USING SWAT TO MODEL WATER QUALITY IN THE CALAPOOIA RIVER BASIN

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Introduction

Soil erosion, off-site movement of nutrients, damage to wildlife habitat, and alteration of biochemistry on a global scale are well documented, albeit unintended, consequences of much human activity, including modern farming methods. Approaches to study these phenomena include monitoring of natural systems and modeling them using computer programs such as the Soil Water Assessment Tool (SWAT). A premiere example of efforts to better understand relationships among farming practices, conservation methods, and the broader environment is the USDA Conservation Effects Assessment Project (CEAP) whose 38 study sites include the Calapooia River Basin in western Oregon. Core elements of all CEAP projects include measurements of nutrient and sediment loads in streams draining study watersheds and modeling effects of landuse changes on water quality using SWAT.

Complex relationships exist amongst hydrology, landuse, and water quality in western Oregon. Our previous analysis of the impact of landuse and farming practices on water quality in the Calapooia River Basin identified a group of crops whose production was linked to higher concentrations of nitrate and total N during the winter in streams draining 40 subbasins. Because that analysis lacked a comprehensive hydrologic model, we were unable to say whether or not the subbasins with highest concentrations of N were truly the most significant exporters. Using time series analysis, we quantified a strong cyclical signal in N concentrations at 28 of the 40 subbasins, with primary peaks in December and secondary peaks near the usual time for application of spring N. Based on concentrations of N and clarity of temporal signals, we grouped the subbasins into four main types: those with low, medium, and high concentrations of total N (or nitrate) and a strong time series signal, and those with high levels of N and a weak (or nonexistent) time signal.

In addition to providing mass balance estimates for sources and sinks of nutrients and sediment, SWAT also offers the opportunity to explore the impact of landuse changes greater than the current range. However, before SWAT can be used to model scenarios for alternate futures, it must first be tested, and if necessary modified and recalibrated to match agricultural landuse, water quality, and hydrologic cycles in locales of interest. Although it has been generalized over the years of its development, the current version of SWAT still remains obviously focused on crops grown in mid-continental regions during the northern hemisphere summer, and many of SWAT's features insist on viewing the cropping year as a subset of the calendar year. In contrast, agriculture in the modified Mediterranean climate of western Oregon typically begins with tillage of the soil in late summer in preparation for an early fall planting of new grass seed stands, winter wheat, or other winter annuals. Even established perennial grasses go dormant in late summer/early fall as a consequence of limited rainfall, and behave like rapidly establishing winter annuals once rains return. In addition to crop choice and default management schemes, the hydrologic cycle in western Oregon is sufficiently foreign to the conditions used to develop SWAT that processes such as denitrification and overland versus groundwater flows may be poorly modeled.

Our specific objectives were to: (1) develop a hydrologic model whose streams and watershed boundaries aligned with locations of our water quality sampling points, (2) identify preexisting crops/landuses within SWAT whose modeled sediment and nitrate concentrations reasonably match observed data for subbasins dominated by single crops, (3) modify management practices within SWAT to improve the agreement between observed and modeled data for those crops, and (4) reexamine our previous conclusions on the role of current landuse practices on water quality from a perspective that included better hydrology.

Methods

Management inputs

Adjustment of default SWAT parameters to more closely model growth of grass seed crops in western Oregon began with changing fertilization from automatic to manual using recommended application rates and dates from OSU Extension Service guides. Dates for planting and harvest were chosen to provide reasonable matches to western Oregon agriculture. Other than copying crops and renaming them for use with manual fertilization and defined growing season dates, the only other change made to the SWAT crops database was switching ryegrass from a cool season annual to a perennial. For crops such as peppermint and meadowfoam that did not exist within the SWAT database, we copied and renamed other crops that possessed generally similar growth patterns.

Sampling procedures

Water quality samples were collected a total of 41 times from Oct. 5, 2003, through Jan. 22, 2007, generally within a single day, although collection from all sampling sites occasionally required a second or third day to complete. No samples could be collected from ephemeral streams that dried up during late summer through early fall. Rainfall data recorded at several nearby weather stations from 2000 through 2007 were interpolated to the 40 subbasins for which water quality data existed and were used in SWAT.

