



Jun 19th, 10:40 AM - 12:20 PM

Challenges/Advances in Distributed Watershed Modeling: A Review and Application of the AgroEcoSystem-Watershed (AgES-W) Model

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Ascough, James C. II; Green, Timothy R.; David, Olaf; Kipka, Holm; McMaster, Gregory S.; Fink, Manfred; Krause, Peter; and Kralisch, Sven, "Challenges/Advances in Distributed Watershed Modeling: A Review and Application of the AgroEcoSystem-Watershed (AgES-W) Model" (2014). *International Congress on Environmental Modelling and Software*. 45.
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Challenges/Advances in Distributed Watershed Modeling: A Review and Application of the AgroEcoSystem-Watershed (AgES-W) Model

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Abstract: Progress in the understanding of physical, chemical, and biological processes influencing water quality, coupled with advances in the collection and analysis of hydrologic data, provide opportunities for significant innovations in the manner and level with which watershed-scale processes may be quantified and modeled. This paper first provides a brief review of current challenges and advances in distributed watershed modeling including quantifying and coping with the uncertainty, data availability, influence of data resolution and scaling issues, and the use of environmental modeling frameworks that help maintain model modularity, reusability, and interoperability (or compatibility). Important findings and observed trends from this work include: 1) limitations in scaling of hydrological/water quality processes for watershed modeling; 2) the impacts of data provisioning (availability and resolution) on watershed modeling capabilities, and 3) recommendations concerning the employment of a more holistic component-based modeling approach that is capable of examining individual processes and systems and the interconnection between them. In addition, an application of the AgroEcoSystem-Watershed (AgES-W) modular, Java-based spatially distributed model to the Upper Gera, Germany and Upper Cedar Creek, Indiana, USA watersheds is presented to demonstrate many of the advances described above that are currently available for watershed management at multiple scales. Model evaluations will include statistical comparisons of AgES-W simulated flows and N/sediment loads using monitoring data from the Upper Gera and Upper Cedar Creek outlets.

Keywords: Watershed model; Hydrologic/water quality (H/VVQ) modeling; Model evaluation; Stream flow; Object Modeling System, Distributed parameter.

1. CHALLENGES AND ADVANCES IN DISTRIBUTED PARAMETER WATERSHED MODELING

Watershed-scale modeling has emerged as an important scientific research and management tool, particularly in efforts to understand and control water pollution. Developments in computer technology have revolutionized the study of hydrologic systems and the subsequent development of distributed parameter watershed models which theoretically involve a more accurate representation of the hydrologic system by considering the spatial variability of model parameters and inputs. Distributed parameter watershed models, such as the AgroEcoSystem-Watershed (AgES-W) model (Ascough et al., 2012) generally subdivide the watershed into smaller sub-basins/hydrologic response units (HRUs) and require data on model inputs such as soil and land use for each of the spatial units. Although this can result in a better representation of the natural hydrologic system, data assembly and input files development for such models can require considerable effort and time on the part of the modeler. The following sections discuss additional challenges and advancements in distributed parameter hydrologic/water quality modeling, in addition to briefly presenting recommendations for future studies. In addition, an application of AgES-W model to two experimental watersheds (Upper Gera, Germany and Upper Cedar Creek, Indiana, USA) is presented.

1.1 Challenges

Performing physically-based, spatially-distributed hydrologic simulations over large catchments or watersheds has historically been hindered by high computational demands (Wood et al., 2011). To

