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Integrated Agricultural System Modeling Using OMS 3: Component Driven Stream Flow and Nutrient Dynamics Simulations

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Abstract: This study reports on the integration of the European J2K-S model (a component-based system for fully distributed simulation of water balance and N dynamics in large watersheds) under the Object Modeling System 3 (OMS3) environmental modeling framework and subsequent evaluation of OMS3/J2K-S performance on the Cedar Creek Watershed (CCW) in northeastern Indiana, USA. Uncalibrated model performance for daily and monthly stream flow response was assessed using Nash-Sutcliffe model efficiency (E_{NS}) and percent bias (PBIAS) model evaluation coefficients. Simulations for nitrogen (N) loadings to Cedar Creek were also performed; however, the OMS3/J2K-S N dynamics sub-model is still undergoing testing so a formal statistical evaluation of this component was not performed. Comparisons of daily and average monthly simulated and observed stream flows for the 1997-2005 simulation period resulted in PBIAS and E_{NS} coefficients ranging from -18.6% to -8.6% for PBIAS and 0.46 to 0.68 for E_{NS}. These values were similar or better than others reported in the literature for uncalibrated stream flow predictions at the watershed scale. The results show that the prototype OMS3/J2K-S watershed model was able to reproduce the hydrological characteristics of the CCW with sufficient quality, and should serve as a foundation on which to better quantify water quality (e.g., N dynamics) at the watershed scale.

Keywords: Hydrologic modeling; Watershed; Stream flow; Model evaluation; OMS3.

1. INTRODUCTION

The Object Modeling System 3 (OMS3) currently being developed by the USDA-ARS Agricultural Systems Research Unit and Colorado State University (Fort Collins, CO) provides a component-based environmental modeling framework which allows the implementation of single- or multi-process modules that can be developed and applied as custom-tailored model configurations (David et al., 2002). The value of continuous watershed simulation models like the Soil and Water Assessment Tool (SWAT) (Arnold et al., 1993) is reflected by programs like the Conservation Effects Assessment Project (CEAP) in the United States and the EU-Water Framework Directive (WFD) in Europe. The ARS CEAP Watershed Assessment Study (WAS) Project Plan (USDA-ARS, 2004) provides detailed descriptions of ongoing research studies at 14 benchmark watersheds in the United States. In order to satisfy the requirements of CEAP WAS Objective 5 ("develop and verify regional watershed models that quantify environmental outcomes of conservation practices in major agricultural regions"), a new watershed model development approach was initiated to take advantage of OMS3 modeling framework capabilities. The European J2K-S model (Krause et al., 2006), a component-based system for fully distributed simulation of the water balance and N dynamics in large watersheds and catchments, was selected to provide the initial process-based model components. Specific objectives of this study were to: 1) implement J2K-S hydrological and N dynamics components under the OMS3, 2) assemble a new modular watershed scale model for fully distributed transfer of water and N loading between land units and stream channels, and 3) evaluate the accuracy and applicability of the modular watershed model for estimating stream flow and N dynamics. The Cedar Creek watershed (CCW) in northeastern Indiana, USA was selected for application of the OMS3-based watershed model.

2. THE OBJECT MODELING SYSTEM 3 (OMS3)

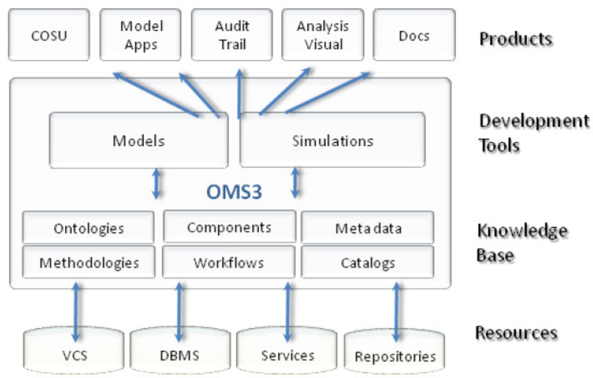


Figure 1. OMS3 principle architecture.