SWAT Model Simulation

The SWAT variable NYSKIP was set to a minimum of 3 years "burn-in" for all simulations, which included monthly printout for all multiple-year simulations and daily printout for single growing season simulations, which ran from Jan. 1 of one year through July 31 of the following year. SWAT output data files were imported into Excel to examine subbasin watersheds and stream reaches of interest, particularly output reaches of the entire Calapooia River Basin and the 40 water quality sampling points previously analyzed without use of SWAT.

Results

Observed precipitation and streamflow patterns

Rainfall in western Oregon typically peaks in December, with a long-term monthly average of 7.1 inches, and then slowly declines to a minimum of less than 0.4 inches in August. Over the sampling period from Oct. 2003 through Jan. 2007, precipitation averaged slightly above normal during late-fall through early winter but near-normal when viewed across the entire 40-month period. The 2004-05 cropping year was drier than the preceding year or the following years, all of which experienced slightly above normal precipitation, especially during winter.

Simulations using SWAT defaults for single landuse in the agricultural region

As a first step in evaluating how well "out of the box" SWAT would perform in the Calapooia River Basin, we modeled single landuses of range (RNGE), hay (HAY), generic agricultural row crops (AGRR), winter wheat (AGRC or WWHT), agricultural land generic (AGRL), winter tall fescue pasture (WPAS), corn (CORN), and red clover (CLVR) in the 57% of the basin for which we had detailed information on crops actually grown over multiple years, using National Land Cover Data (NLCD 2001) landuses for the remaining (mostly forested) 43% of the area (Table 1). Averaged over 5 years of simulations, water yield was the most stable variable, ranging from 22.1 inches for CORN to 27.5 inches for CLVR, or 56 to 70% of precipitation. Sediment loading was the least stable variable, ranging from 196 lb/a for CLVR to 24,103 lb/a for WPAS. Nitrate yield in surface runoff was intermediate, ranging from 0.53 lb/a for CLVR to 1.36 lb/a for AGRL. Sediment loss from AGRR and CORN was slightly less than half that from WPAS, indicating that SWAT defaults handled WPAS poorly as a western Oregon crop. When we examined the SWAT output tables at the locations of our water quality samples, none of these eight default crops generated values for nitrate or sediment that closely matched our raw data. In the case of nitrate, most of our raw data greatly exceeded the modeled results. Two likely causes for the wide discrepancies between modeled and observed data came to mind: (1) the SWAT defaults were not accurately modeling western Oregon conditions and farming methods, and (2) variability in sediment and nutrient fluxes among days within individual months prevented monthly averages in modeled results from matching up well with raw data collected on individual days.

Newly defined crops and modified management operations

Because the odd behavior in sediment loading of WPAS versus AGRR using SWAT defaults (heat unit scheduling and auto-fertilization) suggested that we didn't properly understand how non-cropping periods were being handled by SWAT, we created an explicit extreme fallow condition as crop number 1 by assigning August 1 for planting an eggplant crop (EGGP) followed by harvest on August 2 with no other activity during the year. Sediment loading from this extreme fallow condition averaged 31,747 lb/a (Table 2) or nearly three times that modeled for AGRR. To model growth of various new and established grass seed crops in western Oregon, we used operations that included some period of growth during the fall, a Jan. 1 restart required by SWAT, early summer harvest, and manual fertilization. Sequences of operations used to model establishment of new grass seed stands left the ground vulnerable to erosion at various times in the fall and/or spring. Crops modeled included established stands of perennial ryegrass (GSPR), tall fescue (GSTF), orchardgrass (GSOG), haycrop (TFHC), pasture (TFPA), and peppermint (MINT), new fall plantings of annual ryegrass (GSAR/GSLO), perennial ryegrass (FPPR), tall fescue (FPTF), clover (FPCL), winter wheat (WWHT), and meadowfoam (MDWF), and spring planted tall fescue (SPTF).