remedy this, applications over large river basins typically coarsen the spatial resolution of the domain, limit the temporal extent of the simulation and/or conduct strictly deterministic runs that do not account for uncertainties. For example, macro-scale hydrologic models have become standard in research and operational communities for applications in large catchments or at the continental scale (e.g., Mitchell et al., 2004). While useful, macro-scale approaches have a more limited physical basis as compared to distributed models and do not typically preserve the available land surface and meteorological data in a catchment (Kampf and Burges, 2007). Parameter estimation and calibration of hydrologic models inherently possess an additional set of significant challenges including nonlinearity, data errors, data insufficiency, correlation among parameters, irregular response surfaces that may be insensitive to select model parameters, and single or multi-objective nature of the models. A major challenge is to find efficient ways to analyze the extensive output of distributed parameter hydrological models and to present the results in a transparent way to the intended audience. Successfully setting up and running distributed parameter models as part of a learning process about system dynamics requires developing new approaches where continued observation and modeling go hand in hand (Beven, 2007). Thus, a challenge for future large-scale modeling is to set up models in a flexible manner such that: 1) different processes/compartments can be switched on or off; and 2) nesting of finer-scale models within large-scale models is possible such that the information available at larger scales (or in the environment of the nested area) can also be taken into account. Environmental modeling frameworks such as the Object Modeling System 3 (OMS3, David et al., 2013) can help in this regard. In addition, further work on scaling behavior and parameterization of sub-scale variability is needed. Such approaches would enable modelers to use appropriate process descriptions and complexity for different regions, scales or goals of a study. To decrease uncertainty related to model structure, a better understanding about which processes are most relevant at what spatial scales, and how process conceptualizations are related to scale is necessary but lacking. The challenge of "optimal" data collection requires considerations of practicality and cost, as well as more specific considerations of how to reconcile typically conflicting information from different data types (e.g., Gupta et al., 1998), and how to consider data with varying spatial support.

1.2 Advances and recommendations

With the advent of high performance computing, distributed modeling now has the potential to address a wider range of applications in large watersheds. Several efforts have illustrated the use of distributed hydrologic models of varying capabilities in parallel computing platforms (e.g., Kollet et al., 2010). Parallel algorithms have also been implemented in flood inundation (Sanders et al., 2010) and groundwater models (e.g., Hammond and Lichtner, 2010). As evidenced by this progress, the adoption of high performance, distributed hydrologic modeling (HP-OHM) may be feasible at the large watershed scale, possibly serving as an alternative to macro-scale models, as discussed by Wood et al. (2011). More and better software has become available for pre- and post-processing of distributed parameter hydrological modeling, including GIS integration and automated tools for sensitivity and uncertainty analysis. Development of spatial databases together with GIS and advances made in distributed hydrologic modeling has led to tremendous progress in detailed spatially distributed analysis of hydrologic and water resources systems. It appears to be necessary to extend and enhance sensitivity and uncertainty analyses in large-scale hydrological modeling. For example, we need to find out how sensitivities change with temporal and spatial scales. Guidelines should be created advising model users which tool is appropriate for which kind of sensitivity and uncertainty analysis. Subsequently, methods could be chosen from a "toolbox" that will likely have to be specific for classes of models (e.g., water quality vs. quantity). Not only should complete discharge time series be analyzed, but also characteristic periods, the selection of which depend on the objective of the model application (e.g., drought analysis, flood analysis, etc.). Similar to the case of climate models, ensembles of global and regional hydrology models should be analyzed, as such comparisons allow for characterizing the uncertainty of model outputs and improving models. A discussion on "rules of thumb for good calibration practice" as well as on standard procedures for uncertainty analyses should be initiated within the international hydrological community in order to provide a common methodological inventory for hydrological modeling studies. Models should be set up in a modular fashion such that model runs with different modules being substituted, when compared to observed data, can easily help to increase system understanding and the selection of the appropriate model structure (see also Zhang et al., 2008). Such flexible modeling setups would allow modeling to truly become a learning process (Beven, 2007). They do require, however, a thorough consideration of data exchange and calibration procedures as these depend on the selected module. Finally, current development efforts for environment modeling frameworks need to be reflected critically.

2. AGES-W MODEL APPLICATION CASE STUDIES: UPPER GERA WATERSHED, GERMANY AND UPPER CEDAR CREEK WATERSHED, INDIANA, USA

2.1 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 Object Modeling System 3 (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.

