Laguna de Santa Rosa – Linkage Analysis for Sediment Impairments

Appendices

Prepared for

North Coast Regional Water Quality Control Board

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1.0 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 1-1.

Table 1-1. 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 County Vegetation Mapping and LiDAR Program
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 other methods such as PSIAC (1968).

1.1 RAINFALL-RUNOFF EROSIVITY FACTOR (R)

As was done in the Sonoma Creek RUSLE study, the California Water Boards' isoerodent map (https://ftp.waterboards.ca.gov/#/swrcb/dwq/cgp/Risk/RUSLE/; 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 1-1).

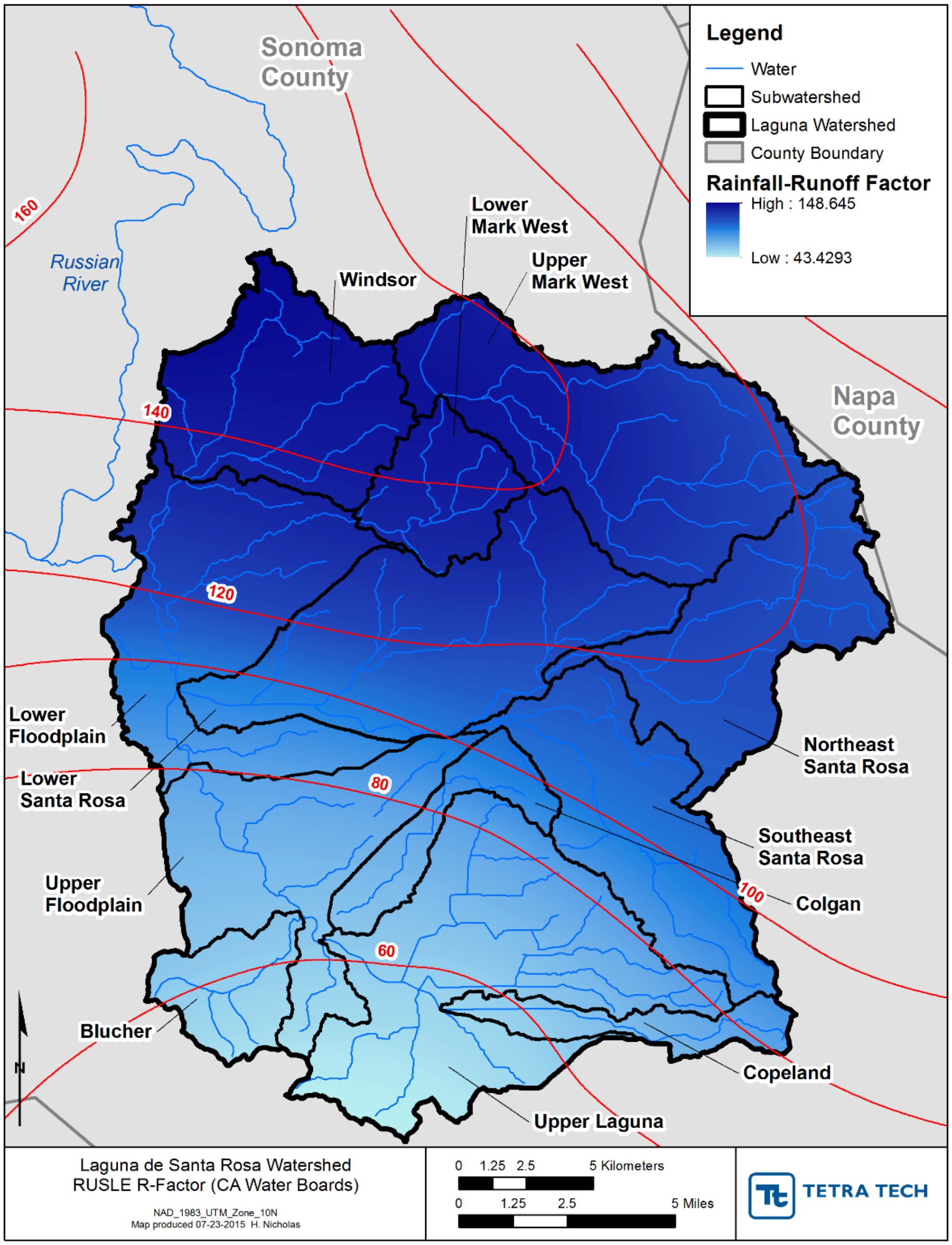

Figure 1-1. RUSLE Rainfall-Runoff Erosivity Factor (R; hundreds of foot-tonf-inch/acre-hour-year)

1.2 SOIL ERODIBILITY FACTOR (K)

The Soil Erodibility Factor is derived from the USDA Soil Survey Geographic Database (SSURGO) and represents the susceptibility of soil to erode because of precipitation events. The distribution of K factors across the watershed is shown in Figure 1-2.

