Modeling river flows and sediment dynamics for the Laguna de Santa Rosa watershed in Northern California

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Abstract: The nonpoint source pollution model Soil and Water Assessment Tool (SWAT) was applied to understand management options that may improve water quality in the Laguna de Santa Rosa watershed in Sonoma County, California. Surface water quality in the Laguna watershed has been significantly impaired over recent years, as natural land cover has been urbanized or converted to agricultural uses. We first generated new maps of land cover and major land uses from satellite and airborne imagery for the watershed. The SWAT model output was checked against six streamflow gauges in the watershed. At the monthly time step, we found that the precalibrated model performed well at all gauges, with the coefficient of determination (r^2) values ranging from 0.81 to 0.92. Calibration by modifications of groundwater extraction in the watershed resulted in notable increases to correlation values at all gauges, except at upstream locations on Santa Rosa Creek and Mark West Creek. Measured seasonal trends in sediment concentrations were tracked closely by the SWAT model predictions. Highest sediment loading rates were associated in the model results with pasture, rangeland, and vineyard cover areas. Model scenarios were tested for vegetation filter strips and improved ground cover conditions applied in subbasins, where soil erosion was shown to be elevated in previous simulations.

Key words: groundwater extraction—land cover—sediment—Soil and Water Assessment Tool (SWAT) model—vegetation cover management—water quality

Many metropolitan areas in California are growing at unprecedented rates, creating extensive urbanized landscapes across former rangelands, wetlands, and woodlands. Urban and suburban land uses can be major contributors to pollutant loadings that seriously impair nearby streams (Dwight et al. 2002; Stein and Ackerman 2007). Sediment runoff from development sites and excess fertilizers, herbicides, and pesticides from park lands and residential areas are frequently found to be important sources of local water contamination.

Management of water quality and rehabilitation of impaired streams require tracking both point and nonpoint source material through a watershed by hydrological processes. However, evaluation of alternative management strategies through field experiments and intensive stream water sampling is often impractical and cost-prohibitive. This makes simulation modeling the only viable means of providing input to management decisions. A number of simulation models have been developed to aid in the understanding and management of surface runoff, sediment, nutrient leaching, and pollutant transport processes, such as ANSWERS (Areal Nonpoint Source Watershed Environment Simulation) (Beasley and Huggins 1980), CREAMS (Chemicals, Runoff and Erosion from Agricultural Management Systems) (Knisel 1980), GLEAMS (Groundwater Loading Effects of Agricultural Management Systems) (Leonard et al. 1987), AGNPS (Agricultural Nonpoint Source Pollution Model) (Young et al. 1989), and SWAT (Soil and Water Assessment Tool) (Arnold et al. 1998).

In any watershed, the amount of runoff added to stream channels after a storm is influenced strongly by the ground's ability to absorb water (permeability), the type of soil, the topography of the land (i.e., slope, aspect, floodplains), and land-cover conditions, such as vegetation types and impervious surfaces. A semidistributed nonpoint source pollution model like SWAT is well suited to study these complex interactions of pollutant transport and erosion for small to medium-sized watersheds. Assuring the quality of hydrologic modeling involves the integration of spatially distributed parameters in the model with a geographic information system (GIS). This paper describes such a GIS-based application of the SWAT model to a polluted watershed in Northern California, the Laguna de Santa Rosa, for estimating potential loadings of sediment into surface water using multiple databases of land use/cover, irrigation, animal production, and chemical applications.

Study Objectives. Remote sensing of land cover and land use, together with watershed modeling using SWAT, can provide unique information about nonpoint source loadings in polluted stream courses. Hence, the objectives of our study were to

(1) Generate new maps of land cover and land uses from satellite and airborne imagery for the Laguna de Santa Rosa watershed

(2) Apply and calibrate the SWAT simulation model to predict the impact of land management practices on water, sediment, and agricultural chemical yields in the Laguna de Santa Rosa watershed

(3) Evaluate model predictions for potential conservation management activities aimed at mitigating nonpoint source loadings into tributaries of the Laguna de Santa Rosa watershed

Watershed Description. The Laguna de Santa Rosa watershed in Sonoma County, California is historically a diverse mixture of oak woodland, grasslands, riparian forests, vernal pools, and wetlands. The Laguna watershed has several major tributaries, including Mark West Creek, Santa Rosa Creek, Copeland Creek, Hinebaugh Creek, Five Creek, Washoe Creek, and Blucher Creek. Urban communities in the watershed include the cities of Santa Rosa, Windsor, Sebastopol, Cotati, and Rohnert Park. The Laguna drainage basin is defined in the east by the Mayacamas and Sonoma Mountains. Rain on these slopes enters fast-

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flowing creeks that channel surface water to the valley floor. The floodplain and adjacent uplands still contain many distinctive natural features, including braided channels, pools, springs, seasonal and perennial wetlands, and riparian and oak woodlands. The Laguna watershed comprises approximately 10% of the entire Russian River drainage, and when the river floods, the Laguna basin can act as a natural storage reservoir, holding up to 98,680,000 m^3 (80,000 ac ft) of water.

Over recent years, the Laguna watershed has undergone profound changes, resulting in altered sedimentation and nutrient loading, impacts to the natural flood cycles, habitat fragmentation, and vegetation shifts from native to invasive weed species. Coinciding with these changes has been increased nutrient and sedimentation loads from the Laguna into the Russian River. With regard to water quality, the Laguna de Santa Rosa is listed as impaired under the federal Clean Water Act for sediment, nitrogen, phosphorus, temperature, mercury, and dissolved oxygen. These listings total to the most for any water body on the Northern Coastal region of California.

Since the natural floodplain is impacted by five expanding urban centers, much of the water and the sediment it carries is captured by a network of flood-control channels designed to move flow quickly through the urban areas and reduce the chance of urban flooding. Where swales and marshes once formed and rainfall slowed and ponded in vernal pools throughout the floodplain, water now runs off in concentrated flow to the Laguna de Santa Rosa main channel, where it is joined by runoff from the western hills. Although the natural drainage system is now confined to the western third of the valley, it remains an impressive 23 km (14 mi) long waterway, with a floodplain of more than 3,035 ha (7,500 ac).

Current land use of the watershed consists of urban and rural areas that include approximately 2,200 ha (5,436 ac) of vineyards, 1,600 ha (3,954 ac) of pasture, 1,100 ha (2,178 ac) of dairies, and 500 ha (1,236 ac) of mixed agriculture. Land use within the 100-year floodplain includes a wastewater treatment facility, beef cattle, dairies, pastures, vineyards, and poultry. We estimate from analysis of remote sensing images of the Laguna de Santa Rosa floodplain that the rainfall events of winter 2006 inundated just over 1,400 ha (3,459 ac) of land, 42% of which was pasture (much of it irrigated in the summer months with organic manure slurry), 24% was vineyard, and 26% was natural woodland and grassland cover.

Coverage patterns of this recent flood event suggest that large tracts of managed pasture and vineyard growing lands that receive regular fertilizer nutrient additions can be completely inundated with Laguna flood waters. These flood waters then recede slowly back into the Laguna main channel, potentially with an altered chemical composition resulting from prolonged contact with the soils of pastures and vineyards.

The climate in the Laguna de Santa Rosa watershed is Mediterranean with cool, wet winters and warm, dry summers. The average monthly minimum and maximum temperatures for Santa Rosa (1971 to 2000) range from 2.8°C to 14.1°C (37°F to 57°F) in January to 10.6°C to 28.4°C (51°F to 83°F) in August (WRCC 2005). Monthly precipitation rates at the same station range from less than 1 cm (0.4 in) in July to nearly 16 cm (6.3 in) in January.