2.2 Watershed descriptions

The Upper Gera watershed has an area of 850 km² and is situated south of the city Erfurt, Germany. The elevation ranges between 983 m in the southwest (SW) and 200 m a.s.l. at the basin outlet (Moebisburg gauge) in the northeast (NE). The main flow direction is from SW to NE and the watershed is divided into three major regions based on elevation and land use ranging from forest, pasture, and agriculture.

The Cedar Creek watershed (CCW) is located within the St. Joseph River basin in northeastern Indiana, USA. The CCW drains two 11-digit hydrologic unit code (HUC) sub-watersheds, Upper Cedar Creek (04100003080, Figure 1a) and Lower Cedar Creek (04100003090), covering a total area of approximately 700 km². The average land slope of the watershed is 2.6%, and topography varies from rolling hills to nearly level plains with minimum and maximum elevations of 232-326 m a.s.l., 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. 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%).

2.3 Data acquisition

The Upper Gera watershed boundary, stream channel network, physiographical hydrological response units (HRUs), and topological (flow) connections between HRUs were delineated using an ArcInfo Workstation 9.3 AML-based tool developed by Pfennig et al. (2009). The HRU delineation was based on classified topographical parameters (elevation, slope, aspect), land-use classes (derived from LANDSAT), soil types (derived from the soil map "Die Leitbodenformen Thuringens" 1:100 000, Rau et al., 1995), and hydrogeological units. The delineation of HRUs for the entire Gera catchment resulted in 779 polygons (Figure 1a) with areas between 0.02-2.5 km². The spatial attributes of the Gera catchment (i.e., coordinates, elevation, slope, aspect, soil type, land use type, hydrogeological type) for each HRU were derived and stored in AgES-W-compliant parameter files. Climatological time series used as drivers for AgES-W model application were available in daily time steps from three synoptical climate stations and 14 precipitation gauges for the period 1/1/1980 to 8/13/2013. The climate stations provided measurements of minimum, mean and maximum temperature, wind speed, sunshine hours, and relative humidity. Observed runoff values for model calibration/validation were available for multiple streamflow gauges (shown in Figure 1a as yellow squares).

In the CCW, the dominant soil is a Blount-Glynwood-Morley silt loam which covers more than 50% of the total area. For this study, a 2001 USDA NASS land use raster map (30x30 m ground resolution) was used. The DEM data used were obtained from the USGS at 10 m elevation resolution. Similar to the Upper Gera watershed, the CCW watershed boundary, HRUs, and flow routing/stream channel networks were delineated using the Pfennig et al. (2009) AML-based tool. The HRU delineation

resulted in 998 polygons featuring areas between 0.05-2.8 km². Site F34 (Figure 1b, the Upper CCW drainage outlet) was gauged and equipped with a continuous recording ISCO 6712 autosampler and flowmeter. Rainfall and temperature data were also measured using a continuous recording rain gauge near the BLG site (Figure 1b). In addition to the BLG climate data, data from the NOAA Waterloo, IN weather station (also located in the Upper CCW) was also used for AgES-W climate input. Water samples were analyzed for sediment, N_{03-N}, NH_{4-N}, soluble P, total Kjeldahl N, and total Kjeldahl P. All nutrient analyses were conducted colorimetrically with a Konelab Aqua 20 clinical chemistry analyzer.

