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AgroEcoSystem-Watershed (AgES-W) Model Evaluation for Streamflow and Nitrogen/Sediment Dynamics on a Midwest Agricultural Watershed

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Abstract: AgroEcoSystem-Watershed (AgES-W) is a modular, Java-based spatially distributed model which implements hydrologic/water quality simulation components under the Object Modeling System Version 3 (OMS3). The AgES-W model was previously evaluated for streamflow and recently has been enhanced with the addition of nitrogen (N) and sediment modeling components refactored from various agroecosystem models including J2K-S, SWAT, WEPP, and RZWQM2. The specific objective of this study was to evaluate the accuracy and applicability of the enhanced AgES-W model for uncalibrated estimation of streamflow and N/sediment loading. The Upper Cedar Creek Watershed (CCW) in northeastern Indiana, USA was selected for model application. AgES-W model performance was assessed using Nash-Sutcliffe model efficiency (E_{NS}) and percent bias (PBIAS) model evaluation criteria. Comparisons of simulated and observed average monthly streamflow, average monthly N loading, and daily sediment load for different simulation periods resulted in E_{NS} and PBIAS values that were within the range of those reported in the literature for SWAT streamflow and N/sediment loading predictions at a similar scale and time step. Considering that AgES-W was applied without calibration, study results indicate that the model reasonably reproduced the hydrological, N, and sediment dynamics of the Upper CCW and should serve as a foundation upon which to better quantify additional water quality indicators (e.g., phosphorus dynamics) at the watershed scale.

***Keywords**:* Watershed model; Hydrologic/water quality (H/WQ) modeling; Model evaluation; Nitrogen; Sediment; Object Modeling System.

1. INTRODUCTION

Nonpoint source (NPS) pollution of streams and lakes has created a critical concern worldwide with agricultural activities identified as the primary sources of NPS pollutants (e.g., sediments, nutrients, and pesticides). Although there are many potential causes for NPS pollution, agriculture is the leading contributor of nutrients and sediment to streams and rivers in the U.S. [USEPA 2000]. Continuous water quality monitoring is very expensive, time consuming, and spatially unrealistic at the watershed level. However, the mechanisms that govern nutrient and sediment sources, transport, and delivery from watersheds to streams can be efficiently evaluated using hydrologic/water quality (H/WQ) simulation models. H/WQ models are available that simulate nutrient and sediment transport from land units within a watershed to a stream, such as the Soil and Water Assessment Tool (SWAT) [Arnold et al. 1998], Annualized Agricultural Nonpoint Source Pollution (AnnAGNPS) [Yuan et al. 2001], and the AgroEcoSystem-Watershed (AgES-W) [Ascough et al. 2012]. One distinguishing feature of the above models is the flow and chemical routing mechanism - the AgES-W and AnnAGNPS models are fully distributed (i.e., runoff, nutrients, and sediment can be routed between individual land units) while SWAT performs routing at the sub-basin level only. This study continues the effort for evaluating the AgES-W model with measured data from the Cedar Creek watershed (CCW) in northeastern Indiana, USA. The CCW is within the larger St. Joseph River watershed which was designated in 2004 as one of the Conservation Effects Assessment Project (CEAP) [Duriancik et al. 2008] benchmark watersheds. AgES-W was previously evaluated for CCW streamflow [Ascough et al. 2012] and has been recently enhanced with the addition of nitrogen (N) and sediment process-based modeling components. Therefore, the specific objective of this study was to evaluate the accuracy and applicability of the expanded AgES-W model for estimating average monthly streamflow/N loading and daily sediment loading in the Upper CCW sub-catchment of the CCW.

2. MATERIALS AND METHODS

2.1 Site description

The Cedar Creek watershed (CCW) is located within the St. Joseph River basin in northeastern Indiana, USA (41° 10' 10" to 41° 32' 38" N, 84° 53' 49" to 85° 19' 44" W) and covers Noble, DeKalb, and Allen counties. The CCW drains two 11-digit hydrologic unit code (HUC) sub-watersheds, Upper Cedar Creek (04100003080, Figure 1) and Lower Cedar Creek (04100003090), covering a total area of approximately 700 km^2. The average land surface slope of the watershed is 2.6%, and topography varies from rolling hills to nearly level plains with minimum and maximum altitudes above sea level of 232 m and 326 m, respectively. Soil types on the watershed were formed from compacted glacial till, and the predominant soil textures are silt loam, silty clay loam, and clay loam [SJRWI 2004]. The annual mean precipitation in the watershed area from 1989 to 2010 was 974 mm. The average temperature during crop growth seasons ranges from 10°C to 23°C. The watershed is mainly used for farmland and livestock production and is characterized by a high percentage of rotationally tilled agricultural row crops (~50%), grassland (~27%), woodland (~12%), and pasture (~8%).