Table 1. Water, surface Q nitrate, and sediment yields averaged from 2003-2007 for the Calapooia River Basin with all agricultural land modeled as a single landuse using SWAT defaults.

Default SWAT landuse in agricultural area	NLCD[1] class number	Total water yield	Surface Q nitrate yield	Total sediment loading/loss
		(inch)	(lb/a)	(lb/a)
RNGE	71	25.6	0.64	205
HAY	81	24.6	0.78	313
AGRR	82	22.6	1.29	10,046
AGRC (or WWHT)	83	25.0	1.12	3,348
AGRL	85	22.4	1.36	7,323
WPAS	---	25.6	0.61	24,103
CORN	---	22.1	1.22	9,555
CLVR	8	27.5	0.53	196

[1] National Land Cover Data (NLCD 2001)

Table 2. Water, surface Q nitrate, and sediment yields averaged from 2003-2007 for the Calapooia River Basin with all agricultural land modeled as a single landuse using newly defined sequences of crop management operations.

Newly defined crop management in agricultural area	New crop code number	Total water yield	Surface Q nitrate yield	Total sediment loading/loss
		(inch)	(lb/a)	(lb/a)
Fallow	1	25.9	0.70	31,747
GSAR or GSLO	2 or 12	24.5	1.68	1,982
SPTF	3	22.1	0.47	4,965
GSPR	4	25.4	1.96	1,750
GSOG or GSTF	5 or 6	23.0	1.59	205
TFHC or TFPA	7 or 10	23.9	0.76	705
MINT	9	21.2	2.57	741
FPPR	13	24.5	1.86	1,974
FPTF	14	21.7	1.17	3,402
FPCL	15	21.7	0.56	3,920
WWHT	16	25.7	2.14	1,348
MDWF	17	25.4	1.14	5,965

Total water yield for the 15 new crops/management options was similar to that for the eight SWAT default crops, and ranged from 21.7 to 25.9 inches (Table 2). Total sediment loading in the new crops/management options ranged from 205 to 31,747 lb/a, with the increase over the eight default crops due to the addition of the extreme fallow case. Surface nitrate yield for six of the new crops/management options exceeded the largest value from the eight default crops, indicating that manual fertilization was now being modeled as leaking more N than default auto-fertilization. Since all of the default crops in Table 1 had under-predicted nitrate, the increased nitrate yield of many crops in Table 2 was a step in the right direction toward matching modeled and observed N losses.

Multiple-year modeling of observed crops/landuses

Scenarios run using observed crop distributions from the 2005, 2006, and 2007 harvest years starting a minimum of three years earlier showed the responsiveness of SWAT to variation in the weather (Table 3). The drier than normal crop year of 2004-05 not only had a total water yield of less than half that seen in other years, but also saw a 7 to 14-fold reduction in surface nitrate yield and a 4 to 6-fold reduction in total sediment loading. When the extremely wet harvest year of 1974 was modeled using the crop distribution of 2007, total water yield and sediment loading were double those seen on average in the three wetter recent years, while surface nitrate yield averaged nearly 3-times that present recently.

Next we extracted observations for individual dates from data files for subbasins aligned with our water quality sampling points (Figures 1 and 2). Because samples had only been collected on 12 to 15 discrete dates over each cropping year (and less than that at sites where the ephemeral streams dried up in late summer), we could not be certain our observations were truly unbiased. Perhaps nitrate and sediment concentrations and fluxes were higher or lower than average during the extreme flow events we tended to miss because sampling sites were inaccessible or the conditions judged too hazardous to attempt to sample. While several methods exist for weighting the observed concentrations of sediment or nutrients by factors that should reduce the sampling condition bias, the most straightforward was to use modeled water flow as the weighting factor, increasing the contribution of samples taken on higher flow days while decreasing the importance of samples taken on lower flow days.

