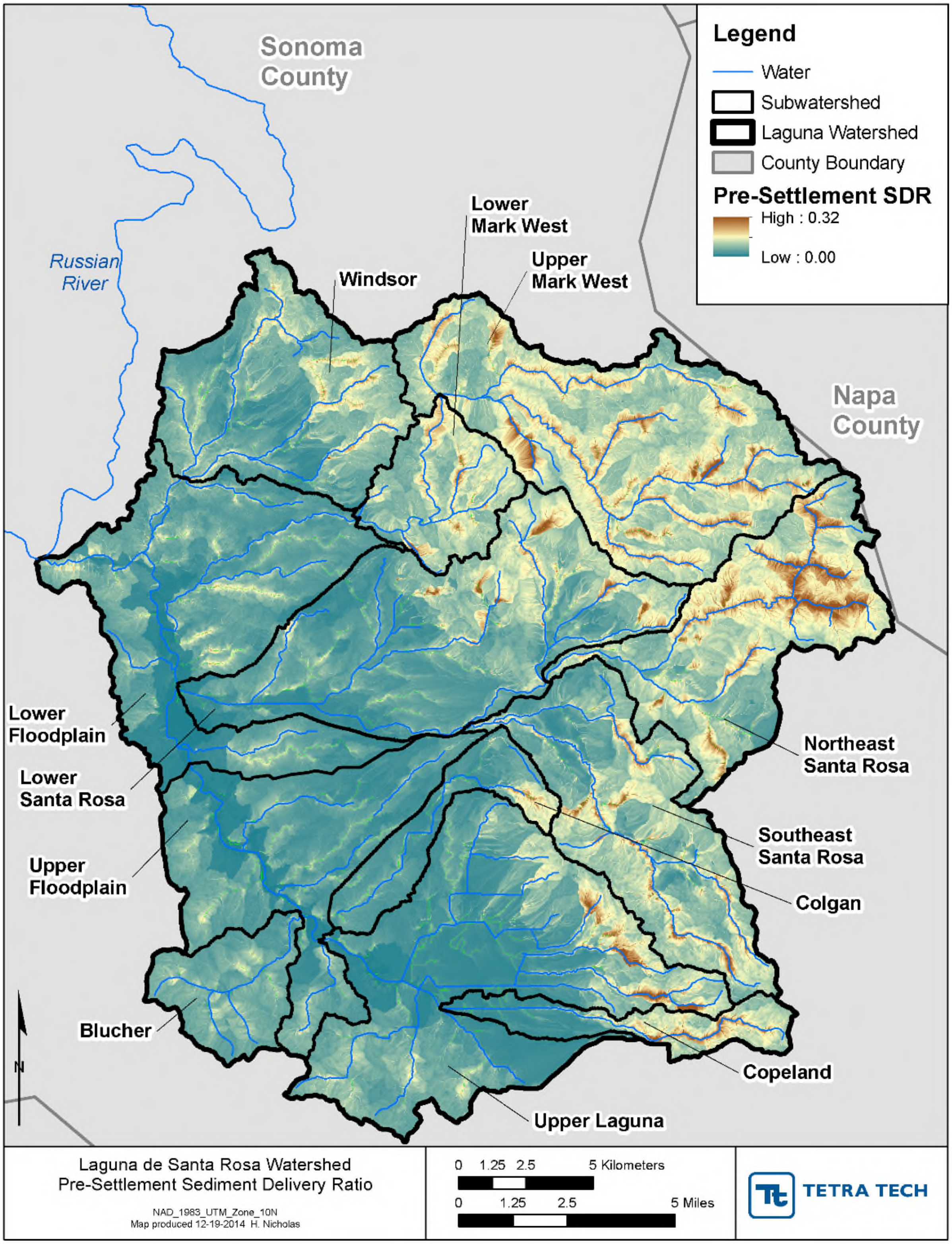

Figure D-3. Pre-Settlement IC-based SDR for Laguna de Santa Rosa Watershed