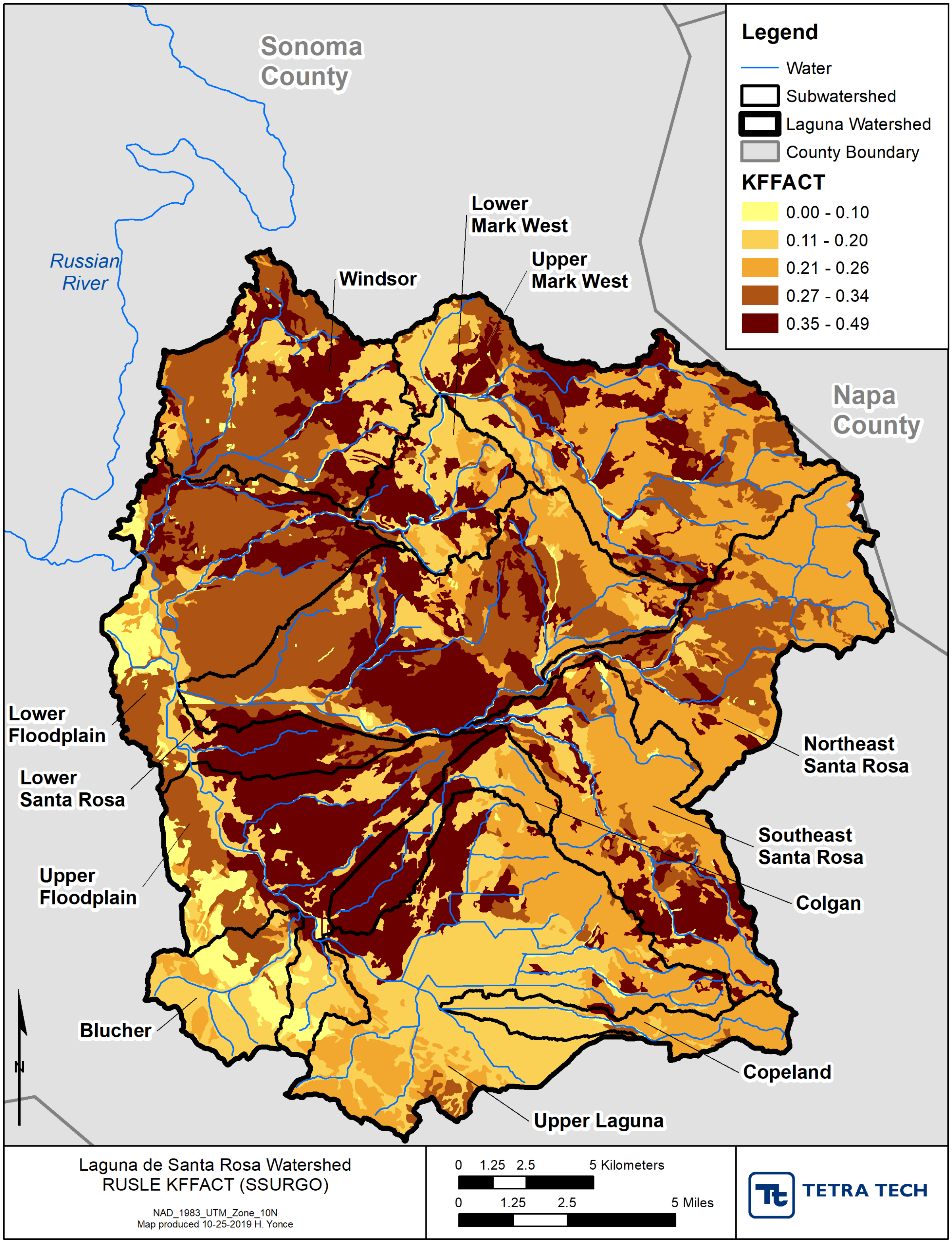

Figure 1-2. RUSLE Soil Erodibility Factor (K; ton-acre-hour/hundreds of acre-foot-tonf-inch)

1.3 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:

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

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:

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

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

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 1-3.

