K2-O2 (KINEROS-Opus) SPATIALLY BASED WATERSHED HYDROLOGIC AND BIOGEOCHEMICAL MODEL

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Abstract Recently a new combined hydrologic and biogeochemical model has been developed. K2-O2 is a comprehensive, spatially-distributed watershed model designed to simulate the hydrologic and biogeochemical processes of small- to medium-sized watersheds. K2-O2 is a combination of KINEROS2, an event-based Kinematic Runoff and Erosion Model, and Opus2, a time-continuous soil moisture and nutrient cycling model. K2-O2 is able to simulate long-term effects due to hydrologic changes and watershed management practices allowing for prediction future ecosystem behaviors. The range of simulations that can be carried out by K2-O2 include: runoff, sediment transport, nutrient cycling (nitrogen, phosphorus and carbon), water quality and chemical runoff. K2-O2 is undergoing rigorous testing using data from two hydrologically distinct watersheds verification and validation: the USDA-ARS (United States Department of Agriculture-Agricultural Research Service) Watkinsville Experimental Watershed P-3 catchment in Watkinsville Georgia and the USDA-ARS Walnut Gulch Experimental Watershed Lucky Hills 104 catchment located near Tombstone, Arizona. P-3 is a cultivated agricultural catchment characterized by a humid sub-tropical climate that experiences a range of management practices. The LH-104 is a natural catchment characterized by a semi-arid desert climate and dominated by desert shrubs. Verification of water, nitrogen and phosphorus submodels were conducted using mass balance calculations. Validation of the hydrologic submodel was conducted using field data measured at each watershed. K2-O2 produced reasonable simulations of the hydrology and nutrient cycling. K2-O2 will continue to undergo testing, verification and validation of hydrologic and biogeochemical submodels with observations from these and other experimental watersheds. K2-O2 will provide watershed managers and natural resource planners with a tool to assess the spatial distribution of hydrological and biogeochemical processes for present and future management of watersheds.

INTRODUCTION

K2-O2 is a spatially-distributed, continuous, hydrologic and biogeochemical simulation model for small to medium sized watersheds. K2-O2 is a combination of KINEROS2, an event-based Kinematic Runoff and Erosion Model (Smith et al., 1995; Semmens et al., 2008), and Opus2, a continuous soil moisture, plant growth, and nutrient cycling model (Smith, 1992). Opus2 contains an adaption of the Century model (Metherall, 1993; Parton, et.al., 1988), which describes the exchange of nutrients (carbon, nitrogen and phosphorus) between atmosphere, plants, soil and microbes. Additionally, the model describes the movement of nitrogen in runoff and erosion, seepage and leaching of plant/crop residue into the soil. K2-O2 can simulate a number of processes including runoff, sediment transport, nutrient cycling (nitrogen, phosphorus and carbon), water quality and chemical runoff. K2-O2 also models the movement of water, chemicals and nutrients through the soil profile (Smith, 1992). K2-O2 is able to simulate long-term and inter-storm processes which allow for predicting future ecosystem behaviors. User-defined management actions allow the model to be applied to a wide variety of study objectives, such as effects of different agriculture management practices on non-point source pollution and water quality, or long-term continuous simulations of hydrological and biogeochemical processes.

The objective of this paper is to examine the validity of K2-O2 for use as a watershed management tool. K2-O2 has been undergoing rigorous verification and validation of the hydrology and nutrient cycling components (nitrogen and phosphorus) using data from two watersheds that are distinctly different in their hydrology, biogeochemistry and management. If the validation analysis determines that the logical, mathematical and causal relationships are "reasonable" (Sargent, 2005), then K2-O2 should provide useful simulations of watershed response on which to base current and future management decisions.

METHODS

All model simulation results presented herein involve no calibration of model parameters.

Model Description K2-O2 was designed to allow users to study the movement of water, nutrients and pollutants within small watersheds in response different management and weather inputs (Smith, 1992). K2-O2 uses the spatial watershed subdivision methods of KINEROS2 (Smith et al., 1995; Semmens et al., 2008; www.tucson.ars.ag.gov/kineros) and the time-continuous process algorithms of Opus2 (Müller et al., 2003; http://eco.wiz.uni-kassel.de/model_db/mdb/opus.html). K2-O2 is intended to enable the simulation of complex catchments composed of up to thousands of hectares, while allowing the user to specify spatial variations in slope, plant communities, soil type, and channel characteristics through individual response elements, in the manner of KINEROS2 (K2). Unlike K2, in which only a single storm event can be simulated, K2-O2 allows continuous simulation through as many days or years as are of interest, including simulation of the growth and senescence of plants, changes at the surface due to management (optional), and seasonal changes in climate. K2-O2 allows users to apply different management actions, such as tillage and application of manure, fertilizer and chemicals to the watershed of interest. Tillage actions include planting, harvesting and soil plowing, among others. Different combinations of management actions can be employed, if appropriate, during simulations. The model monitors the soil profile and traces the flow of water, chemicals and nutrients through the soil. K2-O2 allows a user to apply the model to a wide variety of study objectives. Documentation and a user manual are in preparation.

