White Paper (f) Use of SWAT to Simulate Nutrient Loads and Concentrations in California

1 The SWAT Model

1.1 HISTORY

The Soil and Water Assessment Tool, version 2000 (SWAT2000) was developed by the USDA, ARS, and the Texas A&M Spatial Sciences Laboratory with funding from EPA and is incorporated into EPA's BASINS 3.0 water quality modeling system. SWAT, first developed in the early 1990s, is based directly on the Simulator for Water Resources in Rural Basins (SWRRB, Williams et al., 1985; Arnold et al., 1990) with features from several other ARS models, such as CREAMS (Chemicals, Runoff, and Erosion from Agricultural Management Systems) (Knisel, 1980), GLEAMS (Groundwater Loading Effects on Agricultural Management Systems) (Leonard et al., 1987), and EPIC (Erosion-Productivity Impact Calculator) (Williams et al., 1984).

SWAT has undergone a series of updates and improvements since its first release. In addition to revisions in model process representation, a complete ArcView GIS interface for the model was developed (Neitsch and DiLuzio, 1999) and subsequently incorporated into the EPA BASINS package (U.S. EPA, 2001). The SWAT model is available as a standalone at http://www.brc.tamus.edu/swat/swat2000.html, and as part of the BASINS package at http://www.epa.gov/waterscience/basins/b3webdwn.htm.

1.2 CHARACTERISTICS

SWAT (Neitsch et al., 2001) is a long-term, continuous watershed simulation model. This model simulates land cover impacts with weather, soil, topography, and vegetation data. The SWAT simulation and output is organized by Hydrologic Response Units (HRUs), which are areas with homogeneous land cover and soil properties.

Within SWAT, runoff is simulated separately for each HRU, aggregated to the sub-watershed level, and then routed to calculate total runoff and pollutant delivery. The model considers moisture and energy inputs, including daily precipitation, maximum and minimum air temperatures, solar radiation, wind speed, and relative humidity. SWAT simulates a complete set of hydrologic processes including canopy storage and evapotranspiration. It uses the Modified Universal Soil Loss Equation (MUSLE) to model erosion and sediment yield with runoff. MUSLE variables include aboveground biomass, residue on the soil surface, and the minimum C factor for each species. For sediment deposition and degradation, SWAT defines the maximum sediment transport from a reach segment as a function of peak channel velocity. SWAT simulates the nitrogen and phosphorus cycles, including plant uptake of nutrients and the mineralization of organic nutrients in plant residue. SWAT employs a detailed process-based simulation of plant growth and the effects of plant cover on nutrient balances, making it a useful candidate for evaluating unimpacted nutrient balances. The model differentiates between annual and perennial species as well as woody and non-woody species.

SWAT is particularly well suited for application to large river basins in semi-arid western areas, and has seen many applications to such systems. It has the advantage of describing processes using methods for which parameter information is readily available, such as use of the SCS Curve Number approach as the starting point for surface runoff calculations and a (Modified) USLE approach for erosion. This facilitates efficient extraction of parameters from land use and soil coverages. It also differs from simpler watershed loading functions in a number of important ways, most notably including a full simulation of instream flow and transport (including diversions and transmission losses) and simulation of irrigation. The model provides continuous simulation on a daily time step.

In comparison to other commonly used watershed models, SWAT has the following advantages:

- SWAT explicitly incorporates elevation or orographic effects on precipitation and temperature.
- SWAT was developed for and has been widely applied to simulation of watersheds in arid regions.
- SWAT explicitly incorporates routines for agricultural diversions and irrigation.
- SWAT includes routines designed to address the impacts on flow and pollutant loading of multiple small (or large) farm ponds within a basin.
- SWAT is designed to use either observed meteorological data or statistically generated meteorology, facilitating the development of long-term analyses.

Because the model is physically based and uses commonly available geographic data, it is claimed “Watersheds with no monitoring data…can be modeled”, allowing the efficient evaluation of “relative impact of alternative input data (e.g., changes in management practices, climate, vegetation, etc.) on water quality…” (USEPA CREM, 2004).

1.3 STRUCTURAL LIMITATIONS

While SWAT is a process-based model, it intentionally incorporates simplified representations of most processes so that many parameters can be obtained from readily available geospatial coverages. For upland generation of flow and sediment, SWAT relies on the well-tested, semi-empirical approaches of the SCS Curve Number and MUSLE. The basic time step of the model is one day (although hydrology can be simulated at a finer scale using Green-Ampt infiltration); so actual flow hydrographs are not represented. The MUSLE approach is most applicable to the estimation of cumulative loads, rather than loads from individual events. It should also be noted that the default SWAT algorithm may yield unrealistic results from HRUs that contain a mix of urban pervious and impervious land cover because MUSLE is calculated with the peak flow from the entire HRU, using a weighted curve number, and not from the flow from the pervious section. This is equivalent to assuming that all impervious area runoff proceeds as sheet flow across the pervious sections, rather than being piped or channelized, and can result in a significant over-estimation of sediment load from developed areas.

In SWAT, nutrients in dissolved and sorbed form are moved from uplands to streams with water and sediment, respectively. Nutrient balances in the soil (as well as the cover index for erosion calculations) are determined by the results of plant growth simulation – which is considerably more complex and difficult to validate. At best, the nutrient loads predicted by the model should also be considered as estimates of cumulative yield, rather than loads from individual events.

Routing within streams adds further limitations to SWAT predictions. Because both upland loads and instream routing are simulated at a daily time step, the model will not provide an accurate representation of intra-event concentrations of even conservative constituents in streams with rapid, “flashy” responses. Nutrient kinetic transformations in the stream were added to SWAT in 1996. The approach taken was to implement the kinetic description contained in the documentation for the QUAL2E model (Brown and Barnwell, 1987). The model tracks nutrients dissolved in the stream and nutrients adsorbed to the sediment. Dissolved nutrients are transported with the water while those sorbed to sediments are allowed to be deposited with the sediment on the bed of the channel. However, it is important to recognize that the current implementation of SWAT does not actually evaluate the time derivatives described in the theory. Rather (in subroutine watqual.f), the routing time for nutrients in a reach is forced to be equal to one day. This means that rate constants are actually implemented as step-function reductions. For instance, if a nutrient transformation rate is 40 percent per day, then 40 percent of the influent nutrients will be lost during transport through a reach, regardless of the actual travel time.

As a result of these compromises, the instream concentrations reported by SWAT are not necessarily realistic representations of expected concentrations. Further, the mass transport through reaches of nonconservative parameters will be realistic only when the reach travel time approximates one day.

2 Selection of SWAT for California Background Nutrient Load Evaluation

2.1 PILOT PROJECT EVALUATION NEEDS

The SWAT model was selected for the Ecoregion 6 pilot study as one among several lines of evidence to evaluate unimpacted background concentrations and loads of nutrients, where “unimpacted” refers to natural vegetative cover without point source loads. The unimpacted background is important because it establishes a baseline for nutrient criteria. Another important line of evidence for unimpacted background is obtained from observations at unimpacted reference sites. However, truly unimpacted reference sites may be difficult to locate in some regions. In addition, significant variability in nutrient dynamics at potential reference sites may occur due to variability in soils, slopes, precipitation, and vegetation type. Watershed modeling is expected to provide a basis for examining how background loads and concentrations may vary with these and other controlling factors.

SWAT was selected for the upland simulation based on the desirable characteristics cited in the previous section: the model uses readily available geospatial databases, is intended for uncalibrated application, and accounts for differences due to land cover type. In the pilot project, SWAT was applied to smaller headwater watersheds only. The instream transport components were not used, due to concerns identified above. Instead, load generation by SWAT was combined with the empirical transport component of the USGS SPARROW model (Smith et al., 1997) to provide an evaluation of accumulated nutrient delivery through larger watersheds.

2.2 PREVIOUS EXPERIENCE

SWAT has received wide application in recent years, and a bibliography is available at http://www.brc.tamus.edu/swat/swat-peerreivewed-publications.htm. For example, SWAT has been applied to water balance studies of the entire contiguous United States (Arnold et al., 1999), using only geospatial data available at the 1:125,000 scale, and generally produced adequate results. The application did tend to underpredict runoff in mountainous areas (probably due to orographic effects).

Water quality applications with SWAT have been less thoroughly tested and peer reviewed. Santhi et al. (2001) recently reported on the successful calibration and validation of a SWAT model for sediment and nutrients for the Bosque River watershed in Texas. This was a calibrated application to a 4300 km^2 watershed dominated by pasture, range, and row crop land uses. The validation focuses on monthly cumulative load delivery, apparently reflecting the fact that point-in-time concentration estimates are less reliable.

The Tetra Tech team also had experience with the SWAT model. Of most relevance to simulation in the arid southwest was development of a complete hydrologic, sediment, and nutrient model of the 5500 square mile Verde River watershed in central Arizona (Tetra Tech, 2001). This application achieved an excellent hydrologic calibration and what appeared to be a good representation of nutrient loading from a wide variety of natural vegetation covers.

SWAT simulations of nutrient loading at the scale of 6-digit hydrologic units have been developed as part of the Hydrologic Unit Model for the United States (HUMUS) project (Srinivasan et al., 2000). Maps of predicted nitrogen and phosphorus yield (as kg/ha) are available in an online presentation (http://srph.brc.tamus.edu/humus/slides/index.html), but do not appear to have been formally published or validated against data. These are reproduced below (Figure 1 and Figure 2).