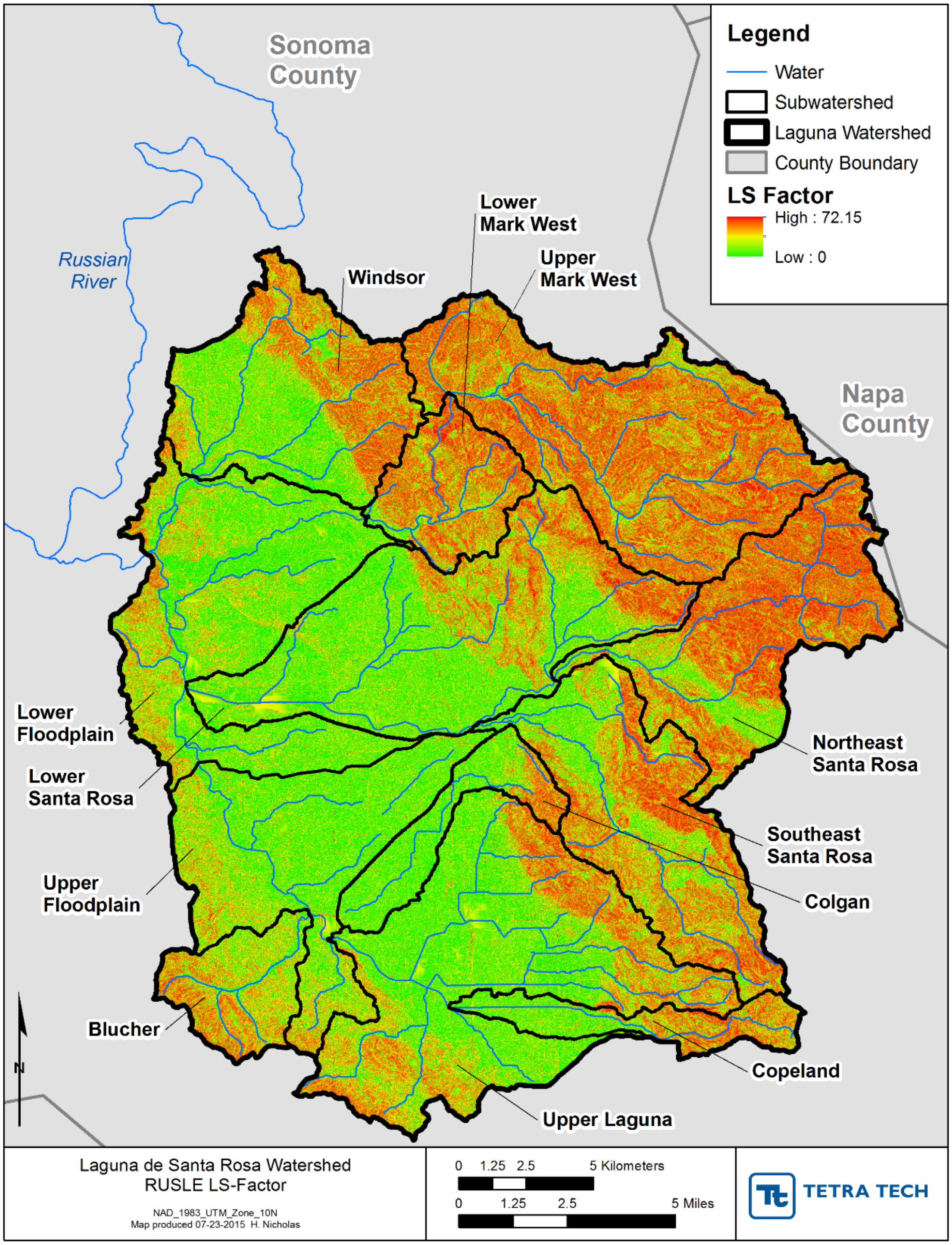

Figure 1-3. RUSLE Slope Length and Steepness Factor (LS; unitless)

1.4 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 and vegetation height at a 1-meer resolution.

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:

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

[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.

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

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

The component factors that are combined with F_i to obtain the gridded SLR estimates are shown in Table 1-2. The resulting spatial distribution of C factors is shown in Figure 1-4. Canopy density was obtained from the LiDAR coverage, while vegetation height was based on zonal statistics using the 1-meter resolution vegetation height raster from the Sonoma County Vegetation map service. Results were tabulated by aggregated Sonoma County Vegetation map classifications (discussed in Section 4 of the main report) to better distinguish between different land categories. This analysis was conducted on only the pervious portions of each land use category (impervious regions were removed from the analysis as provided by the impervious shapefile from the Sonoma County Vegetation map service).

