Effect of best management practice implementation on sediment and phosphorus load reductions at subwatershed and watershed scale using SWAT model

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Abstract

Identification of areas contributing disproportionately high amount of pollutants (i.e., critical source areas (CSAs)) to streams is important to efficiently and effectively target best management practices (BMPs). Process-based models are commonly used to identify CSAs and evaluate the impact of alternative management practices on pollutant load reductions. The objective of this study was to use the Soil and Watershed Assessment Tool (SWAT) to identify CSAs at the subwatershed level and evaluate the impact of alternative BMPs on sediment and total phosphorus (TP) load reductions in the Pleasant Valley watershed (50 km²) in South Central Wisconsin (USA). The Nash-Sutcliffe efficiency, percent bias, and coefficient of determination ranged from 0.58 to 0.71, -12.87 to 38.33, and 0.67 to 0.79, respectively, indicating that SWAT was able to predict stream flow, sediment and TP loadings at a monthly time-step with sufficient accuracy. Based on the SWAT simulation results, annual Average (2006-2012) subwatershed yield for sediment and TP ranged from 0.06 to 3.14 ton ha⁻¹ yr⁻¹ and 0.04 to 1.9 kg ha⁻¹ yr⁻¹,

respectively. The croplands were the major source of sediment and TP in this watershed ($\geq$ 84%). Reduction in sediment and TP loading ranged from 66 to 99% at the subwatershed level after conversion of croplands to Conservation Reserve Program (CRP) grasslands in subwatersheds identified as CSAs. On the other hand, reduction in sediment and TP loading with implementation of no-till practices ranged from only 14 to 25%. At the watershed outlet, sediment and TP loading reduction was $\leq$ 15% after conversion of croplands to CRP grasslands and implementation of no-till practices because only about 8% of the watershed area was targeted for BMPs and/or resuspension of sediment deposited on the stream bed masked the downstream improvements in water quality.

Keywords: SWAT;Critical source areas; Phosphorus; Sediment; Tillage; Watershed modeling

1. Introduction

Sediment and phosphorus (P) are important non-point source pollutants causing impairment of surface waters. Excessive P and sediment delivery to streams results in problems, such as, toxic algal blooms, oxygen deficiency, fish kills and loss of biodiversity (Carpenter et al., 2008). To reduce excessive sediment and P delivery from agricultural landscapes to streams, best management practices (BMPs) need to be implemented at sensitive areas contributing non-point source pollutants to streams. Implementation of BMPs at a watershed scale is expensive and time consuming. Therefore, BMPs should be targeted to areas capable of disproportionate contributions of non-point source pollutants to streams and other water bodies to achieve desired water quality improvement (Nowak et al., 2006).

Source area contributions to streams can vary within a watershed due to variability in topography, hydrology, soil type, land-use, and management practices. Several studies have

shown that only a small portion of a watershed can contribute significant amount of pollutants. For example, White et al. (2009) found that in six Oklahomawatersheds, 5% of the land area contributed 50% of the sediment and 34% of the total P (TP) load. Ghebremichael et al. (2010) reported that only 24% of the total watershed area contributed to 80% of TP losses in a predominantly agricultural Rock River watershed in Vermont. Similarly, Busteed et al.(2009) showed that 85 to 90% of the sediment and TPload originated from 10% of the Wister Lake watershed located in southeastern Oklahoma and southwest Arkansas.

Different methods are used to identify areas contributing disproportionately high amount of pollutants (i.e., critical source areas, CSAs) to streams within a watershed. One approach is to monitor pollutant load to prioritize CSAs. However, measuring pollutant loading from individual fields in a watershed is expensive, labor intensive and impractical (Giri et al., 2012). These experiments also require several years to account for climate fluctuations (Veith et al., 2005). Tools such as the P Index can be used on single or multiple fields within a watershed to prioritize fields for BMP implementation. Conservation planners can also identify CSAs via qualitative evaluation based on their professional judgment (White et al., 2009). However, these methods also face limitation when employed at the watershed scale where the data requirements are extensive. Off-site movement of sediment and P is controlled by both source and transport factors. Therefore, approaches which can capture the hydrologic complexities within a watershed drainage system and incorporate important variables influencing sediment and P transport are needed for effective identification of CSAs.

