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APEX SIMULATION: ENVIRONMENTAL BENEFITS OF AGROFORESTRY BUFFERS ON CORN-SOYBEAN WATERSHEDS

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ABSTRACT

The Agricultural Policy Environmental Extender (APEX) model has the ability to simulate the effects of vegetative filter strips on runoff and pollutant loadings from agricultural watersheds. The objectives of this study were to calibrate and validate the APEX model for three adjacent watersheds and determine optimum buffer dimensions and placement locations. ArcAPEX and APEX0604 versions were used for the simulations. The simulated corn and soybean yields were within ±13% and ±27% of the measured yields, respectively. The agroforestry, grass buffer, and control watershed models were calibrated (1998 to 2001) and validated (2002 to 2008) for event-based runoff with r^2 and Nash-Sutcliffe Coefficients (NSC) values of 0.7-0.8 and 0.4-0.8, respectively. The models could not be calibrated for sediment losses. The simulated grass and agroforestry buffers reduced average annual runoff by 5.2% and 4.3%, respectively. Increase of buffer widths to 5.5 m and 7.5 m were not effective. The buffers located on the backslopes were the most effective for the agroforestry watershed but this trend was not seen in the grass buffer watershed. The study provides guidance on how to parameterize APEX to simulate grass and agroforestry buffers. It contributes to the validation of APEX and will be useful to scientists in need of parameterizing the model for watersheds that include upland buffers.

Keywords: claypan soils, non-point source pollution, soil conservation, upland buffers, watershed modeling

INTRODUCTION

Agricultural practices have often been scrutinized for degradation of water quality in rivers, lakes and estuaries in the U.S. (USEPA 2013). Studies at various scales ranging from small plots, farms, fields, to watersheds are being conducted to evaluate conservation effects on non-point source pollution (NPSP; Mudgal *et al*. 2012; Udawatta *et al*. 2011a, 2011b). However, *In situ* studies at the watershed scale have inherent problems such as high costs due to their large scale and complex nature, private ownership of land and results not timely enough to avoid any negative consequences of current practices.

Hydrological models provide a convenient, efficient, and economically feasible method to evaluate NPSP losses provided sufficient measured data are available at the small watershed scale (Sharpley *et al.* 2003). Among many hydrological models, the Agricultural Policy Environmental eXtender (APEX) model has been widely tested and used to simulate farm level landscapes, cropping systems, and management practices such as filter-strips at both field and watershed scales (Gassman *et al.* 2010; Mudgal *et al.* 2012; Senaviratne *et al*. 2013).

Agroforestry practices have been shown to improve water and soil quality and reduce NPSP losses from agricultural land (Udawatta *et al.* 2002; Abu-Zreig *et al.* 2003). Upland contour buffers, riparian buffers and grass waterways are permanent areas of vegetation designed to remove NPSP from runoff (Dillaha *et al.* 1989). Research prove that 4-4.5 m buffer width as the optimum for 2-9% slopes (Robinson *et al.* 1996; Dillaha *et al.* 1989) and 7.5 m as the optimum buffer width for slopes around 6.5% (Schmitt *et al.* 1999).

The objective of the study was to evaluate environmental benefits of buffers through model simulation. Sub-objectives were to (1) calibrate and validate the APEX model for crop yields, runoff, and sediment for agroforestry, grass buffer and control watersheds, and (2) quantify NPSP reduction efficiencies by varying buffer widths and placement combinations.

MATERIALS AND METHODS

Watershed Characteristics

Three adjacent north-facing no-till corn-soybean (*Zea mays* L.- *Glycine max* (L.)) watersheds (East-1.65 ha, Center-4.44 ha, and West-3.16 ha; Fig. 1a) were established and instrumented in early 1991, at the University of Missouri Greenley Memorial Research Center in Knox County, Missouri, USA (40°01' N, 92°11' W). In 1997, after a 6-year calibration period, contour grass-legume strips (CGS; 4.5-m wide) of redtop (*Agrostis gigantean* Roth), brome grass (*Bromus spp*.), and birdsfoot trefoil (*Lotus corniculatus* L.) were established at 36.5-m (at lower slope positions 22.8 m) apart in the West and Center watersheds. Along the center of the grass strips of the Center watershed a tree line of pin oak (*Quercus palustris* Muenchh.), swamp white oak (*Q. bicolor* Willd.), and bur oak (*Q. macrocarpa* Michx.) were planted alternately at 3-m spacing to establish the agroforestry buffers (AGF). The East watershed was maintained as the control.