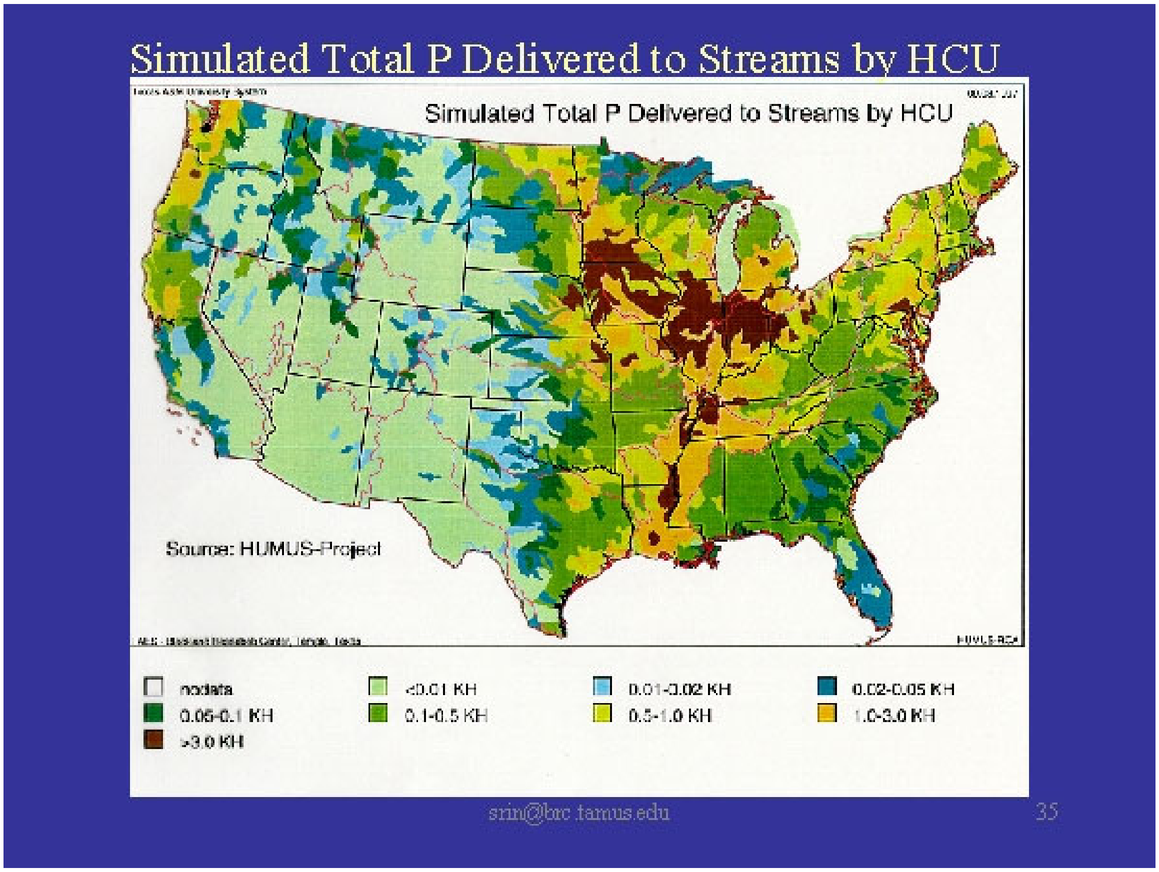

Figure 1. SWAT/HUMUS Predictions of Phosphorus Yield

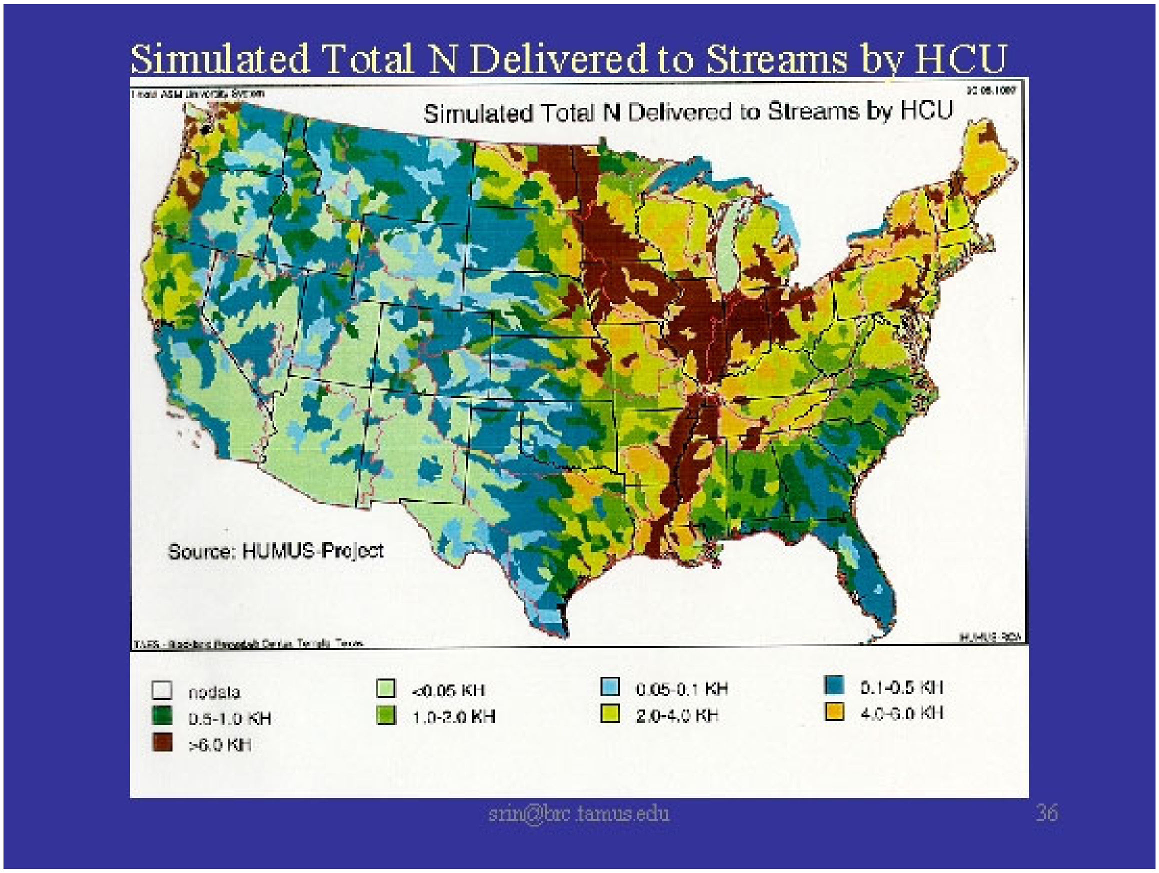

Figure 2. SWAT/HUMUS Predictions of Nitrogen Yield

3 SWAT Application and Validation Results

3.1 APPLICATION TO ECOREGION 6

SWAT applications for natural background load estimation in Ecoregion 6 were initially documented in the 2003 Progress Report (Tetra Tech, 2003), and have since been further revised. Initial applications of SWAT used California land cover (derived from the GAP analysis), California soils (STATSGO), California meteorological stations, and an appropriate Digital Elevation Model. The BASINS-SWAT interface with used to generate all input files, with only minor modifications. This approach was consistent with the intention of using SWAT as a tool that enables rapid evaluation without detailed, site-specific calibration. Nonetheless, some manual adjustment of the parameters produced by the interface was required.

3.1.1 Physical/Chemical Parameters

Several groups of SWAT input must be input manually, as follows:

Elevations and Lapse Rates

In areas of high relief, precipitation and temperature can vary significantly with elevation. SWAT can simulate these effects using lapse rates, but does not set these up by default. To activate this simulation it is necessary to specify an "elevation band" and associated parameters as follows:

Table 1. Augmented input for elevation and lapse rates.

Description	Input	File	Default	Revised
Elevation at the center of the elevation band (m)	ELEVB(1)	.sub	Optional	ELEV
Fraction of subbasin area within elevation band	ELEVB_FR(1)	.sub	Optional	1.00
Precipitation lapse rate (mm/km)	PLAPS	.sub	0.0	1.06
Temperature lapse rate (°C/km)	TLAPS	.sub	0.0	-6.00

Groundwater and Rainfall Nutrient Concentrations

Significant nutrient fluxes – particularly for nitrate – may occur via groundwater pathways. SWAT simulates shallow (only) groundwater flow, but does not calculate nutrient mass balances in groundwater. The SWAT user must specify the nitrate and phosphate concentrations in ground water, otherwise they default to zero.

Shallow groundwater concentration data are difficult to locate. The United States Geologic Survey maintains a database on the Internet (USGS, 2004) that the user can query by county, hydrologic unit, period of record, and well depth, among other attributes. However, well depths are typically large (as the focus is on potable water supplies), and so the data may not be representative of groundwater contributions to streamflow. Further, the concentration discharged into streams is often less than the concentration in adjacent ground water due to biological uptake in stream sediment.

For the validation study, the same approach as that performed for the pilot project was used. Here, the concentration of nutrients in the groundwater contribution to stream flow was determined from California monitoring data for minimally impacted steams during base flow periods. The resultant average values were 0.03 mg N/L for nitrate concentration and 0.01 mg P/L for soluble phosphorus concentration. In fact, base flow concentrations may differ significantly from stream to stream, and use of a regional average value may contribute significantly to uncertainty in model predictions of nutrient concentrations. Further information on research performed for groundwater concentration data is presented in Section 4 below.

SWAT also simulates the contribution of nitrate in rainfall. Only nitrate flux (not ammonium) is simulated, and this is added directly to the soil moisture profile, not partitioned into runoff. The SWAT interface defaults this concentration to 1 mg/L. Information on atmospheric deposition of nitrogen was gathered from the National Atmospheric Deposition Program (NADP, 2004). Isopleth maps of year 2002 nitrate ion concentration and ammonium ion concentration were downloaded from the NADP website. The maps provided data for six monitoring stations located in the state of California. Nitrate and ammonium concentration data was converted to concentration as nitrogen values and then summed to provide a total nitrogen concentration at each station. Data from four stations in the Central Valley were averaged to provide an estimate of loading from areas impacted by urban and agricultural land. Data from one station located at the northern California border was used to provide an estimate of loading to coastal areas unimpacted by urban and agricultural land. The final values used in the validation modeling were 0.30 mg N/L for the Central Valley and areas east, and 0.10 mg N/L for coastal areas, as shown in Table 2 below.

Table 2. Augmented input for groundwater and rainfall nutrient concentrations

Description	Input	File	Default	Revised
Ground Water Nitrate Concentration (mg N/L)	GW_NO3	.gw	0.0	0.03
Ground Water Soluble Phosphorus Concentration (mg P/L)	GWSOLP	.gw	0.0	0.01
Concentration of nitrate in rainfall (mg N/L)*	RCN	.bsn	1.0	0.1 coastal; 0.3 central valley

Kinetic Factors

Several kinetic factors also required correction (Table 3). The soil compensation factors (which control the distribution by soil layer of withdrawal of water and phosphorus by plants) need to be updated from the default of zero to values that are more appropriate for arid climates with deep-rooted plants. Finally, the rate factor for humus mineralization of organic nitrogen appears to be set improperly by the interface to 0.003, whereas the manual states that the default should be 0.0003.

Table 3. Augmented input for kinetic factors

Description	Input	File	Default	Revised
Soil Evaporation Compensation Factor	ESCO	.hru	0	0.5
Plant Uptake Compensation Factor	EPCO	.hru	0	1.0
Rate factor for humus mineralization of active organic nitrogen *	CMN	.bsn	0.003	0.0003[2]

3.1.2 Land Cover/Crop Database

SWAT simulates the removal of water and nutrients from the root zone, transpiration, and biomass yield production based on the combination of soils and the biophysical properties of the land cover. The primary purpose of the SWAT application is to estimate nutrient loading characteristics under natural conditions of native vegetation cover in Ecoregion 6. Although it is a single ecoregion, native vegetation shows considerable variability within the ecoregion, and it is important to specify vegetation types that match the site-specific conditions. Such information is provided by the California GAP Analysis. The GAP land use dataset developed from satellite flyover analyses in the early 1990s was used to estimate the distribution of land cover within each delineated watershed. Human influenced land uses (e.g., urban areas, agricultural land) in the watersheds were converted to undisturbed cover for simulation of unimpacted watersheds.

The National Gap Analysis Program (GAP) has developed this data to provide detailed information on the distribution of common species (USGS, 2003). The data for California provides a list of co-dominant species and habitat type for each small-scale polygon. It provides more detailed information about vegetation type compared to MRLC land cover data. About 5 to 10 polygons were found within each reference watershed.

The SWAT input parameters required to simulate the biophysical processes of each land cover are shown in Table 4.

