DEVELOPMENT AND EVALUATION OF A COMPONENT-BASED WATERSHED MODEL USING THE OBJECT MODELING SYSTEM

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Abstract

This study reports on the integration of the European J2000 model (an object-oriented, modular hydrological system for fully distributed simulation of the water balance in large watersheds) under the Object Modeling System (OMS) environmental modeling framework and subsequent evaluation of OMS-J2K performance on the Cedar Creek Watershed (CCW) in northeastern Indiana, USA. Model parameter values were taken from previous simulation studies where J2K was applied to watersheds with characteristics similar to the CCW. Following initial (uncalibrated) stream flow simulations, modifications were made to input parameters related to evapotranspiration, soil water storage, and soil water lateral flow. 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. 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 OMS-J2K 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 more comprehensive model to better quantify water quantity and quality at the watershed scale.

INTRODUCTION

The Object Modeling System (OMS) 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), and Annualized Agricultural Non-Point Source Pollution (AnnAGNPS) model (Yuan et al., 2001) 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 5-year ARS CEAP Watershed Assessment Study (WAS) Project Plan (USDA-ARS, 2004) provides detailed descriptions of research studies at 14 benchmark watersheds in the United States, each of which has a particular area of special emphasis due in part to watershed location and regional water quality issues. 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 is needed that can take full advantage of OMS modeling framework capabilities for assembling appropriate modules into a model customized to a specific problem and scale of application for a region. The European J2000 model **(**Krause et al., 2006) was selected to provide the initial components for a regionalized watershed model that satisfies the CEAP Objective 5 requirements. J2000 (referred to hereafter as J2K) is an object-oriented, modular hydrological system for fully distributed simulation of the water balance in large watersheds and catchments. The specific objectives of this study were to: 1) implement J2K hydrological modeling components under the OMS, 2) assemble a new modular watershed scale model for fully distributed transfer of water between land units and stream channels, and 3) evaluate the accuracy and applicability of the modular watershed model for estimating daily and average monthly stream flow. The Cedar Creek watershed (CCW) in northeastern Indiana was selected for application of the OMS-based watershed model. A decision was made to first apply the model without formal (e.g., autocalibration) calibration methods, thus eliminating uncertainties related to the use of different optimized model parameter values.

THE OBJECT MODELING SYSTEM (OMS)

The basic OMS concept is the representation of all system and model components as independent entities coupled by software interfaces (David et al., 2002). The principal architecture of OMS is presented in Figure 1.

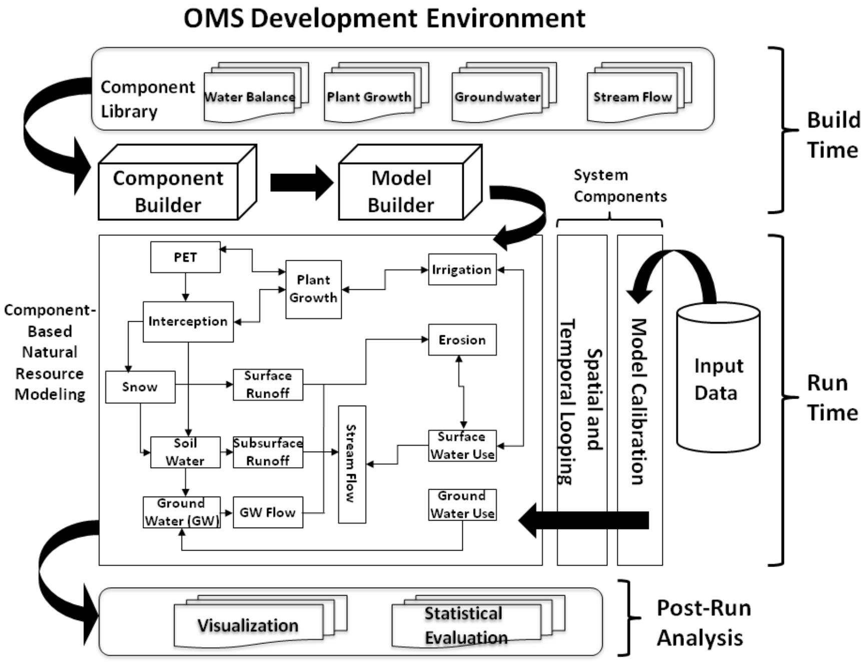

Figure 1 Detailed schematic of major OMS framework components including OMS model, system, and science module components.