Process-based models, such as Soil and Watershed Assessment Tool (SWAT), can simulate complex processes involved in water, sediment and P movement (Ghebremichael et al., 2010; Gitau et al., 2008) and, therefore, are often used to identify CSAs for BMP implementation

at a watershed scale (e.g., Niruala et al., 2013; Shang et al., 2012; Srinivasan et al., 2005; Tripathi et al., 2005; White et al., 2009). SWAT has proven to be an effective tool to identify CSAs, since it incorporates land cover, topography, soil characteristics, rainfall and land-use management, which influence sediment and P transport from source areas to the watershed outlet (White et al., 2009). The SWAT model has been often used to evaluate the impact of BMPs to obtain intended water quality benefits (Arabi et al., 2008; Ulrich & Volk, 2009). For example, Douglas-Mankin et al. (2013) used SWAT to simulate the effect of different tillage practices on sediment loss in the Black Kettle Creek watershed in south central Kansas. Similarly, Kirsch et al. (2002) used SWAT to assess the impact of tillage and nutrient management on sediment and P losses in the Rock River watershed in south-central and eastern Wisconsin. Previous studies indicate that SWAT can be used to identify CSAs (e.g., Niruala et al., 2013; White et al., 2009) and simulate the impact of BMPs on reduction in sediment and TP load. Limited work has been done to simulate the effect of targeting BMPs at CSAs on sediment and P load reductions at the subwatershed and watershed level. Therefore objectives of this study were to: (1) Identify CSAs for sediment and TP at the subwatershed level; (2) Evaluate the impact of cropland conversion to conservation reserve program (CRP) grasslands; and (3) Evaluate the effect of implementing no-till practices on sediment and TP loads at the subwatershed and watershed scale.

2. Methods

2.1 Study site

The study site is the Pleasant Valley watershed located in the non-glaciated area of south-central Wisconsin (Fig. 1a). This watershed is within the Sugar-Pecatonica River Basin and also part of the Upper Mississippi River Basin. The watershed is approximately 50 km² in size with an average slope of 11% on silt loam soils. The major watershed land-uses consist of cropland

34%, Conservative Reserve Program (CRP) grassland 28%, woodland 22% and pasture 12% (Fig. 1b). The Pleasant Valley branch of this watershed is on the WI Impaired Waters 303(d) list due to degraded habitat from non-point source pollution contributions to sediment/total suspended solids (DNR, 2012). The streams in this watershed are dominated by fine sediment deposited on the stream bed. The average D10 (diameter at which 10% of the particle size distribution falls below), D50 (diameter at which 50% of the particle size distribution falls below) and D90 (diameter at which 90% of the particle size distribution falls below) of uplands, stream banks, suspended and stream bed sediment is included in Table 1. Information on particle size diameters was obtained using Malvern Mastersizer 2000 (Malvern Instruments, Worcestershire, UK) on sediment particles dry sieved through a 63 μm sieve and dispersed using 50 g l⁻¹ sodium hexametaphosphate. Particle size diameters were determined as a part of the larger sediment fingerprinting study (Lamba, 2014) conducted in this watershed.

2.2 SWAT model description

SWAT is a physically based, daily time-step and long-term simulation model (Gassman et al., 2007). Major components of this model include weather, hydrology, nutrients, bacteria and pathogens, soil properties, and land management (Gassman et al., 2007). In SWAT, a watershed is divided into subwatersheds and then further divided into Hydrologic Response Units (HRUs) based on homogenous land-use, soil type, and slope (Neitsch et al., 2011). The minimum area required for channel initiation used in this study was 2% of the total watershed area (Arabi et al., 2006), which resulted in delineation of 33 subwatersheds with an average area 150 ha. The HRU partitions in SWAT allow it to more accurately simulate the effect of spatial variations in parameters on hydrology, nutrient and sediment simulations (Parajuli et al., 2009). SWAT does not simulate the interaction among HRUs and the output from each HRU is routed to the stream