Table 4. Input Variables for the SWAT Land Cover/ Plant Growth Database

Variable	Description
BIO_E*	Radiation use efficiency in ambient CO2 (kg/ha)/(MJ/m2)
HVSTI	Potential harvest index for the plant at maturity given ideal growing conditions
BLAI*	Potential maximum leaf area index for the plant
FRGRW1	Fraction of the growing season corresponding to the 1st point on the optimal leaf area development curve
LAIMX1	Fraction of the maximum plant leaf area index corresponding to the 1st point on the optimal leaf area development curve
FRGRW2	Fraction of the growing season corresponding to the 2nd point on the optimal leaf area development curve
LAIMX2	Fraction of the maximum plant leaf area index corresponding to the 2nd point on the optimal leaf area development curve
DLAI	Fraction of growing season at which senescence becomes the dominant growth process
CHTMX*	Plant's potential maximum canopy height (m)
RDMX*	Maximum rooting depth for plant (mm)
T_OPT*	Optimal temperature for plant growth (C)
T_BASE*	Minimum temperature for plant growth (C)
CNYLD	Fraction of nitrogen in the yield
CPYLD	Fraction of phosphorus in the yield
BN1*	Normal fraction of nitrogen in the plant biomass at emergence
BN2*	Normal fraction of nitrogen in the plant biomass at 50% maturity
BN3*	Normal fraction of nitrogen in the plant biomass at maturity
BP1*	Normal fraction of phosphorus in the plant biomass at emergence
BP2*	Normal fraction of phosphorus in the plant biomass at 50% maturity
BP3*	Normal fraction of phosphorus in the plant biomass at maturity
WSYF	Harvest index for the plant in drought conditions, the minimum harvest index allowed for the plant
USLE_C	Minimum value of USLE C-factor applied to the land cover or plant
GSI	Maximum stomatal conductance in drought conditions
VPDFR	Vapor pressure deficit corresponding to the fraction maximum stomatal conductance defined by FRGMAX
FRGMAX	Fraction of maximum stomatal conductance that is achievable at a high vapor pressure deficit
WAVP	Rate of decline in radiation-use efficiency per unit increase in vapor pressure deficit

	(kg/ha)/(MJ/m2)
CO2HI	Elevated CO2 atmospheric concentration (ppmv)
BIOEHI	Radiation use efficiency at elevated CO2 atmospheric concentration value for CO2HI (kg/ha)/(MJ/m2)
RSDCO_PL	Plant residue decomposition coefficient

* The literature search focused on these variables.

To simulate the growth of Southern California vegetation, each land cover class required the input variables listed in Table 4. Therefore, each GAP polygon needed a unique land cover identifier associated with a series of input variables. The GAP species and plant types were aggregated into thirteen groups according to genus and plant type, and each genus-plant type had one set of SWAT input values. The genus-plant types were chosen so that each type included at least one species with SWAT input variables. The thirteen genus-plant types are the following:

1. Chaparral-Adenostoma
2. Chaparral-Arctostaphylos
3. Chaparral- Buckbrush (Ceanothus)
4. Chaparral- Hoaryleaf ceanothus
5. Chaparral- Desert ceanothus
6. Chaparral-Scrub Oak
7. Chaparral- Mountain mahogany
8. Chaparral- Sugarbush
9. Scrub-Shrub
10. Conifer
11. Hardwood-Blue Oak
12. Hardwood-Coast Live Oak
13. Herbaceous

The input values were acquired from the SWAT Land Cover/ Plant Growth database and from literature values obtained for individual species. SWAT provided default values for several of the variables listed in Table 4. The SWAT Land Cover/ Plant Growth database also contained input values for pine, oak, poplar, and honey mesquite trees as well as the more general deciduous, mixed, and evergreen forest classes. The GAP data defined annual grassland as including *Avena* and *Bromus* species; for this land cover, the SWAT input values for *Avena sativa*, *Bromus inermis*, and *Bromus biebersteinii* can be used.

The estimation of input values focused on radiation use efficiency, height, root depth, leaf area index, base and optimal growth temperatures, and nutrient biomass concentrations. A literature search was conducted for key species. Maximum heights were found for all species. Leaf area indices for most species were acquired, and several values for rooting depth and nutrient biomass concentration were found. According to the literature search and personal communication with SWAT co-developer Jim Kiniry, the literature does not provide estimates of radiation use efficiency (RUE; in biomass units) for the Southern California species. With Dr. Kiniry's advice, Tetra Tech estimated RUE by comparing leaf area indices of Southern California species with other species for which RUE values were available.

3.2 VALIDATION RUNS

Results from uncalibrated SWAT applications to nine watersheds in Ecoregion 6 were reported in Tetra Tech (2003), and a number of additional watersheds were modeled subsequently. Results appeared generally reasonable, but some problems were noted, particularly in apparent over-estimation of erosion. It is important, however, to go beyond these qualitative comparisons to examine with greater rigor whether results provided by the model are reasonable. To this end, a validation process was attempted. The validation exercise considered two lines of evidence: comparison to monitored data from unimpacted streams, and comparison of SWAT results to other regional estimates of nutrient loads.

Comparison of model results to monitored data for small, unimpacted watersheds would provide the strongest test of model performance; however, ability to conduct such tests is hampered by data availability. In California, the majority of streams that have been intensively monitored are impacted streams that have extensive agricultural or urban land use and/or hydrologic modification. Much of the monitoring is focused downstream of point sources, which is useful for evaluating wasteload allocations, but of limited use for assessing unimpacted background loads. Where unimpacted streams are monitored, the data are often sparse and intermittent, and frequently do not include a complete representation of nutrient species. This presents a particular problem for comparison to SWAT, where we expect the long-term loads of total nutrients to be more accurate than estimates of the concentration of individual nutrient species.

A typical situation (for watershed 3133) is shown in Figure 3. Observed data are available only for a little over two years, high flow events are under-represented, and there are many non-detects in the data – all of which are problematic for comparison.

An alternative source of information on expected concentrations and loads is provided by the SPARROW work conducted by USGS (Smith et al., 2003; Smith et al., 1997). The complete SPARROW model includes empirical regression models of upland load generation, based on detailed analysis of USGS NASQAN data. Two versions are available. Smith et al. (2003) present estimates of upland loading that are based on runoff regime, a regional indicator, and a correction for atmospheric deposition of nitrogen. Smith et al. (1997) provide a more complex approach in which the nutrient yield from the land surface is a function of fertilizer application, livestock waste production, atmospheric deposition, area of nonagricultural land, while delivery to water depends on soil permeability, stream density, and (for nitrogen only) average temperature. While calibrated to similar data sets, the two estimators can produce rather different results for individual watersheds.

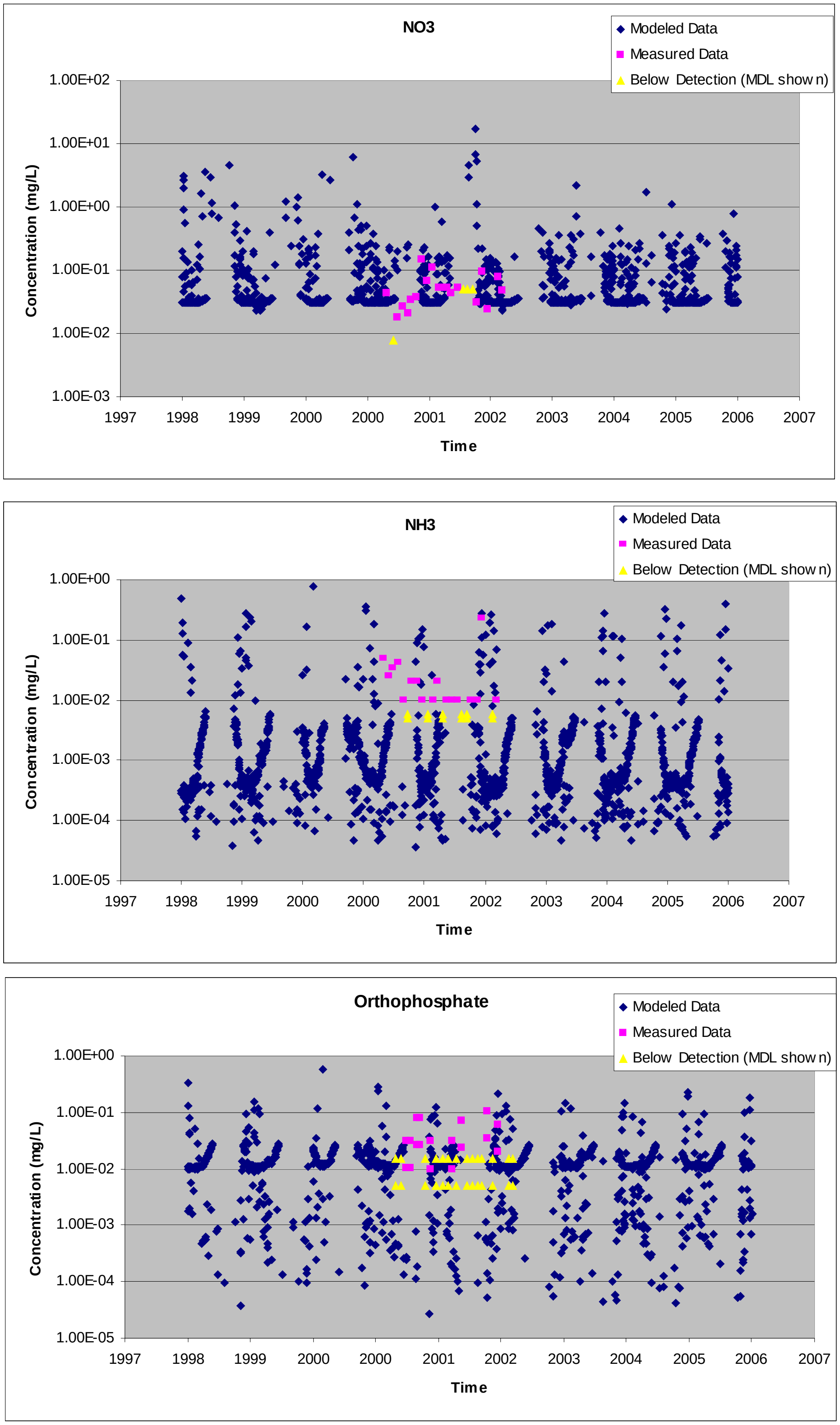

Figure 3. **SWAT Model Output and Monitoring Data for Watershed 3133**

3.2.1 Selection of Validation Watersheds

Validation watersheds were chosen in a manner consistent with the pilot study, in which the SWAT model was used to simulate loadings from small headwater watersheds in unimpacted areas. To this end, validation watersheds were chosen based on their size (ideally 10,000 to 40,000 acres) and their location in areas unimpacted by urban or agricultural loads. Additionally, watersheds were chosen to provide a representative sample across Ecoregion 6 and where there were as many monitored data points as possible. Six validation watersheds were chosen for the study; their locations are shown in Figure 4.

Most of the monitoring stations for which large data sets were available are located on impacted streams, as discussed above. Excluding these watersheds left a much smaller subset of stations from which to choose, so in some cases the above criteria were violated. For example, watershed 455 is 128,000 acres, but was included in the validation subset because it was the only possible station choice located in the Sierra Nevada foothills. The final set of validation watersheds was chosen by balancing the above criteria.