Site Descriptions The data used for initial verification and validation of K2-O2 were collected from two different USDA-ARS watersheds. The USDA-ARS Watkinsville Experimental Watershed P-3 (1.26 hectares) is located in Watkinsville, Georgia and is characterized by a humid subtropical climate (Figure 1) (Smith et al, 1978). P-3 is dominated by the Cecil soil series with textures ranging from sandy to sandy clay loam and a uniform slope of 3% over the entire catchment (Smith et al, 1978). P-3 is a cultivated field undergoing complicated management actions (Smith et al, 1978). During the simulation period, the three-year crop rotation consisted of 11 different management actions, two fertilizations and three crop plantings (Table 1).

USDA-ARS Walnut Gulch Experimental Watershed (WGEW) Lucky Hills 104 (LH-104), a 4.4 hectare subwatershed is located near Tombstone, Arizona (Figure 2). LH-104 is characterized by a semiarid desert environment and dominated by desert shrubs such as creosote (*Larrea tridentata*) and white-thorn (*Acacia constricta*) with sparse perennial and annual grasses (Nearing et al, 2005). LH-104 is dominated by the Luckyhills-McNeal soil series (coarse-loamy, mixed, Ustochreptic Calciorthids) with a gravelly sandy loam texture and slopes ranging from 1 to 3% (Nearing et al, 2005). This catchment is uncultivated and no management actions were performed over the course of the simulation period.

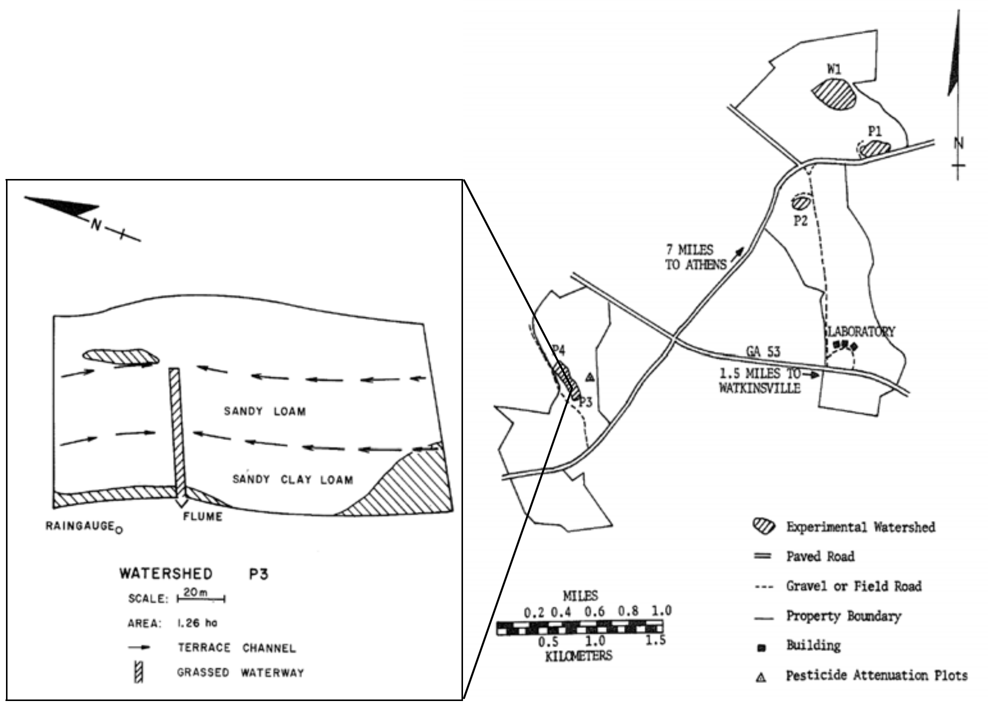


Figure 1. Locations of experimental watersheds, Southern Piedmont Conservation Research Center, Watkinsville, Georgia. Soils and terrace configuration for the P-3 Catchment. (Smith et al, 1978).

Input Data K2-O2's major simulation components are weather, hydrology, soils, nutrient cycling, plant growth, fertilizers and chemicals. Input files consist of meteorological, precipitation, parameter and management files. When input files are created, catchments are abstracted into elemental planes. Elemental planes are created based on the geometry and flow paths of the catchment. Data used for the input files were collected from various sources such as STATSGO (State Soil Survey Geographic Database), SSURGO (Soil Survey Geographic Database), NCDC (National Climate Data Center), USDA-ARS (United States Department of Agriculture-Agricultural Research Service) Tucson DAP database and EPA (Environmental Protection Agency) documents (Goodrich et al, 2008; Keefer et al, 2008; NCDC, 2008; Nichols et al, 2008; Smith et al, 1978; Soil Survey Staff, 2008; Stone et al, 2008). Parameters in which data were unavailable were estimated or defaulted by K2-O2.