The grass waterway of each watershed consists mainly of fescue grass [*Schedonorus phoenix* (Scop.) Holub] and directs flow towards a concrete approach structure and an H-flume. For flow measurement and sampling, ISCO (Lincoln, NE, USA) bubbler flow meters and ISCO 3700 samplers were used. Runoff samples were analyzed for sediment (Udawatta *et al.* 2002, 2011b).

Simulating Watersheds with APEX

The AGF, CGS and Control watersheds were custom delineated (Fig. 1b) using ArcAPEX and ArcGIS 9.3 software. The digital elevation models (created from 25-cm contour survey maps), land use, and soil maps, management information (Udawatta *et al.* 2002, 2011b) and daily measured weather inputs of precipitation, maximum and minimum temperature, and solar radiation obtained from the Novelty weather station were used. Site specific soil data (claypan, texture, cation exchange capacity, organic carbon content, and pH) measured in 80 cores (~1-m deep) for the three watersheds were used to update the soils. The saturated hydraulic conductivity (Ksat), water content, and bulk density were obtained from Seobi *et al.* (2005).

The model options of soil moisture index (SMI) based on continuous curve number (CN) method (SCS 1985; Williams and LaSeur 1976) was selected for runoff estimation in which, the retention parameter, s, is estimated based on soil moisture depletion which is a function of potential evapotranspiration (Williams *et al.* 2012). The modified rational method (Williams 1995) of estimating peak runoff rate was selected for this study. The Hargreaves and Samani, (1985) method was selected to estimate potential evaporation. The MUSS equation (small watershed version; Williams 1995) for estimating soil erosion, which is a variant of the Modified Universal Soil Loss Equation (MUSLE; Williams 1975), was selected for this study. Crop land, buffers, and grass waterways were simulated using subarea parameters (Table 1).

The APEX model was calibrated using the most sensitive parameters reported by Senaviratne *et al.* (2013) for the pre-buffer watersheds and the APEX user manual *(*Williams *et al.* 2008). Storm events (14 events) from 1998 to 2001 were used for the calibration and those from 2002 to 2008 (21 events) were used for the validation of the model. The coefficients of determination *(*r^2), Nash Sutcliffe coefficient (NSC; Nash and Sutcliffe 1970) and percent bias (Pbias) were used to compare the model predictions against the measured outputs.

RESULTS AND DISCUSSION

Crop yields

The APEX model was calibrated and validated for corn and soybean yields with $r^2 > 0.80$ and NSC > 0.72 for AGF, CGS and Control watersheds except for the validation by the CGS watershed (r^2 0.68 and NSC 0.42; Table 2). Pbias values were within ±15% except for the validation. On the same watersheds, Senaviratne *et al.* (2013) reported crop yields within ±13% of the measured yields for the 1991-1997 period. Hu *et al.* (2007) calibrated corn and soybean yields to be within -10 to 6% of measured yield for Soil and Water Assessment Tool model and Mudgal *et al.* (2012) calibrated the APEX model for crop yields to be within ±9% of the measured yields. Proper calibration and validation of the model for crop yield is a requirement for proper simulation of the nutrient balances of the watersheds (Hu *et al.* 2007; Nair *et al.* 2011; *Mudgal et al.* 2012) and proper evaluation of management scenarios *(*Arnold *et al.* 2012).

Runoff

Figure 2 shows the APEX predicted and measured event-based runoff with the corresponding rainfall events of AGF (a), CGS (b) and Control (c) watersheds during the calibration and validation. APEX model was well calibrated and validated for event-based runoff of AGF, CGS and control watersheds with r^2 values ranging from 0.78 to 0.84 for calibration and 0.68 to 0.78 for validation (Table 2). NSC values ranged between 0.68 and 0.76 for calibration and 0.43 and 0.58 for validation for event-based runoff. Performance indicators for event-based runoff were better for the Control watershed than for the other two. Pbias values were within ±25% for calibrations and validations of the watersheds. Observed goodness of fit values were highly satisfactory as specified by Wang *et al.* (2012) for the APEX model. According to Wang *et al.* (2012) $r^2 \geq 0.6$, NSC ≥ 0.5, and Pbias within ±25% are satisfactory for monthly flow calibrations of the APEX model and could be further relaxed for daily or event-based simulations.