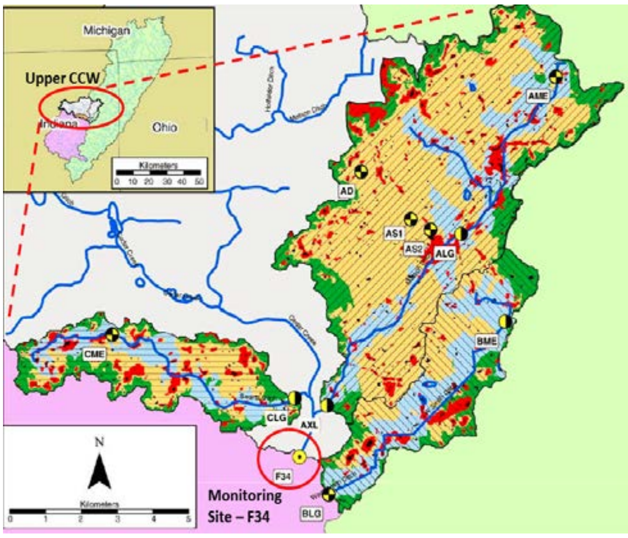

Figure 1. Upper CCW stream network and gauging stations.

2.2 AgES-W model description

AgES-W is a modular, Java-based, spatially distributed H/WQ model that implements hydrological processes as encapsulated process-based modeling components running under the OMS3 environmental modeling framework [David et al. 2012]. The hydrological part of AgES-W (previously described in Ascough et al.

2012) consists of modeling components for interception, snow accumulation and ablation, horizontal-differentiated soil water balance, groundwater balance, runoff generation, and explicitly computed lateral surface and subsurface flows including flood routing in the watershed stream network. The nutrient transport modules evaluated in this study were adopted primarily from SWAT, converted to Java for use in the European J2K-S model [Fink et al. 2007], and further modified for coupling to the AgES-W hydrologic components under OMS3. The nutrient modules include components for simulating soil temperature, crop growth, and N turnover [Neitsch et al. 2009] with some minor adaptations. Five different soil N pools are considered in order to allow modeling of different N inputs (e.g., inorganic fertilizer, organic manure) and N transformations between these pools. N reduction is modeled by a dynamic crop growth module (also adapted from SWAT) and subsequent N uptake by plants (residues and yield) as well as through N denitrification and volatilization. The influence of soil temperature and soil moisture on crop growth and N transformation are modeled synchronously. The AgES-W model estimates soil erosion and sediment yield from landscape hydrologic response units (HRUs) and from in-stream depositional and degradation processes. The HRU sediment yield is calculated by the Modified Universal Soil Loss Equation (MUSLE) [Williams 1975]. Sediment deposition and degradation in stream channels are also calculated during sediment routing where the maximum amount of sediment that can be transported from a reach segment is governed by a modified Bagnold's equation. All AgES-W modules currently operate on a daily time step.

2.3 Data acquistion

In the CCW, eight STATSGO [USDA-NRCS 2012] soil associations are represented. The dominant soil is a Blount-Glynwood-Morley silt loam which covers more than 50% of the total CCW area. For this study, a 2001 USDA National Agricultural Statistics Service (NASS) land use raster map (30x30 m ground resolution) was used [USDA-NASS 2001]. The DEM data used were obtained from the USGS at 10 m elevation resolution, 1/3 arc second, and projected to UTM NAD83 Zone 16 north for Indiana, USA. In order to model streamflow and N/sediment dynamics for the Upper CCW, the watershed boundary, stream channel network, physiographic HRUs, and topological (flow) connections between HRUs were delineated using an ArcInfo Workstation 9.3 [ESRI, Redland, CA, USA] AML-based tool developed by Pfennig et al. [2009]. The DEM, STATSGO soil, and NASS land use GIS layers as described above were used for the HRU delineation and resulted in 998 HRU polygons featuring areas between 0.03 to 2.4 km^2. Site F34 (Figure 1, the Upper CCW drainage outlet) was gauged and equipped with a continuous recording ISCO 6712 autosampler [ISCO Inc., Lincoln, Nebraska] and flowmeter. Rainfall and temperature data were also measured using a continuous recording rain gauge near the BLG site (Figure 1). In addition to the BLG climate data, data from the NOAA Waterloo weather station (also located in the Upper CCW) was also used for AgES-W climate input. Due to concerns about damage during freezing weather, the F34 autosampler typically was installed around late-March each year and removed around early to mid-November. Water samples were analyzed for sediment, NO_3-N, NH_4-N, soluble P, total Kjehldahl N, and total Kjehldahl P. All nutrient analyses were conducted colorimetrically with a Konelab Aqua 20 [EST Analytical, Medina, Ohio].