Table 1-2. C Factor Components by NLCD Land Cover for the Laguna de Santa Rosa Watershed

Aggregated Land Use	Sonoma County Vegetation Map Land Use Categories: Life Form (Forest Life Form) Classes	E(SLR)	Canopy Density E(Fc)	Vegetation Height H (ft)	Alpha Factor
Water/ Wetland	Herbaceous (Herbaceous Wetland); Herbaceous (Aquatic Vegetation); Shrub (Riparian Shrub); Water (Water)	0	0.10	0.00	0
Developed	Developed (pervious portion); Urban Window (pervious portion)	0.057	0.28	0.10	0.0779
Barren	Barren and Sparsely Vegetated	1	0.02	0.00	1.0163
Hardwood Forest	Non-native Forest and Woodland (Non-Native Forest); Native Forest (Hardwood Forest)	0.013	0.60	101.34	0.0130
Conifer Forest	Native Forest (Conifer Forest)	0.013	0.79	216.55	0.0130
Mixed Forest	Forest Sliver (Forest Sliver); Native Forest (Mixed Conifer-Hardwood Forest)	0.013	0.72	150.43	0.0130
Shrub	Shrub; Non-Native Shrub	0.031	0.22	17.25	0.0323
Herbaceous	Herbaceous; Major Roads (pervious portion)	0.026	0.03	4.23	0.0266
Pasture/Hay	Intensively Managed Hayfield; Irrigated Pasture	0.095	0.01	1.48	0.0953
Row Crops	Annual Cropland	0.343	0.01	1.39	0.3466
Orchard/ Vineyards	Vineyard; Vineyard Replant; Perennial Agriculture; Orchard or Grove; Nursery or Ornamental Horticulture Area	0.228	0.04	3.08	0.2350
Woody Wetlands	Native Forest (Riparian Forest)	0.003	0.61	97.40	0.0030

