Problems and Solutions in Applying SWAT in the Upper Midwest USA

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Abstract
We are applying the Soil and Water Assessment Tool (SWAT2000) to the Willow River watershed in western Wisconsin to assess the effects of land use and management changes. The Willow River drains about 735 km², much of which is agricultural land yielding substantial nonpoint-source loads of sediment and nutrients. The upper Midwest USA is a geologically young landscape with many closed drainages, intensive cultivation amid patches of forest, and expanding urban centers. Principal crops include corn, soybeans, and alfalfa typically grown in rotation to support both dairy and cash-crop operations. SWAT had problems with rotations that included alfalfa, wherein alfalfa could not be removed from the landscape once planted. Code changes to the SWAT engine were required to correct this problem. Corn yields were underestimated because of nitrogen stress due to excessive denitrification. Again, code changes allowed parameterization of the nitrification process. About 29% of the landscape drained to closed depressions; the fraction of closed drainage in each subbasin was routed to the Pond routine in SWAT and parameterized to trap all sediment and phosphorus. However, seepage from Ponds was trapped by SWAT in shallow aquifer storage and not included as groundwater recharge, and therefore did not contribute appropriately to stream baseflow. As a surrogate for this missing groundwater discharge, we disallowed Pond seepage and forced slow surficial outflow by increasing the days to reach target storage. Phosphorus loading from subbasins to the channel reaches was complicated by the addition of a subbasin chlorophyll load by SWAT. When the stream water-quality routine was activated, this chlorophyll load was apparently interpreted as algae with significant phosphorus content, and the subsequent release of this phosphorus constituted an additional load unconnected to the land-surface phosphorus budget. To avoid this extraneous phosphorus load, either the stream water-quality routine had to be de-activated, or the phosphorus content of algae had to be reduced to a negligible fraction. Subbasin sediment yields were consistently overpredicted by SWAT with default parameterization. Sediment calibration could be achieved by parameterizing the soil-loss equation to reduce erosion, or by parameterizing the channel to trap excess sediment. Despite these problems encountered during model construction and calibration, the solutions given above have resulted in workable SWAT models for our purposes. We acknowledge other members of the SWAT Midwest America Users Group (SMAUG) in identifying and solving the above problems. Some of these problems have already been addressed in SWAT2005, and we are confident that the code will continue to improve.

KEYWORDS: SWAT, nonpoint source pollution, sediment, nutrients, runoff, agriculture
Introduction

Row-crop agriculture, as typified by corn, is common in the Midwest USA (Figure 1a), and nonpoint-source (NP-S) loads of sediment and nutrient from these lands cause significant ecological problems for receiving waters. Suspended sediment is one of the most prevalent pollutants in streams in the USA (USEPA, 2002). Increased phosphorus loading from watersheds is generally considered the primary cause of eutrophication of freshwater ecosystems (Carlson, 1977; Schindler, 1978). Excessive nitrogen loading has been linked to hypoxia in the bottom waters of the Gulf of Mexico (Goolsby, 2000; Rabalais et al., 2001). Addressing these problems will require improved agricultural practices that reduce soil erosion and the loss of applied fertilizers.

Computer models of watersheds provide an important management tool for planning remedial actions. In conjunction with monitoring programs, modeling can help target critical source areas of NP-S pollution for remediation. More importantly, models can help predict effectiveness of remedial actions.

However, the predictive power of models depends on their ability to simulate hydrological mechanisms of flow and transport. The art of successful model application relies on knowing model strengths and limitations in simulating these mechanisms.

The purpose of this paper is to describe several perceived limitations in a model of an agricultural watershed in the upper Midwest, and to provide methods to circumvent these limitations to achieve successful model calibration and application. The modeling program selected was the Soil and Water Assessment Tool (SWAT2000), a widely used program developed to simulate long-term loading of NP-S pollutants in large basins with diverse land use (Arnold et al., 1998; Di Luzio et al., 2002). In some cases, overcoming model limitations required changes to the engine code; in other cases, alternative parameterizations allowed acceptable model performance. Knowledge of model problems and solutions has implication for all users of SWAT and can lead to improved versions of the model code such as SWAT2005, which addresses some of the issues with SWAT2000 identified here.

Study Site

The Willow River in western Wisconsin, USA, is about 91 km long and drains about 735 km$^2$ of rural lands which are substantially agricultural (Figure 1b). It is tributary to the St. Croix River, a nationally recognized Scenic and Recreational Riverway in the upper
Mississippi River drainage. The Willow watershed was chosen for study because it has been identified as a significant contributor of NP-S pollution (Lenz et al., 2003) and has thus been targeted for remediation by implementation of agricultural best management practices (BMPs). The climate is humid mid-continental with most rainfall in summer; the 1971-2000 normal precipitation was about 813 mm, averaged from two nearby weather stations (NCDC, 2005). Flow averages about 4.7 cms (cubic meters per second) (Lenz et al., 2003). Two reservoirs on the main channel effectively trap sediment and ameliorate flood peaks, though these reservoirs are relatively small (96 and 70 ha) and shallow (1.1 and 2.4 m mean depth).