within a subwatershed (Srinivasan et al., 2005). Areas of identical land use, soil type and slope are lumped into a HRU within a subwatershed and then hydrologic, sediment and nutrient processes are simulated for each HRU. In this study, the thresholds for soil class, land-use % and slope were reduced to 0%, so that all land-use, soil type and slope percentages were represented as HRUs within the watershed. Surface runoff from each HRU was estimated using the modified SCS-CN method (USDA-SCS, 1972). Channel flow was routed using the variable storage routing method (Williams, 1969). Sediment yield in each HRU was estimated using Modified Universal Soil Loss Equation (MUSLE) (Williams, 1975) and sediment was routed through stream channels using a modification of the Bagnold's sediment transport equation (Bagnold, 1977). The deposition or erosion of sediment within the channel will take place, depending on the transport capacity of the flow in the channel. Potential evapotranspiration was calculated using the Hargreaves method (Hargreaves, 1975).

2.3 SWAT input data

Topography (3 m Digital Elevation Model) and land-use data obtained from Dane County Land Conservation Division, Dane County (DCLCD), Wisconsin were used as input for this study. The Soil Survey Geographic (SSURGO) data obtained from USDA Natural Resources Conservation Service was used for soils data input and the SSURGO preprocessing tool was used to create a soil layer compatible with SWAT (Sheshukov et al., 2012). Weather data (daily rainfall and maximum and minimum daily temperature) was obtained from the National Oceanic and Atmospheric Administration (NOAA) weather station located about 8 kilometers away from the watershed outlet in concert with an on-site gage. Solar radiation, wind speed, and relative humidity were simulated using the SWAT built-in weather generator.

Management information for this study was obtained from DCLCD, Dane County, Wisconsin. The management information included crop rotations, manure application rates, tillage, and soil test P. The management information was incorporated in the model at the subwatershed level based on the typical management practices followed in the agricultural fields within a subwatershed. Each subwatershed was assigned a single dominant crop rotation and single dominant tillage practice. The major crop rotations used in this study included: (a) three years of corn grain followed by four years of alfalfa, (b) three years of corn silage followed by four years of alfalfa, (c) corn-soybean and soybean-corn rotations, (d) continuous alfalfa, (e) continuous hay, (f) five years of hay followed by two years of corn. The tillage practices and manure application rates were also incorporated in the model at the subwatershed scale based on the typical tillage practices and manure application rates used in the agricultural fields within a subwatershed. The tillage practices used in this study included no-till, chisel plow, field cultivator and tandem-disc plow. The types of manures used in this watershed include dairy, beef and horse manure. The application rates of manure in croplands ranged from 0 to 31,380 kg ha⁻¹ and average rate of manure application in croplands was 3111 kg ha⁻¹. In pasture, manure application rates ranged from 16 to 7,460 kg ha⁻¹ and average rate of manure application in pastures was 2,637 kg ha⁻¹. The period of manure application included spring and winter (November and January).

2.4 Model calibration, validation and evaluation

SWAT calibration was performed manually by adjusting the sensitive parameters (identified from the literature review) within their permissible limits (Neitsch et al., 2011) at the watershed level (Table 2). The SWAT model was calibrated (using data for October 2006-January 2011 time period) and validated (using data for February 2011-April 2013 period) at a

monthly time-step for stream flow, sediment, and TP at the watershed outlet against observed data measured by a USGS gauge (Gauge # 05432927). The first eight years (October 1998-September 2006) were used as the warm-up period (based on the weather data from a National Oceanic and Atmospheric Administration weather station located about 8 kilometers away from the watershed outlet) to minimize uncertain conditions (e.g., soil moisture, ground water) in the SWAT model from start of the calibration of the model. The model calibration was initiated on October, 2006, corresponding to the start of USGS monitoring at the watershed outlet. The model was first calibrated for stream flow, followed by sediment load, and finally for TP. The parameters used for model calibration with default values, calibrated values, and description are included in Table 2.