No study has calibrated and validated the APEX model for upland contour buffer strips in row-crop watersheds for event-based runoff with long-term data (10 years). Hence this study presents unique results obtained with the APEX model which has satisfactorily simulated the cropland, agroforestry and grass buffers, and grass waterways and their effects on event-based runoff with strong model performance coefficients for calibration and validation.

Sediment

Figures 3a, b, and c illustrate the measured and simulated event-based sediment loadings from AGF, CGS buffer, and Control watersheds, respectively. The model was not well calibrated for event-based sediment; r^2 and NCS values were < 0.1 for all three watersheds. The model over predicted the largest event on the 10th of April, 1999. Annual average sediment loss was within ±10-14% of the measured value when this over predicted value was excluded. The APEX model study for the pre-buffer period reported that the model was calibrated for sediment only for events larger than 50 mm rainfall (Senaviratne *et al.* 2013). They also reported that the sediment depositions at the flume bed prior to sampling point especially during low flow events could have caused under representation of larger sediment particles in the samples and under-estimation of total sediment (Senaviratne *et al.* 2013). Mudgal *et al.* (2008) also reported sediment deposition at the weirs that affected the calibration of the APEX model for event-based sediment especially at low flow events. In-addition, they have observed that event-based sediment was over predicted at high flow events.

The average measured event-based sediment loadings ranged from 0.0084 T ha^{-1} for the AGF and CGS buffer watersheds to 0.0092 T ha^{-1} for the Control watershed. The average measured sediment loadings for pre-buffer Center and West watersheds ranged between 0.099 and 0.1 T ha^{-1} and that for the control ranged between 0.077 and 0.1 T $ha^{-1.}$ (Senaviratne, *et al.* 2013). Post buffer average sediment losses were 88-95% less than pre-buffer losses.

Scenario analysis -- Buffer width and placement of buffers

The calibrated and validated APEX model for AGF and CGS watersheds were simulated with expanded buffer widths from 4.5 m to 5.5 and 7.5 m. The results indicate no significant reduction in average annual runoff (Fig. 4). Studies have found diminishing return in pollutant filtration with the increase of buffer width (Dillaha *et al.* 1989; Robinson *et al.* 1996; Schmitt *et al.* 1999). Studies indicate that increasing the buffer width beyond four to seven meters produce marginal reductions in NPSP (Robinson *et al.* 1996; Schmitt *et al.,* 1999). A review on vegetative filter strips by Liu *et al.* (2008) revealed that the efficiency of a particular buffer width mainly depends on the slope of the land. The results of the current study also revealed that the increase of buffer width from 4.5 m to 5.5 and 7.5 m marginally reduced runoff, possibly because the average slopes of the AGF, CGS, and Control watersheds were 1.3%, 0.9%, and 2.1%, respectively (Udawatta *et al.* 2004).

The models were also simulated to test the effect of location of buffers on runoff by removing all buffers and buffers at summit, shoulder and back slope, and foot slope positions of the landscape at a time (Fig. 5). The simulated AGF and CGS buffers did not significantly reduce average annual runoff but showed 4.3% and 5.2% respective reductions compared to non-buffer simulations. The buffers at the shoulder and back slope positions contributed to the highest reductions in runoff in AGF (1.7%) and CGS (2.4%) buffer watersheds (Fig. 5).

CONCLUSION

The APEX model was reasonably calibrated and validated for crop yield and event-based runoff of the long-term monitored study watersheds located at the Greenley Memorial Research Center, in Northeast Missouri, with upland contour agroforestry and grass buffers, and the control treatment. The r^2 and NSC values were over 0.68 for runoff for calibration and they were over 0.43 for validation. The model was not calibrated for event-based sediment probably due to low concentration as a result of buffers as well as low intensity rainfall events during the study periods. Underestimation of larger particles in the measured samples due to sedimentation on flume beds prior to the sampling point may also have affected sediments calibration results. The long-term scenario analysis showed 4.3 to 5.2% reductions in annual runoff by the buffers. The higher reductions in annual runoff were observed for the CGS buffer watershed. The results of this unique study demonstrated that APEX can be used to evaluate environmental benefits of upland filter strips, provided sufficient long-term data are available for calibration and validation.

Table 1. Subarea parameters used to simulate crop land, buffers, and grass waterways of the three watersheds at the paired watershed study, Greenley Research Center, Missouri, USA.