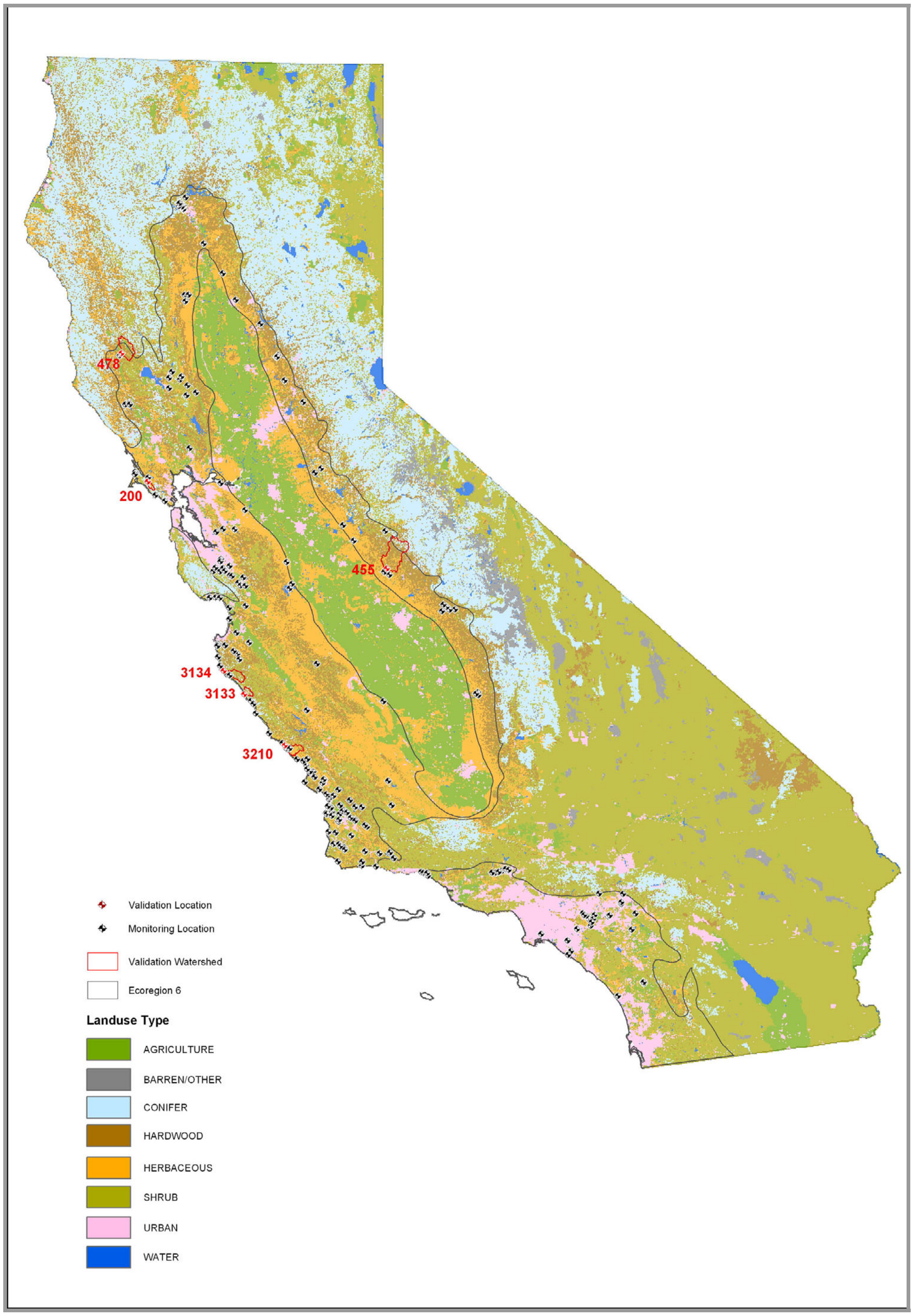

Figure 4. Location of validation watersheds.

3.2.2 Validation Results

Initial validation comparisons revealed only limited correlation between SWAT output, monitoring data, and the two SPARROW methods (Smith et al., 1997; 2003). In many cases, the monitoring data also deviated significantly from the SPARROW estimates.

Some of the discrepancies in the SWAT output were determined to result from problems in the simulation of erosion and biomass, largely related to deficiencies in the SWAT model setup interface. These issues are discussed in detail in Section 4. After correcting for the major issues identified in Section 4, the results for total nitrogen and total phosphorus are presented for six watersheds in Table 5 through Table 10.

For estimation of annual load, the SWAT results can be compared only to Smith et al. (1997, 2003) as data are not sufficient to estimate loads from monitoring. In all but one watershed (3210), the SWAT load estimates for both nitrogen and phosphorus are within the confidence interval of the Smith et al. (2003) results. However, the confidence bounds for this estimator are also typically quite large. SWAT results are generally not in agreement with estimates from Smith et al. (1997), but those results also frequently differ from Smith et al. (2003). It appears likely that the Smith et al. (1997) regression results gain strength primarily from their dependence on information on anthropogenic sources, and are relatively weak in distinguishing among loads from different unimpacted watersheds.

For watershed 3210, the SWAT model results are significantly higher than either SPARROW estimate, for both nitrogen and phosphorus. It is likely that erosion may be over-estimated in this watershed, which has steep slopes and greater than 50 percent of the land area in grass cover.

SWAT concentration output is summarized both as median concentration and flow-weighted mean concentration (total load divided by total flow). The flow-weighted mean concentration is always higher, as it reflects the washoff of pollutant mass during infrequent storm events. This flow-weighted concentration can also be compared to the SPARROW results, with results similar to the comparison of loads.

Comparison of SWAT results to concentrations from monitoring data is problematic, as noted above. Not only is SWAT expected to be a better predictor of yield than concentration, but also the monitoring data are very sparse and potentially biased by small sample sizes. In addition, complete nutrient loads are lacking for many of the validation watersheds, particularly the organic phosphorus component. In most cases the SWAT median concentration for total nutrient is less than the observed mean, while the SWAT flow-weighted mean is greater than the observed mean concentration.

Concentration results for individual nutrient species and for wet and dry seasons are summarized in Figure 5 and Figure 6. There appear to be considerable discrepancies between the model and data, and many of the differences between individual watersheds are not captured. These results may, however, be due to uncertainties in the limited observed data as well as to uncertainties in the model.

Table 5. Watershed 200 Validation Results

Total Nitrogen			
Loading (kg/ha-yr)	**Mean**	**Lower**	**Upper**
SWAT Annual Load	1.63		
Smith et al 1997[1]	3.34	3.27	3.61
Smith et al 2003[2]	0.47	0.05	3.18
Concentration (mg/L)			
SWAT Flow Weighted	0.66		
SWAT Median	0.04		
Smith et al 1997 Flow Weighted	1.34	1.31	1.45
Smith et al 2003 Flow Weighted	0.19	0.02	1.27
Measured TKN	0.17		

Total Phosphorus			
Loading (kg/ha-yr)	**Mean**	**Lower**	**Upper**
SWAT Annual Load	0.21		
Smith et al 1997	0.21	0.21	0.37
Smith et al 2003	0.05	<0.01	0.63
Concentration (mg/L)			
SWAT Flow Weighted	0.09		
SWAT Median	0.01		
Smith et al 1997 Flow Weighted.	0.08	0.08	0.15
Smith et al 2003 Flow Weighted	0.02	<0.01	0.25
Measured Ortho P	0.04		

[1] Lower and upper bounds calculated from 90% confidence interval of model parameters.

[2] Lower and upper bounds calculated from the lower and upper bound of model parameters, based on the parameter standard error.

Table 6. Watershed 455 Validation Results

Total Nitrogen			
Loading (kg/ha-yr)	**Mean**	**Lower**	**Upper**
SWAT Annual Load	1.57		
Smith et al 1997[1]	3.33	3.31	3.50
Smith et al 2003[2]	1.40	0.14	11.93
Concentration (mg/L)			
SWAT Flow Weighted	0.29		
SWAT Median	0.07		
Smith et al 1997 Flow Weighted	0.61	0.61	0.64
Smith et al 2003 Flow Weighted	0.26	0.03	2.19
Measured TKN+NO3	0.30		

Total Phosphorus			
Loading (kg/ha-yr)	**Mean**	**Lower**	**Upper**
SWAT Annual Load	0.20		
Smith et al 1997	0.20	0.19	0.34
Smith et al 2003	0.14	<0.01	3.56
Concentration (mg/L)			
SWAT Flow Weighted	0.04		
SWAT Median	0.01		
Smith et al 1997 Flow Weighted	0.04	0.04	0.06
Smith et al 2003 Flow Weighted	0.03	<0.01	0.65
Measured Ortho P	ND[3]		

[1] Lower and upper bounds calculated from 90% confidence interval of model parameters.

[2] Lower and upper bounds calculated from the lower and upper bound of model parameters, based on the parameter standard error.

[3] Data not available.

Table 7. Watershed 478 Validation Results

Total Nitrogen			
Loading (kg/ha-yr)	**Mean**	**Lower**	**Upper**
SWAT Annual Load	3.91		
Smith et al 1997[1]	2.49	1.73	3.68
Smith et al 2003[2]	2.10	0.13	26.48
Concentration (mg/L)			
SWAT Flow Weighted	0.41		
SWAT Median	0.05		
Smith et al 1997 Flow Weighted	0.26	0.18	0.38
Smith et al 2003 Flow Weighted	0.22	0.01	2.76
Measured TKN+NO3	0.30		

Total Phosphorus			
Loading (kg/ha-yr)	**Mean**	**Lower**	**Upper**
SWAT Annual Load	0.83		
Smith et al 1997	0.11	0.08	0.49
Smith et al 2003	0.20	<0.01	7.12
Concentration (mg/L)			
SWAT Flow Weighted	0.09		
SWAT Median	0.01		
Smith et al 1997 Flow Weighted	0.01	0.01	0.05
Smith et al 2003 Flow Weighted	0.02	<0.01	0.74
Measured Ortho P	ND[3]		

[1] Lower and upper bounds calculated from 90% confidence interval of model parameters.

[2] Lower and upper bounds calculated from the lower and upper bound of model parameters, based on the parameter standard error.

[3] Data not available.

Table 8. Watershed 3133 Validation Results

Total Nitrogen			
Loading (kg/ha-yr)	**Mean**	**Lower**	**Upper**
SWAT Annual Load	1.96		
Smith et al 1997[1]	1.18	0.81	1.72
Smith et al 2003[2]	0.56	0.05	4.18
Concentration (mg/L)			
SWAT Flow Weighted	0.68		
SWAT Median	0.03		
Smith et al 1997 Flow Weighted	0.41	0.28	0.60
Smith et al 2003 Flow Weighted	0.20	0.02	1.45
Measured TKN+NO3	0.08		

Total Phosphorus			
Loading (kg/ha-yr)	**Mean**	**Lower**	**Upper**
SWAT Annual Load	0.43		
Smith et al 1997	0.07	0.04	0.22
Smith et al 2003	0.06	<0.01	0.92
Concentration (mg/L)			
SWAT Flow Weighted	0.15		
SWAT Median	0.01		
Smith et al 1997 Flow Weighted	0.03	0.01	0.08
Smith et al 2003 Flow Weighted	0.02	<0.01	0.32
Measured Ortho P	0.01		

[1] Lower and upper bounds calculated from 90% confidence interval of model parameters.

[2] Lower and upper bounds calculated from the lower and upper bound of model parameters, based on the parameter standard error.

Table 9. Watershed 3134 Validation Results

Total Nitrogen			
Loading (kg/ha-yr)	**Mean**	**Lower**	**Upper**
SWAT Annual Load	1.80		
Smith et al 1997[1]	2.37	1.85	3.13
Smith et al 2003[2]	0.57	0.05	4.34
Concentration (mg/L)			
SWAT Flow Weighted	0.76		
SWAT Median	0.04		
Smith et al 1997 Flow Weighted	1.00	0.78	1.32
Smith et al 2003 Flow Weighted	0.24	0.02	1.84
Measured TKN+NO3	0.07		

Total Phosphorus			
Loading (kg/ha-yr)	**Mean**	**Lower**	**Upper**
SWAT Annual Load	0.48		
Smith et al 1997	0.13	0.10	0.38
Smith et al 2003	0.08	<0.01	1.20
Concentration (mg/L)			
SWAT Flow Weighted	0.20		
SWAT Median	0.01		
Smith et al 1997 Flow Weighted	0.06	0.04	0.16
Smith et al 2003 Flow Weighted	0.03	<0.01	0.51
Measured Ortho P	0.01		

[1] Lower and upper bounds calculated from 90% confidence interval of model parameters.