Model evaluation was performed using qualitative and quantitative methods. Qualitative evaluation included plotting observed and simulated time series of stream flow, sediment and TP data at a monthly time-step. Different model statistical criteria have been used to evaluate model performance. For example, Ahmad et al. (2011) and Green et al. (2007) used (Nash-Sutcliffe efficiency) $NSE > 0.4$ and (coefficient of determination) $R^2 > 0.5$ for the model performance to be considered satisfactory. Santhi et al. (2001) used the criteria of $NSE \geq 0.5$ and $R^2 \geq 0.6$ as criteria for satisfactory model performance. In this study, we used R^2 (Eq. 1), NSE (Eq. 2) and percent bias (PBIAS) (Eq. 3) for quantitative model evaluation. The model performance was considered satisfactory if $NSE > 0.50$, and PBIAS was within $\pm 25\%$ for stream flow, $\pm 55\%$ for sediment and $\pm 70\%$ for TP (Moriiasi et al., 2007) and $R^2 > 0.5$ (Ahmad et al., 2011).

$$R^2 = \left[\frac{\sum_{i=1}^n (O_i - O_{avg})(S_i - S_{avg})}{\sum_{i=1}^n (O_i - O_{avg})^2 \sum_{i=1}^n (S_i - S_{avg})^2} \right]^2 \quad (1)$$

$$NSE = 1 - \left[\frac{\sum_{i=1}^n (O_i - S_i)^2}{\sum_{i=1}^n (O_i - O_{avg})^2} \right] \quad (2)$$

181

$$PBIAS = \left[\frac{\sum_{i=1}^n (O_i - S_i)}{\sum_{i=1}^n (O_i)} \times 100 \right] \quad (3)$$

182 Where O_i and S_i are the monthly observed and simulated values, respectively; O_{avg} is the
183 average of monthly observed values; and S_{avg} is the average monthly of simulated values.

184 2.5 Identification of critical source areas

185 We identified CSAs for sediment and P at the subwatershed level. The smallest number of
186 subwatersheds contributing to 50% of the sediment and TP watershed load to the streams were
187 identified as CSAs. It should be noted that selecting subwatersheds for targeting BMPs based on
188 the threshold for the sediment and TP loading is a function of BMP implementation cost, load
189 reduction goals and desired improvements in water quality and, therefore budget constraints can
190 lead to adjustment of the threshold limits (Niruala et al., 2013). A combined index was also used
191 to identify CSAs for targeting BMPs (Niruala et al., 2013). The combined index can be used to
192 target areas which are important sources of both sediment and TP (Eq. 4).

$$I_j = \sum \omega_i Y_{ij} \quad (4)$$

193

194 Where I_j is the combined index for subwatershed j , Y_{ij} is an index for sediment ($i = 1$) and
195 for TP ($i = 2$) for subwatershed j , and is given by (Eq. 5):

$$Y_{ij} = \frac{R_{i,min} - R_{ij}}{R_{i,min} - R_{i,max}} \quad (5)$$

196 Where, R_{ij} is the rank of watershed j for pollutant i ; $R_{i,min}$ and $R_{i,max}$ are lowest and highest
197 rank for pollutant i , respectively; ω_i is the weighting given to each Y_i , where $\sum \omega_i = 1$. In this

study, equal weighting (0.5) was given to sediment and TP. If the same watershed is ranked first for both sediment and TP, then the value of $I_j = 1$. Similarly, if the subwatershed is ranked last for both sediment and TP, then the value of $I_j = 0$. We used $I_j \geq 0.90$ as the threshold criteria for CSAs.

2.6 Impact of alternative BMPs

The CSAs identified based on the Combined Index ($I_j \geq 0.9$) were used to simulate the impact of alternative BMPs on sediment and TP load reductions at the subwatershed and watershed levels. The two BMPs considered in this study included conversion of croplands to CRP grasslands and change of all tillage practices (e.g., chisel plow, tandem-disc plow, field cultivator) to no-till within subwatersheds identified as CSAs. For the no-till scenario, Manning's roughness coefficient for overland flow was increased to 0.3 (no-till, 2-9 t ha⁻¹ residue) (Neitsch et al., 2011) from the default model value of 0.14 and moisture condition II curve number was reduced by 2 units (Douglas-Mankin et al., 2013). The results of total sediment and TP load, before and after BMP implementation, were compared on the short-term (actual weather conditions) (2006-2012) and on the long-term (32 year weather conditions). For long-term simulation, the built-in weather generator available in SWAT was used.