Parameter	Crop	Agroforestry buffer	Grass buffer	Grass waterway
LUN-Land use number *	5	25	25	22
CHN-Manning's "n" for channel **	0.015	0.14	0.14	0.14
UPN-Manning's "n" for upland **	0.3	0.4	0.4	0.4
RCHN-Channels Manning's for routing reach) **	0.05	0.14	0.14	0.14
RCHC-USLE crop-management factor**	0.01	0.0001	0.0001	0.0001
RCHK-USLE erodibility factor**	0.3	0.2	0.2	0.2
Filter Strip Code**	0	1	1	0
FFPQ fraction of floodplain flow**		0.5 - 0.8 (depending on the buffer	0.5 - 0.8 (depending on the buffer	
RFPW Buffer/Floodplain width**		(Drainage area *10000)/(Floodplian length *1000)	(Drainage area *10000)/(Floodplian length *1000)	
RFPL Buffer/Floodplain length**		Buffer/Floodplain in km	Buffer/Floodplain in km	

* Operation schedule file, ** Subarea file (Williams *et al.* 2008)

Table 2. Agricultural Policy Environmental Extender (APEX) model performance for coefficient of determination (r^2), Nash-Sutcliffe Coefficient (NSC), and Pbias values for crop yield and event runoff for agroforestry buffer, contour grass buffer, and control watersheds at Greenley Research Center, Missouri, USA for calibration (crop yields: 1998 to 2002; runoff events 1 to 14) and validation (crop yields: 2003 to 2008; runoff events 15 to 35).

Model output		Model performance	Agroforestry buffer	Contour grass buffer	Control
Crop yield	Calibration	r^2	0.96	0.97	0.99
		NSC	0.88	0.89	0.98
		Pbias	15.42	-15.91	0.89
	Validation	r^2	0.88	0.68	0.80
		NSC	0.77	0.42	0.72
		Pbias	15.48	22.45	-4.38
Runoff	Calibration	r^2	0.78	0.84	0.80
		NSC	0.68	0.75	0.76
		Pbias	10.98	-22.58	22.63
	Validation	r^2	0.68	0.73	0.78
		NSC	0.58	0.51	0.43
		Pbias	5.06	-23.65	25.85

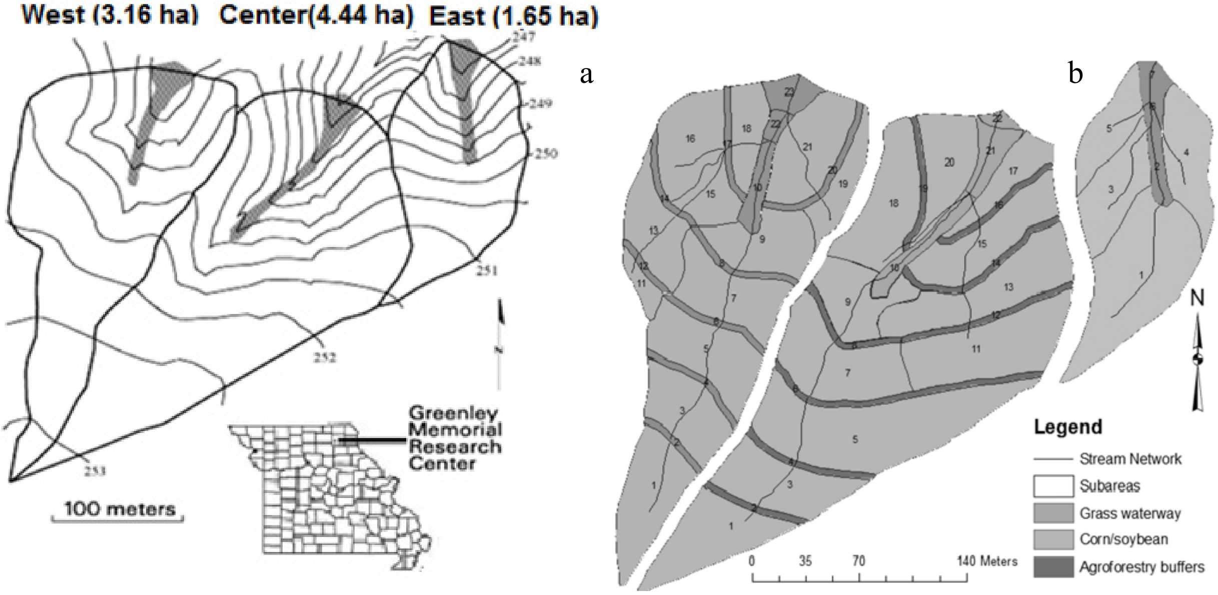

Figure 1. Topographic map (0.5-m interval) of West, Center and East watersheds (a; After Udawatta *et al.* 2004). Grey lines represent contour lines (thin) and grass waterways (wide). The inset map shows the approximate location of watersheds in Knox County, Missouri. ArcAPEX model delineated subareas, and stream network of the three watersheds (b).