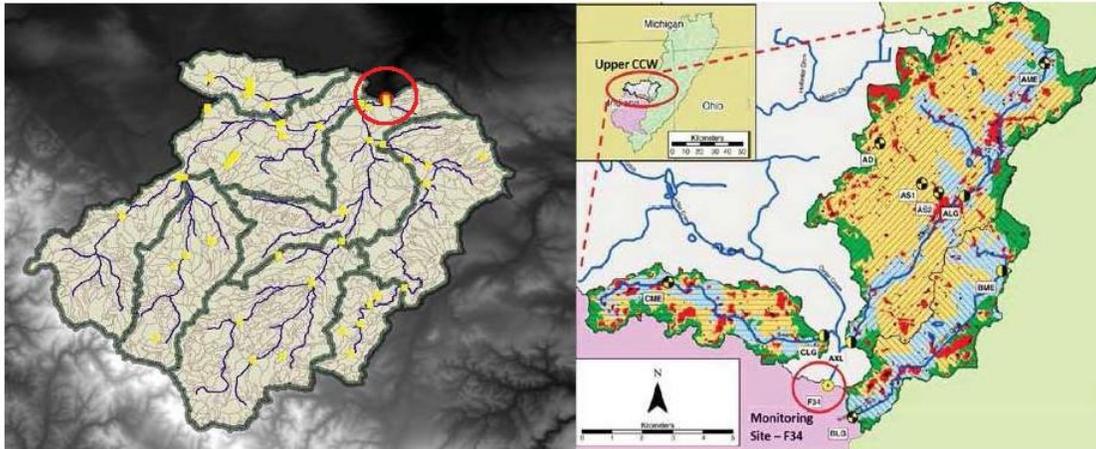


Figure 1. Upper Gera (a) and Upper CCW (b) stream network and gauging stations. The Upper Gera (Moebisburg) and Upper CCW (F34) outlets are delineated with a red circle.

2.4 AgES-W model parameterization and statistical evaluation

AgES-W requires 20 total input files for model execution which can be categorized as follows: 1) climate (11 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. An enhancement of the OMS3 framework is the integration of the LUCA autocalibration tool, developed by the USGS (Hay et al., 2006). The LUCA tool utilizes the shuffled complex evolution (SCE) algorithm that allows for the calibration of model parameters based on the minimization of a single or multi-objective function (Duan et al. 1992). LUCA was employed to calibrate sensitive AgES-W parameters that govern Upper Gera and Upper CCW responses for soil water, nitrogen, groundwater, and flow routing processes. Nash-Sutcliffe efficiency coefficient (ENs) and percent bias (PBIAS) statistical evaluation criteria were used to assess daily/monthly streamflow and nitrogen/sediment loadings simulated by AgES-W. A positive PBIAS value indicates a bias toward overestimation whereas a negative value indicates a model bias toward underestimation.

2.5 AgES-W model application results

2.5.1 Upper Gera watershed

Table 1. Statistical evaluation for AgES-W simulated daily and average monthly Upper Gera streamflow.

Statistical evaluation coefficient	Calibration period (1/1/2009 to 2/28/2011)		Entire simulation period (1/1/2007 to 2/28/2011)	
	Daily streamflow (m ³ s ⁻¹)	Average monthly streamflow (m ³ s ⁻¹)	Daily streamflow (m ³ s ⁻¹)	Average monthly streamflow (m ³ s ⁻¹)
ENS	0.84	0.94	0.67	0.70
PBIAS	0.57		16.6	

•Note: ENs =Nash-Sutcliffe efficiency; PBIAS =bias or relative error(%).

The AgES-W simulation period for the Upper Gera Watershed was 4+ years (1/1/2007 to 212812011). Historical measured streamflow data for the Upper Gera measurement gauge at Moebisburg (Figure 1b) were used for a 2-yr. calibration period (1/1/2009 to 2128/2011); the subsequent validation period for streamflow was from 1/1/2007 to 12/31/2008. The historical measured data were compared with daily and average monthly streamflow. Daily and monthly observed vs. AgES-W simulated streamflow results for the calibration period are given in Table 1 and Figure 2. In general, the AgES-W model performed extremely well for the calibration period with slightly overestimated streamflow on a daily time-step (PBIAS = 0.57%; ENs= 0.84). The statistical results for average monthly streamflow in Table 1 for the calibration period show that ENs improved to 0.94. The PBIAS value for average monthly streamflow is not shown as it is essentially the same as for the daily streamflow. Table 1 and Figure 3 show that AgES-W performed less well when the validation period was included in statistical evaluation criteria calculation. Daily streamflow ENs and PBIAS for the full simulation period were 0.67 and 16.6%, respectively; the average monthly streamflow ENs for the full simulation period was 0.70.