OMS core system components include reusable features such as simulation control across time and space, auxiliary tools for model calibration, and control of data input/output. OMS modeling components, such as the Component Builder and Model Builder, support model development whereby multiple scientific components can be assembled into a complex model (Figure 1). Science model components usually implement specific approaches for representing environmental processes, e.g., water balance, etc. The Component Builder supports development of scientific Java components and also allows the adaptation of legacy source code written in the FORTRAN and C/C++ programming languages. The Model Builder supports visual integration and configuration of complex models from standalone model components with an easy-to-use graphical user interface which offers capabilities for the mapping of component output to input of subsequent components. The OMS also provides various tools for model data analysis such as statistical evaluation and plotting/geospatial visualization capabilities (Figure 1).

THE J2K WATERSHED MODEL

The J2K modeling system (Krause, 2002; Krause et al., 2006) was used for the simulation of the hydrological dynamics of the Cedar Creek Watershed in Indiana. J2K is a modular, spatially distributed hydrological system which implements hydrological processes as encapsulated process components. J2K operates at various temporal and spatial aggregation levels throughout the watershed. For example, runoff is generated at the Hydrologic Response Unit (HRU) level with subsequent calculation of runoff concentration processes (through a lateral routing scheme) and flood routing in the stream channel network. The generation of four separate runoff components [surface runoff (RD1), interflow from the unsaturated soil zone (RD2), interflow from the saturated weathering layer of the underlying hydro-geological unit (RG1), and saturated baseflow (RG2)] is simulated inside the modeling core of J2K for each HRU (Figure 2).

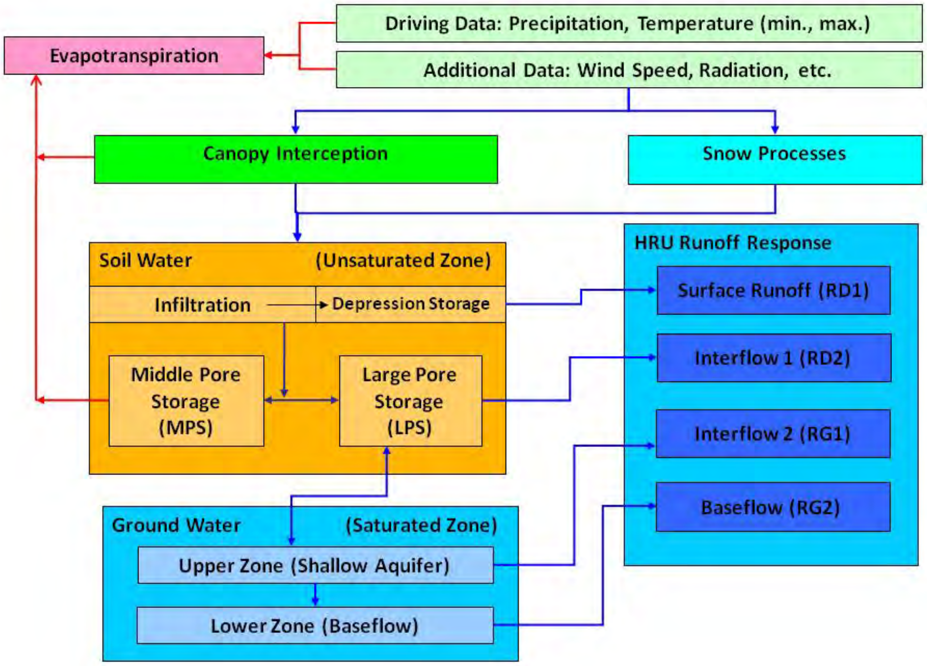

Figure 2 Conceptual diagram of the OMS-J2K model showing critical storages and processes.