OMS3 closely resembles the generic architecture for environmental integrated modeling frameworks as presented by Rizzoli et al., 2008). It contains four primary foundations (Figure 1): modeling resources, the knowledge base of the system (e.g., metadata and ontologies), development methods and tools (e.g., science models), and various modeling products. The core consists of an internal knowledge base and development tools for model and simulation creation. OMS3 is based on the Java platform; however, it is highly interoperable with C, C++, and FORTRAN on all major operating systems and architectures. Model development under OMS3 is component-based and there are only minimal requirements for plain objects (POJOs) to be represented as an OMS3 component. In OMS3, as well as most other modeling frameworks, the term component refers to a concept in software development which extends the reusability of code from the source level to the executable. Components are context-independent, both in the conceptual and technical domain, and represent self contained software units that are separated from the surrounding framework environment. Furthermore, the OMS3 modeler does not have to learn and use framework data types or an extensive Application Programming Interface (API).

To allow for scalable models and processing with complex data sets, the execution of components under OMS3 is always multi-threaded (i.e., components are executed in parallel if the data flow allows it and no explicit thread coding is required). OMS3 utilizes the Domain Specific Language (DSL) concept to provide for a concise, robust, and flexible representation of model simulations. With easy to setup DSLs, simple simulations (e.g., model calibration, sensitivity and uncertainty analysis setups) can be created and executed in OMS3 from different environments such as IDEs, the OMS3 modeling console, the command line, or any application that embeds an OMS3 runtime version. Finally, OMS3 is a non-invasive modeling framework as there are no framework interfaces to implement, no classes to extend and polymorphic methods to overwrite, and most importantly no need to replace common native and custom language data types with framework-specific data types.

3. THE OMS3/J2K-S WATERSHED MODEL

The J2K-S modeling system (Krause et al., 2006; Krause et al., 2009) integrated in OMS3 was used for the simulation of the hydrological and N dynamics of the CCW in Indiana. J2K-S is a modular, spatially distributed system which implements hydrological and N processes as encapsulated process components and operates at various temporal and spatial aggregation levels throughout the watershed. The J2K-S model was developed in the JAMS (Jena Adaptive Modeling System) modeling framework which is derived from an earlier, more API-based OMS Vers. 1. Therefore, the JAMS J2K-S model was already componentized and its classes followed the general modeling framework IEF (Init/Execute/Finalize) lifecycle-approach. For component integration into OMS3, framework-specific JAMS data types for component exchange-data were substituted with generic native data types and super class dependencies became obsolete. Moreover, JAMS-specific annotations had to be converted into more generic OMS3 annotations. The overall migration process was automated using scripts with regular expression string substitutions that automated roughly 90% of the JAMS to OMS3 conversion. The remaining 10% of the conversion was performed manually, consisting mainly of transforming JAMS model XML representations into Java code and DSL simulation files, introducing classes for complex (i.e., spatial) types such as hydrologic response units and stream reaches, and finally optimizing HRU processing for parallel execution under OMS3. Since JAMS and OMS are closely related with respect to component conceptualization and implementation, the migration process was limited to the source statement level, i.e., no structural change in components was necessary.

The OMS3/J2K-S hydrological model contains components for climate data regionalization, evapotranspiration, interception, snow accumulation and ablation, water and N balance in the unsaturated zone, water and N balance in the saturated zone, surface runoff and N concentration, and explicitly computed lateral surface and subsurface water/N routing and stream channel/river network flood routing in catchments (Krause et al. 2006). The N dynamics model contains components that are mainly adopted from the Soil Water Assessment Tool (SWAT) model (Arnold 1998) and coupled to the hydrologic components (Figure 2). The N dynamics modules include process components for simulating soil temperature, crop growth and N turnover according to Neitsch et al. (2002) and Williams et al. (1984) with some minor adaptations. Five different soil N pools are considered in order to allow modeling of different N inputs (e.g., mineral fertilizer, organic manure) and N transformations between these pools. N flows are modeled by a dynamic crop growth module and subsequent N uptake of plants (residues and yield), as well as through denitrification and volatilization. The land use management routines include modules for fertilizer management, tillage, and harvest operation (Krause et al., 2009).

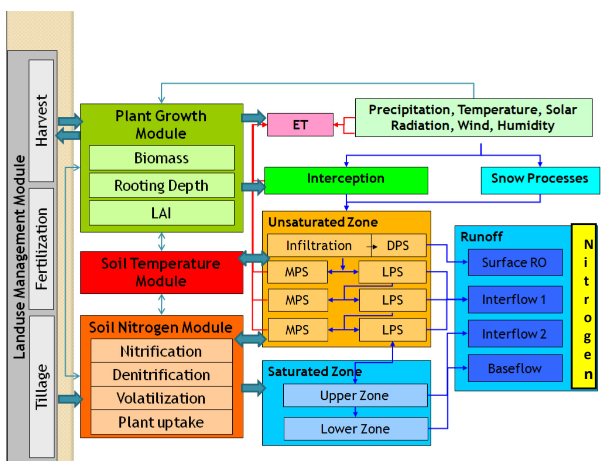


Figure 2. OMS3/J2K-S science component structure (adapted from Krause et al., 2009).