Figure 2. Daily Upper Gera Watershed AgES-W simulated and observed streamflow ($\text{m}^3 \text{s}^{-1}$) at the Moebisburg gauge (validation period -1/1/2007 to 6/30/2012).

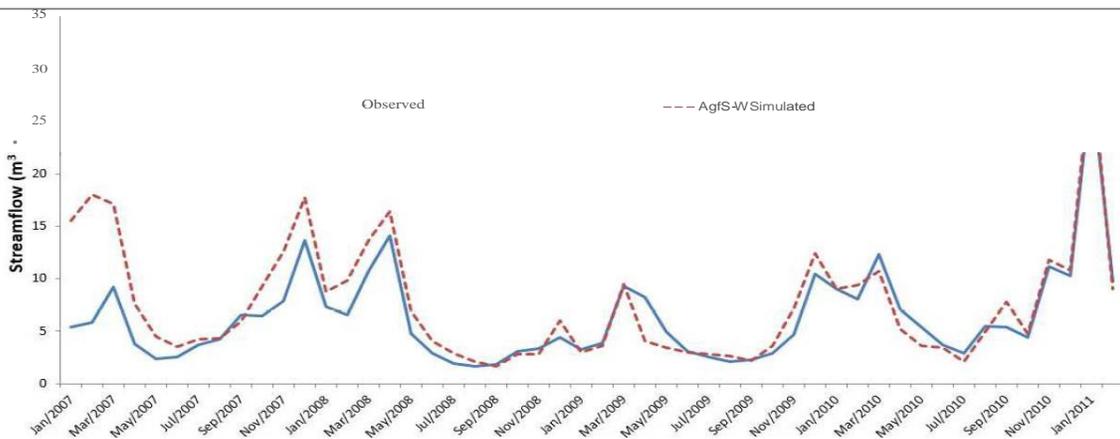


Figure 3. Monthly Upper Gera Watershed AgES-W simulated and observed streamflow ($\text{m}^3 \text{s}^{-1}$) at the Moebisburg gauge (validation period -1/1/2007 to 6/30/2012).

2.5.2 Upper CCW

The AgES-W simulation period was 8 years (2004-2011); however, the first two years were not used for model evaluation in order to allow model state variables to reach equilibrium with actual physical conditions. Historical measured streamflow and nitrogen data for Upper CCW measurement gauge F34 (41° 13' 8" N, 85° 4' 35" W) were used for a 1-yr. (2006) calibration period for runoff and total N; the subsequent validation periods for runoff, total N load, and sediment load were 2007-2012, 2007-2011, and 2010-2011, respectively. The historical measured data was compared with daily and average monthly streamflow/total N load, and daily sediment load. The calibrated parameter values for streamflow were subsequently used for total N load calibration for 2006, and both the calibrated streamflow and nitrogen-specific parameters were then used for the streamflow and total N load validation periods. Daily observed and AgES-W simulated streamflow results for the 2006 calibration period are given in Table 2. In general, the AgES-W model slightly underestimated streamflow on a

daily time-step as shown by the negative value for PBIAS (-7.52%). The ENs value (0.74) is considered satisfactory according to Moriasi et al. (2007), and the PBIAS value is also acceptable since it is well under 25%. The statistical results for average monthly streamflow in Table 2 for the 2006 calibration period show that ENs improved to 0.75. The PBIAS value for average monthly streamflow is not shown as it is essentially the same as for the daily streamflow.

Table 2. Statistical evaluation for AgES-W simulated daily and average monthly Upper CCW streamflow.

Statistical evaluation coefficient ^a	Calibration period (2006)		Validation period (2007-2012)	
	Daily streamflow (m ³ s ⁻¹)	Average monthly streamflow (m ³ s ⁻¹)	Daily streamflow (m ³ s ⁻¹)	Average monthly streamflow (m ³ s ⁻¹)
ENS	0.74	0.75	0.70	0.72
PBIAS	-7.52		8.44	

^a Note: ENs = Nash-Sutcliffe efficiency; PBIAS = bias or relative error(%).

