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Surface runoff contribution of nitrogen during storm events in a forested watershed

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Abstract We examined total Kjeldahl nitrogen (TKN) loading to a small forested stream during storm events. We hypothesized that upper soil and litter layers in riparian area are primary source of higher TKN concentrations during storm. A storm water sampling program was carried out to gather requisite flow and water quality data to calibrate and validate water and nutrient components of the Riparian Ecosystem Management Model for TKN. Water quality and storm flow data collected from January 2000 to December 2003 were used to simulate the hydrology and nitrogen transport over a second-order watershed within the Fort Benning Military Installation, Georgia. Intensive sampling conducted from October 2002 to May 2003 provided the necessary data to characterize the rising limb, peak, and recession limb of six major storm events. Simulated runoff and storm TKN loads were compared with their corresponding observed or calculated values. Hydrology and nitrogen data collected from February 21, 2003 to December 31, 2003 were used for the model validation. The hydrology component of the model showed a Nash-Sutcliffe efficiency of 87% for the validation period. The average absolute difference between simulated and calculated TKN loads was 25%. Even though the monthly water budget indicated the dominance of subsurface flow, TKN contribution from direct runoff was significantly greater than that from subsurface flow. On an average, 73% of the observed total TKN load at the watershed outlet was contributed by surface runoff during storm events. The results suggested that the surface runoff during the storm events washed off the nitrogen from the forest floor and transported to the stream.

Keywords Forested watershed · Fort Benning · Low nutrient systems · REMM · Riparian area · Total Kjeldahl nitrogen

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Introduction

Nitrogen is often a limiting nutrient in watersheds and in streams (Duff and Triska 2000). Some of the major factors that contribute to fate and transport dynamics of nitrogen in forested watersheds include plant biomass (Yeakley et al. 2003), physical and biological properties of soil (Heathwaite et al. 1996), and dominant hydrologic flowpaths through upper soil and litter layers to the stream (Michalzik et al. 2001).

Hydrology plays an important role in transporting nutrients during stormflow. In forested watersheds, one mechanism explaining increased nitrogen in streams during stormflow was a flushing from upper soil and litter horizons in the riparian ecotone (Frank et al. 2000). Studies of nitrogen and dissolved organic carbon during flood events or storm flows in forested watersheds have been reported in the past. Such studies have demonstrated an increase in both constituents with increased discharge (Peters 1994; Campbell et al. 2000; Frank et al. 2000; Houser et al. 2006).

Previous research has focused primarily on the water quality impacts of urban and agricultural land uses, whereas few examined the impacts of military activities on watershed hydrology and water quality (Bhat et al. 2006; Houser et al. 2006). Watershed uplands in military settings typically are subject to maneuvers of large, tracked and wheeled vehicles, and foot traffic (Whitecotton et al. 2000; Quist et al. 2003). Heavy vehicles used in mechanized military training disturb soil's physical properties (Iverson et al. 1981), which in turn affect multiple hydrological characteristics of the land (Thurow et al. 1993). Bhat et al. (2006) found at Fort Benning, Georgia measurable stream flow and nutrient impacts when only 5–6% of the watershed was used for training.

This paper presents results of a study of riparian and stream water dynamics in conjunction with pathways of nitrogen loads during storm events to a stream from a watershed located on Fort Benning military reservation in southwest Georgia. For this specific study, we used Riparian Ecosystem Management Model (REMM) developed by the U.S. Department of Agriculture's (USDA) Agricultural Research Service (ARS) to characterize the role of the riparian area on stream water quality. REMM has been tested and applied on high-nutrient riparian buffers adjacent to agricultural fields in the past (e.g., Inamdar et al. 1999a, b; Lowrance et al. 2000); however, the physics and chemistry embedded in model are transferable to other landscapes where carbon and nutrient cycling are likely to be strongly linked to water dynamics in the riparian buffer. The specific objectives of this study are to characterize the hydrology and nitrogen fluxes during storm events, and to quantify the variability of nitrogen loads on interannual basis. We hypothesize that the washoff of nutrients from upper soil and litter layers in riparian area are primarily responsible for higher concentrations of nitrogen during storm events.