Flow-weighted averages for observed sediment concentrations among our 40 sample sites ranged from a low of 5.8 ppm to a high of 40.3 ppm in the 2005 harvest year, with an average of 20.6 ppm. In the wetter 2006 harvest year, flow-weighted averages for observed sediment concentrations ranged from a low of 11.7 ppm to a high of 141.7 ppm, with an average of 66.5 ppm. Differences between years in sediment yield were even more dramatic, with an average of 45.2 lb/a in the 2005 harvest year compared to 406.4 lb/a in 2006. Modeled yearly sediment yield was substantially larger than observed sediment yield at most but not all sites (modeled was greater than twice observed sediment yield at 35 of 40 sites in 2005 and 31 of 40 sites in 2006). Even in the wetter year (2006), modeled soil loss in Calapooia River subbasins only exceeded the usual NRCS soil erosion tolerance “T value” of 1.5 tons/a at 9 of the 40 locations, with the flow-weighted observed erosion never exceeding that tolerance level. Plotting modeled versus observed sediment yield clearly shows the existence of many locations where SWAT greatly over-predicted sediment loss (Figure 1). Since SWAT even modeled too much sediment coming out from the densely forested upper end of the Calapooia River Basin, variables still needing to be better calibrated must include some that have no direct connection to agriculture.

Flow-weighted averages for observed total N concentrations among our 40 sample sites ranged from a low of 0.3 ppm to a high of 11.9 ppm in the 2005 harvest year, with an average of 3.6 ppm. In the wetter 2006 harvest year, flow-weighted averages for observed total N concentrations ranged from a low of 0.3 ppm to a high of 8.9 ppm, with an average of 2.6 ppm. Lowest concentrations in both years occurred at site #4 located at the upper end of the Calapooia River Basin in a densely forested region. Despite generally lower concentrations of N in the 2006 harvest year, average flow-weighted observed yearly total N yield increased from 7.4 lb/a in 2005 to 15.7 lb/a in 2006. Only 1 of the 40 sites had lower flow-weighted observed total N yield in 2006 than in 2005. Average modeled yearly nitrate yield exceeded flow-weighted observed total N yield by 79% (13.3 vs. 7.4 lb/a) in 2005 and by 98% (31.0 vs. 15.7 lb/a) in 2006. Modeled yearly nitrate yield was lower than observed total N yield at 11 of 40 sites in 2005, but only 1 of 40 sites in 2006. Plotting modeled nitrate versus observed total N yield showed a general tendency of SWAT to over-predict N at a majority of sites, along with under-prediction at some sites (Figure 2). Since inclusion of other dissolved forms of N along with nitrate would only serve to further increase the problem of over-prediction of N by SWAT at most sites, model parameters affecting factors such denitrification will need to be recalibrated before SWAT can provide truly reliable estimates of N fluxes in western Oregon.

Consistency of N-impact type groups

The four main subbasin groups previously identified in terms of their maximum total N concentrations and their temporal patterns were examined in terms of their performance in explaining variation in N transport among sample sites. In 2005, N-impact types 1 (low), 2 (medium), 3 (high), and 4 (high without strong temporal trends) had flow-weighted averages for total N of 0.6, 2.2, 5.4, and 4.9 ppm. In 2006, N-impact types 1, 2, 3, and 4 had flow-weighted averages for total N of 0.5, 1.6, 3.5, and 3.9 ppm. For observed yearly total N yield, N-impact types 1, 2, 3, and 4 averaged 1.5, 4.9, 10.7, and 10.0 lb/a in 2005 and 2.9, 9.6, 21.0, and 23.5 lb/a in 2006. For modeled yearly total N yield, N-impact types 1, 2, 3, and 4 averaged 2.6, 9.4, 12.9, and 24.0 lb/a in 2005 and 5.5, 22.0, 42.4 and 44.0 lb/a in 2006. It is clear that the N-impact type 1 subbasins exported the least N, with the type 2 subbasins exporting more N than the type 1 but less than the types 3 and 4. The type 3 and 4 subbasins differed relatively little in how much total N they lost over

Table 3. Water, surface Q nitrate, and sediment yields for the Calapooia River Basin with agricultural landuse modeled as known mixtures of 16 classes for the 2005, 2006, and 2007 harvest years.