[2] Lower and upper bounds calculated from the lower and upper bound of model parameters, based on the parameter standard error.

Table 10. Watershed 3210 Validation Results

Total Nitrogen			
Loading (kg/ha-yr)	**Mean**	**Lower**	**Upper**
SWAT Annual Load	6.95		
Smith et al 1997[1]	3.88	3.56	4.54
Smith et al 2003[2]	0.11	0.02	0.37
Concentration (mg/L)			
SWAT Flow Weighted	11.74		
SWAT Median	0.14		
Smith et al 1997 Flow Weighted	6.55	6.02	7.67
Smith et al 2003 Flow Weighted	0.18	0.04	0.62
Measured TKN+NO3	3.20		

Total Phosphorus			
Loading (kg/ha-yr)	**Mean**	**Lower**	**Upper**
SWAT Annual Load	1.39		
Smith et al 1997	0.30	0.32	0.36
Smith et al 2003	0.02	<0.01	0.09
Concentration (mg/L)			
SWAT Flow Weighted	2.36		
SWAT Median	0.01		
Smith et al 1997 Flow Weighted	0.51	0.54	0.62
Smith et al 2003 Flow Weighted	0.03	<0.01	0.15
Measured Ortho P	0.30		

[1] Lower and upper bounds calculated from 90% confidence interval of model parameters.

[2] Lower and upper bounds calculated from the lower and upper bound of model parameters, based on the parameter standard error.

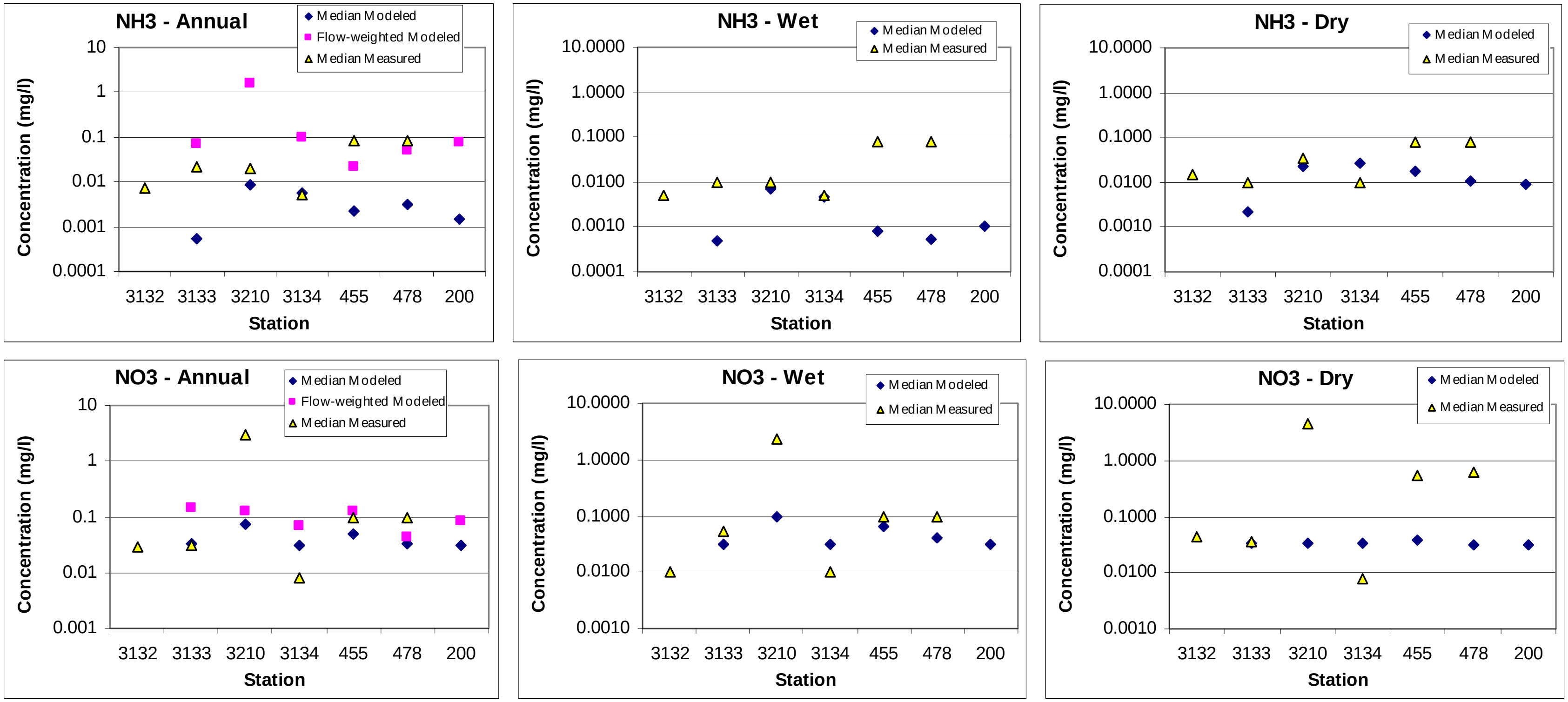

Figure 5. **Comparison on Ammonia and Nitrate measured and modeled concentrations across six validation watersheds (modeled medians use output greater than 0.01 cms; wet season is November 1 through April 30; dry season is May 1 through October 31).**

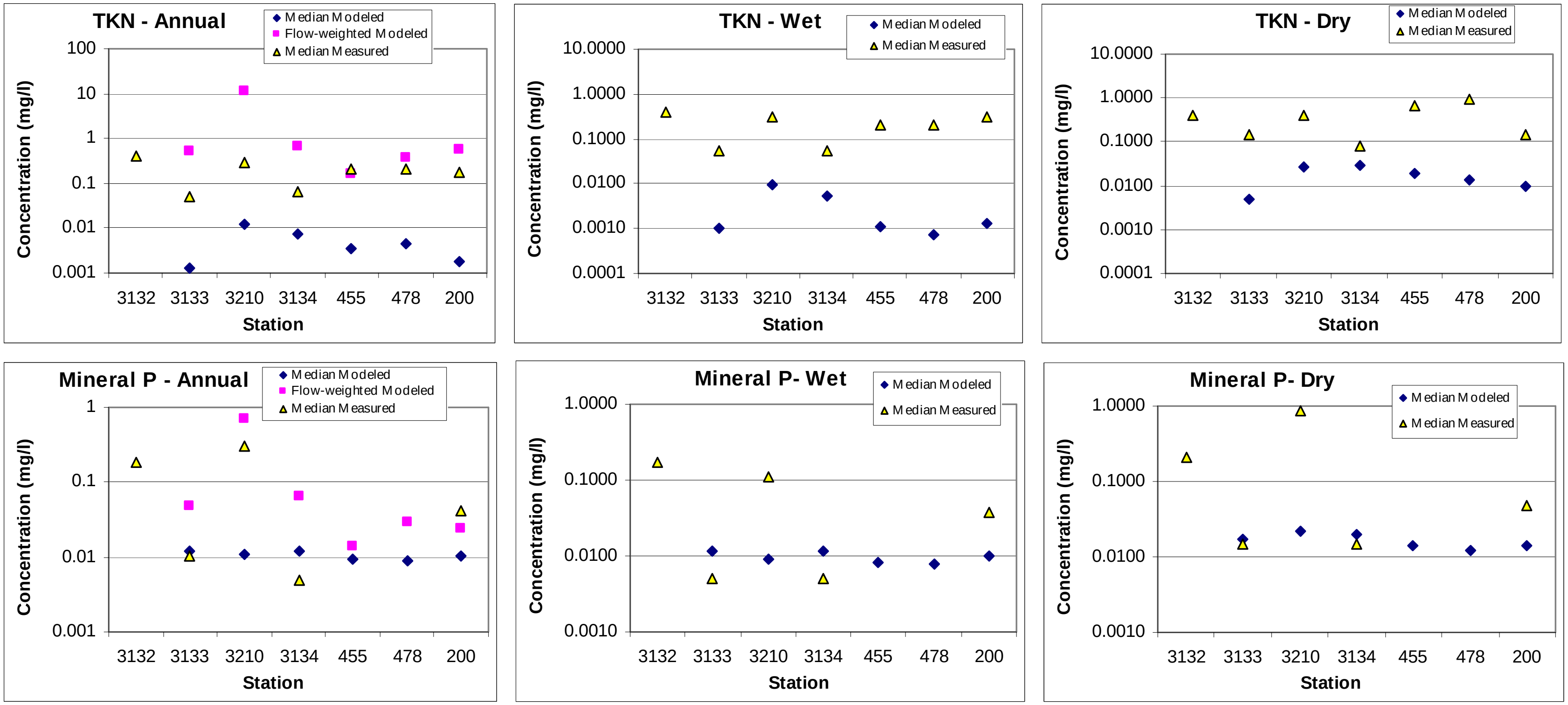

Figure 6. Comparison of TKN and Mineral Phosphorus measured and modeled concentrations across six validation watersheds (modeled medians use output greater than 0.01 cms; wet season is November 1 through April 30; dry season is May 1 through October 31).

4 SWAT Applications in Ecoregion 6: Lessons Learned

The initial validation runs revealed a number of potential problems with the SWAT model setup from defaults, even after the site-specific modifications described in Section 3.1. Diagnostic work with the model determined that erosion tended to be over-estimated, while biomass was often unrealistically low. These problem areas and partial solutions are described below. Additionally, further information is provided on the research performed for groundwater concentration of nutrients.

4.1 EROSION ESTIMATION

Initial Residue Cover

Rainfall detachment of soil particles is mitigated by the presence of organic residue on the surface. The initial residue cover (RSDIN in the .hru file) is set by the SWAT interface to 0, which is inappropriate for untilled natural vegetation. Further, in arid climates, residue buildup may be slow, affecting many years of simulation and potentially depleting the soil by erosion before a realistic biomass growth simulation is obtained. To remedy this issue, it is necessary to specify an initial value of RSDIN. Few data were located on this parameter; however, an estimate of 150 kg/ha appeared to provide reasonably stable estimates of sediment yield.

Slope Length

The MUSLE erosion calculation includes a Length-Slope (LS) factor, which is calculated from slope length. The SWAT interface attempts to calculate an appropriate slope length from the DEM. However, this calculation does not always succeed when slopes are steep. When a slope length is not calculated, the interface defaults to a slope length of 50 m. The default slope length of 50 m is appropriate for relatively flat watersheds, but in watersheds with steep average slopes (> 25 percent), SWAT will simulate excessive sheet erosion. The average slope length was revised from the default 50 m to 5 m for watersheds with steep average slopes. This revision notably reduced total nitrogen, total phosphorus, and sediment loading in the five steeply sloping watersheds, as shown in Figure 7. For the more gently sloping watershed 455, BASINS calculated a slope length of 15 m during model set-up and a default slope length was not necessary.