Study area

The study was conducted at the Fort Benning military reservation, located in southwest Georgia. Long, hot summers and mild winters characterize the region's climate. Average annual precipitation is approximately 740 mm with a monthly average of about 62 mm. Most of the precipitation occurs in the spring and summer as a result of thunderstorms. Heavy rains are typical during the summer, but can occur in any month. Snow accounts for less than 1% of the annual precipitation. A second-order watershed, Bonham-South, was selected for this study. The Bonham-South watershed has an area of 2.21 km^2, a minimum elevation of 91 m, a maximum elevation of 159 m, and an average slope of 8.0%. Patchy land cover, formed from a mosaic of open or forested areas, characterizes the watershed (Fig. 1). The study watersheds' land cover predominantly consists of either forested or open areas. Mixed pine and hardwoods or pine (30–50 years old) characterizes the forested area in the study watershed. The dominant soils in the study watershed are loamy sand and sandy loam. Soils in A horizon range approximately 1–10 cm in depth (Garten et al. 2003). A detailed description of this site is provided in Bryant et al. (2005) and Bhat et al. (2006).

The riparian area covers approximately 2.5% of the total watershed area with a length of 3500 m and a 24 m width along the stream. The riparian buffer is divided into three 4 m zones (Zones 1, 2, and 3) each with three soil layers (Soil layers 1, 2, and 3) in each zone. Riparian area parameters are listed in Table 1. To apply REMM at a watershed scale, the watershed area was converted into an equivalent hillslope by adjusting the geometry of watershed. Using the riparian buffer's length and width, the upland

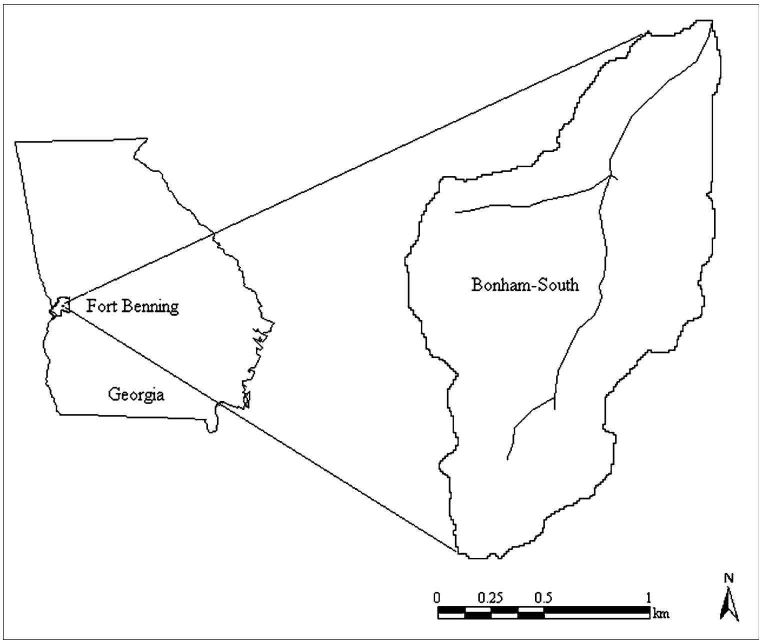

Fig. 1 Study area. Bonham-South is a second-order watershed within the Fort Benning military installation in Georgia

contributing field width of the watershed was scaled to represent the watershed area.

Methodology

Data and model setup

From January 2000 to December 2003, daily weather measurements were taken within the military installation for the Strategic Environmental Research and Development Program's (SERDP) Ecosystem Management Project (SEMP). These data included precipitation amount and duration, maximum and minimum air temperatures, solar radiation, wind speed, and dew point temperature. Daily average stream flow values for the watershed were calculated from 10-min continuous stage records using rating curves and the area-velocity method. Routine onsite inspections during the storm events were conducted to observe the watershed's response to the precipitation. Negligible upland surface runoff was observed during the study period. The subsurface flow from the upland to the riparian area was estimated as the baseflow fraction in the measured stream flow. The measured stream flow from January 2000 through December 2003 was partitioned into baseflow and surface runoff using constant slope base flow separation technique (McCuen 1998).