After calculation of HRU surface and subsurface runoff and N dynamics, runoff and N routing is performed based on topological interconnections of the single HRU polygons, i.e., water and N flows are passed to a receiving HRU defined by its topological position (derived by GIS analysis), or to a receiving stream reach if the HRU is connected to one. Runoff and N routing inside the stream network is simulated by connecting the reach storages, receiving the runoff and N from the topologically connected HRUs by a hierarchical storage cascade approach, and calculating flow velocity inside the stream channel using the Manning-Strickler equation. The outflow of each specific stream reach is then transferred as inflow to the connecting downstream reach.

4. MATERIALS AND METHODS

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 and 84°53'49'' to 85°19'44''W). The CCW drains two 11-digit hydrologic unit code (HUC) watersheds, the Upper (04100003080) and Lower Cedar (04100003090), covering an area of approximately 700 km^2. The DEM data used in this study were obtained from the USGS at 10-m elevation resolution, 1/3 arc second, and a map-scale of 1:24,000 quadrangle sheet. The average land surface slope of the watershed is 2.6%, and the predominant soil textures are silt loam, silty clay loam, and clay loam with six STATSGO soil associations represented. The annual mean precipitation in the watershed area from 1989 to 2005 was 962 mm. For this study, a land use map from the National Agricultural Statistics Survey (NASS) was used collected between the dates of April 29, 2001 and September 5, 2001 with an approximate scale of 1:100,000 and a ground resolution of 30 x 30 m. Both standard ArcGIS 9.2 (ESRI, 2008) geoprocessing tools (e.g., overlay) and customized Avenue scripts for deriving HRU flow connectivity were used for HRU delineation which consisted of partly reclassifying and combining (by overlay analysis in ArcGIS 9.2) DEM topographical parameters (e.g., elevation, slope, aspect) with STATSGO soil and NASS land use GIS layers. The delineation of HRUs for the entire CCW resulted in 4,174 HRU polygons featuring areas between 0.02 to 2.5 km^2. Figure 3 shows the stream channels and HRU polygons of the CCW, together with topological connections as red arrows draped over the HRU polygons.

The OMS3/J2K-S simulation period in this study was 1997 through 2005. Daily precipitation, solar radiation, wind speed, relative humidity, and maximum/minimum air temperatures for these years were obtained from the NOAA National Climate Data Center (NOAA-NCDC, 2004) for the Garret and Waterloo weather stations within the CCW. Regionalization pre-processors in OMS3/J2K-S automatically distributed the climate data from the two gauges over the watershed. Historical measured data for Cedar Creek stream flow Gauge 04180000 (41°13'08"N, 85°04'35"W) were supplied by the USGS for the 9-year period from January, 1997 to December, 2005. Initial model parameter values were taken from simulation studies successfully applying J2K-S to watersheds in Germany and elsewhere exhibiting physical characteristics (e.g., topography, size, and agricultural land use) very similar to the CCW.

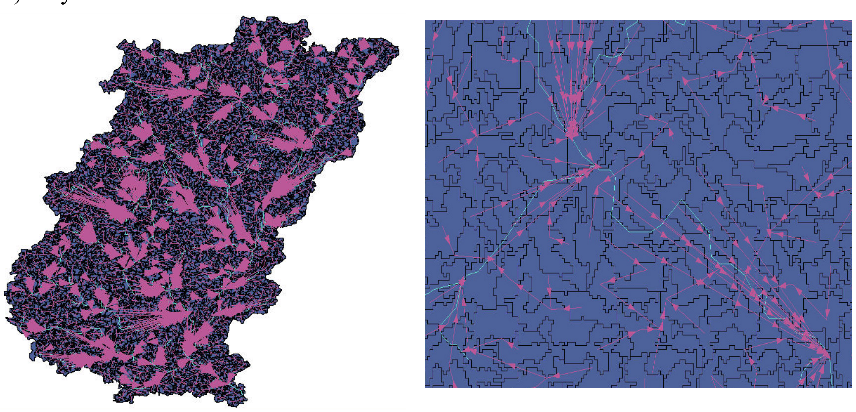


Figure 3. Routing topology with overland flow routing vectors for the CCW including an expanded view of flow routing vectors with HRU and stream channel flow linkages.