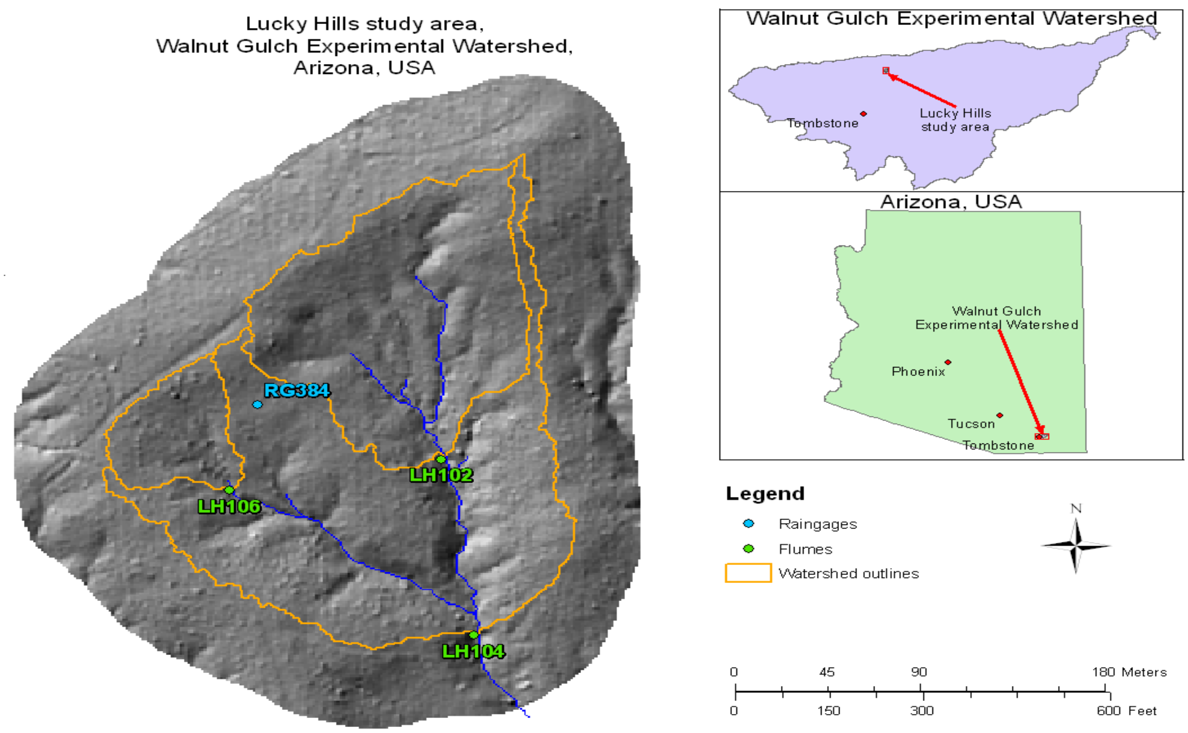


Figure 2. Map of subwatershed LH-104 in the Walnut Gulch Experimental Watershed, Tombstone, Arizona (Burns et al, 2010).

Simulation K2-O2 can simulate continuously in daily, monthly or yearly time steps for hydrology, soil, nutrients, chemicals, plant growth and management applications. P-3 and LH-104 simulations were conducted for different time intervals. P-3 was simulated for three-years from 1973 to 1975 and LH-104 was simulated for an eight year period from 1999 to 2007.

Model Evaluation The model performance of K2-O2 was evaluated using verification of mass balance and validation by comparing simulation with an uncalibrated parameter set versus measured output.

Verification Calculating mass balance the Δ Storage = Inputs – Outputs. Because the model employs many numerical solutions to differential equations, some numerical error is always present. Mass balance was verified for hydrology, nitrogen, and phosphorus. Percent error was calculated using either total rainfall (hydrology) or total nitrogen/phosphorus (nutrients). Model debugging and refinement continued until the mass balance verification was within approximately 1%.

Validation Validation involved comparing measured runoff to simulated runoff. A simple t-test was used to determine the statistical similarity between linear regression slopes of simulated and measured data and a 1:1 slope. A level of α = 0.05 (95% confidence interval) was used in the statistical analyses.

Table 1. Agricultural management actions for Watkinsville P-3 catchment.