Most of the watershed has 15–60 m of Pleistocene glacial drift overlying Ordovician sandstone and dolostone (Feinstein et al., 2005). This geologically young landscape has many closed drainages totaling about 29% of the watershed area. Soils derived from this glacial parent material are predominately loamy and include well-drained to moderately poorly-drained areas (USDA, 1978). From 1992-93 satellite data, land use in the study area was estimated to be 43% agriculture cropland, 30% grassland, 18% forest, 7% water/wetland, and only 2% urban (WDNR, 1998). By 1999, about 10% of this cropland was converted to other land uses, largely rural-residential developments (Almendinger and Murphy, 2005). Principal crops are corn (Zea mays L.), soybeans (Glycine max L.), and alfalfa (Medicago sativa L.) typically grown in rotation to support both dairy and cash-crop operations.

Methods – Model Construction and Data Comparisons

A SWAT model was constructed for the Willow River watershed to help guide remediation efforts. The AVSWAT interface discretized the watershed into 27 subbasins based on 10-m digital elevation model datasets (USGS, 2005). The intersection of the subbasin boundaries, soils data set (NRCS, 2006), and 30-m land use grid (WDNR, 1998) produced 532 hydrologic response units (HRUs). The soils data were simplified by averaging the properties of soils in the same hydrologic group within each subbasin prior to the intersection to avoid an excessive number of HRUs. The primary calibration data set consisted of daily flows and monthly loads of sediment and total phosphorus from water year 1999 (October 1998 through September 1999) (Lenz et al., 2003). Because model calibration to a single year of data may be unreliable, additional data were used to constrain the model, including crop yields, estimates of reservoir sedimentation, and phosphorus content of trapped sediment. To simplify interpretation, the model was parameterized to preclude both sediment erosion or deposition in the channel. In comparison to the water-year 1999 data set, the model simulated daily flows with a Nash-Sutcliffe coefficient of efficiency ($E_{NS}$) of 0.70, monthly sediment loads with an $E_{NS}$ of 0.63, and monthly total phosphorus loads with an $E_{NS}$ of 0.47 (Nash and Sutcliffe, 1970; Legates and McCabe, 1999).

A number of problems arose during model calibration, where the model did not behave as described, or where model output deviated from observed data or expected values enough to bring into question model algorithms. We describe below some of the more important of these problems, and how each problem was either solved or avoided in our construction of a workable SWAT model of the Willow River watershed, hereafter referred to as the calibrated model. In most examples, results are presented as a contrast between the problematic model runs and the calibrated model runs. Typically the models were run for 15 years, with annual average output being calculated from the last 10 years, ignoring the first 5 years for model warm up.
Results and Discussion – *Modeling Pitfalls to Avoid*

**Persistent Alfalfa**

Dairy farmers commonly grow alfalfa in rotation with corn and sometimes soybeans. Representative rotations included in the Willow model are two years of corn followed by three years of alfalfa (C2A3), and three years of corn, one year of soybeans, and three years of alfalfa (C3S1A3). Both corn and soybeans require annual tillage and planting, whereas alfalfa is a perennial that requires no tillage after planting the first year. Consequently, sediment and nutrient loads are typically much greater from corn and soybean fields than from alfalfa fields. Because of the large areas of these crops grown in the Midwest USA, and because of the large differences in sediment and nutrient yields between alfalfa and row crops (corn and soybeans), it is critical that SWAT be able to simulate rotations of these crops properly.

However, in simulations using the downloaded SWAT2000 engine, once alfalfa was planted it persisted for all remaining years of the simulation. In some respects, parts of the model may be rotating corn with alfalfa, as calculated nitrogen fixation for a C2A3 rotation rises and falls in a 5-year sequence as might be expected. Nonetheless for HRUs with either C2A3 or C3S1A3 rotations, model yields of sediment and phosphorus approach those for alfalfa alone and are thus critically underestimated.

To avoid the problem, one could disallow rotations and grow only continuous corn, soybeans, and alfalfa. However, continuous monocultures could result in unrealistic soil nutrients balances and cause significant errors in nutrient yields. A better solution was to correct the model code, as was done by Baumgart (2005), who kindly provided the executable copy that was used to build the calibrated model of the Willow watershed. Compared to Baumgart’s SWAT version, the original SWAT code underpredicted sediment yields by 75% and phosphorus yields by 63% for the C2A3 rotation.