Regionalized climate input data sets are used as driving parameters, together with the physiogeographic parameters of each HRU derived from various GIS data layers (e.g., soil and land use). The most complex part of J2K is the soil-water balance module (Figure 2), which reflects the primary role of the soil zone as a regulation and distribution system and interacts with nearly all other J2K process modules. The module implements a unique storage water concept based on two different compartments for the soil profile unsaturated zone. The first storage compartment is the middle pore storage (MPS), describing the water storage capacity of the middle-sized pores (diameter = 0.2-50 μm) in which stored water is held against gravity and can only be drained by an active tension. The second compartment is the large pore storage (LPS), describing the water storage capacity of the large and macro-pores (diameter > 50 μm) which are not able to hold water against gravity. The LPS storage compartment is the source of vertical and horizontal flows occurring inside the unsaturated soil profile. The total amount of outflow from the LPS ($LPS_{outflow}$, mm d^{-1}) is calculated by a nonlinear relationship taking the relative saturation of the storage into account:

$$LPS_{outflow} = actLPS * \Theta_{LPS}^{LPSout} \tag{1}$$

where actLPS = the actual LPS storage content, Θ_{LPS} = the LPS water saturation, and LPS_{out} = a user-defined calibration parameter. The total amount of outflow is then distributed to horizontal (interflow) and vertical (percolation) components, with the contribution to each of the components calculated by taking geomorphological (e.g., slope) as well as pedological (e.g., hydraulic conductivities, thickness of soil horizons) parameters into account.

The groundwater domain is conceptualized by two storages, RG1 and RG2, for each HRU. RG1 represents the water movement in the shallower withering zone of the bedrock and RG2 represents the water movement in the deeper aquifer and/or in fractures and is synonymous with baseflow (Figure 2). The water input (i.e., percolation) into the groundwater module from the LPS is distributed among the two storages based on slope and a calibration parameter. Outflow from the two RG storages is calculated from the actual storage content, a recession coefficient, and another calibration parameter. After calculation of the runoff generation processes, runoff concentration is computed based on topological interconnections of the single HRU polygons, i.e., each of the four runoff components generated on single HRU polygons 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). The flood routing inside the stream network is simulated by connecting the reach storages, receiving the water from the topologically connected HRUs by a hierarchical storage cascade and calculation of the flow velocity inside the stream bed with the Manning-Strickler equation. The outflow of the specific stream reach is transferred as inflow to the downstream reach.

MATERIALS AND METHODS

Study Area

The Cedar Creek Watershed (CCW) is located within the St. Joseph River Basin in northeastern Indiana ($41^{o}10'10''$ to $41^{o}32'38''$ N and $84^{o}53'49''$ to $85^{o}19'44''$W) and covers Noble, DeKalb, and Allen Counties. 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 average land surface slope of the watershed is 2.6%, and the predominant soil textures are silt loam, silty clay loam, and clay loam. The annual mean precipitation in the watershed area from 1989 to 2005 was 962 mm. The watershed is mainly used for farmland and livestock production, and is characterized by a high percentage of rotationally-tilled agricultural row crops (48.9%, which mainly consists of corn, soybean and winter wheat including 5.3% fallow).

Cedar Creek Watershed Soil Types and Land Use

In the CCW, six STATSGO soil associations are represented. STATSGO polygon IN004 (52.9% of the watershed area) is dominated by the Crosby and Treaty soil series, Blount-Glynwood-Morley; STATSGO polygon IN005 (26.7%) is comprised primarily of the Crosby and Cyclone soil series, Blount-Pewamo-Glynwood; STATSGO polygon IN025 (7.9%) is dominated by Sebewa-Gilford-Homer; IN016 (6.9%) is dominated by Miami-Wawasee-Crosier; IN019 (3.6%) is comprised of Houghton-Adrian-Carlisle; and IN028 (2.0%) is comprised of Martinsville-Whitaker-Rensselaer. For this study, a land use map from the National Agricultural Statistics Survey (NASS) was used. The NASS land use map is a raster, geo-referenced, categorized land use data layer produced using satellite imagery from the Thematic Mapper (TM) instrument on Landsat 5 and the Enhanced Thematic Mapper (ETM+) on Landsat 7. The land use data was 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. The remotely sensed land use data is used to produce a GIS data layer that is interfaced with OMS-J2K as model input.