Date		Management Actions
1973	April 12	Harvest Winter Barley
	May 22	Fertilizer (rate = 105.3 kg/ha), Disk Harrow
	June 4	Fertilizer (rate = 124.3 kg/ha), Rolling Cultivator
	June 14	Trifluralin (rate = 1.12 kg/ha), Diphenamid (rate = 3.36 kg/ha), Paraquat (rate = 1.53 kg/ha)
	June 15	Plant Soybean
	October 5	Plant Winter Rye
	November 7	Harvest Soybean
1974	January 14	Winter Rye replanted with grain drill
	May 1	Harvest Winter Rye
	May 22	Fertilizer (rate = 85.12 kg/ha), Disk Harrow
	May 28	Rolling Cultivator
	May 29	Triflualin (rate = 1.12 kg/ha), Diphenamid (rate = 3.36), Paraquat (rate = 1.53)
	May 30	Plant Soybean
	June 13	Rolling Cultivator
	July 5	Rolling Cultivator
	October 18	Harvest Soybean
	October 22	Disk harrow, Plant Barley
1975	April 15	Harvest Barley
	May 8	Fertilizer (rate = 15.01 kg/ha)
	May 13	Disk Harrow
	May 27	Triflualin (rate = 1.12 kg/ha), Diphenamid (rate = 3.36), Paraquat (rate = 1.53)
	May 28	Plant Soybean
	June 16	Sweep Cultivator
	July 9	Sweep Cultivator
	Nov 5	Harvest Soybean

RESULTS AND DISCUSSION

Verification ***Hydrology*** Verification affirms the model's level of accuracy and its capability in representing the spatial distribution of hydrologic response and the cycling of N and P. Both data sets used for verification consisted of observed inputs, initial states and simulation output data with no calibration or adjustment of initial or default model parameters.

Mass balance errors were small for the simulations examined. Over the simulation period, verification of hydrology for both P-3 and LH-104 catchments was judged as relatively good with 1% or smaller balance error for each model element on an annual basis (data not shown). Due to limited data, the P-3 catchment verification was only calculated for three years (1973-1975). Conservation of mass over the long-term LH-104 simulation showed good accuracy. Depending on the amount of rainfall, evapotranspiration, runoff, runon and seepage, the balance errors showed either a slight cumulative overestimation or underestimation when examined through time. Due to higher evapotranspiration demands and low precipitation in the semiarid environment of LH-104, the program generally slightly underestimated the amount of runoff. Again because the model employs many numerical solutions to differential equations, some error is always to be expected.

Nutrients Nitrogen (N) and phosphorus (P) simulations showed slightly higher balance errors than hydrology. Due to the number of days during the each simulation and for the purpose of clarity, these calculations are not shown.

LH-104 resulted in relatively good verification with daily N and P balance errors less than 1%. However, the initial mass balance errors at or near the start of the simulation were slightly larger at 3% due to poor initial estimates of total nitrogen and phosphorus.

The P-3 catchment simulations had daily N and P balance errors below 1%. The monthly balance errors range from approximately 6% to 1%, with errors below 3% being indicators of a good mass balance. Two of the 24 months were found to be above 3%, and the P-3 catchment had the largest monthly N error (6.84%), occurring in the 1974. The catchment experienced 6-10 management operations per year during the three year simulation. Management actions increased the complexity of processes within a watershed. Added management actions may explain the higher N error due to pulsing, i.e. the nearly instantaneous nature of many management effects and fertilizer or chemical applications. However, the goal for continued testing and model development is to decrease the error to less than 1%.

Validation ***Hydrology*** Validation simulations for LH-104 estimated runoff and sediment yield reasonably well. Figure 3 shows observed versus simulated daily runoff volumes (per unit area) when events occurred (days of zero observed runoff were excluded). The slope of the linear regression (slope = 0.9213, R^2=0.64) indicates a strong correlation between the simulated and observed runoff data. We failed to reject the null hypothesis when performing a t-test (α = 0.05) and concluded that the slope of the regression line is statistically similar to one. Thus, the uncalibrated model simulates daily event runoff volumes for LH-104 reasonably well.

Validation of the hydrology for LH-104 was further explored by plotting long-term runoff data. Figure 4 shows a continuous simulation of LH-104 catchment for measured versus simulated daily runoff from 1999 to 2007. The two graphs depict K2-O2's ability to model similar runoff trends as measured at LH-104. However, during 2006 and 2007, K2-O2 did somewhat overestimate the amount of runoff, but still showed a similar trend in peaks.

Sediment yield is a more difficult quantity to estimate. Figure 5 plots the sediment yield for LH-104 from 1999 to 2007. K2-O2 simulated a similar trend as the measured sediment yield. However, with the erosion parameters chosen, K2-O2 tended to underestimate the sediment yield for a majority of sediment events. Validation and testing of sediment yield will continue in an attempt to improve the accuracy of K2-O2's ability to accurately predict sediment yield.