Upper reaches of the watershed begin as high as 828 m (2,717 ft), with slopes as steep as 27%, and flow west into the floodplain, which comprises around half the watershed area. Well-drained loam soils occupy much of the upland portions of the watershed, while much of the lowland areas are dominated by loams with a layer of very low permeability near the soil surface.

Materials and Methods

General Attributes of the Soil Water Assessment Tool Model. The SWAT is designed to simulate river basin–scale watersheds with diverse land covers, soil types, and management scenarios over long periods of time (Arnold et al. 1998; Gassman et al. 2007). The SWAT is a physically based model that estimates surface and subsurface flow, plant growth, erosion, and nutrient loading at the daily or subhourly time step. The USDA Natural Resources Conversation Service (NRCS) curve number (CN) method is commonly used to estimate surface runoff rates in SWAT at the daily time step, and the Green-Ampt method is used when running subhourly time intervals. Other major components of SWAT include the Modified Universal Soil Loss Equation (MUSLE) for sediment loading simulation, the Environmental Impact Policy Climate (EPIC) plant growth model, and QUAL2E for processing in-stream nutrient routing (Gassman et al. 2007). The SWAT model accepts daily climate inputs including temperature, rainfall, wind speed, and solar radiation from multiple stations in a watershed and includes options to use the Penman-Monteith, Priestly-Taylor, or Hargreaves method of estimating potential evapotranspiration.

As a semidistributed model, SWAT utilizes a GIS with digital elevation data to delineate subbasins, which are then populated with hydrologic response units (HRU) to represent unique combinations of soil type, land cover, and slope. Surface runoff, subsurface water, evapotranspiration, sediment yield, nutrient loading, and other constituents are calculated at the HRU scale before being routed through the watershed at the subbasin level.

Primary strengths of the SWAT model include its ability to address changes in land use, land management, and climate, with moderate computational requirements. Modeling scenarios can incorporate a wide range of point and nonpoint source pollutants, water storage and reallocation, and naturally occurring water bodies, such as ponds and wetlands. Potential weaknesses of SWAT within the Laguna De Santa Rosa watershed are an inability to account for tidal backflow in coastal watersheds and limited ability in simulating flood events that may frequently inundate low lying areas of the watershed for several days.

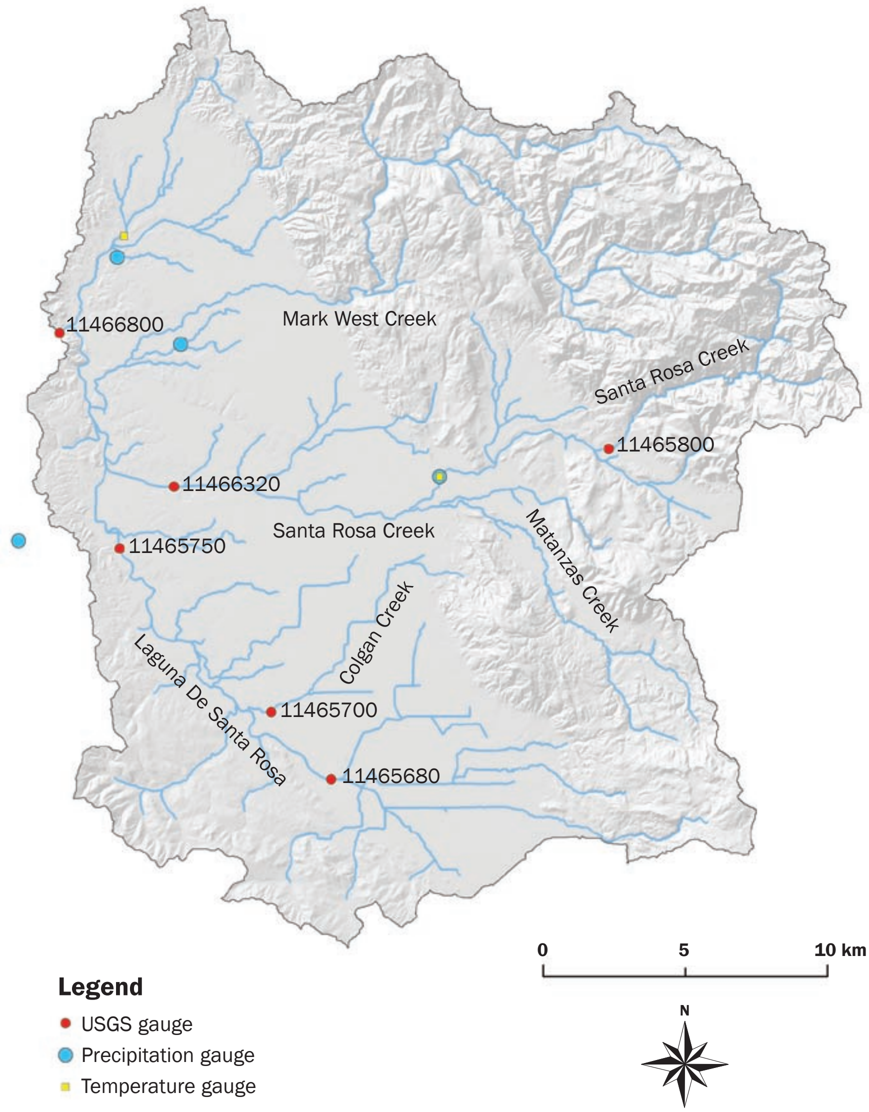
Land Cover, Topography, Soils, and Climate. The SWAT model requires topography, soil, and land-use data to define stream channels and characterize surface and subsurface conditions in the watershed. The land-cover data used in SWAT was based initially on the 1992 National Land Cover Dataset (NLCD). This land cover is derived from 30 m (98 ft) resolution Landsat satellite imagery and has been shown to have a high level of accuracy in the western United States (Wickham et al. 2004).

We initially used the US Geological Survey (USGS) National Elevation Dataset (NED 2006) 30 m (98 ft) resolution topography layer to delineate subbasins. National Hydrology Data (NHD) flow-line vector data was added to the NED to improve channel routing in SWAT. While this produced a reasonably good representation of channel reaches through most of the watershed, boundaries of two subbasins extended into an adjacent watershed due to inadequate definition in the 30 m data. Replacing the 30 m data with a 10 m (32 ft) resolution NED layer resolved the issue.

By default, State Soil Geographic Data (STATSGO) data can be read into SWAT. However, the map scale for STATSGO is 1:250,000, whereas the map scales for the Soil Survey Geographic Data (SSURGO) typically range between 1:12,000 and 1:63,360 (USDA NRCS 2008). Post-calibration flow-rate values have been reported as more accurate when SSURGO is used in place of STATSGO (Geza and McCray 2008). To improve HRU characterizations for the Laguna watershed, SSURGO data were converted to the SWAT format using the preprocessing extension described in Peschel et al. (2003).

Observed daily precipitation and surface air temperature data from five stations in the watershed were used to generate a SWAT climate database (figure 1). These data were made available though the National Climate Data Center (NCDC 2007) and the California Irrigation Management Information System (CIMIS 2000). Data records used for this application of SWAT extended from 1951 to 2007. The climate input data for any particular subbasin is assigned from the weather station record nearest the centroid of that subbasin. Any dates missing values from a particular station were populated by values from neighboring stations. Although all attempts were made to represent climatic variation throughout the drainage basin, there are no climate station data available for the uppermost portions of the Laguna watershed.