Table 2 shows that all statistical evaluation coefficients for daily streamflow decreased slightly for the validation period from 2007-2012. In particular, the ENs coefficient decreased from 0.74 to 0.70 and PBIAS decreased from -7.52% to 8.44%, meaning that AgES-W switched from slight underprediction to slight overprediction for daily streamflow. Table 2 also shows that all statistical evaluation coefficients for average monthly streamflow worsened slightly for the validation simulation period as compared to the calibration simulation period. Average monthly decreases were of similar magnitude as the decreases in daily streamflow. Average monthly observed and AgES-W simulated streamflow for the validation period from 2007-2012 are shown in Figure 4.

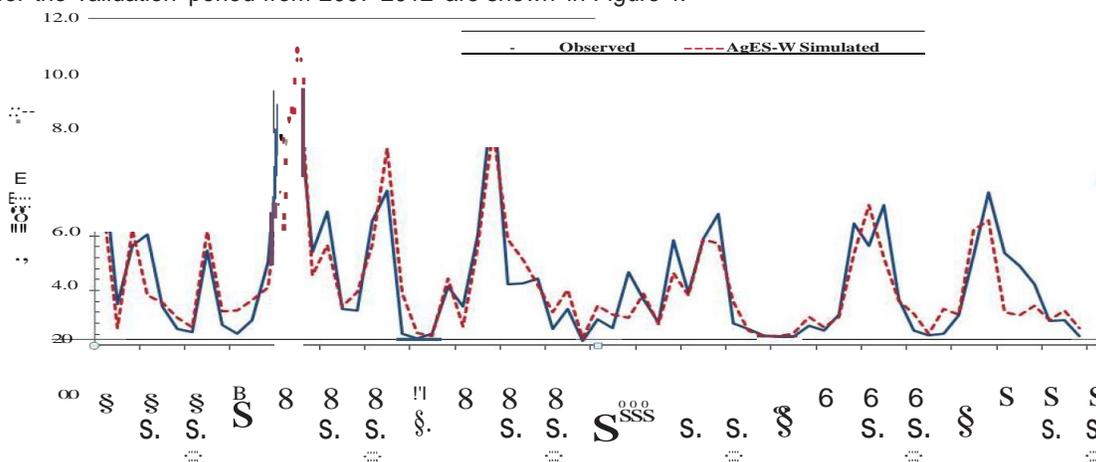


Figure 4. Monthly Upper Cedar Creek Watershed AgES-W simulated and observed streamflow (m³ s⁻¹) at gauge F34 (validation period-1/1/2007 to 6/30/2012).

Daily observed and AgES-W simulated total N results for the 2006 calibration period are shown in Table 3. In general, the AgES-W model slightly underestimated total N on a daily time-step for the calibration as shown by the negative value for PBIAS (-9.11%) in Table 3. The ENs (0.68) value in Table 3 is considered satisfactory according to Moriasi et al. (2007), and the PBIAS value is also acceptable since it is under 25%. Similar to streamflow prediction, the statistical results for average monthly total N in Table 3 for the 2006 calibration period show that ENs improved to 0.72. The PBIAS value for average monthly total N is not shown as it is essentially the same as for the daily total N.

Similar to streamflow prediction, Table 3 shows that most of the statistical evaluation coefficients for daily total N decreased slightly for the validation period from 2007-2011 as compared to the calibration simulation period. In particular the ENs coefficient decreased from 0.68 to 0.66; however, PBIAS improved from -9.11% to 3.63% meaning that AgES-W switched from slight underprediction to slight overprediction for daily total N (similar to calibration vs. validation for streamflow prediction). Table 3 also shows that all statistical evaluation coefficients for average monthly total N worsened slightly for the validation simulation period as compared to the calibration simulation period. Average monthly decreases were of similar magnitude as the decreases in daily total N. Average monthly observed and AgES-W simulated total N for the 2007-2012 validation period are shown in Figure 5. This figure

shows that simulated average monthly total N for the validation period captured most of the observed peak total N load events quite well.