Harvest year (previous Aug. 1 through current July 31)	Total water yield	Surface Q nitrate yield	Total sediment loading/loss
	(inch)	(lb/a)	(lb/a)
2005 crops (2004 weather)	25.0	1.37	1,697
2005 crops and weather	10.2	0.14	268
2006 crops and weather	26.3	0.98	1,063
2007 crops and weather	28.9	1.88	1,215
2007 crops (1974 weather)	55.4	4.09	3,242

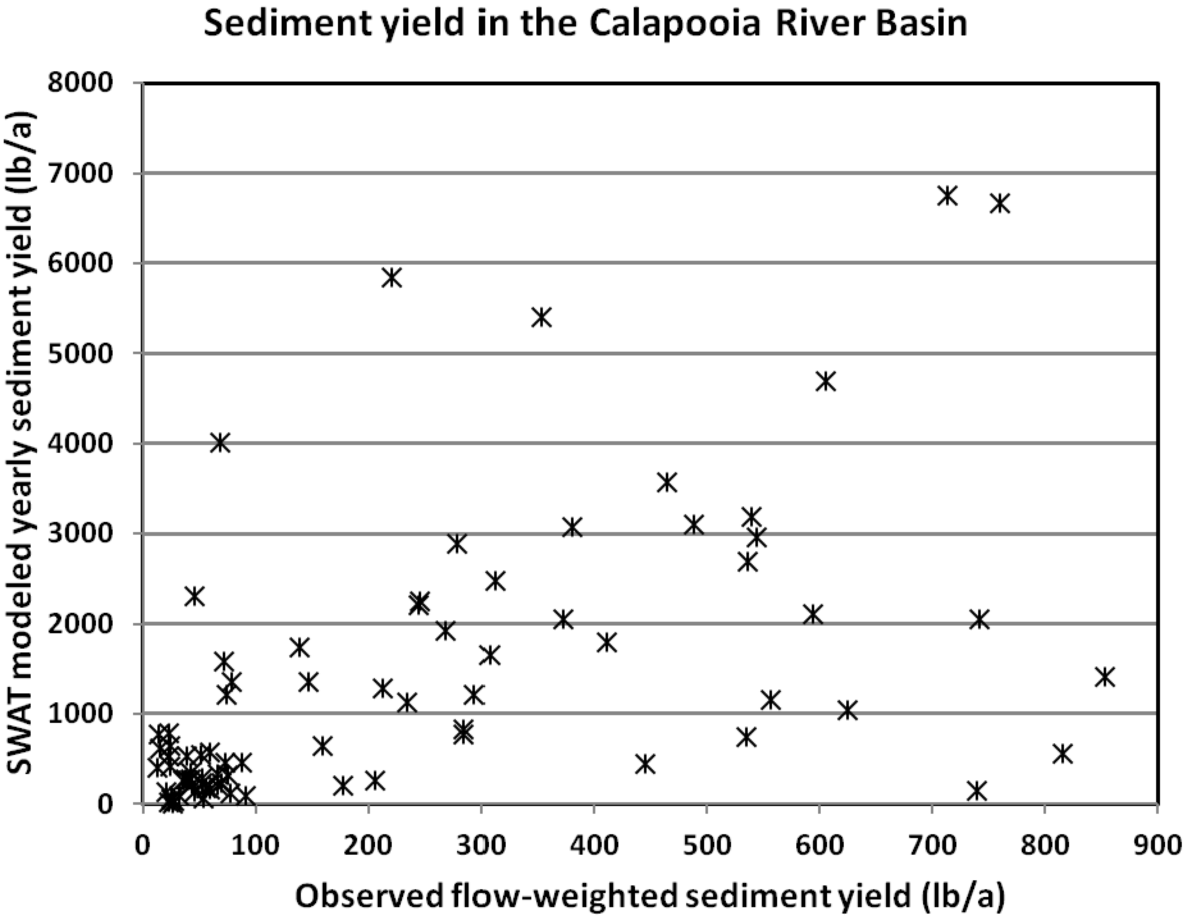

Figure 1. Yearly sediment yield in lb/a at 40 sample collection sites in the Calapooia River Basin for harvest years 2005 and 2006. X-axis values are the observed concentrations multiplied by modeled stream flows scaled to yearly totals. Y-axis values are modeled sediment yields from SWAT.