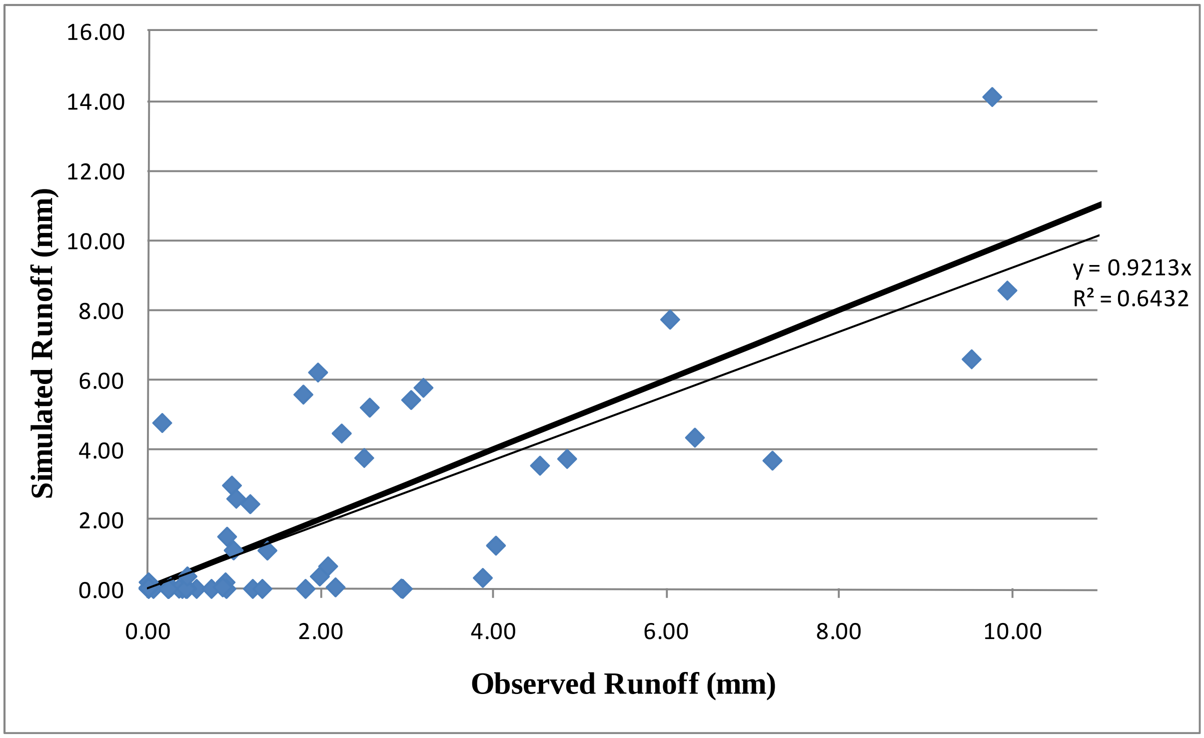
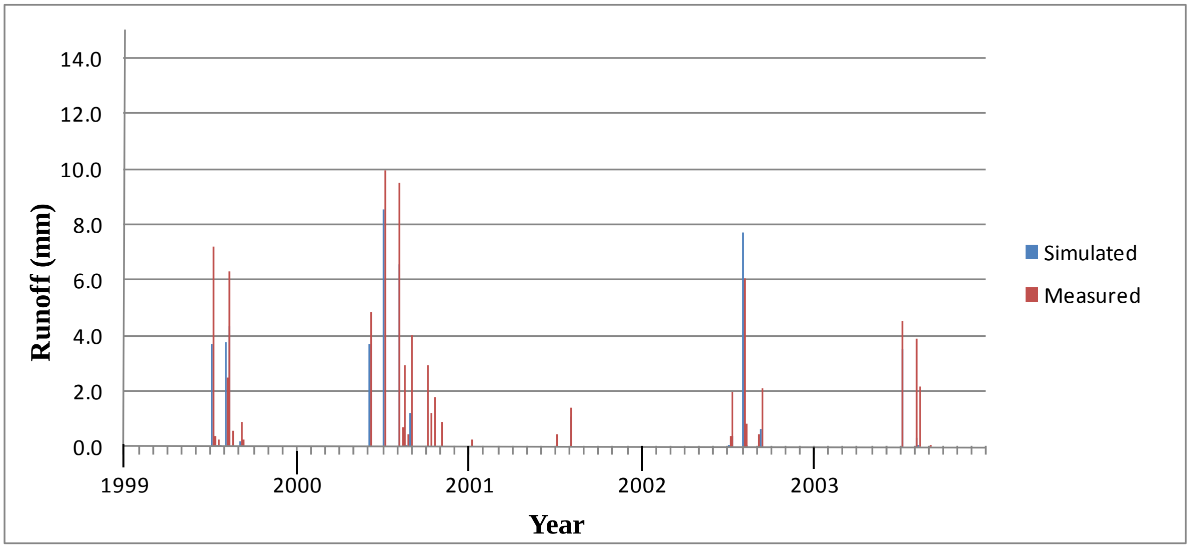


Figure 3. Simulated versus observed daily runoff (mm) during 1999-2007 for LH-104. Thick solid black line denotes the 1:1 line, while the thin black line denotes the linear regression line.