2.4 AgES-W model parameterization

AgES-W requires 20 total input files for model execution which can be categorized as follows: 1) climate (7 files), 2) "static" management for crop, fertilizer, and tillage input parameters (3 files), 3) "dynamic" management for cropping systems (including crop rotations) and tillage operations (3 files), 4) HRU and stream reach connectivity or topology (2 files), and 5) "core" input files containing information (including spatial relationships) for HRUs, hydrogeology, soils, and land use (4 files). In addition to the files containing spatial attributes as described above, an additional file contains non-spatial parameters describing coefficients used in AgES-W initialization, interception, snow processes, soil water, N transport processes, groundwater, and flood routing science module components. A subset of critical AgES-W parameter values and recommended ranges are listed in Table 1 (see Ascough et al. [2012] for further information on parameter value derivation).

Table 1. Key AgES-W input parameters used for Upper CCW simulations.

	Parameter	Description	Recommended range	Parameter value
General initialization	initRG1	Initial storage of RG1 relative to maximum storage	0.0 to 1.0	0.50
	initRG2	Initial storage of RG2 relative to maximum storage	0.0 to 1.0	0.50
Soil water	soilPolRed	Potential reduction coefficient for AET computation	0.0 to 10.0	5.0
	soilLinRed	Linear reduction coefficient for AET computation	0.0 to 10.0	8.0
	soilDiffMPSLPS	MPS/LPS diffusion coefficient	0.0 to 10.0	2.0
	soilOutLPS	Outflow coefficient for LPS	0.0 to 10.0	1.0
	soilLatVertLPS	Lateral/vertical distribution coefficient for LPS	0.0 to 10.0	1.0
	soilMaxPerc	Maximum percolation rate (mm d^{-1})	0.0 to 20.0	5.0
Nitrogen	N_delay_RG1	Relative size of the groundwater N damping tank for RG1	0.0 to 10.0	5.0
	N_delay_RG2	Relative size of the groundwater N damping tank for RG2	0.0 to 10.0	5.0
	N_concRG1	N recession coefficient for RG1	0.0 to 10.0	10.0
	N_concRG2	N recession coefficient for RG2	0.0 to 10.0	10.0
Groundwater	gwRG1RG2dist	RG1/RG2 distribution coefficient	0.0 to 1.0	0.80
	gwRG1Fact	Adaptation of RG1 outflow	0.0 to 10.0	1.0
	gwRG2Fact	Adaptation of RG2 outflow	0.0 to 10.0	1.0
	gwCapRise	Capillary rise coefficient	0.0 to 1.0	0.0
Flood routing	flowRouteTA	Flood routing coefficient controlling flood wave velocity	0.0 to 100.0	1.0

2.5 AgES-W model statistical evaluation

Two evaluation criteria were used to assess monthly streamflow and nitrogen/sediment loadings simulated by AgES-W. The criteria are quantitative statistics that evaluate the overall correspondence of simulated output to observed values and include the Nash-Sutcliffe efficiency coefficient (E_{NS}) and percent bias (PBIAS). The E_{NS} and PBIAS statistics are defined as:

$$E_{NS} = 1 - \frac{\sum_{i=1}^{n} (O_i - P_i)^2}{\sum_{i=1}^{n} (O_i - \overline{O})^2} \quad (1) \qquad \text{PBIAS} = \frac{\sum_{i=1}^{n} (P_i - O_i) \times 100.0}{\sum_{i=1}^{n} O_i} \quad (2)$$

where P_i is the i^{th} output response value predicted by the AgES-W model, O_i is the i^{th} observed value, $\overline{O}$ is the average observed value for the simulation period and n is the number of observations. E_{NS} indicates how well the plot of observed versus simulated values fits a 1:1 line. The value of E_{NS} in Eq. 1 may range from $-\infty$ to 1.0, with 1.0 representing a perfect fit of the data. PBIAS is a measure of the average tendency of simulated model output responses to be larger or smaller than corresponding observed values. The optimal PBIAS value is 0.0; a positive value indicates a bias toward overestimation, whereas a negative value indicates a model bias toward underestimation.