Figure 1
Distribution of climate and US Geological Survey (USGS) gauge stations for stream flow rates in the Laguna De Santa Rosa watershed.



Specific Modifications for the Laguna Watershed. We have made two major refinements for the Laguna watershed to datasets used in the SWAT model, namely updates to the NLCD land cover data and the introduction of a vineyard cover class to the land-cover SWAT plant database. The 1992 NLCD map was improved by incorporating data sets that reflect more recent changes in land use and have strengths over the NLCD map in terms of characterizing particular land cover classes. These datasets included the California Department of Water Resources (California DWR 1993) county land-cover map from 1999, the 2004 Sonoma County parcel GIS data containing land use codes, and the USDA National Agriculture Inventory Program (NAIP 2005) high-resolution aerial imagery from 2005. Significant edits to the NLCD map included expansion of urban areas due to residential development in the mid- and late-1990s, distinction between vineyard and orchard crops, and delineation of irrigated versus nonirrigated pasture lands. An additional advantage to these adjustments was a reduction in the amount of "speckling" in the final land-cover map (figure 2). Since HRUs in SWAT are defined by the user setting thresholds based on the percent area of overlaying slope, land cover, and soil type within each subbasin, heterogeneity in any of the three GIS layers can potentially eliminate meaningful HRUs.

Each plant type in SWAT requires 34 different parameters to be defined, such as maximum leaf area and rooting depth. The standard SWAT plant database does not include parameters for vineyards, which occupy over two thousand hectares within the Laguna watershed. By default, SWAT interprets the NLCD orchard/vineyard class as apple orchard. We addressed this problem by entering a new set of parameters specific to vineyards into the SWAT plant database (J. Kiniry, personal communication). A detailed description of these parameter values is listed in table 1.

Land Management Scenarios. The SWAT model has been used in other watersheds to evaluate the effectiveness of various management practices on sediment and nutrient loading. Modeled "best management" practices have included simulating cropland terracing, vegetated channel cover, grade stabilization structures, forage harvest management, and vegetation filter strips (Santhi et al. 2005; Bracmort et al. 2006).

Vegetation filter strips have been shown in field studies to reduce sediment in runoff from cropland by as much as 93% and nitrate by around 50% (Daniels and Gilliam 1996; Schmitt et al. 1999). In the case of pasture lands, the first 6 m (20 ft) of vegetation buffer have been found to remove approximately 75% of total nitrogen, phosphorous, and suspended solids from runoff (Lim et al. 1998). We used SWAT in the Laguna watershed to assess the impact of using 6 m (20 ft) vegetation filter strips to capture sediment, nitrogen, and phosphorous along vineyard and pasture boundaries. The SWAT model calculates the trapping efficiency of filter strips for sediment, nutrients, and pesticides as

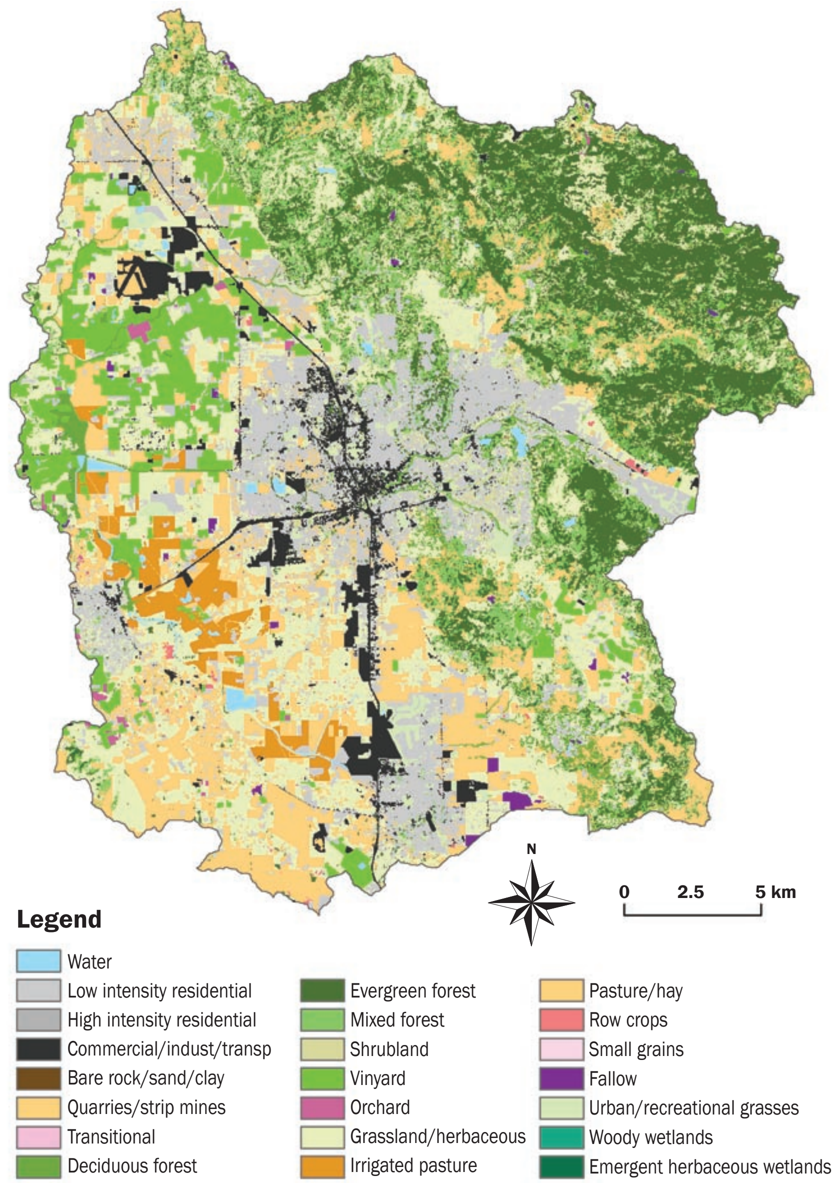
$$trap_{ef} = 0.367(width_{filtstrip})^{0.2967}, \quad (1)$$

where $trap_{ef}$ represents the fraction of the constituent captured by the filter strip and $width_{filtstrip}$ represents the filter strip width in meters (Neitsch et al. 2002).

The USLE cover and management (C) factor adjustments have been made in SWAT by researchers to evaluate improvements to heavily degraded rangeland through seeding and critical area planting (Santhi et al. 2006). The C factor value is defined as the ratio of soil loss for soil managed under specified conditions to losses from clean-tilled, continuous fallow. Calculation of the C value for a particular crop involves several variables, including crop canopy, tillage practices, residue mulch, and land-use residual (Wischmeier and Smith 1978). When accounting slope, ground cover, and surface roughness, percent ground cover has been found to be the most significant factor in determining soil erosion rates in vineyards (Battany and Grismer 2000). We adjusted the USLE C factor to simulate the effects of increased ground cover in vineyard areas, as well as degraded grass cover conditions in grazed pasture.