3. Results and discussion

3.1 Calibration and validation

Based on qualitative analysis of overall trends, the SWAT model captured changes in monthly stream flow, sediment and TP (Fig 2a, Fig. 2b and Fig. 2c). The values of NSE, R^2 and PBIAS for the calibration and validation time periods for stream flow, sediment and TP are included in Table 3. Based on the selected model evaluation statistical criteria, SWAT stream flow simulation results were considered "satisfactory" (Moriiasi et al., 2007). The model

simulation captured the trends in sediment load during the calibration and validation time periods and model performance was “satisfactory” (Moriassi et al., 2007). However, the model did not simulate sediment loads as well as the stream flow, attributable possibly to channel processes, such as, stream bank erosion observed along some reaches in this watershed and role of legacy sediment deposited on the stream bed (Lamba et al., 2015, 2015b). SWAT uses a simple channel sediment transport model, which is likely to be inadequate in capturing the in-stream sediment processes occurring in our study watershed (Ahmad et al., 2011). The TP loads predicted by the model followed the trends in observed TP loads and the model performance was “satisfactory” (Moriassi et al., 2007). However, uncertainties in capturing in-stream sediment transport dynamics was transferred to TP simulations as well. It should be noted that sediment fingerprinting studies conducted in this watershed did not provide any information regarding bank erosion rates, which could be used to improve the model calibration.

3.2 Critical source areas

Five subwatersheds covering about 24% of the total watershed area and contributing about 50% of the total sediment watershed load were identified as CSAs of sediment. Similarly for TP, five subwatersheds were identified as CSAs, which contributed to 50% of the total TP watershed load and covered about 28% of the total watershed area. Subwatersheds #1, 2, 7, 10, and 16, were identified as CSAs for sediment and subwatershed # 1, 7, 9, 10, and 16 were identified as CSAs for TP (Fig. 3). Four subwatersheds were common CSAs for sediment and TP, and there was strong correlation between sediment and TP losses ($R^2 = 0.94$) among different subwatersheds within this watershed based on SWAT simulation results. Control of particulate P losses is, therefore, critical for this watershed. Since particulate P losses are important in this watershed, results from watershed modeling in conjunction with sediment

fingerprinting (Lamba et al., 2015a,2015b) can be used to target BMPs to control excessive sediment and P delivery to streams. SWAT subwatersheds contained within the subwatersheds delineated based on the suspended sediment sampling sites (Lamba et al., 2015a) can be prioritized for BMPs. For example, at sites where relative contributions from agriculture is greater than stream banks (Lamba et al., 2015a), subwatersheds with the greater sediment yield within the drainage area of suspended sediment sampling sites should be prioritized for BMPs. Sediment and TP yield at the subwatershed level ranged from 0.06 to 3.14 ton $\text{ha}^{-1}\text{yr}^{-1}$ and 0.04 to 1.9 kg $\text{ha}^{-1}\text{yr}^{-1}$, respectively (Fig. 3). Similarly, Gassmann et al. (2011) reported wide range in sediment and TP subwatershed yield from 0.43 to 9.8 t ha^{-1} and 0.33 to 2.65 kg ha^{-1} , respectively on an average annual basis in the agricultural dominated Racoon River watershed in Iowa. Giri et al. (2012) reported that sediment and TP subwatershed yield varied from 0.0 to 6.9 tons ha^{-1} and 0.0 to 10.4 kg ha^{-1} in a mixed land use type Saginaw River watershed in east central Michigan. The subwatersheds identified by Giri et al. (2012) with greater sediment yield were predominantly agricultural subwatersheds. In our study, we also observed strong relationships between subwatershed sediment and TP losses and area under croplands based on SWAT simulation results (Fig. 4). Similar trends were found based on the results from sediment fingerprinting analysis in this watershed (Lamba et al., 2015, 2015a, 2015b).