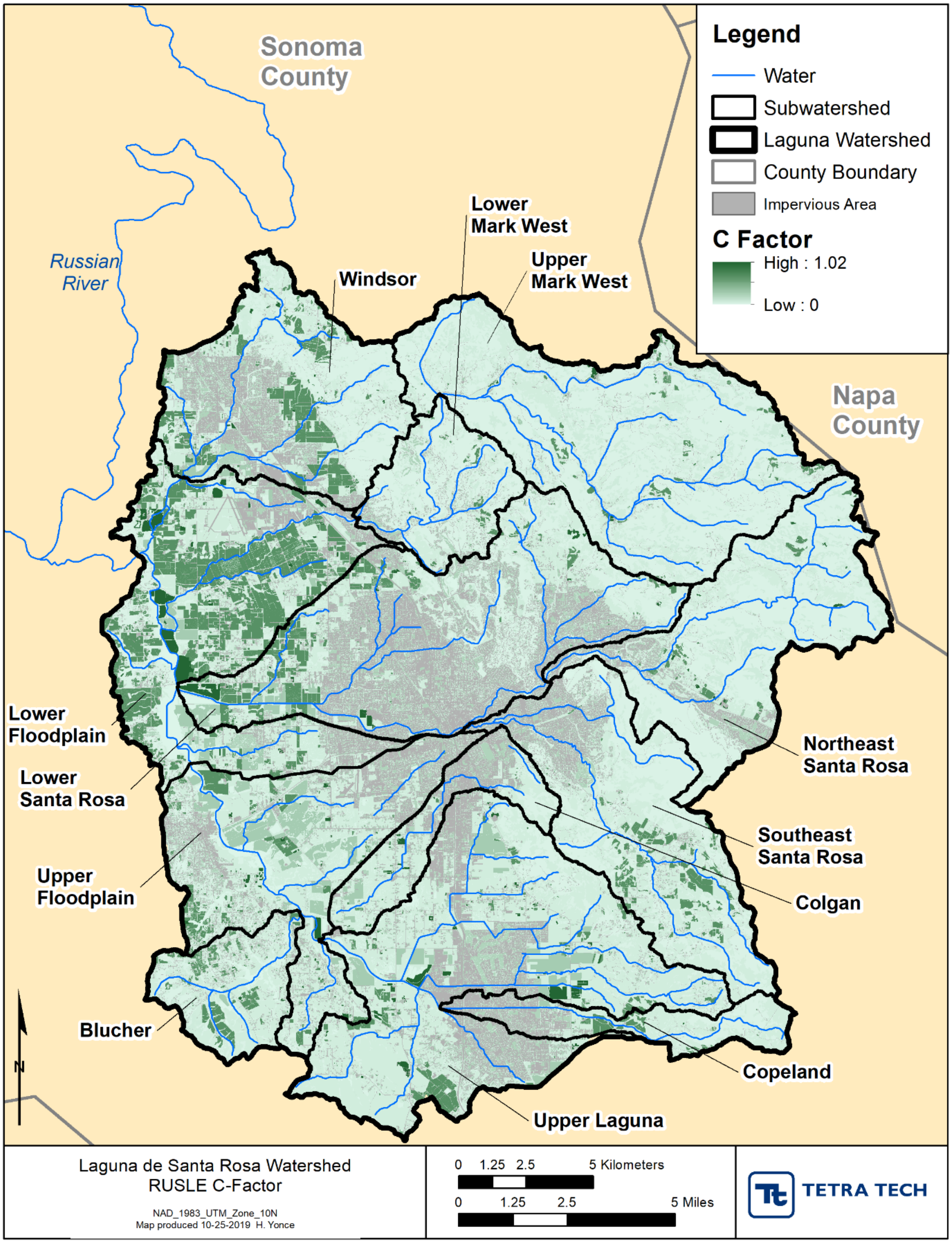

Figure 1-4. RUSLE Cover-Management Factor (C; unitless)

1.5 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.

1.6 RESULTS

The predicted field-scale soil losses produced by the RUSLE method are shown in Figure 1-5. 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 shown in Table 1-3

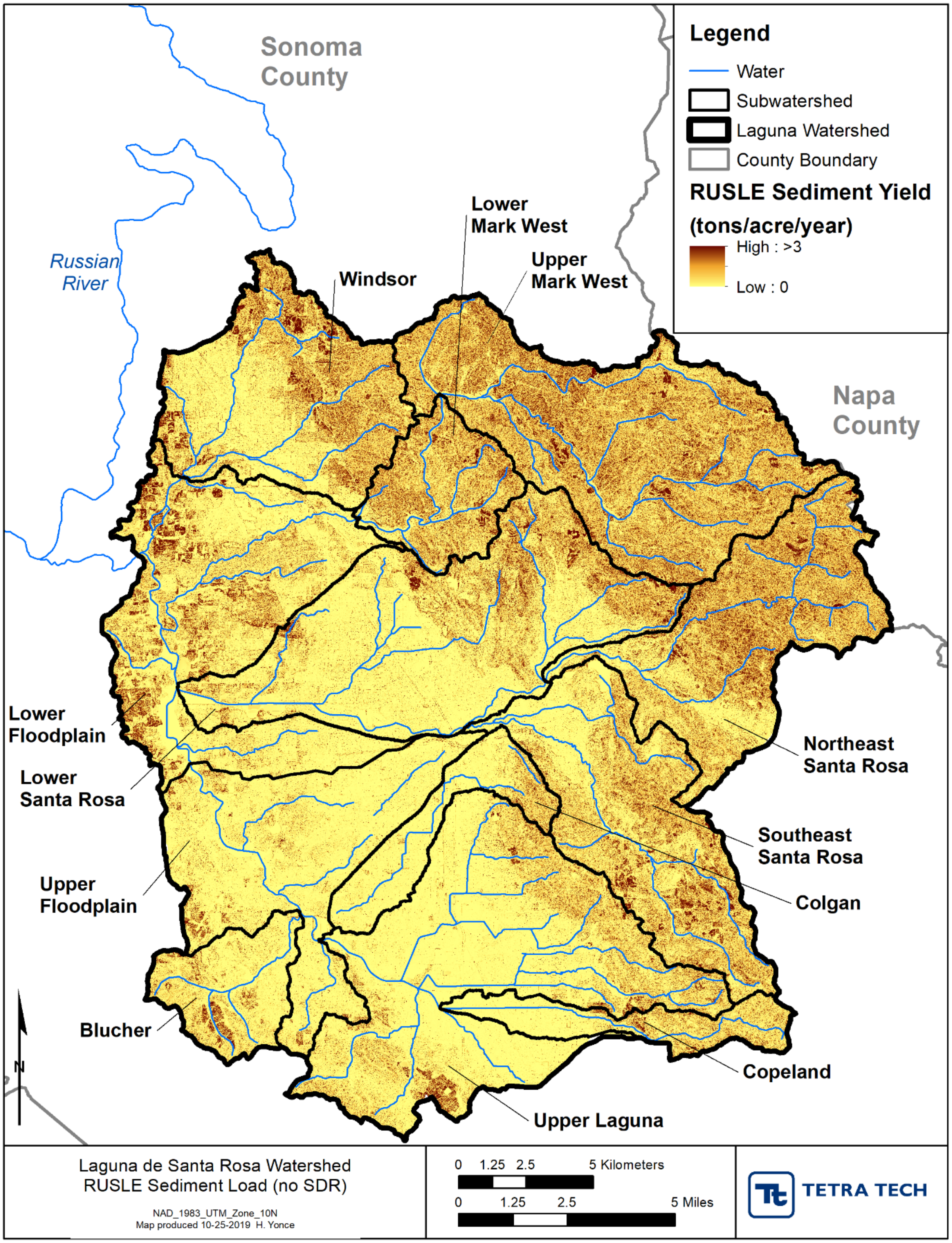

Figure 1-5. Field-scale Soil Loss Predicted by RUSLE for Pervious Land in the Laguna de Santa Rosa Watershed