Table 3. Statistical evaluation for AgES-W simulated daily and average monthly Upper CCW total nitrogen (N) loading and daily sediment loading.

Statistical evaluation coefficient	Total N-calibration period (2006)		Total N-validation period (2007-2011)		Sediment load (2010-2011)
	Daily total N (mg l-1)	Average monthly total N (mg l-1)	Daily total N (mg l-1)	Average monthly total N (mg l-1)	Daily sediment load (g l-1)
ENS	0.68	0.72	0.66	0.70	0.45
PBIAS	-9.11		3.63		-21.8

• Note: ENS = Nash-Sutcliffe efficiency; PBIAS = bias or relative error(%).

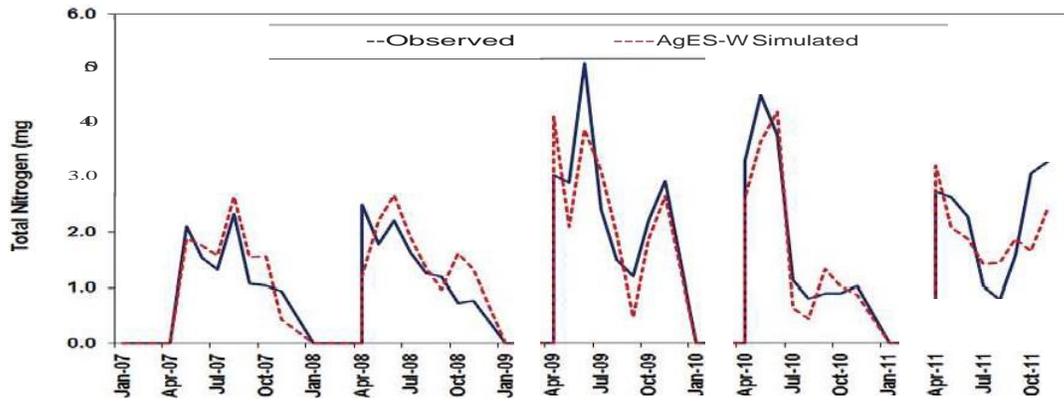


Figure 5. Monthly Upper Cedar Creek Watershed AgES-W simulated and observed total N (mg l⁻¹) at gauge F34 (validation period-4/11/2007 to 11/19/2011).

Daily AgES-W simulated sediment loading results from April 2010 to June 2011 are also shown in Table 3. Although streamflow was slightly overestimated for the validation period, sediment loading was underestimated. Model prediction of sediment loading should be highly correlated to surface runoff prediction. Observed surface runoff data for individual Upper CCW HRUs were unavailable; however, AgES-W underestimated streamflow for the April 2010 to June 2011 sediment loading simulation period by approximately 17% (data not shown). Table 3 shows that the daily sediment ENS and PBIAS for the simulation period were 0.45 and -21.8%, respectively.

3. DISCUSSION

The range of relative error (e.g., PBIAS) and ENs values for calibrated predictions in this study (e.g., daily/monthly streamflow, monthly total N, and 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 ENs values ranging from 0.43 to 0.86 for different gauge stations in the Cannonsville Reservoir in upstate New York. Kirsch et al. (2002) reported SWAT 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 on the Upper Cedar and Upper CCW watersheds 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 Green-Ampt might help in this regard. 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; therefore, it is possible that the distribution of rainfall over the entire watershed may be inaccurately represented. Considerable uncertainty exists in the observed precipitation data, and this uncertainty 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 balance simulations, particularly during the summer months when ET demand is higher.

4. SUMMARY AND CONCLUSIONS

AgES-W reasonably reproduced (for both calibration and validation periods) the hydrological dynamics for the Upper Gera and Upper CCW watersheds and the N/sediment dynamics for 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 for water quantity and quality prediction 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 such as SWAT. 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 enable easier long-term maintenance and updating of model code and reduce duplication of work by modelers for developing common basic components.

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