**Excessive Denitrification**

During model calibration runs, corn yields were consistently underpredicted because of nitrogen stress. Model output indicated that about 75% of nitrogen applied to corn HRUs was being lost to denitrification, whereas literature values were closer to 15%. The original SWAT2000 engine did not give access to denitrification parameters. Again Baumgart (2005) provided a modified SWAT executable that allowed denitrification to be tuned. The Willow model was then parameterized to allow only about 11% denitrification, which improved corn yields substantially. Even still, the model had problems with nitrogen stress caused by loss to leaching, and to bring corn yields up to observed values the nitrogen auto-fertilization routine in SWAT was activated. Auto-fertilization is very useful, but it does complicate interpretation of soil nitrogen budgets and consequent loads to aquatic systems. Because nitrate loads to the Mississippi River from the Midwest are the primary cause of hypoxia in the Gulf of Mexico (Goolsby, 2000), refining model algorithms that simulate nitrogen transport is important. Apparently SWAT2005 has incorporated access to denitrification parameters, which is a useful step in this direction.

**Closed Drainages and Loss of Infiltration**

Closed drainages are a common landscape feature in the glaciated Midwest USA. About 29% of the Willow River watershed drains to closed depressions identifiable from 1.5-m contours of 1:24,000-scale topographic maps; conceivably additional areas drain to unidentified closed depressions shallower than 1.5 m. Under current conditions, such depressions rarely if ever spill. Consequently they play an important role in trapping
sediment and phosphorus that otherwise would be delivered to the channelized network. However, during the processing of the digital elevation grid by the AVSWAT interface, such depressions are artificially filled in order to clarify the delineation of subbasins. Closed depressions, and their important water-quality function, are thereby lost from the model.

Fortunately, SWAT provides tools to address such a problem. In SWAT, Ponds are conceptual water bodies, one per subbasin, that receive drainage from a specified fractional area of that subbasin. In the Willow model, the aggregate area of closed drainage within each subbasin was routed to a Pond, which was parameterized to trap all sediment and phosphorus, and to infiltrate all influent water. In theory, this would allow the model to closely mimic closed drainages by trapping all sediment and phosphorus while passing water to groundwater recharge, which after some time should smoothly contribute to baseflow in the main channel.

In practice, Ponds in the model did trap sediment and phosphorus correctly; however, they also incorrectly trapped all infiltrated water as well, rather than contributing to groundwater recharge. When Ponds were added to the Willow model to simulate the 29% of landscape occupied by closed depressions, the basin-wide yields of sediment, phosphorus, and water all declined by about the same percent (29-31%). The infiltrated water was apparently being trapped in the model’s shallow aquifer storage component, rather than being passed along to groundwater recharge. According to model output, the water in shallow aquifer storage continued to increase by about 50 mm each year the model was run, corresponding approximately to the annual reduction in water yield from the basin. Infiltration from other surface-water bodies in SWAT may suffer the same fate, though we investigated only Ponds.

This problem appears to be a relatively simple error in model code wherein water in shallow aquifer storage is not passed along to groundwater recharge. In the absence of a code correction, we developed a work-around by allowing Ponds to spill as slowly as possible, in an attempt to mimic groundwater discharge to the river. To do this, Pond infiltration was disallowed by setting bottom hydraulic conductivity to zero, and each Pond was given a large emergency volume and a long hydraulic response time (parameter NDTARG set to 500-1000 days) to smooth outflow. The result was marginally successful: Pond outflow could be slightly smoothed, but not to the degree we presume necessary to mimic groundwater discharge well. Still, overall the Pond tool in SWAT did allow closed drainages to be effectively simulated: sediment and phosphorus were trapped, and slow surficial outflow allowed water yields to match observed values.

**Extraneous Phosphorus Loads as Chlorophyll from Subbasins**

In a SWAT model, if reservoirs are removed and stream water-quality routines deactivated, the amount of phosphorus leaving the land (subbasins) should be effectively the same as that leaving the watershed outlet (lowermost reach), because the channel simply passively transports phosphorus loads without alteration. This was true for the Willow model. However, when stream water-quality routines were activated, phosphorus yields from the Willow watershed suddenly increased by 19%, which was very odd, because the losses from the land remained the same as before. The watershed was losing more phosphorus at its outlet than was being lost from the land. What was the source of the extra phosphorus reaching the outlet?

The answer is that in addition to the phosphorus load transported from the land to the channel, SWAT also adds a chlorophyll load. From the perspective of the land, this chlorophyll load appears to be phosphorus-free and unrelated to the phosphorus budget of the soil. If stream water-quality routines are not activated, then the channel likewise ignores this chlorophyll load; it is simply passed downstream, unaltered. However, if stream water-
quality routines are activated, then the stream interprets this chlorophyll load as algae, and further presumes that this algae has a phosphorus content. Upon decomposition of this perceived algal load, its presumed phosphorus content is released, thereby providing the source of phosphorus loading that suddenly appeared in the Willow model upon simply activating the stream water-quality routines. This phosphorus load appears to be extraneous and unrelated to the actual phosphorus budget of the land surface.