3. RESULTS

The AgES-W simulation period was 8 years (2003-2010); however, the first two years were not used for model evaluation in order to allow model state variables (particularly the soil water variables in Table 1) to reach equilibrium with actual physical conditions [e.g., Santhi et al. 2001]. The simulation periods for monthly streamflow, monthly N loading, and daily sediment loading were 5/2005 to 12/2010, 5/2005 to 12/2009, and 4/2010 to 7/2010, respectively. Monthly observed and AgES-W simulated streamflow from May 2005 to December 2010 is presented in

Figure 2. For uncalibrated conditions, overall model performance was variable, i.e., there were significant and frequent underestimations of streamflow (PBIAS of ~ -35% for spring monthly peaks in 2007-2009) and also some overestimation (PBIAS of ~ 5% for the summer monthly peak in 2005) by AgES-W compared to the measured data. Overall, the model appeared to correctly capture the temporal pattern in streamflow. AgES-W streamflow underestimation may be due in part to having rainfall input data for only two weather stations in the Upper CCW. Heathman et al. [2009] reported that daily rainfall records for CCW weather stations show many periods of time when significant rainfall events were recorded (with a subsequent response or spike in simulated streamflow data using the SWAT model), yet little or no response was observed in the USGS discharge data at the CCW watershed outlet. They hypothesized that these were extremely localized rainfall events that did not significantly contribute to the total measured watershed streamflow. Monthly streamflow PBIAS varied from a low of -6.6% in 2005 and a high of -23.1% in 2009 (data not shown). Table 2 shows that the monthly streamflow E_{NS} and PBIAS for the simulation period were 0.40 and -14.1%, respectively.

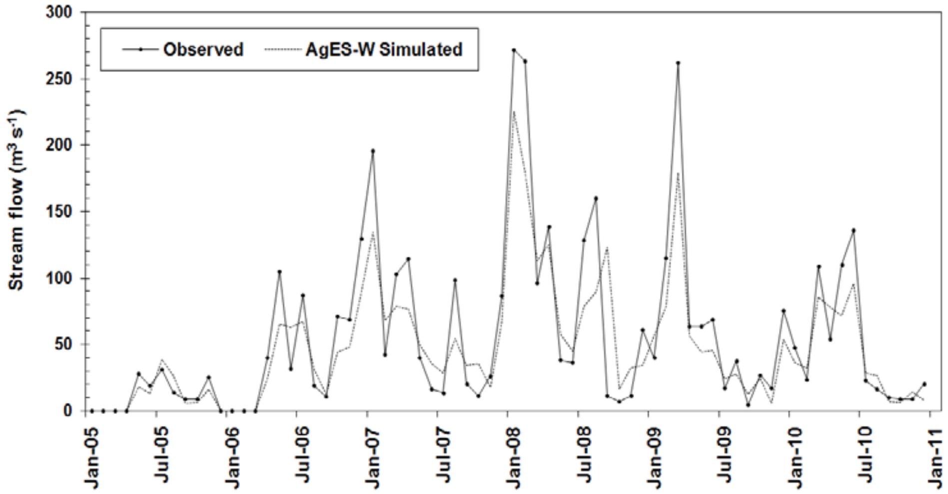

Figure 2. Average monthly Upper CCW streamflow (m^3 s^{-1}) at gauge F34 (January 2005 to December 2010).

Monthly observed and AgES-W simulated total N (organic-N plus NO_3-N) from May 2005 to December 2009 is presented in Figure 3. Unlike streamflow which was primarily underestimated, there were pronounced periods of both underestimation and overestimation for simulation of total N. For example, total N was underestimated in 2005 and 2006 (-24.1 and -12.4%, respectively), overestimated in 2007 and 2008 (38.6 and 24.4%, respectively) and underestimated again in 2009 (-19.6%). This resulted in a relatively poor E_{NS} of 0.22 for the simulation period; however, the “balanced” periods of both underestimation and overestimation resulted in a PBIAS of only 1.4% (Table 2).