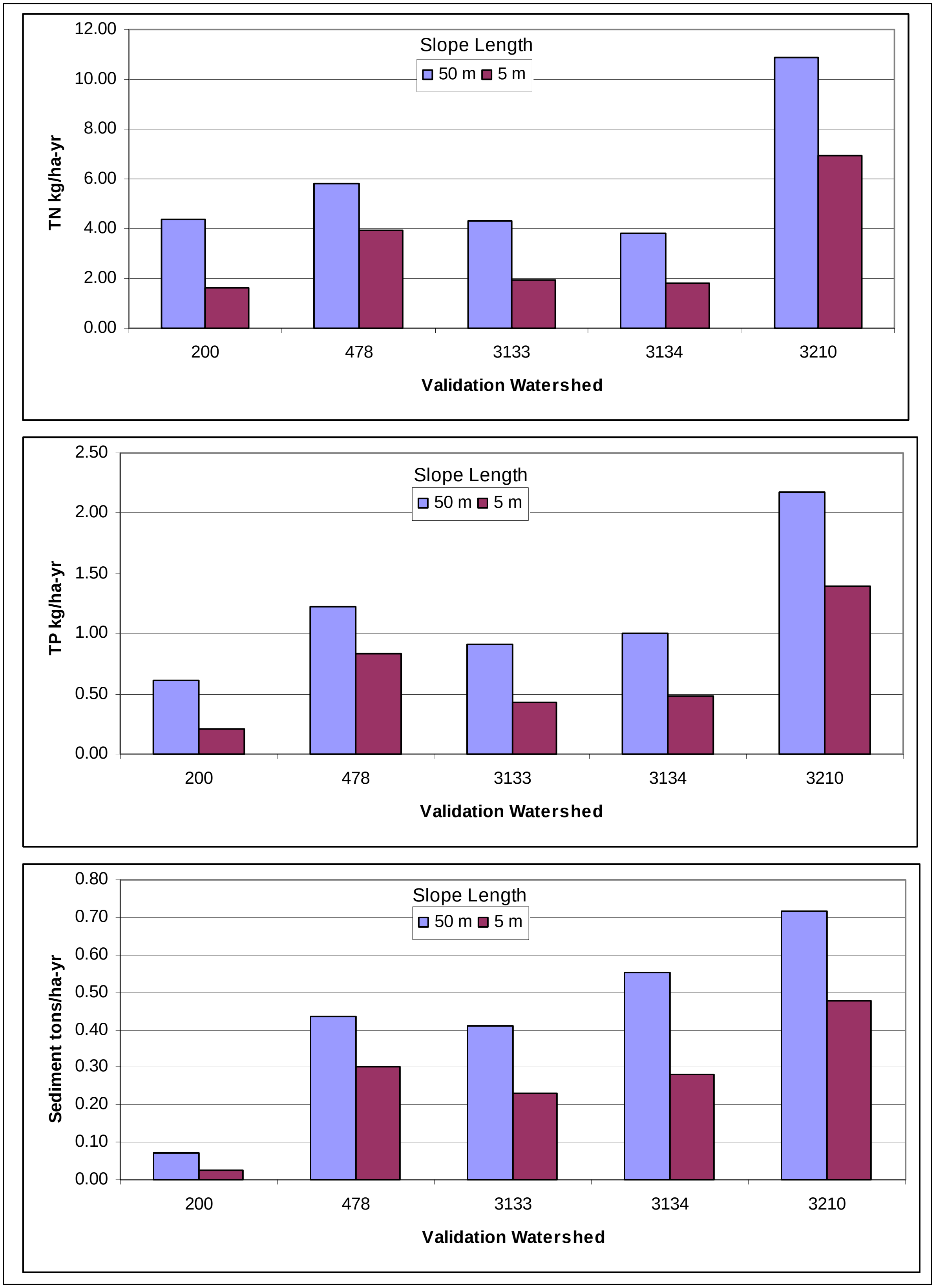

Figure 7. **Comparison of TN (a), TP (b), and Sediment (c) loads with 50 m and 5 m slope lengths for 5 validation watersheds.**

4.2 BIOMASS SIMULATION

Significant problems occurred with the SWAT biomass simulation for native vegetation, which in turn introduced errors into the erosion and nutrient simulations. SWAT develops the biomass simulation primarily on the basis of information in the CROP database, which was modified to reflect appropriate parameters for regional cover types. However, these parameters also interact with information in the .MGT file for each HRU. Default information entered into this file by the SWAT interface creates problems for a realistic simulation.

SWAT simulates plant growth using a heat unit approach that is most appropriate for perennials, but can be used for annuals (only the new growth biomass, not woody biomass, is simulated by the program). Plant heat units are defined as the difference between plant base temperature and the daily temperature, summed for all days when temperature is above the base temperature, while base zero heat units are calculated relative to freezing. By default, SWAT specifies a “planting” (growth start) operation and a “kill” (stop growth and convert to residue) operation for each cover. Planting time defaults to 15 percent of the base-zero heat units, and the kill operation corresponds to 120 percent of the plant heat units required for maturity. The program will also calculate potential heat units (PHU) required to reach maturity.

Each of these entries is problematic, for different reasons. The PHU calculation should be accurate, given an appropriate estimate of growing season length, even though the user would have to enter this value manually rather than retrieving it from the CROP database. However, the calculation is carried out in a dynamic link library (PHU.DLL) that appears to have an undocumented, internal limit of 100 different crop/vegetation types. When more than 100 crop types are added to the database (as in the California application), the PHU for all cover types with index greater than 100 is set to zero. This in turn causes the SWAT program to assume a default PHU of 700. In Southern California, reversion to the default value of PHU means that the plants mature and reach senescence in only a few months, resulting in an underestimate of biomass and leaf area.

The default number of heat units (HUSC) that control start and stop of growth are appropriate for an annual crop that is planted after danger of frost and allowed to dry-down before harvest, but not for many annuals. Setting the initiation of growth at the default of 15% of the base zero heat units means that trees do not start leafing out until the beginning of April in many of the test watersheds, which is clearly too late. Finally, setting the heat units for the “kill” operation to the default of 1.20 is probably too large for woody plants in arid areas, as it would mean that leaves are likely to be retained for a long period after the completion of the annual growth cycle.

It is also important to recognize that SWAT has a built-in, hardwired dormancy period for perennials that is based on day length as determined by latitude. This cannot be modified by the user, and forces growth to stop during the shorter days of December and January. In fact, many Southern California plants are adapted to grow during this period, when water is available. When dormancy is activated, the model sets the leaf area index (LAI) to 0.75, while reducing biomass to a fraction of the pre-dormancy biomass. This can result in some odd interactions with the heat unit scheduling. For instance, if the PHU value is sufficiently high, a perennial crop may not experience a “kill” operation (conversion to biomass). Further, if the HUSC value for the kill is such that the growth cycle is completed, at which point leaf area declines, but the heat units for the kill have not been reached before dormancy is triggered, the simulated leaf area may suddenly increase from near zero to the dormancy default of 0.75.

In sum, SWAT experienced problems in simulating biomass production for native California land cover even when all parameters in the CROP database were correctly specified. In addition, cover-specific modifications of the .MGT files, for each HRU, were required to achieve what appeared to be reasonable biomass simulations. Initial efforts to improve the simulation by generalized cover type are summarized below.

4.2.1 Biomass Simulation for Deciduous Oaks

Modification of model behavior for deciduous oaks was tested using information for Blue Oak (*Quercus douglasii*), which is simulated with a base temperature for growth of 5 °C. According to reported ecological characteristics of Blue Oak at http://www.fs.fed.us/database/feis/plants/tree/quedou/botanical_and_ecological_characteristics.html, leaf out typically occurs in early March, with acorn maturation and leaf fall in August to November. These characteristics can be reproduced with the following changes:

*.MGT file – Planting Operation (1):

HUSC (Grow): 0.10

HEATUNITS: 2250

*.MGT file – Kill Operation (8)

HUSC (Kill): 1.1

With these changes, the biomass and leaf area simulations become more realistic, with leaf development in March and decline of leafy biomass in late September to mid-October.

A remaining concern regards the leaf area simulation (which in turn determines the biomass accretion rate). For the example given above, the maximum leaf area (BLAI) was specified as 3.61, but this is never reached in the simulation. Instead, summer leaf area is limited by the accumulation of water and nutrient stress. To achieve a greater LAI prior to stress limitation it would be necessary to reduce the values of FRGRW1 and FRGRW2 in the crop database. These are the fractions of the growing season HEATUNITS corresponding to the defined points on the leaf area development curve, with FRGRW2 determining when the leaf area approaches the maximum. Lower values would cause greater LAI accumulation during the spring wet season.

Ideally, the values of FRGRW1 and FRGRW2 should be set by comparing the time of year at which maximum leaf area is expected to the accumulated HEATUNITS at that time. Initial experimentation suggests that values of 0.10 and 0.16 may be reasonable approximations.

4.2.2 Evergreen Species

To simulate evergreen species, it seems preferable to make use of the built in dormancy option in SWAT. For these species, the simulation can eliminate the kill operation and assign a large value of HEATUNITS that is close to the number of growing degree days for the area. Growth will continue to be limited by water, nutrient, and temperature stress, and will go dormant during the short-day period of the winter; however, LAI will not go to zero as it does with deciduous plants. Experiments with watershed 3210 showed that a value of HEATUNITS=3000 was not sufficient to prevent LAI drop off from senescence.

Templates for evergreens considered the ecological characteristics of the California Live Oak (*Q. agrifolia*) and the Canyon Live Oak (*Q. chrysolepis*). The former species has active biomass accumulation from December to April, with acorns ripening in September-October. The Canyon Live Oak appears to have its active growth a little later in the season.

Assigning an artificially high value of HEATUNITS to allow leaves to be held until dormancy also requires a correction to FRGRW1 and FRGRW2 to have sufficient leaf area develop before water stress takes over.

For evergreen trees, HUSC (Grow) is not an important parameter if a kill is not simulated. This is because no new growth-initiation will be simulated after the start up year. The simulation of the first year would be improved if HUSC(Grow) is set to a nominal small value (say 0.01) in the **.mgt* files. Note that even if a kill is not simulated, the value of HEATUNITS read at the first year start of growth is retained for subsequent years of the simulation.

The general behavior shown by the model for evergreen simulations is attractive, but not an exact replication of expectations. In particular, the hardwired dormancy period may not be appropriate for California Live Oak, which has maximum biomass accumulation in December through April. However, this may be a result of the particular latitude of the test watershed , which is at 35.6° N, apparently a little further north than the range of this species. SWAT calculates dormancy based on a period when daylight hours are within a calculated distance of the annual minimum daylight hours. Between 20 and 40° latitude, this threshold (in hours) is calculated as $(\theta-20)/20$, where θ is the latitude in degrees. Thus, the length of the dormancy period decreases as we move south. It may, however, be advisable to consider modifying the dormancy assumptions in the program executable (in subroutine *dormant.f*).

Evergreen conifers can likely be simulated in the same way as outlined above for evergreen oaks – but with different growth characteristics as defined in *crop.dbf* and appropriate values of HEATUNITS.

4.2.3 Status of Biomass Simulations

SWAT simulated more realistic biomass production following the above revisions – but further work will evidently be necessary. Typical results of the current simulations are shown below. LAI for evergreen land covers decreased to and remained at 0.75 through the winter (Figure 8, Figure 11, and Figure 12). Biomass for deciduous trees and annual herbaceous plants decreased to zero in the fall, simulating leaf fall (Figure 9, Figure 10, and Figure 13). Growth slowed during the summer due to water and temperature stress, and in some years, growth increased in the early fall with more rain and lower temperatures.