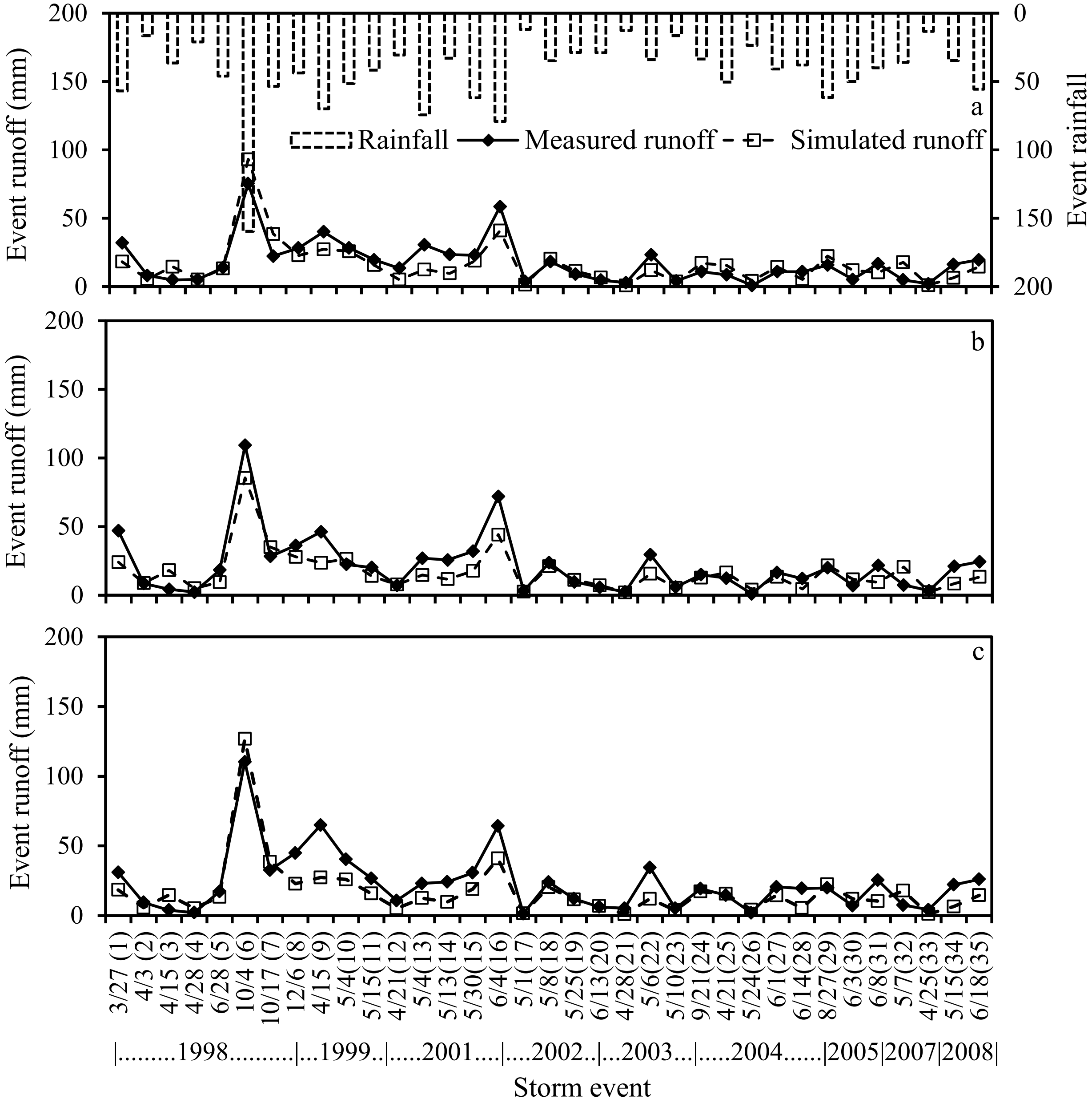

Figure 2. Measured and simulated event-based runoff for Agroforestry buffer (a), Grass buffer (b), and Control (c) watersheds during the study period at the paired watershed study, Greenley Research Center, Missouri, USA. The events 1 to 14 (1998-2001) represent results for calibration while events 15 to 35 (2002-2008) represent results for validation of all three watersheds.