A combination of different factors contributed to elevated sediment and TP losses in these subwatersheds. Within all the subwatersheds identified as CSAs for sediment and TP, croplands were the dominant land-use type (Table 4) and a major source of sediment and TP ($\geq 84\%$). The crop rotation in subwatershed 7 was three years of corn silage followed by 4 years of alfalfa, and in subwatersheds 1, 2, 9, 10, and 16 the crop rotation was three years of corn grain followed by 4 years of alfalfa. Tillage practices in subwatershed 7 included chisel plow in fall and field

cultivator in the spring. In subwatersheds 1, 2, 9, 10, and 16 tillage practices included chisel plow and tandem-disc plow in spring. The soils under cropland land-use within all the subwatersheds, identified as CSAs for sediment and TP, consisted primarily ($\geq 60\%$) of Hydrologic Soil Group (HSG) D (Table 5). The HSG D soils mainly consist of clay soils that have a very slow infiltration rates and high runoff potential, resulting in greater sediment and TP losses. Consequently, a combination of corn cropping systems (grain or silage) and absence of no-till practices in soils classified as HSG D could be responsible for elevated sediment and TP losses within these subwatersheds compared to other subwatersheds. Based on the $I_j \geq 0.90$, three subwatersheds (subwatershed # 1, 2, and 7) were identified as CSAs for sediment and TP. These watersheds covered about 12% of the total watershed area, but contributed to 35% of the total watershed sediment load and 33% of the total watershed TP load to streams.

3.3 Impact of alternative management scenarios

The conversion of croplands to CRP grasslands resulted in significant sediment and TP load reduction at the subwatershed and watershed levels (Table 6). Sediment and TP loading at the subwatershed level was reduced by $\geq 98\%$ and $\geq 84\%$, respectively, over the short-term (2006-2012). Similar trends in sediment and TP load reduction were evident on a long-term (32 year) basis as well. Jha et al. (2007) also reported a significant sediment reduction (71%) when all croplands were converted to CRP grasslands in the Raccoon River Watershed in West-Central Iowa. The increase in land-use under CRP grassland is an effective method for soil and water conservation, since growing perennial grass results in reduced surface runoff and soil erosion (Jha et al., 2007). The reduction of sediment and TP loading at the watershed level was not as significant as at the subwatershed level (Table 6). At the watershed outlet, the modeled reduction in sediment and TP loading was $\leq 15\%$ during both short and long-term simulations. For the pre-

BMP period, SWAT simulated significant deposition of sediments within the streams in this watershed. For example, in stream reaches of subwatersheds 1, 2, 4, 5, 7, 9, 10, 11, 12, 13, 21, 22 (stream reaches impacted by the BMPs), the average annual (2006-2012) ratio of the sediment load at the outlet of a subbasin (after channel routing which accounted for sediment erosion/deposition processes in a channel) to the sediment load delivered to the stream reach (before channel routing) during the pre-BMP period was very high (0.94), indicating net deposition of sediment within stream reaches. However, despite BMP implementation, this ratio increased to 1.07, indicating the likelihood of resuspension of streambed sediments. Therefore, improvements in water quality as a result of implementation of BMPs were masked by the resuspension of streambed sediments. Previous study (Lamba et al., 2015b) in this watershed confirms that resuspension of fine sediment deposited on the stream bed can contribute to suspended sediment load during larger storm events. These results indicate sediment and sediment-bound P deposited within the streams can create a “legacy” effect (i.e., effect of historical/past sediment deposited on the stream bed on the present water quality status) in this watershed.

Change of tillage practices (e.g., field cultivator, chisel plow) to no-till resulted in sediment and TP loading reduction compared to the pre-BMP period. The reduction in sediment and TP loadings (2006-2012) at the subwatershed level ranged from 22 to 25% and 21 to 22%, respectively (Table 6). Similarly over the long-term, sediment and TP reduction ranged from 20 to 21% and 14 to 19%, respectively. The reduction in sediment and TP loading with incorporation of no-till cropping systems could be the result of low mixing efficiency (0.05) and lower mixing depth (~25 mm) of the no-till operation in comparison with the chisel plow (mixing efficiency = 0.3; depth of mixing = 100 mm), tandem-disk regular (mixing efficiency = 0.6 depth of mixing =

75 mm), and field cultivator (mixing efficiency = 0.3; depth of mixing 100 mm) in SWAT. No-till operation results in more residue on the soil surface and minimizes soil erosion, especially during the early part of the crop growing season when the fields are bare and more susceptible to erosion (Yang et al., 2012). Additionally, no-till operation helps to reduce surface runoff and increase infiltration over time, thereby preventing soil erosion in comparison with the other tillage practices (e.g., chisel plow or field cultivator) (Lindstrom et al., 1998). At the watershed level, the reduction in sediment and TP loading was less than 3% during short and long-term due to no-till practices.