To simulate increased vineyard ground cover, USLE_C was set to three different values (the default value of 0.1, plus 0.03 and 0.003) in order to represent varying degrees of coverage. A USLE_C factor of 0.1 is the recommended value for vineyards (J. Kiniry, personal communication), 0.03 is the estimated minimum value for annual ryegrass, and 0.003 is the recommended minimum USLE_C factor for western wheatgrass (Neitsch et al. 2002). The USLE_C for pasture was set at 0.009 to represent well-managed pasture and was set at 0.03 for moderate reductions in cover. Ground-cover change and vegetation-strip scenarios were run independently of each other, with the exception of pasture, in which case USLE_C was set to 0.03 for the filter strip simulation.

Figure 2
Final land cover classification map of the Laguna De Santa Rosa watershed.



Irrigation and fertilization timing and amounts can be directly specified in SWAT or simulated automatically based on plant stress thresholds. Stress thresholds in SWAT range from 0 to 1, where 0 represents no plant growth due to (severe) stress, and 1 represents the absence of stress. In management scenarios described above, pastures were modeled with 10 kg ha^{-1} of dairy manure deposited daily for 120 days, beginning early in the year. Vineyards received applications of elemental nitrogen when the nitrogen stress factor (N_STRS) dropped below 0.95, which is the recommended value according to the SWAT documentation (Neitsch et

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Table 1
Parameters entered into the Soil and Water Assessment Tool (SWAT) crop database for vineyards.

SWAT parameter	Description	Value	Units
BIO_E	Biomass-energy ratio	30	kg ha^{-1} per MJm^{-2}
HVSTI	Harvest index	0.02	kg ha^{-1} per kg ha^{-1}
BLAI	Max potential leaf area index	2	m^2 m^{-2}
FRGRW1	Fraction of growing season corresponding to 1st point on optimal leaf area development curve	0.05	fraction
LAIMX1	Fraction of max LAI corresponding to 1st point on optimal leaf area development curve	0.01	fraction
FRGRW2	Fraction of growing season corresponding to 2nd point on optimal leaf area development curve	0.5	fraction
LAIMX2	Fraction of max LAI corresponding to 2nd point on optimal leaf area development curve	0.95	fraction
DLAI	Fraction of growing season when leaf area declines	0.9	heat units per heat units
CHTMX	Max canopy height	2	m
RDMX	Max root depth	2	m
T_OPT	Optimal temperature for plant growth	30	degrees C
T_BASE	Minimum temperature for plant growth	10	degrees C
CNYLD	Normal fraction of nitrogen in yield	0.02	kg N per kg seed
CPYLD	Normal fraction of phosphorus in yield	0.0025	kg P per kg seed
BN1	N uptake #1: normal fraction of N in plant biomass at emergence	0.01	kg N per kg biomass
BN2	N uptake #2: normal fraction of N in plant biomass at 50% maturity	0.004	kg N per kg biomass
BN3	N uptake #3: normal fraction of N in plant biomass at maturity	0.003	kg N per kg biomass
BP1	P uptake #1: normal fraction of P in plant biomass at emergence	0.0014	kg P per kg biomass
BP2	P uptake #2: normal fraction of P in plant biomass at 50% maturity	0.0008	kg P per kg biomass
BP3	P uptake #3: normal fraction of P in plant biomass at maturity	0.0006	kg P per kg biomass
WSYF	Lower limit harvest index	0.01	kg ha^{-1} per kg ha^{-1}]
USLE_C	Minimum value of USLE C factor for water erosion applicable to plant	0.1	—
GSI	Maximum stomatal condutance at high solar radiation and low pressure deficit	22.5	m s^{-1}
VPDFR	Vapor pressure deficit corresponding to 2nd point on stomatal conductance curve	1	kPa
FRGMAX	Fraction of max stomatal conductance corresponding to 2nd point on stomatal conductance curve	0.75	fraction
WAVP	Rate of decline in radiation use efficiency per unit increase in vapor pressure deficit	8	rate
CO_2HI	Elevated CO_2 atmospheric concentration corresponding the 2nd point on the radiation efficiency curve	660	ml L^{-1}
BIOEHI	Biomass-energy ratio corresponding to the 2nd point on the radiation efficiency curve	40	ratio
RSDCO_PL	Plant residue decomposition coefficient	0.05	fraction
ALAI_MIN	Minimum LAI for plant during dormant period	0.01	m^2 m^{-2}
BIO_LEAF	Fraction of tree biomass converted to residue during dormancy	0.3	fraction
MAT_YEARS	Number of years required for tree to reach full development	2	years
BMX_TREES	Maximum biomass for a forest (0 to 5,000)	1	t ha^{-1}
EXT_COEF	Light extinction coefficient (0 to 2)	0.5	–

al. 2002). To account for deficit irrigation strategies, vineyards were irrigated when the water stress factor (W_STRS) fell below 0.75 (Chaves et al. 2007; Williams 2001).

Results and Discussion

Soil and Water Assessment Tool Model Flow Calibration. For comparisons to measured stream gauge flows, SWAT was run at the daily time step from January 1958 to March 2007. This allowed for a two-year initialization period before the first date of streamflow comparison and extended SWAT results to the most recent date for which climate data was available at all three stations. The SWAT model output was checked against six USGS streamflow gauges in the watershed. Two of these gauges are located along Santa Rosa Creek (SRC 11466320 and 11465800), two along the Laguna de Santa Rosa channel (LSR 11465680 and 11465750), one at the base of Colgan Creek (CC 11465700), and one at the outlet gauge on Mark West Creek (MWC 11466800) (figure 1).

For each gauge, the coefficient of determination (r^2) value was calculated to evaluate relationship between measured gauge and modeled flow, and Nash-Sutcliffe efficiency (E_{NS}) was used to compare modeled to measured flow values along the 1:1 line (Nash and Suttcliffe 1970). As a general rule, r^2 and E_{NS} values greater than 0.5 are considered acceptable in watershed simulations (Moriasi et al. 2007). At the monthly time step, we found that the precalibrated model preformed very well at all gauges, with r^2 values ranging from 0.81 in the upper LSR, to 0.92 along the SRC west of Santa Rosa at Willowside Road. Nash-Sutcliffe values ranged from 0.71 to 0.91 at the same gauges, respectively.

Table 2

Parameters used in Latin Hypercube–One factor At a Time (LH-OAT) sensitivity analysis.

Rank	Parameter	Description	Minimum	Maximum	Varied by
1	Cn2	SCS runoff curve number for moisture condition II	–25	25	Percent
2	Gwqmn	Threshold depth of water in shallow aquifer required for return flow to occur (mm)	0	2,400	Replaced value
3	Esco	Soil evaporation compensation factor	0	1	Replaced value
4	Sol_Z	Soil depth	–25	25	Percent
5	Rchrg_Dp	Groundwater recharge to deep aquifer (fraction)	0	1	Replaced value
6	Slope	Average slope steepness (m m^{-1})	–25	25	Percent
7	Gw_Revap	Groundwater 'revap' coefficient	0.02	0.2	Replaced value
8	Revapmin	Threshold depth of water in the shallow aquifer required for "revap" to occur (mm)	0	500	Replaced value
9	Sol_K	Soil conductivity (mm h^{-1})	–25	25	Percent
10	Alpha_Bf	Baseflow Alpha factor (days)	0	1	Replaced value
11	Surlag	Surface runoff lag coefficient	0	10	Replaced value
12	Ch_K2	Effective hydraulic conductivity in main channel alluvium (mm h^{-1})	0	150	Replaced value
13	Ch_N	Manning coefficient for channel	0.01	0.5	Replaced value
14	Gw_Delay	Groundwater delay (days)	–10	10	Add to value
15	Slsubbsn	Average slope length (m)	10	150	Replaced value
16	Epco	Plant evaporation compensation factor	0	1	Replaced value

A sensitivity analysis was conducted to identify the most meaningful SWAT parameters for the Laguna watershed and to avoid over-parameterization of the model. We selected the LH-OAT (Latin Hypercube–One factor At a Time) method, which has recently been embedded in the ArcSWAT GIS interface and is described in Van Griensven et al. (2006). The parameters and value ranges chosen for the sensitivity analysis are listed in table 2. The top-ranked seven of seventeen flow-related parameters included the surface runoff curve number (CN2), water depth in the shallow aquifer required for return flow to occur (GWQMN), soil evaporation compensation factor (ESCO), soil depth (SOL_Z), the fraction of percolation from the root zone that recharges the deep aquifer (RCHRG_DP), average slope steepness (SLOPE), and the groundwater "revap" coefficient (GW_REVAP). A GW_REVAP of 0 indicates that water in the shallow aquifer is restricted from the root zone. As the value approaches 1, the transfer of water to the root zone approaches the rate of potential evapotranspiration (PET) (Neitsch et al. 2002).