Two options exist to avoid this problem. The first is to avoid activating the stream water-quality routines. The second is to reduce the phosphorus content of algae in the model (parameter AI2) to a very small value, thereby making the added phosphorus from the subbasin chlorophyll load negligible. Both options are functional, though neither is satisfying. We believe that the algorithm that adds a chlorophyll load from the subbasins to the channel needs to be re-examined, or at least integrated with the phosphorus fractions transported from the subbasins.

Large Sediment Yields and Alternate Calibrations

Under default parameterization, SWAT produced sediment yields nearly twice those expected from the landscape in the Willow model, about 44 t km\(^{-2}\) compared to the expected 23 t km\(^{-2}\). In our case, the “expected” value is admittedly poorly known, as it was determined from a series of considerations including approximate trapping efficiencies of reservoirs, estimated sediment thicknesses in the reservoirs, sediment delivery ratios from watersheds the size of the Willow, and estimated gross erosion rates from cropland and pasture. Yet it is our belief that other colleagues in the Midwest have had similar experiences, and that typically SWAT has had to be parameterized to dial down sediment yield, rather than the converse. In the Willow model, sediment yield was reduced by two main parameterizations. First, another code modification by Baumgart (2005) changed runoff time-of-concentration calculations to be based on subbasin area and channel length, rather than on HRU area and channel length. Second, the modified universal soil-loss equation cropping practice (MUSLE P) factor was reduced from 1.0 to 0.7, which we used simply as a scaling factor to reduce sediment yields by 30%.

We offer this observation more as a comment rather than critique of SWAT. In the model, HRUs are depicted as contiguous uniformly sloping landscape units draining directly to channels without intermediate sediment traps. In reality, however, an HRU likely comprises many disaggregated, non-contiguous land parcels, and runoff from these parcels has a tortuous path from upland to stream channel with many potential intermediate sediment traps. One might therefore expect that net erosion from real landscape units would be less than that predicted by MUSLE calculations and the HRU concept.

Alternatively, if one accepts the sediment yields from the landscape as calculated by SWAT, yet the consequent modeled loads in the stream are greater than measured loads, then the excess sediment must be trapped at the upland/stream interface, namely in the floodplain and channel system. Up to this juncture our calibrated model had disallowed any channel processes, hence it was called the “passive channel” model. We next created an alternate calibrated model, called the “active channel” model, which received greater sediment and nutrient loads from the uplands (by re-setting the MUSLE P factor back up to its default value of 1.0), but then deposited these excess loads in the channel and floodplain system by adjusting sediment entrainment and phosphorus settling parameters. The net effect on loads at the watershed outlet was minimal, and the active channel model achieved nearly identical Nash-Sutcliffe calibration statistics as the passive channel model. In using SWAT to test relative effectiveness of agricultural BMPs, conclusions will likely depend on which calibrated model – the passive channel, or active channel, version – is chosen as the baseline scenario.
Summary and Conclusions

Application of SWAT2000 to an agricultural watershed in the upper Midwest USA uncovered several issues that needed to be addressed to achieve model calibration. Changes in model code allowed proper rotation of alfalfa with other crops and a reduction in denitrification loss of applied nitrogen. While the Pond tool in SWAT was very useful in simulating sediment and phosphorus trapping by closed depressions, infiltration from these depressions was excluded from groundwater recharge and thus did not correctly contribute to stream baseflow. SWAT added a chlorophyll load from the subbasins to the channel, which was converted to phosphorus when stream water-quality routines were activated, thereby resulting in an extraneous phosphorus load that was unrelated to the phosphorus budget of the soil column. SWAT appeared to deliver greater than expected sediment yields under default parameterization, and whether the modeler decides to trap this excess sediment in the uplands or floodplain can lead to alternate calibrated models. This problem points to a fundamental gap in our knowledge base. There are many field-scale studies that have verified the USLE and its variants in calculating gross erosion. There are many watershed-scale studies that have measured net erosion (total sediment yield) leaving the watershed at its outlet. But what happens between the field and the watershed outlet remains difficult to characterize.

The Midwest USA is one of the most agriculturally productive and intensively cultivated regions of the world. Nonpoint-source loads of sediment and nutrients from this agricultural activity have had significant impacts on the water quality of both freshwater and marine systems. Watershed modeling is an important tool to facilitate balancing the need for agricultural production with the desire to protect aquatic resources. The development of SWAT has made important contributions to the science of watershed modeling. The issues with SWAT raised in this paper are mostly soluble by model code revisions, which we feel would incrementally, but significantly, increase the power of SWAT to solve real problems in watershed management.

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