4. Conclusions

The results of this study indicate that the SWAT model performed satisfactorily in this watershed. The model did not simulate bank erosion that is known to occur in this watershed. The results confirm that croplands are the dominant source of sediment and TP. Three subwatersheds were identified as CSAs for sediment and TP covering about 12% of the total watershed area and contributed about 35% of the sediment and TP load to streams. The impact of alternative management practices indicates that conversion of croplands to CRP and implementation of no-till practices could alleviate problems associated with excess off-site transport of sediment and TP at the subwatershed scale. It should be noted that practically conversion of entire croplands to CRP within a subwatershed might not be possible from a food/grain perspective. The impact of BMPs on sediment and TP loads reduction at the watershed level was not significant. This could be because only about 8% of the watershed area was targeted for BMPs and/or resuspension of sediment deposited on the stream bed during previous storm event(s) masked the downstream improvements in water quality.

Future studies to quantify long-term bank erosion rates and fine sediment deposition/resuspension rates on stream beds in this watershed can help in developing more effective management strategies and the data generated from these studies can be used to improve the model calibration. Field scale tools, such as the Wisconsin P Index (Good et al., 2012), can be used to prioritize fields for BMP targeting and could be used in combination with larger watershed-scale models. In addition, incorporation of improved channel routines within the watershed model to adequately represent bank erosion due to cattle grazing, freeze-thaw activity and impact of cattle access to streams on in-stream sediment transport processes will improve our understanding of linkages between uplands and in-stream sediment processes within an agricultural watershed.

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485 Table 1. The average D10 (diameter at which 10% of the particle size distribution falls below),
 486 D50 (diameter at which 50% of the particle size distribution falls below) and D90 (diameter at
 487 which 90% of the particle size distribution falls below) $\pm$ standard errors of uplands (n = 41),
 488 stream banks (n = 38), stream bed (n = 48) and suspended sediment (n = 102).

Sample type	D10 (μm)	D50 (μm)	D90 (μm)
Uplands	4.8 $\pm$ 0.3	25.2 $\pm$ 1.2	68.8 $\pm$ 2.5
Stream banks	4.5 $\pm$ 0.2	22.6 $\pm$ 0.7	59.6 $\pm$ 1.7
Stream bed sediment	5.5 $\pm$ 0.2	26.9 $\pm$ 0.6	66.8 $\pm$ 1.4
Suspended sediment	4.4 $\pm$ 0.1	21.5 $\pm$ 0.4	61.9 $\pm$ 1.5

489 .

490 Table 2.Parametersused for calibration in SWAT.

Parameter	Description	Model range	Default value	Calibrated value
ESCO	Soil evaporation compensation factor	0-1	0.95	0.08
EPCO	Plant uptake compensation factor	0-1	1	0.1
SMFMX	Melt factor for snow on June 21(mm H ₂ O/°C-day)	0-10	4.5	2
SMFMN	Melt factor for snow on December 21 (mm H ₂ O/°C-day)	0-10	4.5	1.75
SNOCOV MX	Minimum snow water content that corresponds to 100% snow cover (mm)	0-500	1	195
SNO50CV	Fraction of snow volume represented by SNOCOV MX that corresponds to 50% snow cover	0-1	0.5	0.76
SOL_AWC	Available water capacity of the soil layer (mmH ₂ O/mmsoil)	0-1	Varies	-15%
CN2	Initial SCS runoff curve number for moisture condition II	35-98	Varies	-22%
PRF	Peak rate adjustment factor for sediment routing in the main channel	0-2	1.0	0.104