Table 1-3. Sediment Yield Estimates and Delivered Load to the Laguna by Individual Subbasin

Subbasin	Subbasin Pervious Area (acres)	RUSLE Field-Scale Soil Loss (short tons/ac/yr)	RUSLE Delivered Sediment Yield with IC-based SDR (short tons/ac/yr)
Lower Santa Rosa	15,011	8.87	3,151
Lower Mark West	5,310	10.69	1,148
Colgan	3,520	2.95	182
Blucher	4,606	4.81	323
Upper Mark West	20,955	11.84	5,098
Southeast Santa Rosa	12,419	8.88	741 [2]
Northeast Santa Rosa	13,235	10.10	2,869
Upper Laguna	19,832	3.68	1,531
Windsor	11,304	13.76	2,463
Copeland	3,236	4.80	319
Upper Floodplain	11,951	2.92	533
Lower Floodplain [1]	16,211	10.62	2,748
Total Watershed	*137,590*	*8.48*	*21,106*

Notes: 1. Lower Floodplain excludes drainage area below Ritchurst Knob.

2. Delivered sediment estimate for Southeast Santa Rosa and Total Watershed omit loads upstream of Ilsanjo and Matanzas reservoirs.

1.7 ADDITIONAL REFERENCES

(see also Section 11 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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2.0 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 2-1 and Figure 2-1. 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 2-1. 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.