HRU Delineation and Model Parameterization

Both standard ArcGIS 9.2 (ESRI, 2008) geoprocessing tools (e.g., overlay) and customized scripts for deriving HRU flow connectivity were used for HRU delineation. The delineation was based on GIS layers derived from digital elevation model (DEM) data and the STATSGO soil type and reclassified NASS land use maps as described above. 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 DEM was projected to Universal Transverse Mercator (UTM) NAD83, Zone 16 north for the state of Indiana. For final HRU delineation, the DEM topographical parameters (e.g., elevation, slope, aspect) were partly reclassified and combined (by overlay analysis in ArcGIS 9.2) with the STATSGO soil and NASS land use GIS layers. The resulting unique polygons were then aggregated (based on their attribute set and neighborhood proximity) to reduce the overall number of spatial HRU entities. The delineation of HRUs for the entire Cedar Creek Watershed resulted in 4,174 HRU polygons featuring areas between 0.02 to 2.5 km^2. A script for the topological routing scheme was derived in ArcGIS 9.2 for the simulation of lateral runoff generation processes, which determines the watershed spatial connections (e.g., HRU to HRU and HRU to stream reach). Figure 3 shows the stream channels and HRU polygons of the Cedar Creek Watershed, together with topological connections as red arrows draped over the HRU polygons. From Figure 3, the dynamic spatially distributed character of the OMS-J2K HRU flow routing approach that separates this model from other watershed models (e.g., SWAT) becomes apparent.

The OMS-J2K 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 Cedar Creek Watershed. Regionalization pre-processors in OMS-J2K 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 to watersheds in Germany and elsewhere exhibiting physical characteristics (e.g., topography, size, and agricultural land use) very similar to the CCW. Since the J2K model has not previously been applied in the United States, the initial parameter values represent an attempt at establishing a reasonable input parameter set without resorting to a detailed calibration procedure.

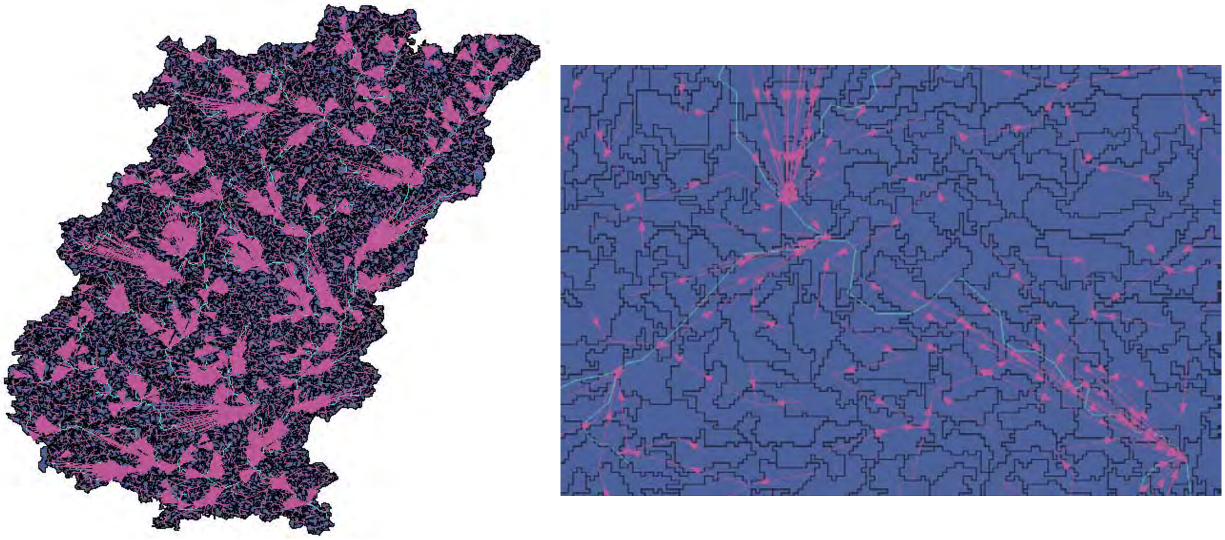

Figure 3 Routing topology with overland flow routing vectors for the Cedar Creek Watershed including an expanded view of flow routing vectors with HRU and stream channel flow linkages.