Table 2. Statistical evaluation for AgES-W simulated average monthly streamflow, average monthly total nitrogen (N) loading, and daily sediment loading for the Upper Cedar Creek watershed. [a]

Statistical evaluation coefficient [b]	Average monthly streamflow	Average monthly total N loading	Daily sediment loading
E_{NS}	0.40	0.22	-0.68
PBIAS	-14.1	1.4	-13.9

[a] The simulation periods for streamflow, N loading, and sediment loading were 5/2005 to 12/2010, 5/2005 to 12/2009, and 4/2010 to 7/2010, respectively.

[b] E_{NS} = Nash-Sutcliffe efficiency; PBIAS = bias or relative error (%).

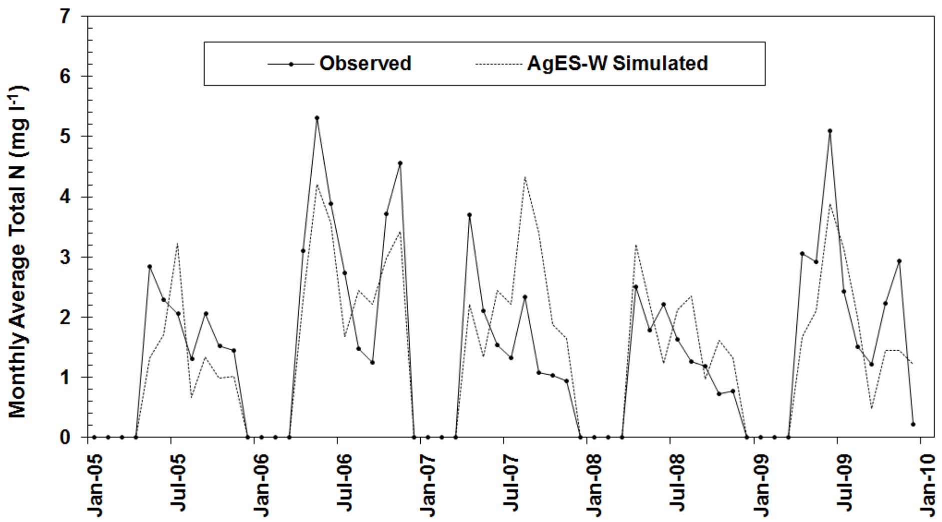

Figure 3. Average monthly Upper CCW total N (mg l^{-1}) at gauge F34 (May 2005 to December 2009).

Daily AgES-W simulated sediment loading from April 2010 to July 2010 is presented in Figure 3. Similar to streamflow prediction, sediment loading was predominantly underestimated. This was expected as model prediction of sediment loading is highly correlated to surface runoff prediction. Observed surface runoff data for Upper CCW HRUs were unavailable; however, AGES-W underestimated streamflow for the April 2010 to July 2010 sediment loading simulation period by approximately 20% (data not shown). Table 2 shows that the daily sediment E_{NS} and PBIAS for the simulation period were -0.68 and -13.9%, respectively.

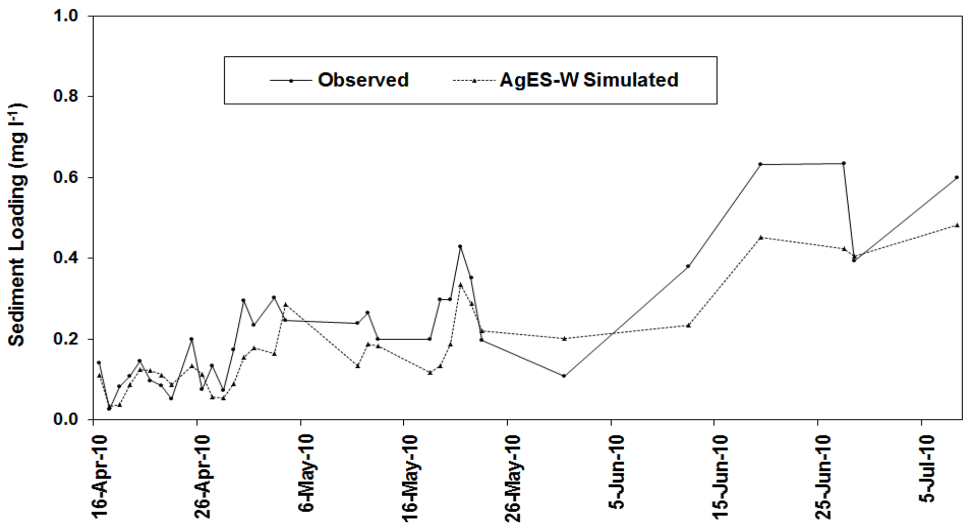

Figure 4. Daily Upper CCW sediment loading (mg l^{-1}) at gauge F34 (April 2010 to July 2010).