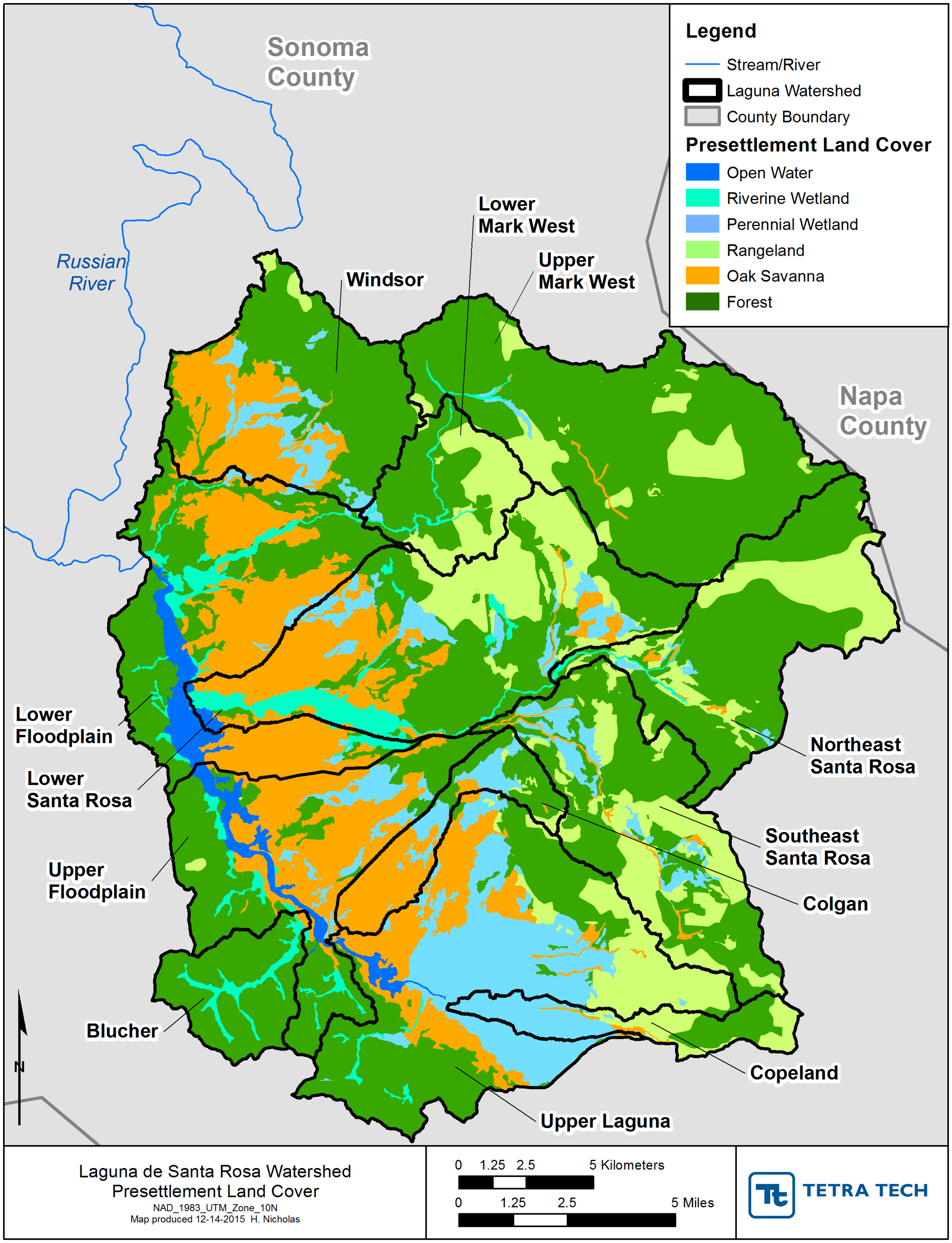

Figure 2-1. Land Cover prior to European Settlement for the Laguna de Santa Rosa Watershed (based on Butkus, 2011)

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 2-2.

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 2-3) 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.