OMS-J2K Model Statistical Evaluation

Two evaluation criteria were used to assess daily and average monthly stream flow simulated by OMS-J2K. The criteria are quantitative statistics that measure the agreement between simulated and observed values. The 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. The E_{NS} and PBIAS statistics are defined as:

$$E_{NS} = 1 - \frac{\sum_{i=1}^{n} \left(\mathrm{O_i} - \mathrm{P_i}\right)}{\sum_{i=1}^{n} \left(\mathrm{O_i} - \overline{\mathrm{O}}\right)^2} \tag{2}$$

$$\mathrm{PBIAS} = \frac{\sum_{i=1}^{n} \left(\mathrm{P_i} - \mathrm{O_i}\right) * 100.0}{\sum_{i=1}^{n} \mathrm{O_i}} \tag{3}$$

where P_i is the ith value of stream flow ($m^3\ s^{-1}$) predicted by the OMS-J2K model, O_i is the ith observed value of stream flow ($m^3\ s^{-1}$), $\overline{O}$ is the average observed stream flow during the simulation period ($m^3 s^{-1}$), and n is the number of observations. E_{NS} indicates how well the plot of observed versus simulated values fits a 1:1 line; E_{NS} values were computed for both daily and average monthly streamflow. 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. The PBIAS evaluation statistic has been presented by Gupta et al. (1999) and others in the literature with a positive value indicating a bias toward underestimation and a negative value indicating a model bias toward overestimation. However, we find this to be counterintuitive which explains the different form of Eq. 3 presented herein.

RESULTS AND DISCUSSION

Results

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 OMS-J2K noncalibrated stream flow. The stream flow data obtained from the USGS is composed of baseflow and surface runoff, therefore no baseflow filter program was applied to the OMS-J2K stream flow predictions. Daily observed and OMS-J2K simulated stream flow from January, 1997 to December, 1997 and January, 2000 to December, 2000 are presented in Figures 4 and 5, respectively.

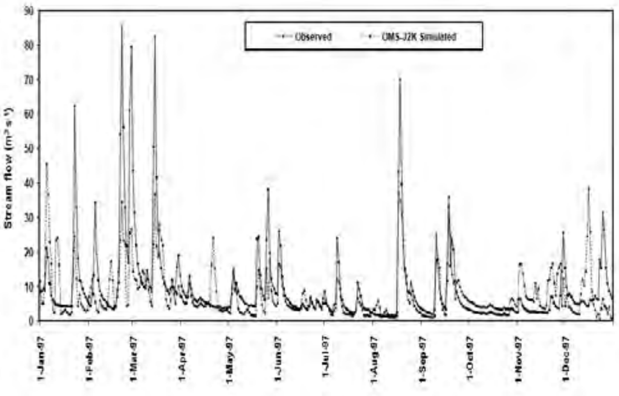

Figure 4 Daily CCW stream flow for observed and OMS-J2K initial parameter set simulated values (Jan. 1997 to Dec. 1997).

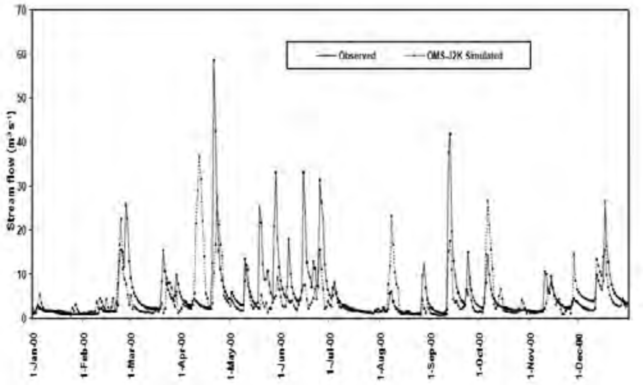

Figure 5 Daily CCW stream flow for observed and OMS-J2K initial parameter set simulated values (Jan. 2000 to Dec. 2000).