Beginning with the most sensitive parameters, we made several calibration and gauge comparison iterations and found that r^2 and E_{NS} values were most improved when RCHG_DP was increased from 0.05 to 0.3, and GW_REVAP was increased from 0.02 to 0.1. These parameter adjustments largely corrected the most consistent pattern of model error (table 3), which was elevated flow during the seasonal recession period (figure 3). It appears, therefore, that increasing the groundwater aquifer capacity is a more accurate representation of the actual subsurface hydrology in the Laguna watershed than the original SWAT input parameter values would indicate. Adjusting parameters other than RCHG_DP or GW_RVAP yielded mixed results over different years and gauges within the watershed. Therefore, these other parameters were left unchanged from their original settings.

Because the Laguna watershed is highly populated and intensively used for agriculture, we also investigated the effect of groundwater extraction on modeled flows. According to USGS records (USGS 2007), the groundwater extraction rate for Sonoma County in 2000 was 33 × 10^4 m^3 (88 million gal) per day. The population of Sonoma County in 2000 was 458,600. To roughly estimate the amount of groundwater extracted in the Laguna watershed, we calculated the per capita extraction rate, and then summed the amount of water extracted for the Laguna watershed based on the combined population of the cities of Santa Rosa, Rohnert Park, Cotati, and Sebastopol.

Table 3

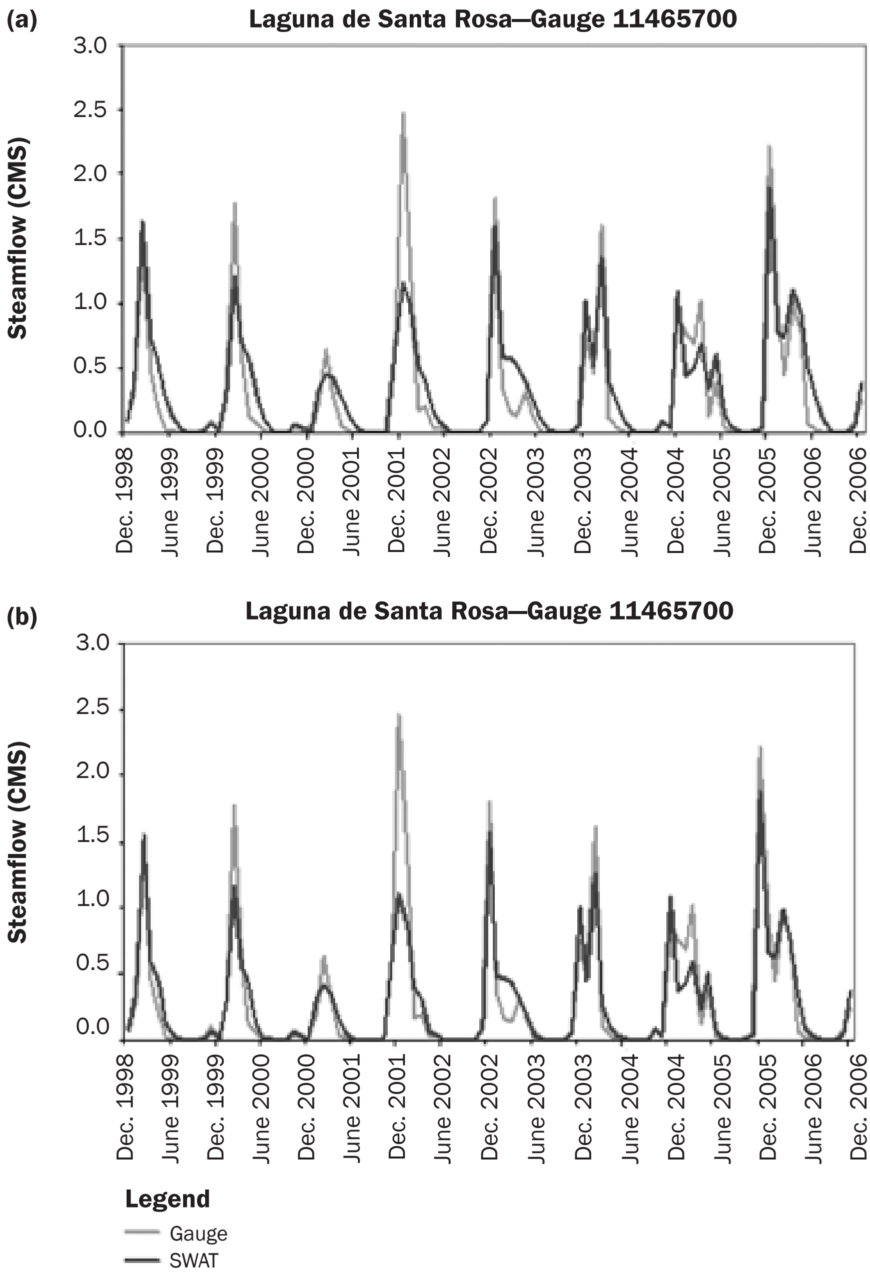
Performance of the Soil and Water Assessment Tool (SWAT) model for initial runs (I), flow calibration (FC), and groundwater extraction (GWE). Model errors by goodness of fit can be inferred from the Nash-Sutcliffe efficiency index (E_{NS}) values.

Gauge	Location	E_{NS} (I)	E_{NS} (FC)	E_{NS} (GWE)	r^2 (I)	r^2 (FC)	r^2 (GWE)
11465700	Colgan Creek	0.81	0.83	0.85	0.82	0.85	0.86
11465680	LSR Stony Point	0.74	0.86	0.84	0.86	0.90	0.91
11465750	LSR Sebastopol	0.76	0.85	0.83	0.87	0.89	0.90
11466320	SRC Willowside	0.92	0.93	0.94	0.93	0.94	0.95
11465800	SRC upstream	0.85	0.84	0.85	0.89	0.88	0.89
11466800	MWC at Trenton	0.81	0.82	0.84	0.84	0.83	0.86
—	Average	0.82	0.85	0.86	0.87	0.88	0.89

Notes: E_{NS} = Nash-Sutcliffe efficiency. r^2 = coefficient of determination. LSR = Laguna de Santa Rosa channel. SRC = Santa Rosa Creek. MWC = Mark West Creek.

Figure 3

Noncalibrated (a) and calibrated (b) predictions on the Laguna de Santa Rosa. The seasonal recession period is generally after April 30 of each year.