Nash-Sutcliffe Efficiency coefficient (E_{NS}) and percent bias (PBIAS) statistical evaluation coefficients were used to evaluate the overall correspondence of simulated output to measured values. E_{NS} indicates how well the plot of observed versus simulated values fits a 1:1 line. PBIAS is a measure of the average tendency of the simulated flows to be larger or smaller than their 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. In this study, E_{NS} and PBIAS values were computed for both daily and average monthly stream flow.

5. RESULTS AND DISCUSSION

Historical measured data for Cedar Creek stream flow from the USGS for a 9-year period from January, 1997 to December, 2005 at Gauge 04180000 (41°13'08"N, 85°04'35"W) near Cedarville, IN was compared with daily and average monthly OMS3/J2K-S noncalibrated stream flow. In general, the OMS3/J2K-S model underestimated stream flow on a daily time-step as shown in the 1:1 plot in Figure 4 where all data points are included for the 9-year simulation period. The negative value for PBIAS (-18.55%) indicates that the model underestimated stream flow, and the E_{NS} value (0.46) is considered unsatisfactory according to Moriasi et al. (2007) (although the PBIAS value is acceptable since it is under 25%).

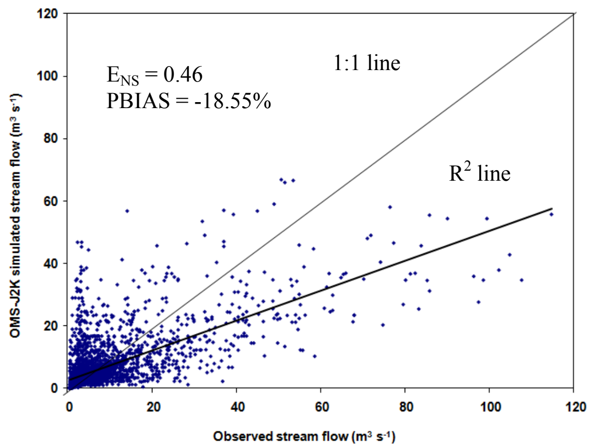
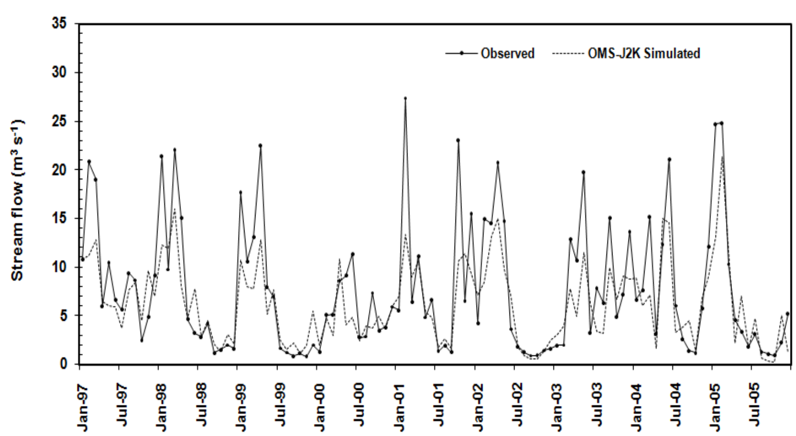


Figure 4. Daily CCW stream flow 1:1 plot of OMS3/J2K-S initial parameter set simulated values versus observed (Jan. 1997 to Dec. 2005).

Average monthly observed and OMS3/J2K-S simulated stream flow from January, 1997 to December, 2005 are presented in Figure 5. This figure shows that the trend in simulated average monthly stream flow followed the observed values much more closely than the simulated daily stream flow results. Furthermore, it is extremely easy to discern that simulated average monthly stream flow in Figure 5 was significantly underestimated for nearly all of the 9-year simulation period. The E_{NS} coefficient increased to 0.60 for average monthly stream flow (as compared to 0.46 for daily stream flow) with the average monthly PBIAS value remaining essentially the same as daily stream flow. The initial uncalibrated simulation results exhibited a rather large overprediction of ET on the



watershed (data not shown) in addition to a systematic underprediction of stream flow

Figure 5. Monthly CCW stream flow for observed and OMS3/J2K-S initial parameter set simulated values (Jan. 1997 to Dec. 2005).