These graphs serve as a 1-year subset of results from the 9-year simulation period, and represent the highest (1997) and lowest (2000) annual average stream flow years for the CCW. For initial uncalibrated conditions, overall model performance on a daily time-step was average; however, the trend in stream flow appeared to be captured correctly. There were significant overestimations by the OMS-J2K model on some days compared to the measured data - these may be due in part to having rainfall input data for only two weather stations in the CCW. In general, the OMS-J2K model underestimated stream flow on a daily time-step as shown in the 1:1 plot in Figure 6 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

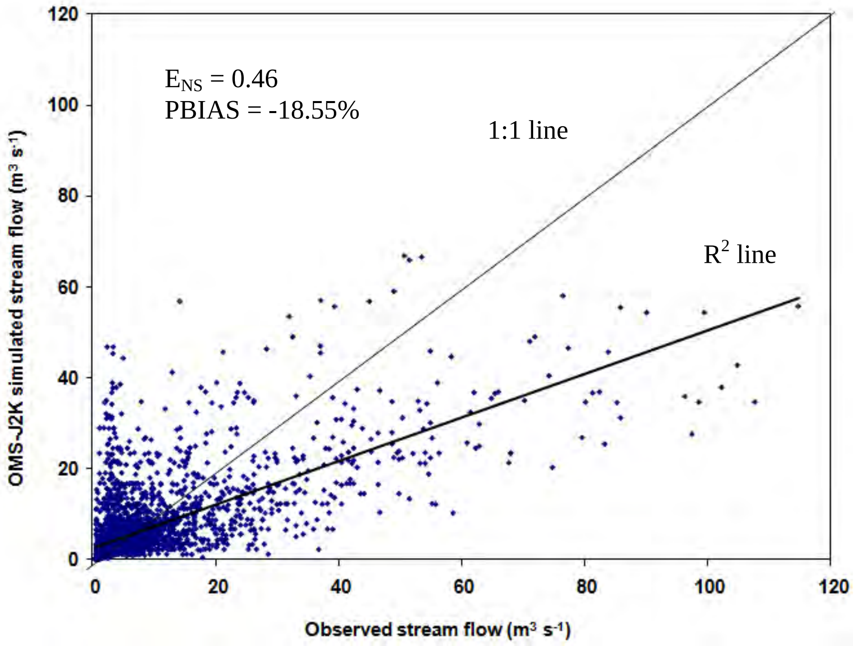

Figure 6 Daily Cedar Creek Watershed stream flow 1:1 plot of OMS-J2K initial parameter set simulated values versus observed (Jan. 1997 to Dec. 2005).