The P-3 catchment incorporates management actions, creating a more complicated watershed to simulate. Simulation of the P-3 catchment illustrated K2-O2 was able to reasonably estimate daily runoff. Figure 6 illustrates observed versus simulated daily runoff volumes (per unit area) when events occurred (days of zero observed runoff were excluded). Figure 6 shows a tendancy for the model to overestimate runoff when the daily runoff is close to zero and is mixed for larger events (slope =0.7156, R^2=0.51). When performing a t-test of the slopes (α = 0.05), we rejected the null hypothesis of statistical similar slopes between the regression and 1:1 line.

When comparing simulated versus measured runoff over a continuous scale, the model tended to overestimate runoff, especially during 1974 and in late 1975. Figure 7 illustrates some instances in which K2-O2 does simulate runoff during times in which runoff was not measured.

Validation of hydrology and sediment yield further illustrated that K2-O2 is generally able to model the primary hydrologic processes of these catchments. Simulated hydrographs and sediment yields were in fair agreement with the measured data. However, additional validation is required for nitrogen, phosphorus and other model components over a wider range of conditions.



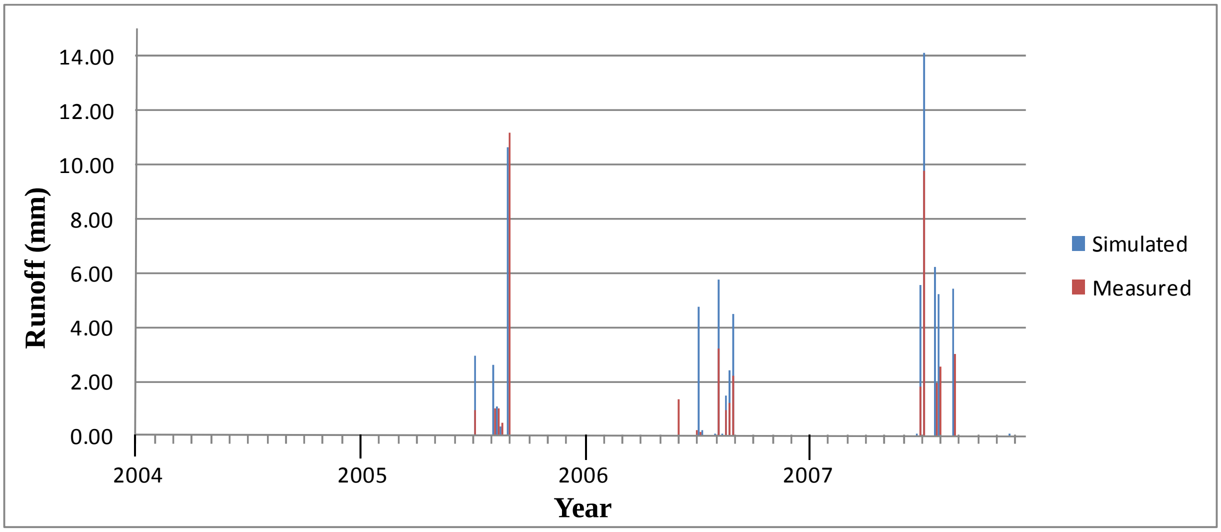
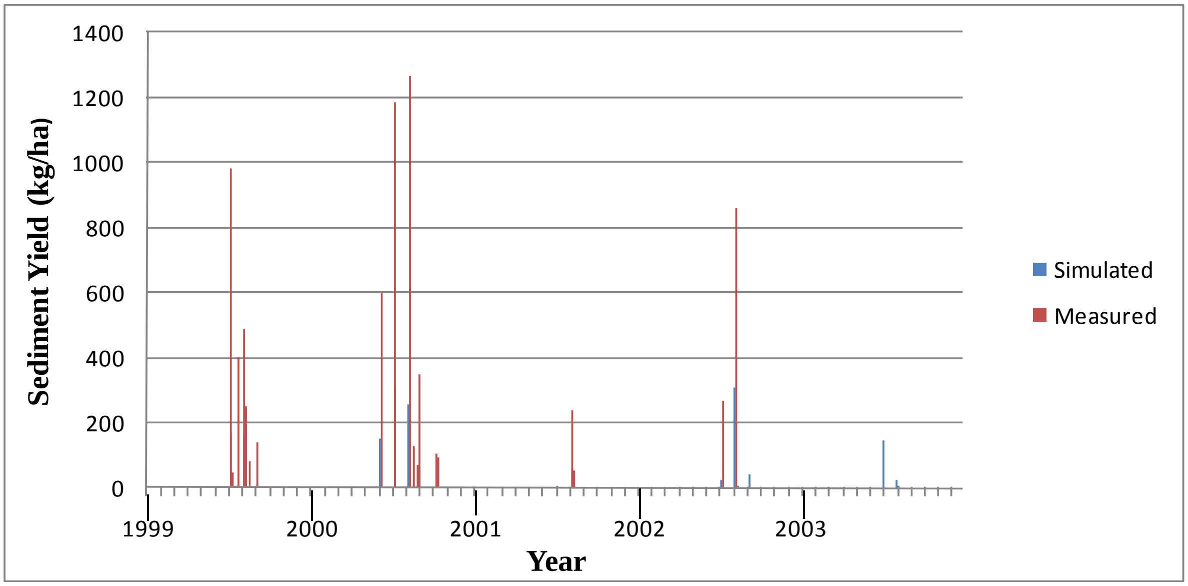