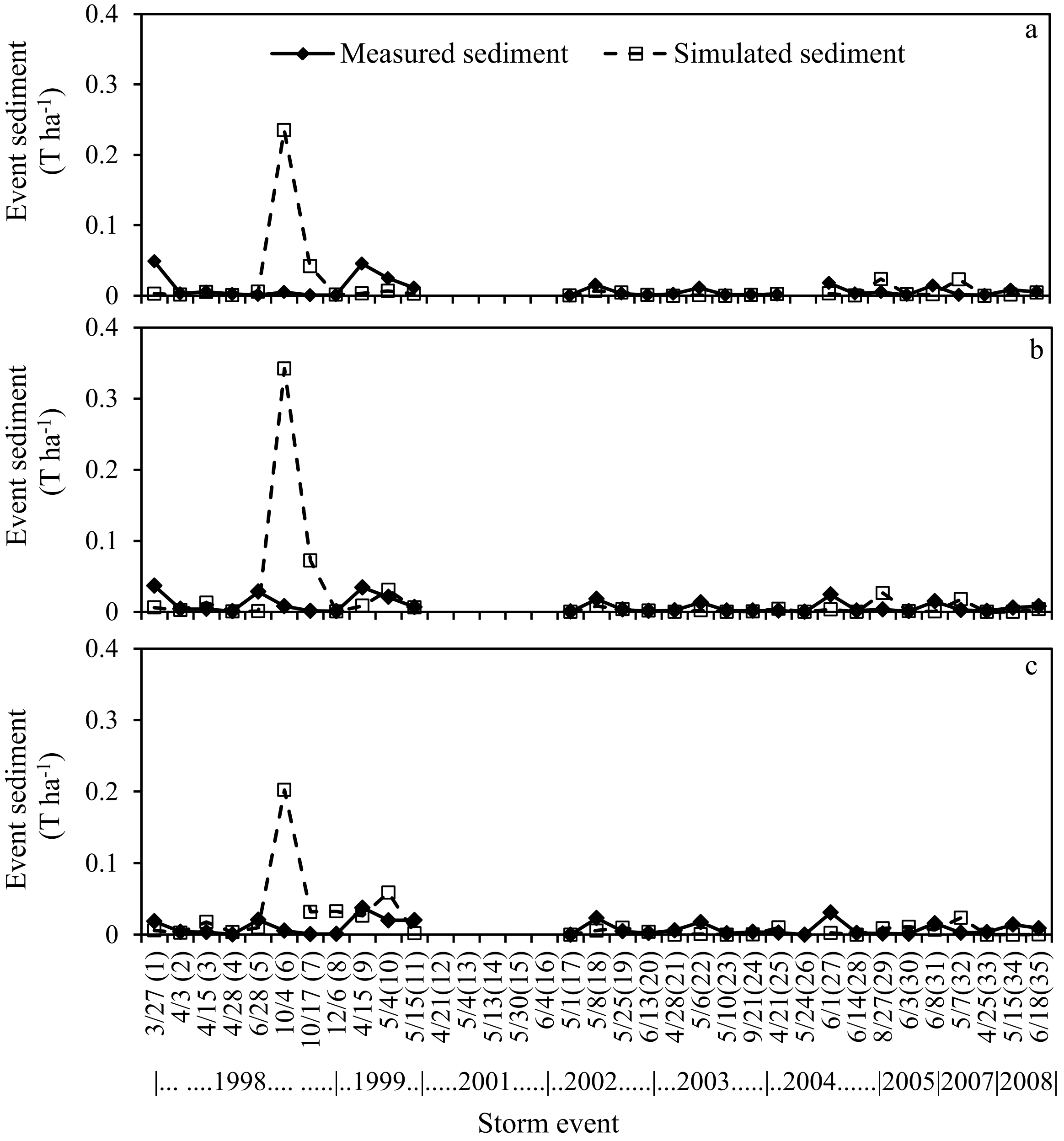

Figure 3. Measured and simulated event-based sediment for Agroforestry buffer (a), Grass buffer (b), and Control (c) watersheds during the study period at the paired watershed study, Greenley Research Center, Missouri, USA. The events 1 to 14 (1998-2001) represent results for calibration while events 15 to 35 (2002-2008) represent results for validation of all three watersheds.