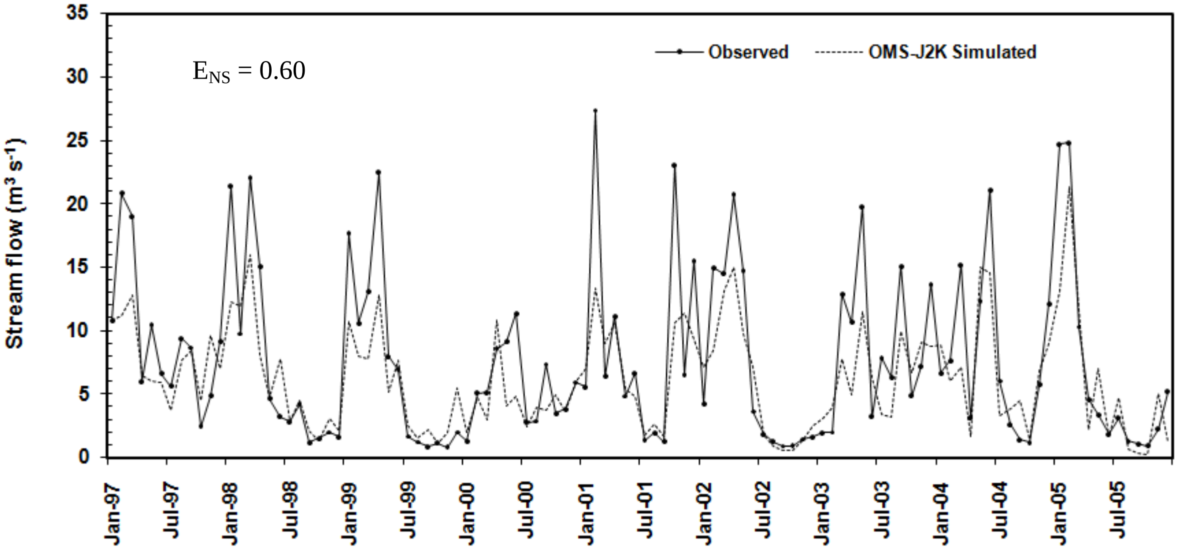

Figure 7 Monthly Cedar Creek Watershed stream flow for observed and OMS-J2K initial parameter set simulated values (Jan. 1997 to Dec. 2005).

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%). Average monthly observed and J2K simulated stream flow from January, 1997 to December, 2005 are presented in Figure 7. 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 7 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 across all time scales. Land use on the CCW is quite diverse, furthermore, the simplistic representation of evapotranspiration dynamics in OMS-J2K 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 OMS-J2K 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 OMS-J2K 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 OMS-J2K model still underestimated stream flow on a daily time-step (as shown in the 1:1 plot in Figure 8). 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 J2K simulated stream flow from January, 1997 to December, 2005 for the modified parameter set are shown in Figure 9.

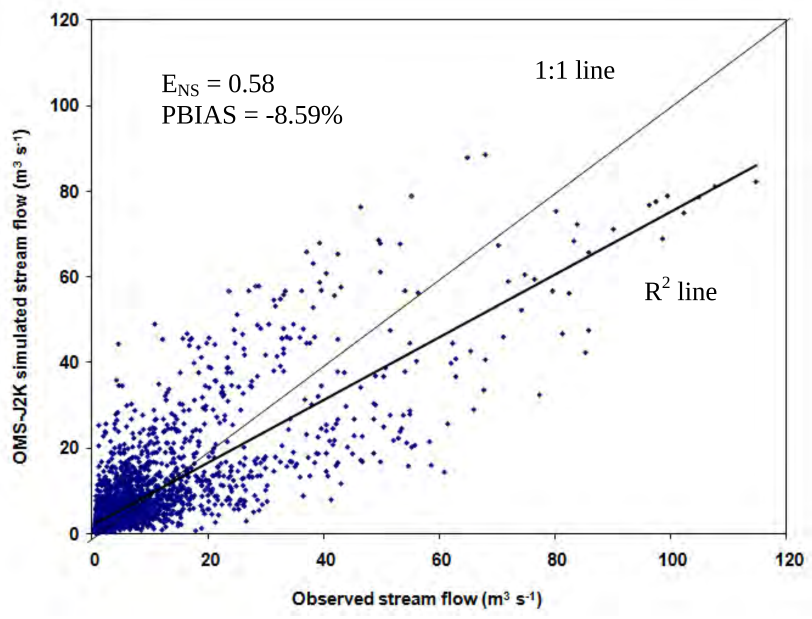

Figure 8 Daily Cedar Creek Watershed stream flow 1:1 plot of OMS-J2K modified parameter set simulated values versus observed (Jan. 1997 to Dec. 2005).