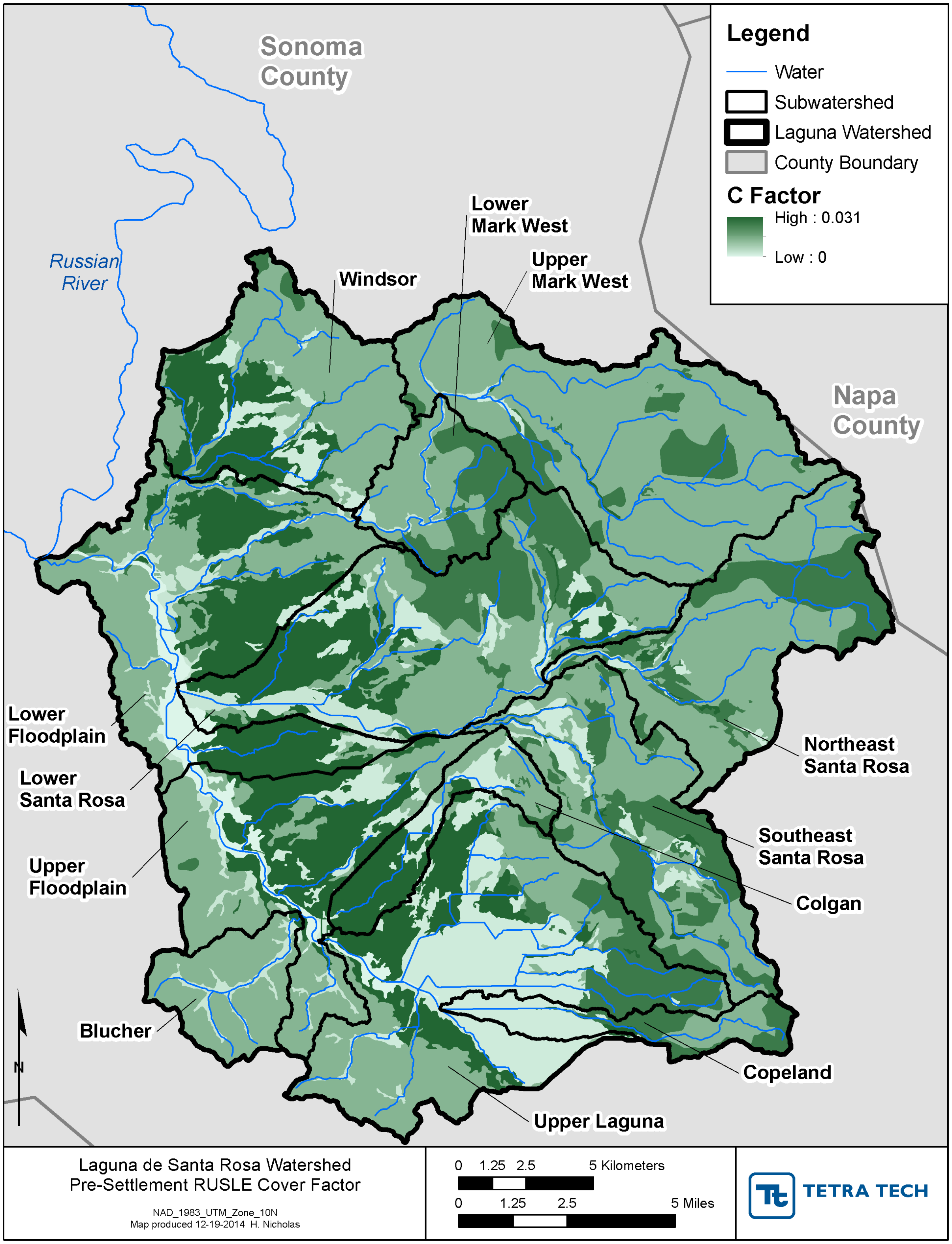

Figure 2-2. Pre-Settlement RUSLE C Factor for Laguna de Santa Rosa Watershed

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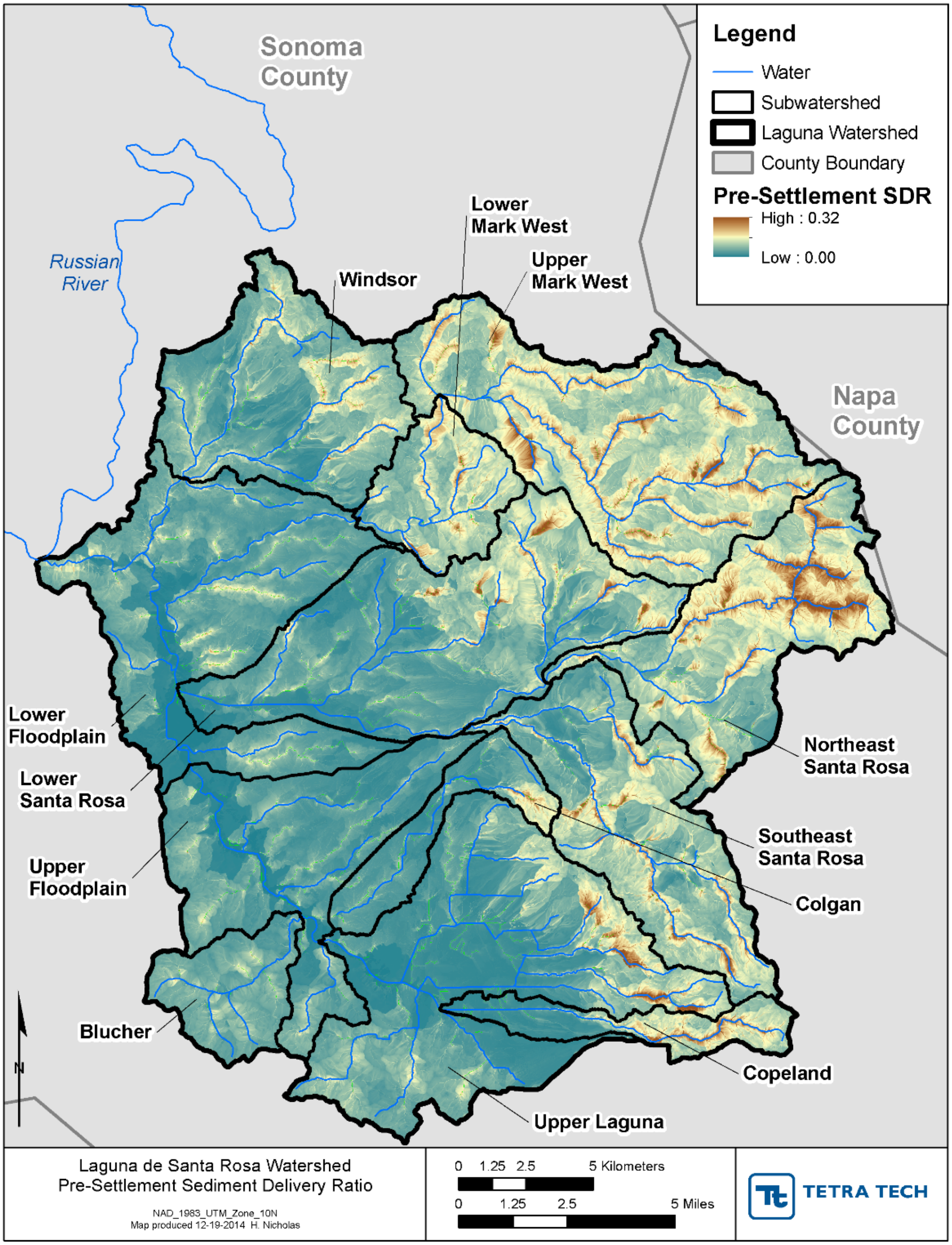

Figure 2-3. Pre-Settlement IC-based SDR for Laguna de Santa Rosa Watershed