Notes: CMS = cubic meters per second. SWAT = Soil and Water Assessment Tool.

This method produced an extraction rate of 466×10^4 m^3 (1,230 million gal) per month, which was then distributed evenly across all 192 subbasins of the Laguna watershed for SWAT simulations.

Although this is a simplification of the groundwater extraction in the watershed, our approach resulted in notable increases to E_{NS} and r^2 values at all gauges except the upstream Santa Rosa Creek gauge (11465800), where very little change was observed (table 3). Hydrograph comparisons indicate that simulated groundwater extraction corrects modeled flow at the appropriate time of year, (after April 30 in figure 4) and has very little impact in upland areas where flow recessions were already a close match to measured flows (figure 5). Further modifications to flow-related parameters yielded mixed results, despite making soil type and land-cover specific adjustments.

As a final evaluation of SWAT flow prediction accuracies for certain extreme water years (starting in October to the following September), we compared relative error estimates for periods 2000 to 2001 (extreme low flow) and 2005 to 2006 (extreme high flow). As measures of model error by goodness of fit, Nash-Sutcliffe efficiencies and percent bias (*PBIAS*) values were calculated for the four gauge locations (11465700, 11465680, 11466320, 11465750) with records for these dates. The *PBIAS* measures the percent deviation between simulated and observed data, and is calculated as

$$PBIAS = \left[\frac{\sum_{i=1}^{n} (Y_i^{obs} - Y_i^{sim}) \times (100)}{\sum_{i=1}^{n} (Y_i^{obs})} \right] . \quad (2)$$

A negative *PBIAS* indicates that simulated values are higher than observed, and a positive *PBIAS* indicates that simulated values are lower than observed (Yapo et al. 1996; Moriasi et al. 2007).

At the monthly time step, the model generally performed better when flow rates were higher. The mean E_{NS} from the four gauges for the 2000 to 2001 water year was 0.84 and was 0.92 for the 2005 to 2006 water year. The SWAT model over-predicted flows during both periods, although more so when flow rates were low. The average *PBIAS* in 2000 to 2001 was –21.7, and the average for 2005 to 2006 was –11.2. The *PBIAS* errors were smallest at the Santa Rosa Creek gauge 11466320 (–2.6 in 2000 to 2001 and 8.3 in 2005 to 2006) and were greatest along the Laguna de Santa Rosa gauge 11465680 (–40.1 in 2000 to 2001 and –14.5 in 2005 to 2006).

Sediment Loading Predictions. Sediment discharge predictions from SWAT were compared with grab-sample measurements made on selected dates at gauge stations LSR 11465750 (n = 5), MWC 11466800 (n = 12), and SRC 11466320 (n = 5) (USGS 2007). In addition to having a limited number of sediment samples for calibration, considerable differences between predicted and observed flow rates on sediment sample collection dates further complicates sediment loading comparisons (table 4). For this reason, we focused our comparisons on suspended sediment concentrations (figure 6).

Moreover, we were primarily interested in the relative differences between land management options and were not trying to make any absolute claims about sediment concentrations in the streams as a function of land cover treatments.

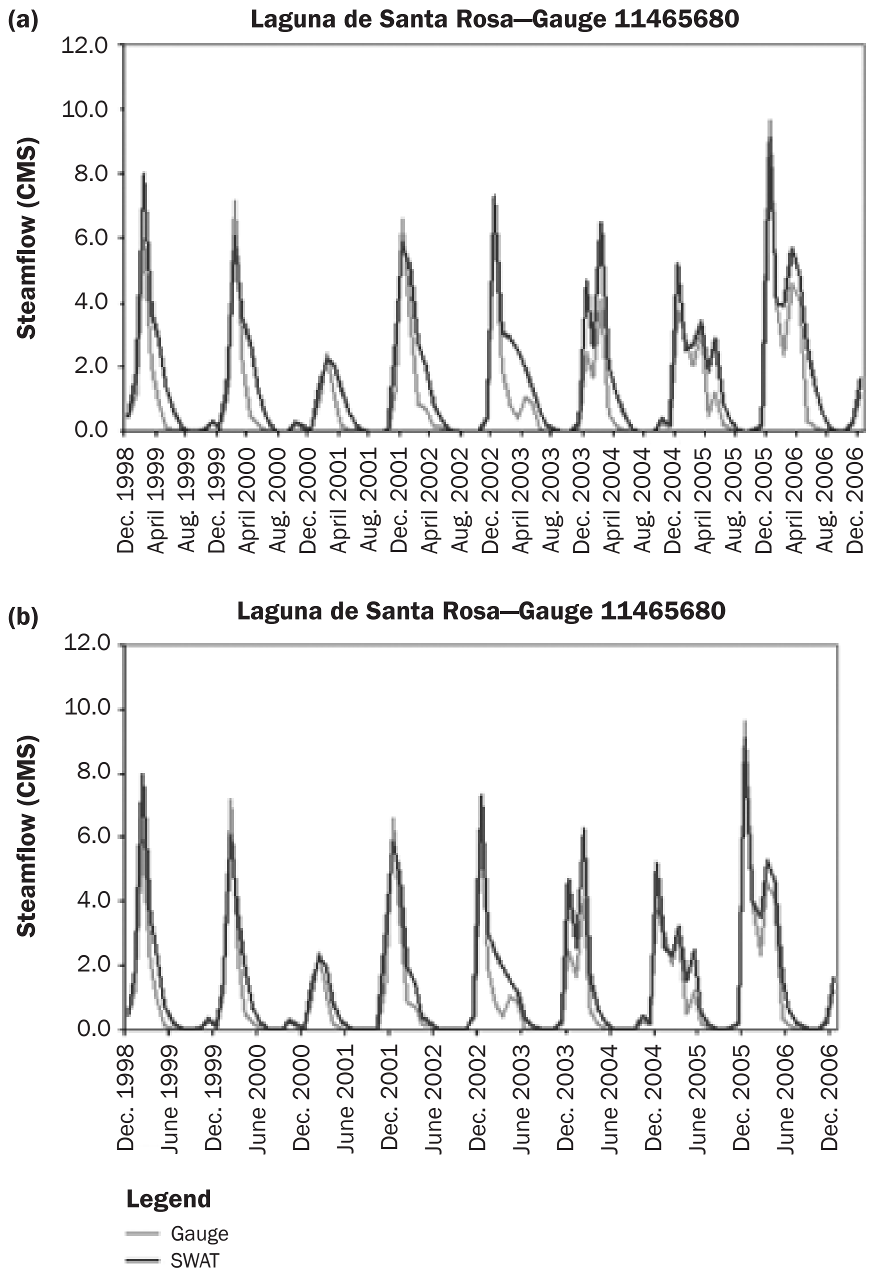
Simulated suspended sediment values on sample dates were lower than observed at all three gauges 11465750 (*PBIAS* = 52.6), 1146800 (*PBIAS* = 26.5) and 11466320 (*PBIAS* = 73.9). Nash-Suttcliffe efficiencies for flow ranged from –2.4 to 0.13, whereas for sediment concentrations, E_{NS} values were higher overall (–0.33 to 0.0). In the case of flow rates, comparisons with continuous data over a longer time period showed marked improvement in accuracy indices, which indicated the inherent difficulties in assessing whether a limited number of sample comparisons are adequate for evaluating sediment loading. Nevertheless, it appeared that SWAT may slightly under-represent sediment loading contributions in this drainage basin.