Riparian zone characteristics used in REMM listed in Table 1 were derived from measured data and previously published literature (Garten et al. 2003). Topographic measurements were derived using digital elevations maps. Soil and litter C and N pools were based on literature values (Inamdar et al. 1999a, b; Lowrance et al. 2000) and these values are also listed in Table 1.

Measured parameters in the study area included nutrient concentrations, total Kjeldahl nitrogen (TKN), nitrate, and ammonium in the stream and shallow groundwater. Bhat et al. (2006) describes the sample analysis procedures for the chemical constituents. A total of 16 storm events were sampled using an event triggered ISCO sampler that was collocated with the stage recorder in Bonham-South from September 2002 to September 2003. The ISCO sampler collected hourly samples based on the flow depth. Nitrate and ammonium were often below detection limits; hence TKN was adopted for further analysis. Observed loads of TKN during storm events were calculated by integrating over the storm duration the transient product of measured nutrient concentrations and stream flows.

Table 1 Specified REMM model parameters values by the riparian zone for the Bonham-South watershed in Fort Benning, Georgia

Parameters	Units	Values
Riparian zone length	m	3500
Riparian zone width	m	4
Slope	%	3.0^1, 3.8^2, 4.2^3
Total soil profile thickness	m	3.3
Individual soil horizon thickness	m	
Soil layer 1		0.3
Soil layer 2		1.0
Soil layer 3		2.0
Litter and soil carbon	kg/ha	
Litter		18100
Soil layer 1		29280
Soil layer 2		24640
Soil layer 3		11560
Litter and soil nitrogen	kg/ha	
Litter		1134
Soil layer 1		655
Soil layer 2		644
Soil layer 3		252
Riparian area	ha	4.2
Field drainage area (surface)	ha	216.8
Field drainage area (subsurface)	ha	221.0

The dimension of riparian area from the upland to the stream perpendicular to the stream is referred to as width, and the distance along the stream is referred to as length. The parameter values are identical for Zone 1, Zone 2, and Zone 3 except for the slope. The superscripts 1, 2, and 3 of the slope values represent the Zone 1, Zone 2, and Zone 3, respectively

Daily TKN loads were determined for the six events lasting more than 24 h. REMM predictions of TKN load are the sum of dissolved and particulate organic nitrogen and dissolved ammonium.

Model calibration and validation

Model calibration and validation involved comparisons of simulated stream flow and TKN output with measured values. Model parameters including saturated hydraulic conductivity, soil porosity, wilting point, clay content, carbon decay rate, and denitrification rate in each zone and soil layers of the riparian buffer were adjusted during model calibration. Hydrology and nitrogen data from January 2000 to February 20, 2003 were used to calibrate the model. The same types of data from February 21, 2003 to December 2003 were used for REMM validation. The division of data into two sets was predicated on a desire that each would include three of the six storms lasting more than 24 h.

Fox (1981) recommends mean biased error (MBE) and mean absolute error (MAE) to measure the difference between observed and model predicted parameters. Mean biased error is calculated as the average error between predicted and observed values accumulated over the total number of data points. Mean absolute error considers the absolute values of the errors. In the present study, MBE and MAE are modified to calculate the percent difference of modeled stream flow and TKN load from the observed values. Mean biased difference (MBD) calculates the average difference accumulated over the total number of events, expressed as a percent of the observed value. Mean absolute differences (MAD), also expressed as a percent, are the absolute values of the differences. Mean absolute difference takes negative values and replaces them with their absolute values. Model calibration and validation can also be evaluated using the Nash-Sutcliffe efficiency. This criterion is based on the normalized least square objective function that evaluates the sum of the squares of residuals (Nash and Sutcliffe 1970).