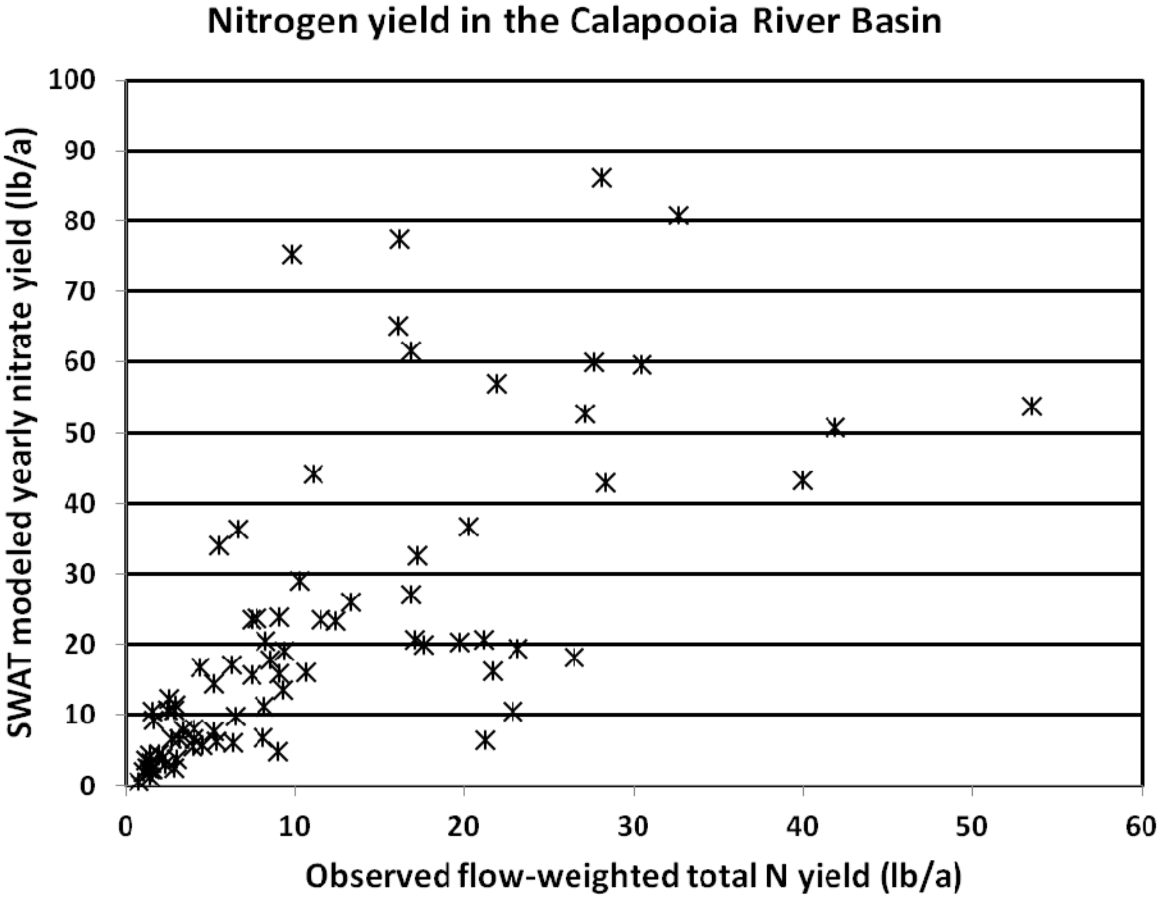

Figure 2. Yearly nitrogen yield in lb/a at 40 sample collection sites in the Calapooia River Basin for harvest years 2005 and 2006. X-axis values are the observed concentrations of total nitrogen multiplied by modeled stream flows scaled to yearly totals. Y-axis values are modeled nitrate yields from SWAT. The majority of nitrogen present in the samples and modeled by SWAT was in the form of nitrate.

the year. The primary difference between total N concentrations in the type 3 and 4 subbasins had been the presence or absence of peaks in December and minimums in the summer. Subbasin types 3 and 4 differed primarily in the size of the secondary peak in early spring, with the higher peak in the type 4 subbasins coinciding with the general timing of spring fertilizer application.