At the watershed scale, the average annual sediment loading rate predicted by SWAT from 2001 to 2006 was 3.66 t ha^{-1} (1.66 tn ac^{-1}). When sediment loading is averaged for HRUs by land cover type, vineyard and shrubland ranked highest (table 5). The predicted sediment loading rates averaged 19 t ha^{-1} (8.5 tn ac^{-1}) for vineyards and 10 t ha^{-1} (4.5 tn ac^{-1}) for shrubland, followed by grassland and mixed forest cover at 4.2 and 4.1 t ha^{-1} (1.9 and 1.8 tn ac^{-1}), respectively.

Subbasins with the highest loading rates were generally in steeper upland areas where rangeland or pasture was the dominant land use and shallow soils predominated with relatively low saturated hydraulic conductivity values in the top-soil layer. Based on the average annual values from 2003 to 2006, the Crane Creek subbasin had the highest total sediment loading rate at 13.7 t ha^{-1} (6.1 tn ac^{-1}) over 914 ha (2,260 ac). The HRU contributing the greatest amount of sediment in this subbasin was characterized as grassland with a mean slope of 22%.

The HRU contributing the highest loading per unit area (75.4 t ha^{-1} [33.7 tn ac^{-1}]) occurred along Mark West Creek, where vineyards were situated on hill slopes averaging 20%. Sediment discharge rates have been reported for nearby Napa County by the Resources Conservation District to range from 5 to 50 t ha^{-1} (2.2 to 22 tn ac^{-1}) on hill slopes (Battany and Grismer 2000). Edaphic or topographic conditions in the Laguna de Santa Rosa watershed may be responsible for relatively high rates of erosion in vineyards. However, due to the apparent sensitivity of sediment loading from vineyards to ground cover conditions (discussed further below), a small reduction to the recommended USLE factor of 0.1 may better represent ground cover in vineyard HRUs.

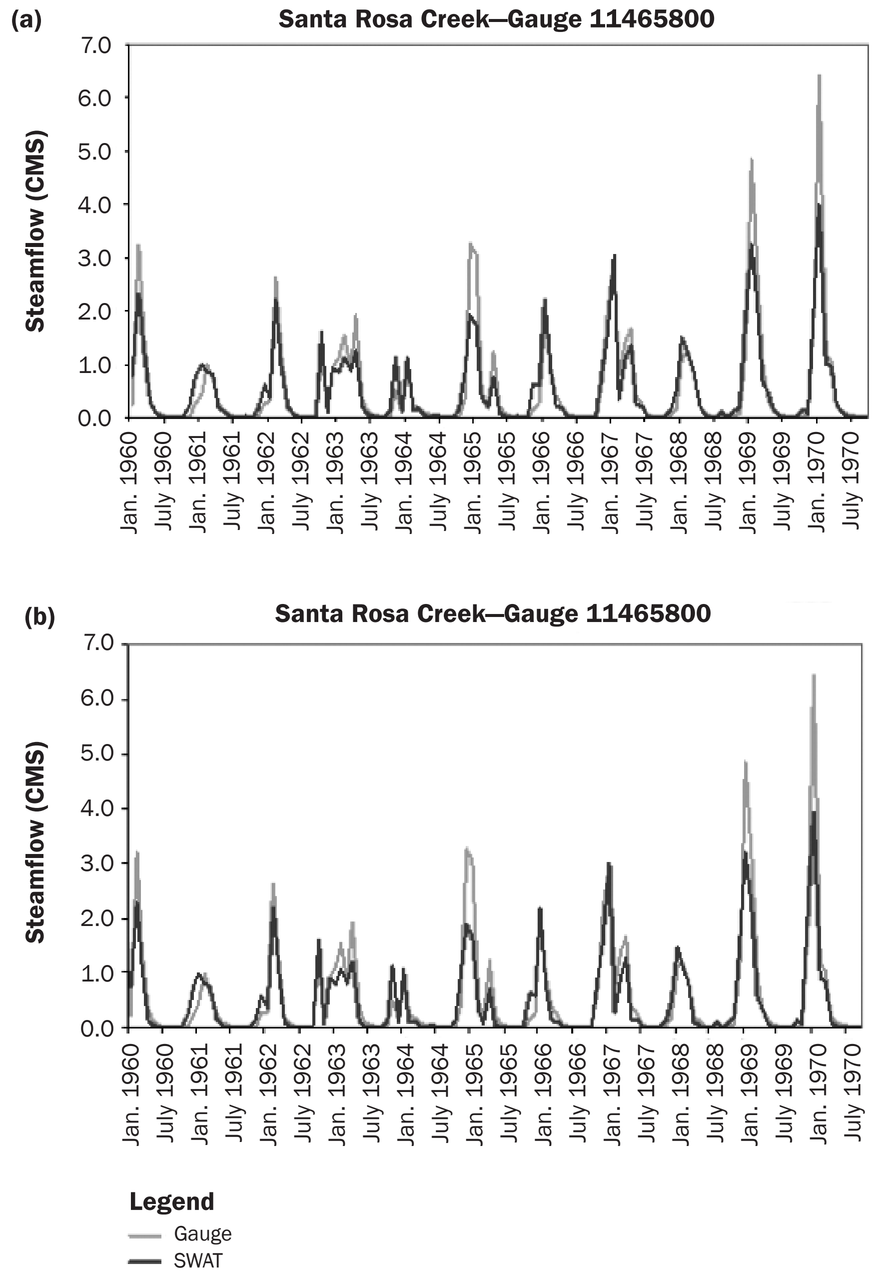
Figure 4
Laguna de Santa Rosa at Stony Point hydrograph recessions before groundwater extraction (a) and after (b).



Notes: CMS = cubic meters per second. SWAT = Soil and Water Assessment Tool.

Management Scenario Results. The SWAT simulations were run for vegetation filter strips placed in the model along HRUs where soil erosion was shown to be highest in previous simulations. Six-meter (20 ft) wide vegetation filter strips placed along the

Figure 5
Santa Rosa Creek hydrograph recessions (a) before groundwater extraction and (b) after (bottom).



Notes: CMS = cubic meters per second. SWAT = Soil and Water Assessment Tool.

boarder of vineyard and pasture HRUs captured an average of 62% of sediment entering the filter zone (table 6). For the watershed as a whole, filtering only vineyards resulted in a 17.8% reduction in sediment. When vegetation strips were set for pasture (USLE C = 0.03) only, average sediment loading was reduced by 10.3% (table 7).

Modifying the USLE C factor in SWAT to reflect establishment of Italian ryegrass ground cover (USLE_C = 0.03) reduced sediment loading in vineyard HRUs by 70%, which was somewhat more effective than establishing a 6 m (20 ft) wide vegetation strip. However, when ground cover was made to reflect healthy wheatgrass coverage (USLE_C = 0.003), reductions in sediment were more substantial, decreasing sediment load by 97%. In basin-wide results, a vineyard USLE_C of 0.03 reduced sediment by 19.9%. This reduction value was increased to 27.6% when USLE_C was set to 0.003. A moderate decrease in the quality of pasture (USLE_C = .03) produced approximately 200% more sediment discharge from pasture HRUs. In basin-wide results, this amounted to a 12% increase in average annual sediment loading for the watershed.

Summary and Conclusions

Surface water quality in the Laguna watershed has been significantly impaired over the past 150 years, as natural land cover has been urbanized and converted to agricultural uses. The watershed nevertheless remains one of northern California's most abundant wildlife habitats and is prioritized by local, state, and federal regulatory agencies for conservation and restoration. The Laguna watershed also serves as an important holding basin during the wet winter season and as an overflow area for the Russian River during major floods.