Figure 4. Daily runoff (mm) from 1999-2007 for LH-104.



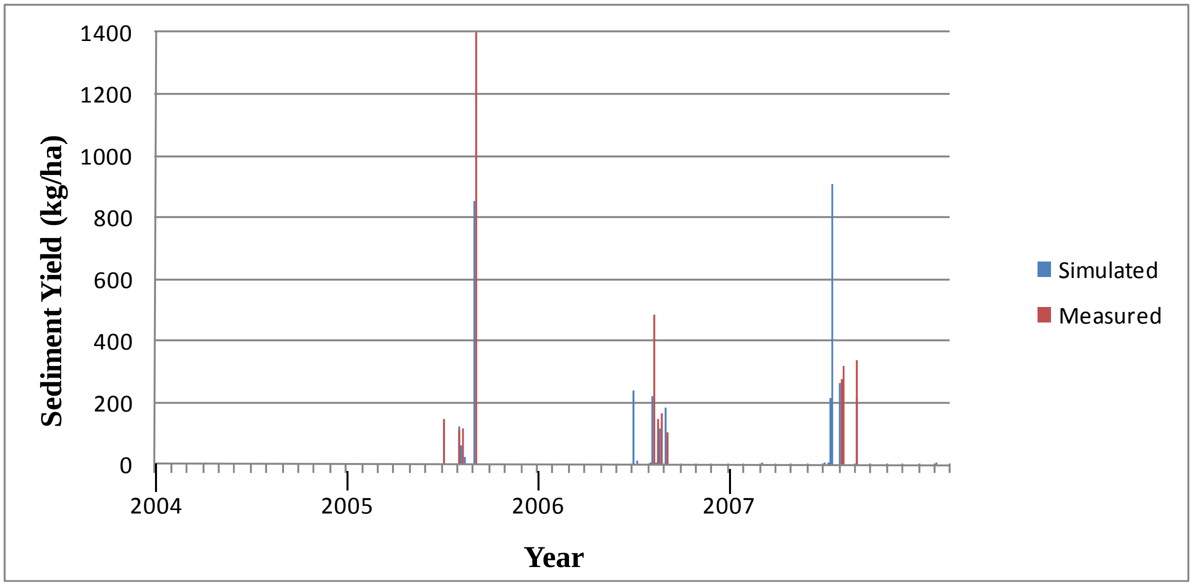


Figure 5. Daily sediment yield (kg/ha) from 1999-2007 for LH-104.