across all time scales. Land use on the CCW is quite diverse, furthermore, the simplistic representation of evapotranspiration dynamics in OMS3/J2K-S may not adequately capture complex soil-water-plant interactions occurring on the watershed. Therefore, the *soilLinRed* coefficient was increased. This coefficient controls the partitioning of PET to AET, i.e., increasing *soilLinRed* decreases the amount of PET partitioned to AET. In addition, an attempt was made to account for areas of tile drainage on the Cedar Creek Watershed. A logical way to represent the effects of tile drainage in OMS3/J2K-S was to increase both the amount of water available in the LPS and the rate of outflow from LPS. Therefore, the *soilDistMPSLPS* and *soilOutLPS* coefficients were both decreased. Decreasing *soilDistMPSLPS* increases the amount of infiltrated water available for LPS; decreasing *soilOutLPS* increases the outflow rate from LPS. These adjustments approximate the more rapid removal of water from tile drains than what would normally be expected with the absence of tile drainage. All OMS3/J2K-S CCW simulations were then re-run using the modified values for *soilLinRed*, *soilDistMPSLPS*, and *soilOutLPS*.

All statistical evaluation coefficients for daily stream flow improved substantially for the modified parameter set, in particular, the E_{NS} coefficient increased from 0.46 to 0.58 and PBIAS decreased from -18.55% to -8.59%. The OMS3/J2K-S model still underestimated stream flow on a daily time-step (as shown in the 1:1 plot in Figure 6). The E_{NS} coefficient for average monthly stream flow improved for the modified parameter set (E_{NS} = 0.68) as compared to the initial parameter set (E_{NS} = 0.60). Average monthly improvement was of similar magnitude as the improvement in daily stream flow. Average monthly observed and OMS3/J2K-S simulated stream flow from January, 1997 to December, 2005 for the modified parameter set are shown in Figure 7. This figure shows

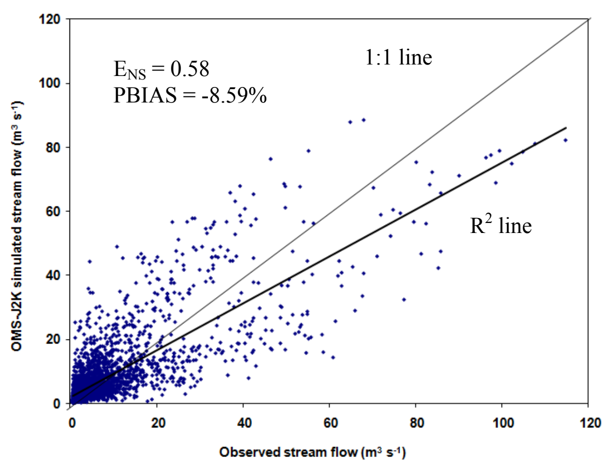


Figure 6. Daily CCW stream flow 1:1 plot of OMS3/J2K-S modified parameter set simulated values versus observed (Jan. 1997 to Dec. 2005).

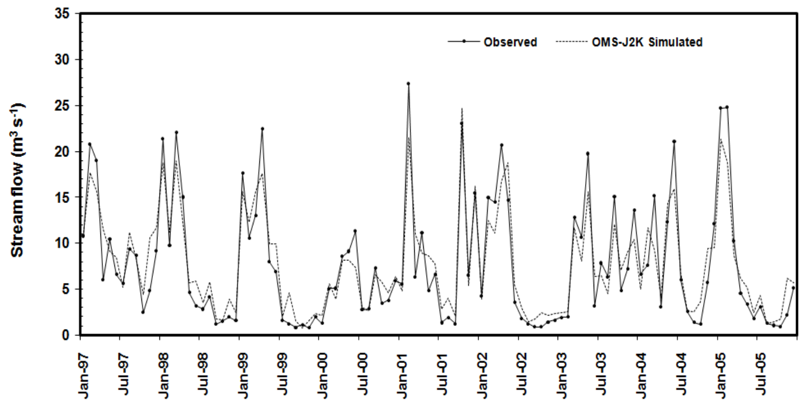


Figure 7. Monthly CCW stream flow for observed and OMS3/J2K-S modified parameter set simulated values (Jan. 1997 to Dec. 2005).