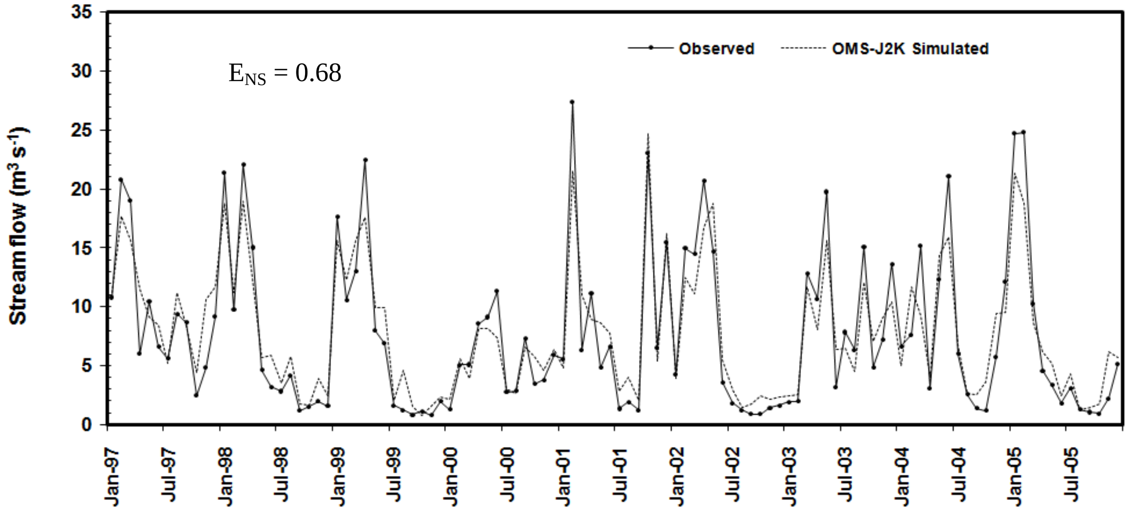

Figure 9 Monthly Cedar Creek Watershed stream flow for observed and OMS-J2K modified parameter set simulated values (Jan. 1997 to Dec. 2005).

This figure shows 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 7.

Discussion

The range of relative error (e.g., PBIAS) and E_{NS} values for uncalibrated daily stream flow predictions in this study (for both parameter sets) are similar or better than others reported in the literature for various watershed models. There is a considerable collection of literature that demonstrates the use of the SWAT model in effectively modeling monthly stream flow (e.g., Van Liew and Garbrecht, 2003; Di Luzio et al., 2005; White and Chaubey, 2005; Wang and Melesse, 2006; Gassman et al., 2007; Larose et al., 2007). The statistical analysis results reported in this study for uncalibrated daily (PBIAS = -18.55% and -8.59%; E_{NS} = 0.46 and 0.58 for the initial and modified parameter sets, respectively) and average monthly (E_{NS} = 0.60 and 0.68) stream flow predictions fall within the range of those found throughout the literature. For the SWAT model, Van Liew and Garbrecht (2003) reported uncalibrated daily stream flow E_{NS} values as low as -3.24 that were improved with calibration to values as high as 0.60 for the Little Washita River watershed in Oklahoma. Van Liew and Garbrecht (2003) also showed that the SWAT model underestimated average annual stream flow by 18.4% using default values for model parameters affecting stream flow prediction. On a year-by-year basis, SWAT underestimated one year by as much as 98.4% while overestimating another year by 156.9%. Larose et al. (2007) and Heathman et al. (2009) used the SWAT model to estimate daily, average monthly, and average annual stream flow for the Cedar Creek watershed. Larose et al. (2007) reported E_{NS} coefficients for daily and monthly stream flow calibration and validation ranging from 0.51 to 0.66, respectively. Heathman et al. (2009) reported best model performance values of E_{NS} = 0.58, R^2 = 0.66, and PBIAS = 21.93% for uncalibrated monthly stream flow predictions.

Even with stream flow prediction improvements using the modified parameter set, OMS-J2K 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 (RG1 and RG2). Other studies (e.g., Krause, 2002) have shown the J2K model to be particularly sensitive to the recession coefficients (used for final calculation of RG1 and RG2). 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 OMS-J2K. 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. In summary, we chose to evaluate noncalibrated stream flow results considering that OMS-J2K was developed for applications on ungaged 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 (i.e., RD1, RD2, RG1, and RG2) on the simulated stream flow results.

CONCLUSIONS

The long-term continuous hydrologic simulations of OMS-J2K 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, OMS-J2K 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 parameter sets were within the satisfactory ranges as suggested by Moriasi et al. (2007). Furthermore, the range of E_{NS} and PBIAS values for uncalibrated daily stream flow predictions in this study using both parameter sets were similar or better than other evaluation results reported in the literature for various watershed models. It was unclear whether OMS-J2K 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 OMS-J2K 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 OMS-J2K (thus allowing the simulation of lateral processes important for the modeling of runoff concentration dynamics) is much more robust than quasi-distributed routing schemes used by other watershed scale natural resource models (e.g., SWAT). The largest advantage of the OMS-J2K routing approach is a process-oriented view of spatial watershed characteristics that drive hydrological behavior. With a fully-distributed routing concept, 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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