It is anticipated that future land use changes in the watershed could further alter hydrologic and sediment processes by changing runoff volumes and peak discharge rates. As what today are considered relatively extreme climate events become more common, increases in sediment production in the upper watershed and mobilization along channels are possible. This would have several adverse consequences, including increases in flood elevation on the Santa Rosa Plain for any given water discharge rate and frequent water back-up events into the tributaries, creating increased flood risk in the smaller Laguna subbasins.

This SWAT model application is but one of several studies that must be conducted to form the emerging scientific basis of an assessment framework for flood protection, ecosystem health, water quality, and water management in the Laguna de Santa Rosa watershed. Looking to the future, our results lead to several noteworthy findings that can be continuously evaluated in subsequent studies:

• Streamflow and sediment loading rates throughout the Laguna watershed can be accurately predicted for past years by the SWAT model.

• Groundwater aquifer capacity must be accurately represented in the Laguna watershed to correctly predict the seasonal recession period.

• Highest sediment loading rates have been associated historically with pasture, rangeland, and vineyard cover areas.

• Improvements to sediment and nutrient loading predictions may be possible with better information regarding grazing, tillage, irrigation, and other management operations, in concert with a longer record of sediment sampling.

New applications of the SWAT model for the Laguna watershed are planned, including settings to evaluate the historical capacity of the watershed to absorb or process pollutant runoff on the 100-year floodplain. We are also designing SWAT simulations for presettlement scenarios dating back to land cover conditions of approximately 150 years ago. Both of these types of applications should aid in prioritizing remediation options for contemporary pollution sources.

The SWAT model is also designed to run climate change scenarios. Regional climate studies indicate that California is likely to experience average annual temperature increases of 1°C to 2°C (3°F to 4°F) in the next century, with winters 3°C to 4°C (5°F to 7°F) warmer. Summer streamflow and soil moisture available for plant growth are likely to decrease (Field et al. 1999). El Niño conditions may occur more frequently in the future, bringing more extreme weather events. We plan to test all of these potential climate impacts on the Laguna watershed in simulations driven by a range of climate model predictions from global change studies.

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Table 4
The Soil and Water Assessment Tool (SWAT) sediment concentration comparisons with measured stream data.

Gauge	Statistic	Total sediment	Concentration	Flow rate
SRC 11466320	E_{NS}	−0.22	0	−0.11
	r^2	0.99	0.74	0.93
	PBIAS	98.4	73.9	88.1
MWC 11466800	E_{NS}	−0.13	−0.24	0.13
	r^2	0.17	0.51	0.18
	PBIAS	54	26.5	39.7
LSR 11465750	E_{NS}	0.41	−0.33	−2.41
	r^2	0.51	0.49	0.29
	PBIAS	15.6	52.6	−173.1

Note: *PBIAS = percent bias.*

Figure 6
Suspended sediment concentration from grab sample measurements and Soil and Water Assessment Tool (SWAT) model simulations: (a) Mark West Creek near Mirabel Heights, (b) Laguna De Santa Rosa near Sebastopol, (c), Santa Rosa Creek at Willowside.

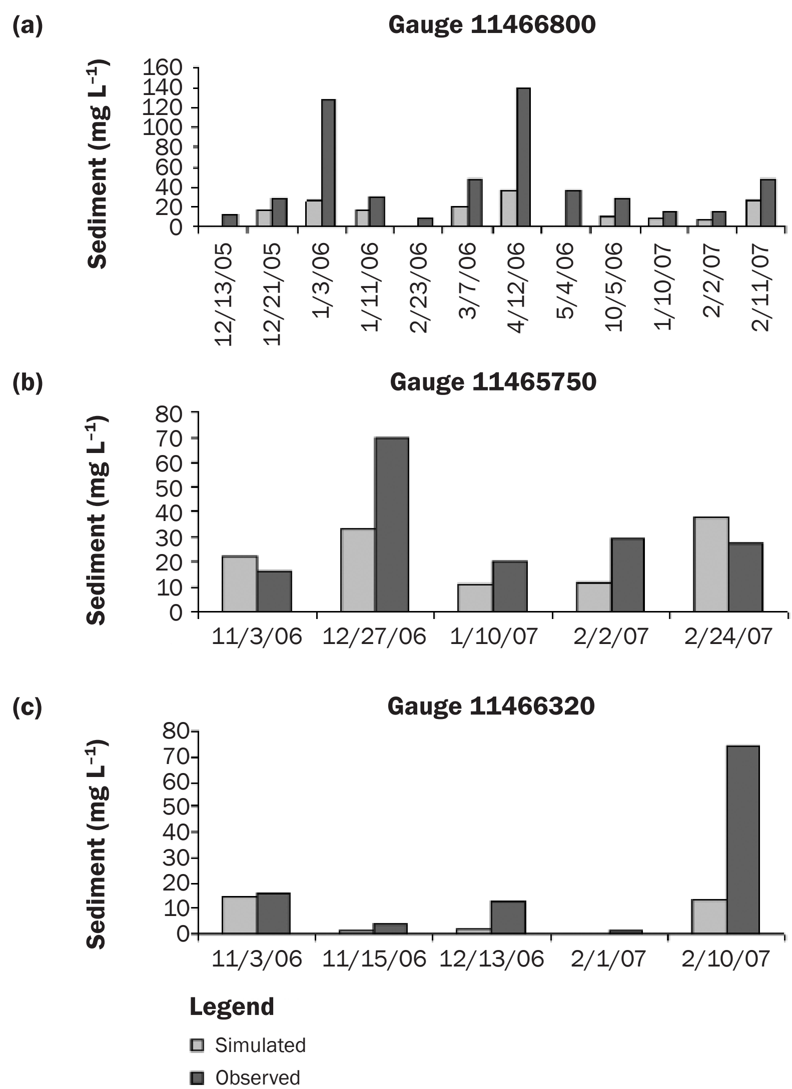

Table 5
Sediment contributions from Soil and Water Assessment Tool (SWAT) land cover classes, ranked by sediment yield rates.

Land use/cover	Sediment yield (t ha^{-1})
Vineyard	18.99
Shrubland	9.95
Grassland	4.21
Mixed forest	4.06
Pasture	1.54
Evergreen forest	1.45
Urban	1.05
Deciduous forest	0.92
Pasture (irrigated)	0.33
Orchard	0.01

Table 6
Sediment and nutrient transport results from Soil and Water Assessment Tool (SWAT) vineyard cover quality scenarios and one 6 m filter strip management scenario.

Vineyard	Soil yield (t ha^{-1})	Reduction organic P (%)	Reduction NO_3 (%)
Standard (USLE C = 0.1)	19.0	—	—
Cover same as spring wheat (ULSE C = 0.03)	5.7	48	–5
Cover same as pasture (ULSE C = 0.003)	0.58	93	–5
Standard with 0.1 with 6 m filter	7.1	62	63

Notes: P = phosphorus. NO_3 = nitrate.

Table 7
Sediment and nutrient transport results from Soil and Water Assessment Tool (SWAT) pasture cover quality scenarios and one 6 m filter strip management scenario.

Pasture	Soil yield (t ha^{-1})	Reduction organic N (%)	Reduction organic P (%)
Good condition	1.5	—	—
Degraded	4.7	–136	–142
Degraded with filter	1.75	12	9

Notes: N = nitrogen. P = phosphorus.

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