that the trend in simulated average monthly stream flow for the modified parameter set followed the observed values much more closely (both in trend and in better estimation of peak stream flow events) than the simulated monthly stream flow results for the initial parameter set shown in Figure 5. Even with stream flow prediction improvements using the modified parameter set, OMS3/J2K-S underestimated stream flow at all time scales. Additional possible explanations for the underprediction may be attributed to using inappropriate values for recession coefficient parameter that govern simulated flow through the shallow and deep groundwater storage. Other studies (e.g., Krause, 2002) have shown the OMS3/J2K-S hydrologic model to be particularly sensitive to the recession coefficients used for groundwater storage calculations. Underprediction of monthly stream flow may be due to the lack of measured data for solar radiation and wind speed which are needed to estimate potential ET based on the Penman-Monteith equation in OMS3/J2K-S. Furthermore, the lack of available measured ET data for the study period makes it difficult to validate simulated ET results. Under or over estimates of ET could thereby affect the overall water balance, particularly during the summer months when ET demand is higher. Simulations for N loadings on each HRU and runoff N loading to Cedar Creek were also performed; however, the OMS3/J2K-S N dynamics sub-model is still undergoing testing so a formal statistical evaluation of this component was not performed. Figure 8 shows N pools simulated by OMS3/J2K-S averaged across all HRUs for the CCW.

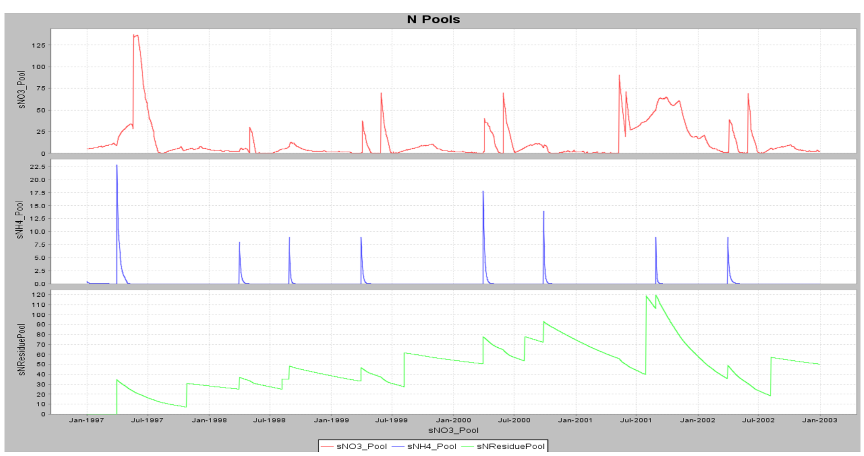


Figure 8. N pools simulated by OMS3/J2K-S averaged across all HRUs for the CCW.

In summary, we chose to evaluate noncalibrated stream flow results considering that OMS3/J2K-S was developed for applications on ungauged watersheds. More importantly, however, is the potential for formal model calibration to introduce a level of bias that could ultimately mask or eliminate the impact of the simulated runoff generation processes.

6. CONCLUSIONS

The long-term continuous hydrologic simulations of OMS3/J2K-S performed reasonably well in predicting daily, monthly, and annual average flows on the Cedar Creek (Gauge 04180000) near Cedarville, IN. For initial and modified parameter sets, OMS3/J2K-S underpredicted the majority of the peak flows during the 9-year simulations of the Cedar Creek Watershed, with some individual storm events underpredicted by many orders of magnitude. Despite the underprediction, the majority of the evaluation statistics for E_{NS} and PBIAS for both uncalibrated and manually adjusted parameter sets were within the range of other evaluation results reported in the literature for various watershed models such as SWAT. It was unclear whether OMS3/J2K-S needs enhancements in storm event simulations for improving high and peak flow predictions, or whether the distribution of rainfall over the entire watershed was misrepresented due to the use of only two climate stations.

The results show that the OMS3/J2K-S prototype watershed model was able to reproduce the hydrological dynamics of the Cedar Creek Watershed with sufficient quality, and should serve as a foundation on which to build a regionalized model for the CEAP initiative that is able to quantify the impact of conservation practice implementation on water quantity and quality at the watershed scale. In particular, the topological routing scheme employed by OMS3/J2K-S (thus allowing the simulation of lateral processes important for the modeling of runoff concentration dynamics) is much more physically based and robust than quasi-distributed routing schemes used by other watershed scale natural resource models (e.g., SWAT). The largest advantage of the OMS3/J2K-S routing approach is a process-oriented view of spatial watershed characteristics that drive hydrological behavior. With a fully-distributed routing concept (Figure 3), the dynamic spatially distributed character of the OMS3/J2K-S watershed model that separates it from other watershed models (e.g., SWAT) becomes apparent. Furthermore, higher spatial resolution in combination with the lateral transfer of water between HRUs and stream channel reaches can be considered a very important advancement (in hydrological modeling) towards deriving suitable conservation management scenarios for CEAP.

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