4. DISCUSSION

The range of relative error (e.g., PBIAS) and E_{NS} values for uncalibrated predictions in this study (e.g., monthly streamflow, monthly total N, daily sediment) are within the range of others reported in the literature for various watershed models. For SWAT monthly streamflow predictions, Tolson and Shoemaker [2007] reported E_{NS} values ranging from 0.43 to 0.86 for different gauge stations in the Cannonsville Reservoir in upstate New York. Sarangi et al. [2007] used AnnAGNPS to predict runoff and sediment losses from forested and agricultural watersheds on the island of St. Lucia in the Caribbean and reported errors of 7% to 36% for annual streamflow prediction. Kirsch et al. [2002] reported uncalibrated sediment loading results for a single year ranging from underestimation of -50% to overestimation of 29% for eight USGS gauges in the Rock River Basin, Wisconsin, USA. Many different factors impact the simulation of streamflow and N/sediment loading on the Upper CCW. Because the model time step is daily, it is difficult to accurately capture sub-daily (i.e., individual storms) and even daily results because of potential time shifts in the precipitation and flow data. The addition of a more physically based infiltration component, such as the Green-Ampt infiltration model used by SWAT and other agroecosystem models, might help in this regard. Additionally, subsurface tile drains are present on the Upper CCW and may significantly impact water yield, streamflow, and N loading. Simulations were performed without the explicit inclusion of a tile drainage component, the addition of which should improve streamflow and N loading prediction accuracy. The availability of accurate climate data also plays an important role in model performance and accuracy. The effects of spatial and temporal variability in rainfall on model output uncertainty has been previously documented [e.g., Chaubey et al. 1999], and spatial variability of precipitation data represents one of the major limitations in large-scale hydrologic modeling. The HRUs in the AgES-W simulations accessed data from only two weather stations in the Upper CCW, the BLG experimental site and the NOAA Waterloo weather station; therefore, it is possible that the distribution of rainfall over the entire watershed may be inaccurately represented. The streamflow and N/sediment loading simulation results for AgES-W almost certainly would improve if additional stream gauge and weather data were used. Ascough et al. [2012] noted that the Penman-Monteith equation used in AgES-W to estimate ET requires significant data, including, but not limited to, solar radiation, wind speed, soil characteristics, and canopy cover characteristics. Not all of this data were readily available; therefore, other required meteorological data were obtained by using the CLIGEN weather generator. Considerable uncertainty exists in weather generation, and this uncertainly is propagated in the final ET values calculated by AgES-W. Furthermore, a lack of available measured ET data for the study period makes it difficult to validate simulated ET results. Underestimation or overestimation of ET could thereby affect the overall water and N balances, particularly during the summer months when ET demand is higher. Finally, while the distribution (i.e., the approximate percentage) of each cropping system rotation was generally known, the exact location of the various cropping systems was not. Additional efforts are underway to provide better assessment of cropping system location.

5. SUMMARY AND CONCLUSIONS

Considering that AgES-W was applied uncalibrated, study results indicate that the AgES-W model reasonably reproduced the hydrological, N, and sediment dynamics of the Upper CCW. Additional model enhancement (e.g., the addition of Green-Ampt infiltration and tile drainage components) should provide a solid foundation on which to improve AgES-W in order to better quantify water quantity and quality at the watershed scale. In particular, the topological routing scheme employed by AgES-W (thus allowing the simulation of lateral processes important for the modeling of runoff and chemical concentration dynamics) is potentially more robust than the quasi-distributed routing schemes used by other watershed-scale natural resource models (e.g., SWAT). With a fully distributed routing concept, higher spatial resolution in combination with the lateral transfer of water and chemicals between HRUs and stream channel reaches will hopefully result in improved H/WQ modeling for mixed-use watersheds such as the Upper CCW. Finally, the development and application of AgES-W is a significant step toward demonstrating the OMS3 framework as a viable tool for the development and maintenance of environmental models. From the natural resources modeling viewpoint, environmental modeling frameworks such as OMS3 have the potential to: (1) enable easier long-term maintenance and updating of model code (the complex and convoluted code structures for most current natural resource models do not facilitate maintainability); (2) reduce duplication of work by modelers for developing common basic components, as has previously occurred with considerable duplication of code in other watershed model development efforts (e.g., SWAT, AnnAGNPS, etc.); and (3) lead to better standardization of science components over time.

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