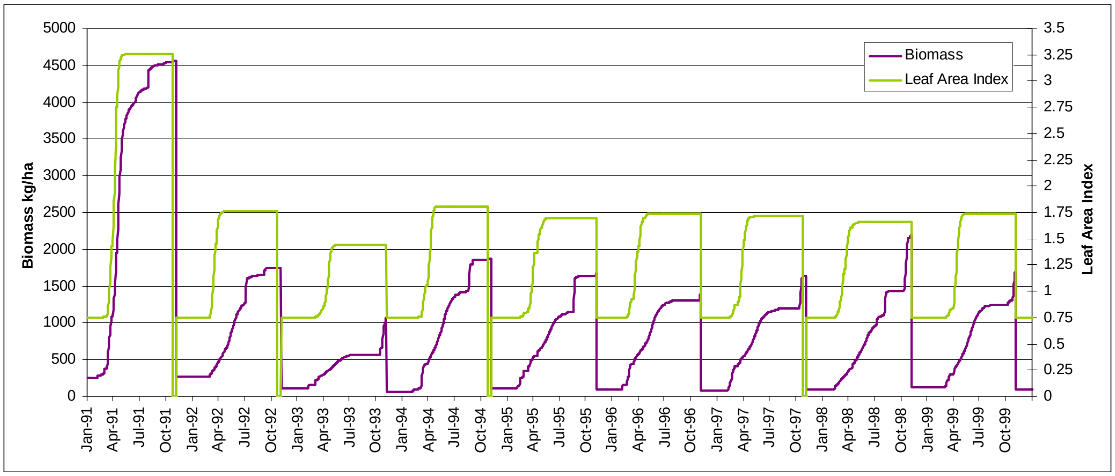

Figure 8. Watershed 3210: HRU 5; Evergreen, Coast Live Oak

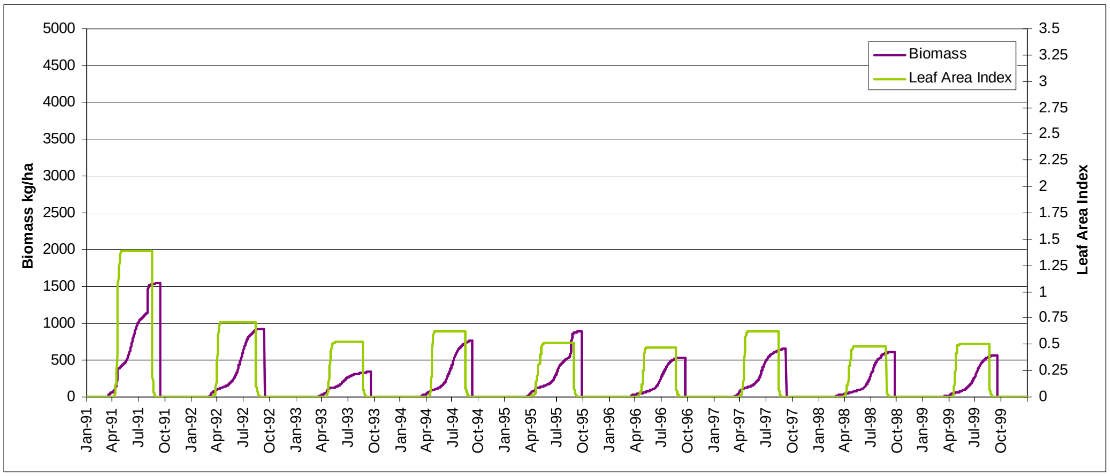

Figure 9. Watershed 3210: HRU11; Deciduous, Blue Oak and Annual Grassland

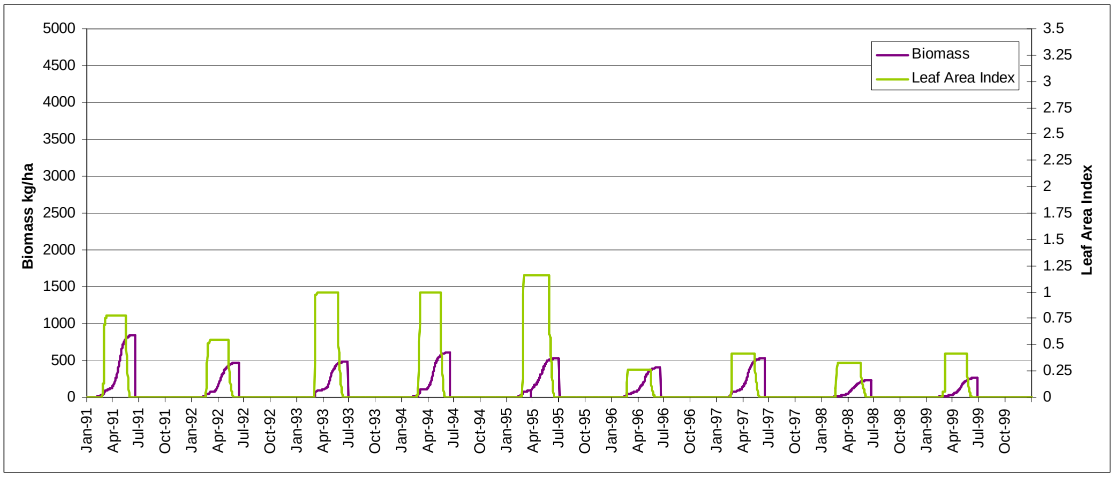

Figure 10. Watershed 3210: HRU16; Annual Grassland

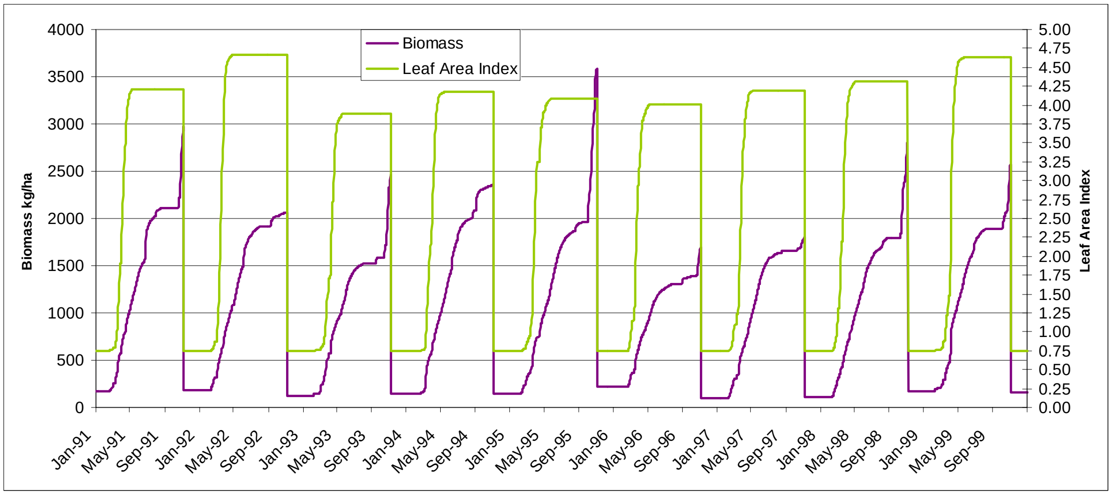

Figure 11. Watershed 200: HRU5; Evergreen, Coast Redwood

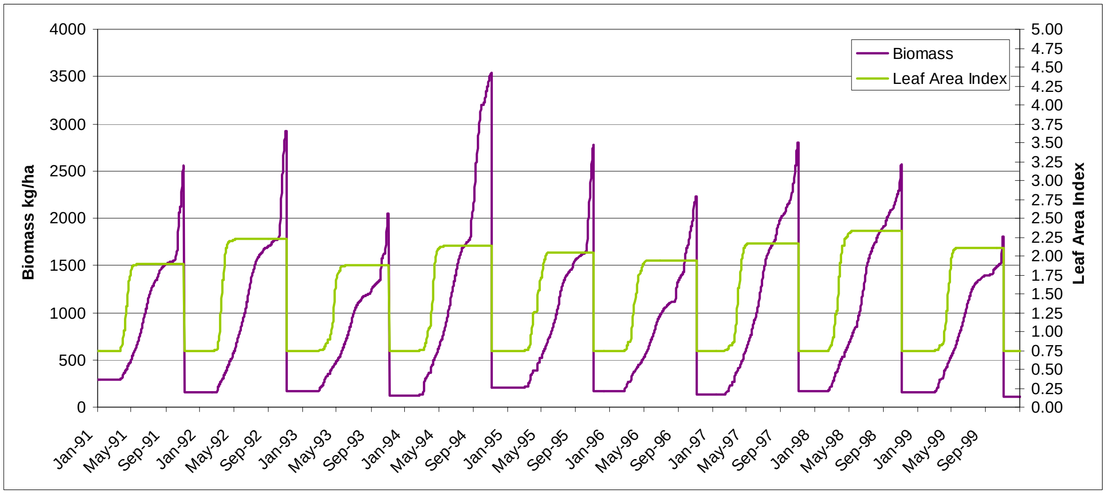

Figure 12. Watershed 478: HRU4; Evergreen, Conifer and Coast Live Oak

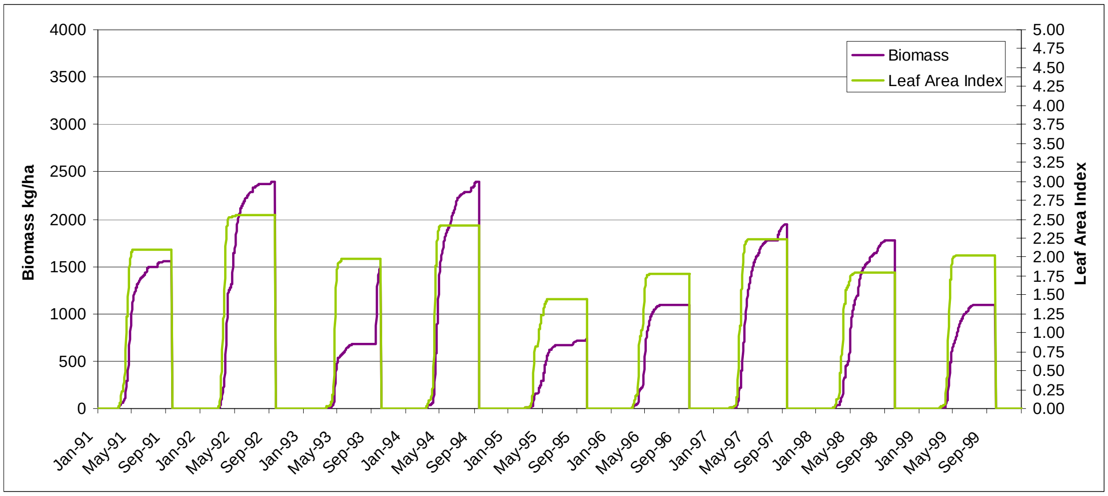

Figure 13. Watershed 3134: HRU18; Deciduous, Chaparral, Ceanothus

The problems with the biomass simulation reveal that biomass will need to be reviewed and adjusted after each new watershed model is developed. At a minimum, a simulation of leaf fall for deciduous trees and dormancy for evergreen trees will need to be verified for each watershed, possibly for each major HRU. To prevent absence of growth in Year 1, all watersheds could be set with land cover growing at the beginning of the simulation. Beyond these measures, further research will be needed to determine if model inputs can be selected that produce reliable biomass simulations for the major plant communities and climates of Ecoregion 6.

The performance of SWAT's plant simulation could be greatly improved by refining the growth parameters for the major plant species. Ideally, further research would obtain the following information for each major land cover and a location typical of its distribution:

- Evergreen or deciduous (for woody plants)
- Typical date of leaf out/start of growth
- Typical date for leaf area to approach maximum
- Date of conclusion of annual growth cycle (including leaf and/or seed drop)
- Base temperature for growth
- Number of heat units available above the base temperature at the corresponding location
- Information on amount of leaf area retained during dormancy (for evergreen trees/shrubs and perennial grasses)

With this information it would be possible to fine-tune the growth representation to replicate typical behavior of the species. This could be done by adjusting growth parameters so that the life cycle events occur with the correct seasonal timing and biomass production for the representative location.