Discussion

Performance of SWAT

Before results of SWAT modeling can be used to describe alternate agricultural practice scenarios with the potential to reduce contamination of surface waters through changes in crops grown and management practices employed in their production, the issue of how well SWAT actually models the real world must be faced. For crops such as corn and soybeans in the Midwest, agreement between observed flows of N and sediment can be so close that conversion of Conservation Reserve Program grasslands to these row crops was both modeled and observed as an average increase in nitrate-N yield of 27 lb/a. Our current SWAT model for the Calapooia River Basin falls well short that level of precision. Water yield in SWAT simulations closely matched historical USGS gage data when averaged over months or years, but performs more poorly when measured on a daily basis. Automatic calibration of SWAT using a Beowulf cluster and genetic algorithms has been shown to successfully recreate daily flow patterns in western Oregon, and will be used in future simulations once crop models and management operations have been adequately refined. Uncalibrated SWAT appears to direct unrealistically large fractions of precipitation into subsurface and deep ground water flows at the expense of surface flows, a phenomenon that should also be improved by better calibration of daily flows.

Our current group of management practices for 16 crops appears to seriously overestimate sediment flow in western Oregon. It would be simple enough to adjust dates for planting/begin growth and harvest to alter predicted sediment flow by assuming that crops are in the ground and growing for longer fractions of the year. But since we created our new management sequences to match up with real planting and harvest dates, it would be rather unfair to fix sediment problems by simply pretending the crops are growing for more (or less) of the year than is the case.

Implications of landuse on water quality

Even though limitations in the precision of the current SWAT model for western Oregon grass seed crops restricts our ability to make quantitative predictions of the effects of changing crops and management practices, some general findings still hold. Grass seed crops export less nitrate in surface water than winter wheat or mint, but differences are probably less than 30%. Grass seed crops reduce sediment loading compared to most available alternatives, though no-till methods for winter wheat production might come close to approaching the efficiency of established grass seed crops in retaining soil on fields. Higher rainfall years will see greater total flux of N but lower concentrations in the water, with differences in nitrate yield among years easily spanning a factor of 10X. The low, medium, and high N concentration subbasin types identified without regard to total water yield retained their distinctiveness when water flow was factored in to provide estimates of nitrate or total N yield over time. The fourth N-impact type (the one lacking strong temporal signal in concentration) did not differ greatly from the third N-impact type in terms of N yield although more of the N was lost to runoff in early spring around the normal time for spring fertilizer application. Despite overestimating nitrate yield in general, our current SWAT model does not reproduce the N spikes seen in the spring-time at some but not all of the sampling locations. This strongly suggests that those spikes do indeed represent either direct application fertilizer to water flowing across the surface of fields or rainfall events shortly after application intense enough to transport N in surface water rather than moving it into the soil profile.

Conclusions

Our revised crops and management operations produced more realistic simulations of N and sediment dynamics in the Calapooia River Basin than the SWAT defaults. Both observed and modeled quantitative estimates for N yield confirmed the existence of the low, medium, and high N-impact types of subbasins we previously identified. Although our model is currently biased slightly upward for N yield, cases where the observed N concentrations in late winter and early spring substantially exceed the predicted values imply that urea-based fertilizers may have been applied too near in time to heavy rainfall or too close in space to running water. The primary flush of nitrate occurs in December, and represents inadequate growth in the fall by new seedlings and previously established perennial plants coming out of their late summer, moisture-stress induced dormancy to use up the available mineralized N. The hydrologic cycle simply overwhelms the cropping cycle, and nothing short of massive seasonal redistribution of water through expanded use of irrigation and water storage mechanisms could control this flush of nitrate. Discrepancies between observed and modeled losses of sediment and N indicate that SWAT must be thoroughly calibrated for western Oregon conditions before its results could be reliably used as the basis for defining impact of conservation programs and rewarding producers for adherence to standards.