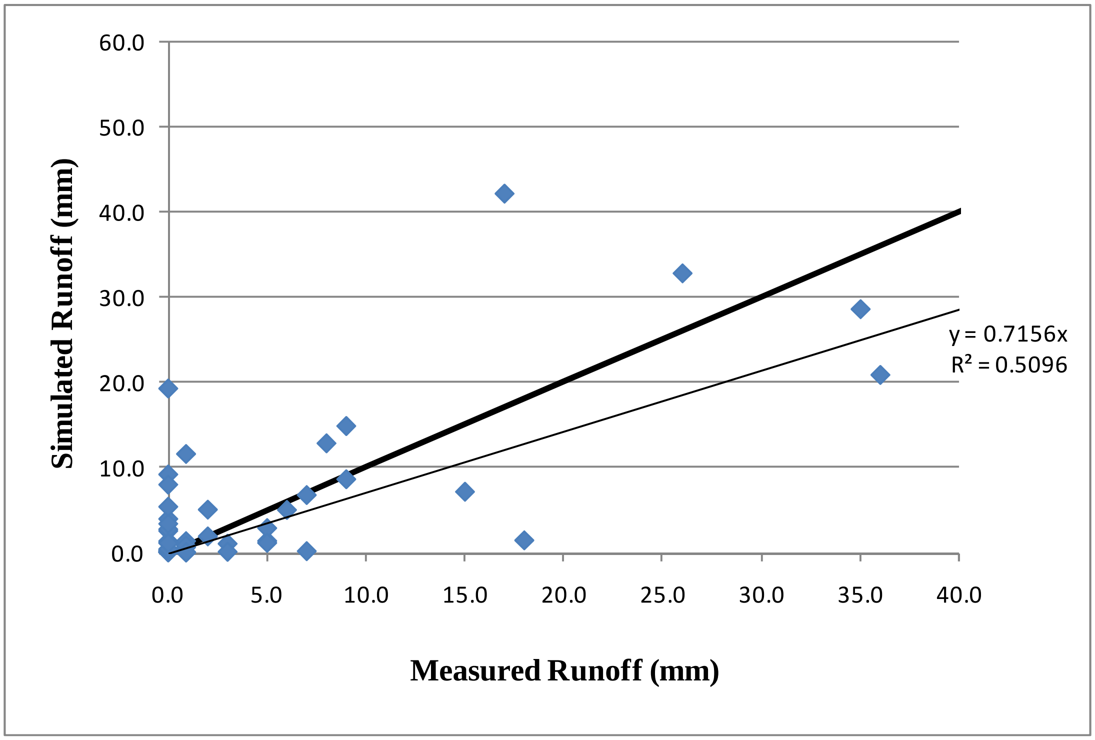


Figure 6. Simulated versus daily runoff (mm) for the P-3 catchment from 1973-1975. Thick solid black line denotes the 1:1 line, while the thin black line denotes the linear regression line.

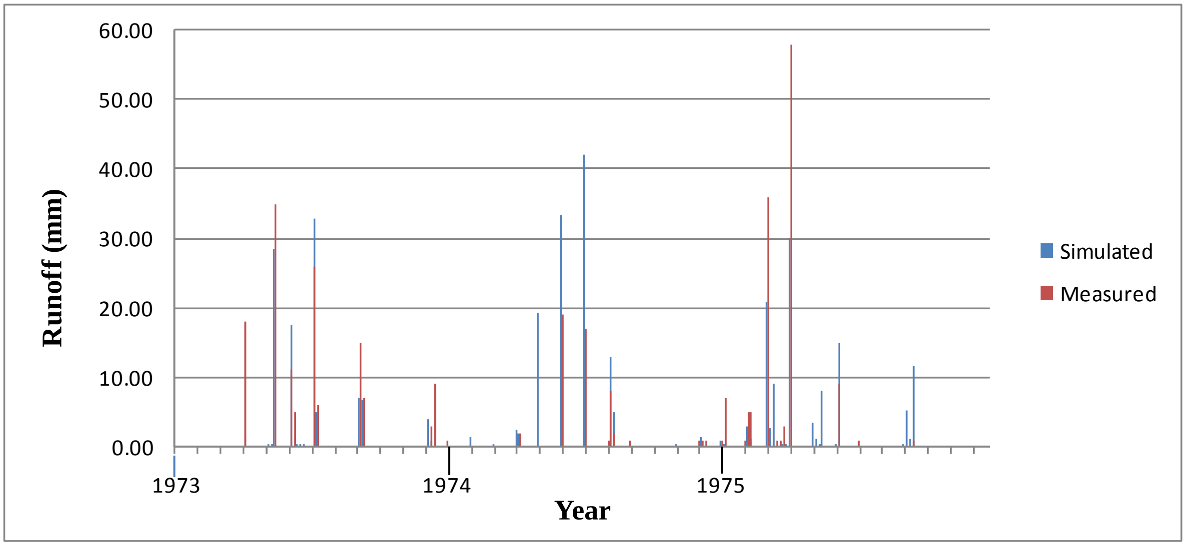


Figure 7. Daily runoff (mm) from 1973-1975 for the P-3 catchment.

CONCLUSION

K2-O2 has been shown to reasonably model hydrology and biogeochemical processes reasonably well without using calibration. When calibrated, the model should yield more accurate simulation results. Continued testing, verification and validation are needed to further evaluate the model for hydrologic and, biogeochemical processes and other model components on a variety of watersheds.

FUTURE RESEARCH

Targeted testing of additional model components will be undertaken, particularly for biogeochemistry and nutrient cycling. Testing in a snow-dominated catchment has also just been initiated. As K2-O2 has only been verified and validated using two watersheds (semiarid and subtropical humid), expanding the number of data sets will greatly increase the confidence in using K2-O2 as a watershed management tool.

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