Parameter	Description	Model range	Default value	Calibrated value
SPCON	Linear parameter for calculating the maximum amount of sediment that can be re-entrained during the channel sediment routing	0.0001- 0.01	0.0001	0.0045
SPEXP	Exponent parameter for calculating re-entrained in the channel sediment routing	1-1.5	1	1.4
ADJ_PRF	Peak rate adjustment factor for sediment routing in the subbasin(tributary)	0.5-2	1.0	0.5
ALPHA_BF ^ψ	Baseflow recession factor (days)	0-1	0.048	0.014
PHOSKD	Phosphorus soil partitioning coefficient (m ³ /Mg)	100- 200	175	180
PSP	Phosphorus availability index	0.01- 0.7	0.4	0.55
GW_DELAY	Groundwater delay time (days)	0-500	31	210
USLE P	USLE support practice factor	0-1	1	0.75

Parameter	Description	Model	Default	Calibrated
		range	value	value
P_UPDIS	Phosphorus uptake distribution factor	0-100	20	100
491	Ψ Determined from baseflow filter program (Arnold et al., 1999)			
492				

493 Table 3. The values of NSE, R^2 , and PBIAS during calibration and validation of the SWAT
 494 model at a monthly time-step.

Variable	Calibration			Validation		
	NSE	R^2	PBIAS	NSE	R^2	PBIAS
Flow	0.63	0.68	-1.52	0.71	0.74	3.52
Sediment	0.59	0.67	-12.87	0.58	0.79	33.96
Total phosphorus	0.62	0.69	26.99	0.62	0.78	38.33

495 Table 4. Dominant land-use (%) and area of each subwatershed (km²) identified as critical source
 496 areas based on sediment and total phosphorus.

Subwatershed	Dominant land-use (%)					Area (km ²)
	Cropland	Grassland	Woodland	Pasture	Urban	
1	54	14	26	1	4	2.45
2	66	9	11	9	5	0.97
7	71	7	19	1	3	2.63
9	36	22	29	3	7	2.61
10	57	11	17	5	9	3.50
16	36	35	13	10	6	2.51

497 Table 5. Percentage sediment and total phosphorusload of the total
 498 subwatershed load along with the corresponding hydrologic soil group in
 499 croplands in the subwatersheds identified as critical source areas of
 500 sediment and total phosphorus.

Subwatershed	Hydrological soil group	Area (%)	Sediment load (%)	TP (%)
1	B	3.6	0.7	0.9
	D	96.4	99.3	99.1
2	B	14.3	6.3	4.7
	D	85.7	93.7	95.3
7	B	18.7	7.3	8.1
	D	81.3	92.7	91.9
9	B	40.4	20.7	23.3
	D	59.6	79.3	76.7
10	B	22.5	8.5	10.2
	C	4.1	2.5	2.4
	D	73.4	89.1	87.4
16	B	34.7	10.5	15.8

D	65.3	89.5	84.2
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501 Table 6. Sediment and TP load at the subwatershed and watershed level after BMP implementation scenario along with the percentage
502 of the total watershed area targeted for BMPs.

Location	No-till short-term*		No-till long-term Ψ		Conversion to CRP grasslands short-term		Conversion to CRP grasslands long-term		Watershed area targeted for BMPs (%)
	Sediment reduction (%)	TP reduction (%)	Sediment reduction (%)	TP reduction (%)	Sediment reduction (%)	TP reduction (%)	Sediment reduction (%)	TP reduction (%)	
Subwatershed 1	22	21	20	14	99	84	96	66	2.7
Subwatershed 2	22	22	20	19	98	86	95	80	1.3
Subwatershed 7	25	22	21	15	99	88	97	69	3.7
Watershed outlet	2	3	4	2	9	15	6	8	-

503 *Short-term (actual weather conditions) (2006-2012)

504 Ψ Long-term (32 year weather conditions)

505

Figure Captions

Fig. 1. (a) Location of the Pleasant Valley Watershed, and (b) dominant land-use in the Pleasant Valley Watershed.

Fig. 2. SWAT simulated and observed monthly: (a) stream flow, (b) sediment load, and (c) TP load.

Fig. 3. Total phosphorus ($\text{kg ha}^{-1} \text{yr}^{-1}$) and sediment yield ($\text{tons ha}^{-1} \text{yr}^{-1}$) at the subwatershed level on an annual average basis (2006-2012).

Fig. 4. (a) Relationship between subwatershed sediment yield and land-use under cropland, and (b) relationship between total phosphorus yield and land-use under cropland.

Figure

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