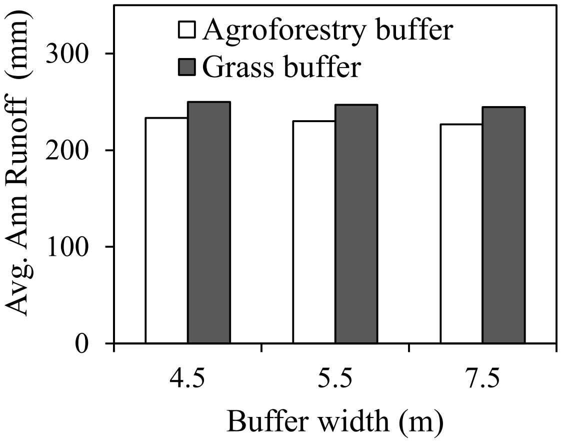

Figure 4. APEX model predictions for average annual runoff for agroforestry and grass buffer watersheds, at the paired watershed study, Greenley Research Center, Missouri, USA, with 4.5, 5.5, and 7.5 m buffer widths.

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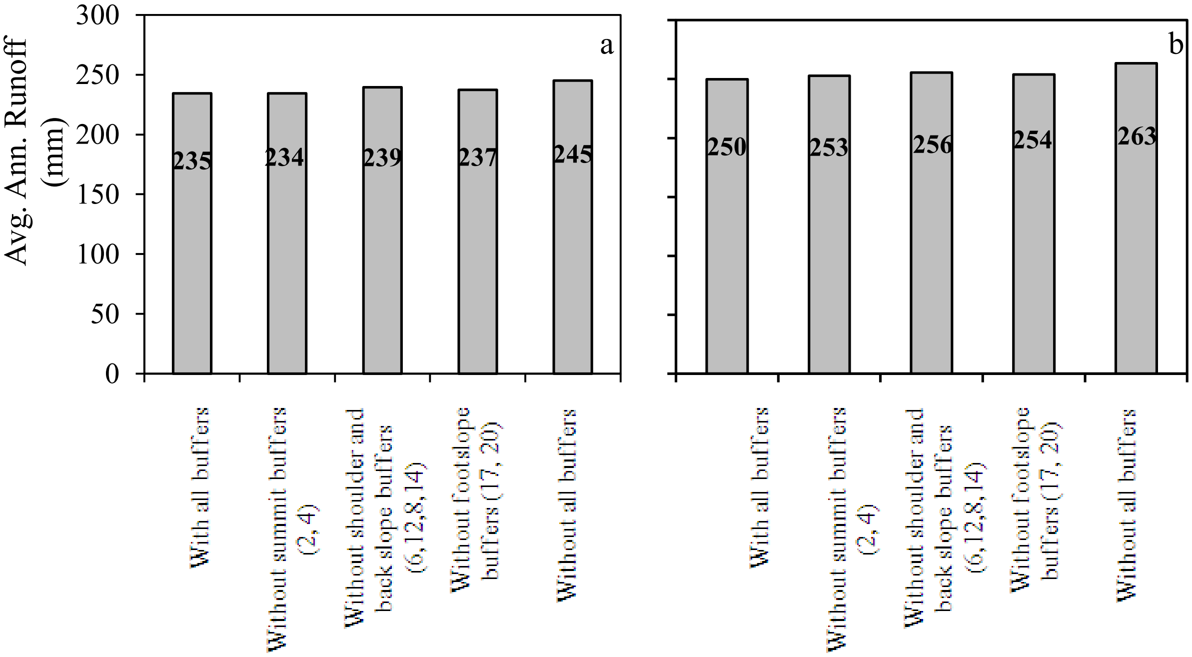

Figure 5. APEX model predictions for average annual runoff for agroforestry buffer (a) and grass buffer (b) watersheds, at the paired watershed study, Greenley Research Center, Missouri, USA, with varying buffers at summit, shoulder and back slope, and foot slope positions of the watershed landscape.

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