4.3 GROUND WATER CONCENTRATION RESEARCH

The concentrations of nutrients in groundwater contributions to stream flow are important inputs to the SWAT model, as they largely determine the dry season concentration values in the stream. Nutrient concentrations in groundwater were collected from the United States Geologic Survey (USGS, 2004) via the Internet. For each of the six validation watersheds, the USGS water quality database was queried by county, hydrologic unit, and for well depths no greater than 100 feet. Nutrient data are presented in Table 11, along with the corresponding well depth range. Data were found for only two of the six validation watersheds. Nitrate plus nitrite values were 1.8 mg/l and 1.1 mg/l for watersheds 478 and 3210, respectively. Phosphate was 0.02 mg/l for watershed 478. Well depths ranged from 28 to 100 feet. These data are not likely to be representative of groundwater contributions to stream flow because of the large well depths.

For the purpose of comparison, Table 11 also presents dry season (May through October) median measured stream values for the six stations. Additionally, dry season nutrient data is presented for the Malibu Creek watershed for reference stream sampling stations (HTB, 2004). The Malibu Creek watershed is an extensively studied watershed located in Ecoregion 6. Reference sites represent pristine or near-pristine conditions. The nutrient data values used in the pilot project are also presented for comparison. These values were determined from California monitoring data for minimally impacted streams (see Table 4-8 in Tetra Tech, 2003).

A comparison of the nitrate values illustrates that the range of the dry season data for the validation watersheds, 0.008 mg/l to 4.6 mg/l, encompasses all the other nitrate data. In general, the USGS groundwater values are larger than the dry season stream values, with the exception of the nitrate value at Station 3210 – which is sufficiently high to suggest a possible anthropogenic impact. Phosphate values are generally similar across the data sources, with the exception of the dry season phosphate value at Station 3210. The pilot study values, 0.03 mg-N/L and 0.01 mg-P/L for nitrate and phosphate, respectively, were used in the validation modeling. In the absence of true shallow groundwater discharge data, they provide the best general representation of groundwater contributions of nutrients to the stream.

Table 11. Comparison of groundwater nutrient data and dry season nutrient stream data.

	USGS Groundwater Data		**Dry Season Median Measured Stream Values**	
Station Key	**Average NO_3+NO_2-N, mg/l (Depth range in feet)**	**Average PO_4-P, mg/l (Depth range in feet)**	**NO_3-N, mg/l**	**PO_4-P, mg/l**
478	1.8 (28 - 100 ft)	0.02 (28 - 100 ft)	0.6	-
200	-	-	-	0.047
455	-	-	0.55	-
3133	-	-	0.036	0.015
3134	-	-	0.008	0.015
3210	1.1 (30 - 84 ft)	-	4.6	0.85
Malibu reference locations	NA	NA	0.015 [1]	0.074
Pilot study values[2]	NA	NA	0.03	0.01

Notes:

1. NO3 + NO2 - N, mg/l
2. Average value during low flow (less than 3.14 cfs)

\- = Not available

NA = Not applicable

5 Use of SWAT to Evaluate Existing Loads

Use of SWAT for estimating natural background loads from unimpacted watersheds with natural vegetative cover has been discussed in detail in the preceding sections. In general, the program structure appears capable of providing such estimates, but estimates without site-specific calibration due not appear to be reliable.

There are particular concerns regarding the SWAT simulation of biomass, plant residue, and plant-soil nutrient cycling for native plant cover in California. SWAT does not appear to do a good job of simulation with default available parameters, and much work needs to be done to establish appropriate plant growth parameters. Inherent limitations in the program (such as the forced dormancy period for perennials) may also not be appropriate for the Mediterranean climate of southern California.

SWAT performance on agricultural lands is expected to be much better. The SWAT developers have put considerable effort into developing and documenting appropriate plant growth and management parameters for most major crop types, and these are available in the default databases. Indeed, simulation of natural vegetative covers seems to have been somewhat of an afterthought in SWAT development, and forcing perennial cover to fit the structure set up for crop simulation is an awkward fit at best.

SWAT2000 also provides the capability to simulate nutrient loading from developed lands. Loadings of sediment and nutrients are determined using one of two options. The first is a set of linear regression equations developed by the USGS (Driver and Tasker, 1988) for estimating storm runoff volumes and constituent loads. The other option is to simulate the buildup and washoff mechanisms, similar to SWMM - Storm Water Management Model (Huber and Dickinson, 1988). With these options, a reasonable simulation of nutrient loading from developed lands can usually be obtained. It should be recalled, however, that the default SWAT erosion algorithm may yield unrealistic results from HRUs that contain a mix of urban pervious and impervious land cover because MUSLE is calculated with the peak flow from the entire HRU, using a weighted curve number, and not from the flow from the pervious section. This is equivalent to assuming that all impervious area runoff proceeds as sheet flow across the pervious sections, rather than being piped or channelized, and can result in a significant over-estimation of sediment load from developed areas.

For all watersheds, the lack of a parametric basis for setting groundwater nutrient concentrations can be a source of significant error, particularly where nitrogen is of concern. All nitrogen simulation applications will need to evaluate baseflow nitrate concentrations appropriate to the setting. This is usually best accomplished through calibrating the model to field observations under baseflow conditions when groundwater dominates flow.

The lack of a full groundwater balance in the model (only shallow groundwater is simulated) may also be problematic for waterbodies that receive regional groundwater discharge. This problem can be addressed by adding groundwater flows and loads as external inputs to the model, but this will require significant site-specific knowledge.

The SWAT model also provides capabilities to simulate impoundments, water diversion, and irrigation. These have been applied successfully to nutrient simulations in large watersheds in the arid Southwest (e.g., Tetra Tech, 2001). However, the SWAT interface does not automatically configure these options, so site-specific model development is needed.

In sum, SWAT remains a useful tool for the evaluation of existing loads, as well as management alternatives. Despite claims by the model developers, it does not, however, appear to be reliable for evaluation without site-specific calibration. Therefore, when SWAT is applied to a watershed study, the usual process of model validation and calibration should be followed.

6 Summary Evaluation of Appropriate Uses of SWAT for California Nutrient Simulation

SWAT was adopted for use in the Ecoregion 6 pilot project as a tool to estimate natural background loading from native soils, cover, geography, and meteorology. Attempts at validation of SWAT predictions for unimpacted watersheds have thus far been inconclusive. Without calibration, it appears that the model is most appropriate for a qualitative or relative evaluation of nutrient loads. Even when used in this way, however, care must be taken to ensure that the plant biomass simulation is realistic, as this will affect both the sediment and nutrient simulations.

For specific watershed studies, the model appears to be an appropriate tool for estimating nutrient loads, but less confidence should be placed in individual concentration predictions due to the model’s daily time step and simplifying assumptions for instream transport. The most appropriate use is likely for agricultural watersheds. Model results should not be applied quantitatively for regulatory purposes without site-specific calibration. However, proper calibration would require monitoring data sets of sufficient size (along with flow) to estimate seasonal and annual loads for comparison to the model.

Finally, additional research work is clearly needed to identify appropriate plant growth characteristics appropriate to the natural cover types found in California.

7 References

Arnold, J.G., J.R. Williams, A.D. Nicks, and N.B. Sammons. 1990. SWRRB: A basin scale simulation model for soil and water resources management. Texas A&M Univ. Press, College Station, TX.

Arnold, J.G., R. Srinivasan, R.S. Muttiah, P.M. Allen and C. Walker. 1999. Continental scale simulation of the hydrologic balance. *J. American Water Resources Association,* 35(5):1037-1052.

Brown, L.C. and T.O. Barnwell, Jr. 1987. The Enhanced Water Quality Models QUAL2E and QUAL2E-UNCAS, Documentation and User Manual. EPA/600/3-87/007. USEPA, Athens, GA.

Driver, N.E. and G.D. Tasker. 1988. Techniques for Estimation of Storm-Runoff Loads, Volumes, and Selected Constituent Concentrations in Urban Watersheds in the United States. U.S. Dept. of the Interior, U.S. Geological Survey: Open-File Reports 88-191.

HTB, 2004. Heal the Bay Stream Team Water Chemistry Data. Available online at: http://www.healthebay.org/Streamteam/data/chem/

Huber, W.C. and R.E. Dickinson. 1988. Storm Water Management Model, Version 4: User's Manual. U.S. Environmental Protection Agency, Athens, GA.

Knisel, W.G. 1980. CREAMS, a Field Scale Model for Chemicals, Runoff and Erosion from Agricultural Management Systems. USDA Conservation Research Report No. 26.

Leonard, R.A., W.G. Knisel, and D.A. Still. 1987. GLEAMS: Groundwater loading effects on agricultural management systems. *Trans. ASAE*, 30(5):1403-1428.

NADP. 2004. National Atmospheric Deposition Program/National Trends Network. Available online at: http://nadp.sws.uiuc.edu/.

Neitsch, S., J.G. Arnold, J.R. Kiniry, and J.R. Williams. 2001. Soil and Water Assessment Tool, User's Manual, Version 2000. USDA Agricultural Research Service, Blackland, TX. Available online at http://www.brc.tamus.edu/swat/swat2000doc.html.

Neitsch, S. and M. DiLuzio. 1999. ArcView Interface for SWAT 99.2, User's Guide. Blackland Research Center, Texas Agricultural Research Station, Temple, TX.

Santhi, C., J.G. Arnold, J.R. Williams, W.A. Dugas, and L. Hauck. 2001. Validation of the SWAT model on a large river basin with point and nonpoint sources. *J. American Water Resources Association*, 37(5):1169-1188.

Smith, R.A., R. B. Alexander, and G.E. Schwarz. 2003. Natural background concentrations of nutrients in streams and rivers of the conterminous United States. *Environmental Science and Technology*, 37(14): 3039-3047.

Smith, R.A., G.E. Schwarz, and R.B. Alexander. 1997. Regional interpretation of water-quality monitoring data. *Water Resources Research*, 33(12): 2781-2798.

Tetra Tech. 2001. Verde River Assimilative Capacity Study, Modeling and Assimilative Capacity Report. Prepared for Arizona Department of Environmental Quality by Tetra Tech, Inc., Research Triangle Park, NC.

Tetra Tech. 2003. 2003 Progress Report, Ecoregion 6 (Southern and Central California Oak and Chaparral Woodlands) Pilot Study for the Development of Nutrient Criteria. Prepared for US EPA Region IX Regional Technical Advisory Group and CA SWRCB State Regional Board Advisory Group. Tetra Tech, Inc., Lafayette, CA

U.S. EPA. 2001. Better Assessment Science Integrating Point and Nonpoint Sources, BASINS Version 3.0., User's Manual. EPA-823-B-01-001. Office of Water, U.S. Environmental Protection Agency. Available online at http://www.epa.gov/waterscience/basins/bsnsdocs.html.

US EPA CREM. 2004. Models Knowledge Base. U.S. Environmental Protection Agency Center for Regulatory Environmental Modeling. http://cfpub.epa.gov/crem/knowledge_base/knowbase.cfm; accessed 4/9/04.

USGS, 2004. Water Quality Samples for California. Available online at: http://nwis.waterdata.usgs.gov/ca/nwis/qwdata.

Williams, J.R., C.A. Jones and P.T. Dyke. 1984. A modeling approach to determining the relationship between erosion and soil productivity. *Trans. ASAE*, 27(1):129-144.

Williams, J.R., A.D. Nicks, and J.G. Arnold. 1985. Simulator for water resources in rural basins. *Journal of Hydraulic Engineering*, 111(6): 970-986