A sensitivity analysis was performed to determine the effects of key hydrological, soil, and vegetation parameters on stream flow and TKN loads. The parameters such as canopy cover fraction, riparian zone width, soil layer thickness, maximum carbon decay rate for litter and humus, maximum denitrification rate, soil saturated hydraulic conductivity, soil porosity, and soil clay content were considered for the sensitivity analysis. Each parameter was changed by +10% and −10% from the values used as the best estimates for the calibration simulations.

Results and discussion

Model calibration and validation

Table 2 lists the hydrology and nutrient performance measures for both calibration and validation periods.

Table 2 Model performance measures of hydrology and nutrient components of REMM

Model components	Parameter	Calibration			Validation		
		MAD	MBD	NSE	MAD	MBD	NSE
Hydrology	Total flow	10	13	77	10	13	87
	Surface flow	17	6	76	29	10	63
	Base flow	35	20	77	50	17	75
Nitrogen	Total Load	22	13	42	25	22	64

Abbreviations MAD, MBD, and NSE represent mean absolute difference, mean bias difference, and Nash-Sutcliffe efficiency, respectively. All values are expressed in percentage

MBD and MAD between observed and predicted stream flow during calibration and validation were 10% and 13%, respectively. The model had an average Nash-Sutcliffe efficiency of approximately 87%. Simulated daily flows for the study watershed closely matched the observed flows (Fig. 2). However, REMM tends to underestimate the stream flow during low flow and overestimate during the storms. Overall, REMM provided a reasonable simulation of daily stream flow.

Nitrogen loads from three of the six storm events were used to calibrate REMM while the remaining three storms were used for model validation (Fig. 3). Computed TKN loads in total flow during the storm events were comparable to the observed values (Fig. 4a), with total simulated TKN loads having somewhat higher errors during the validation period. Subsurface flow was separated from the total flow to determine the TKN loads corresponding to direct runoff (Fig. 4b) and baseflow (Fig. 4c). Modeled TKN loads from direct runoff exhibited a small bias (MBD of 10%), but this was variable among the storms. Overall, the results demonstrated modeled storm loads were quite reasonable. The largest errors occurred with predicted TKN loads associated with simulated subsurface flows during the validation period.

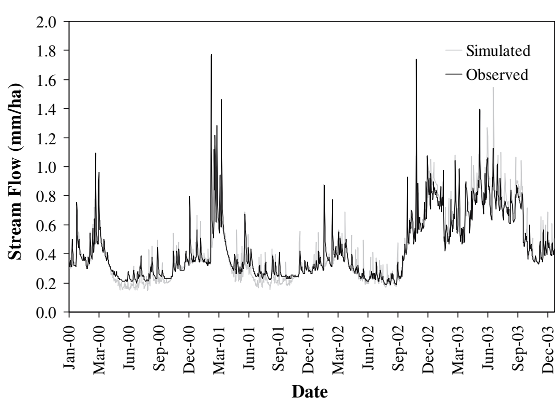

Fig. 2 Comparison of REMM simulated daily flow with the observed daily flow for the Bonham-South watershed

Sensitivity analyses were performed to elucidate parameters of primary importance. This analysis indicated that a ±10% parameter variation resulted in relatively modest responses in stream flow and TKN outputs. TKN was particularly sensitive to variations in saturated hydraulic conductivity, soil layer thickness and soil porosity. Decreasing the hydraulic residence time in soil layers (by decreasing soil layer thickness or increasing hydraulic conductivity or decreasing soil porosity) tended to decrease nitrogen losses. Under decreasing hydraulic residence time, flow through the soil layers effectively increases. This, in turn, creates less opportunity for nitrification to occur within the soil layers. These circumstances suggest that the nitrification is relatively constant and hence nitrate concentrations in water leaving the soil layers are reduced. Reduced nitrification in the soil layers, in turn, may have increased TKN loads in both ground and surface waters.

Hydrologic and nitrogen budgets

Table 3 summarizes the hydrologic budget for the 4-year study period. There was considerable variability between and within years for measured precipitation and stream flow data. Because the runoff to precipitation ratio was fairly constant,

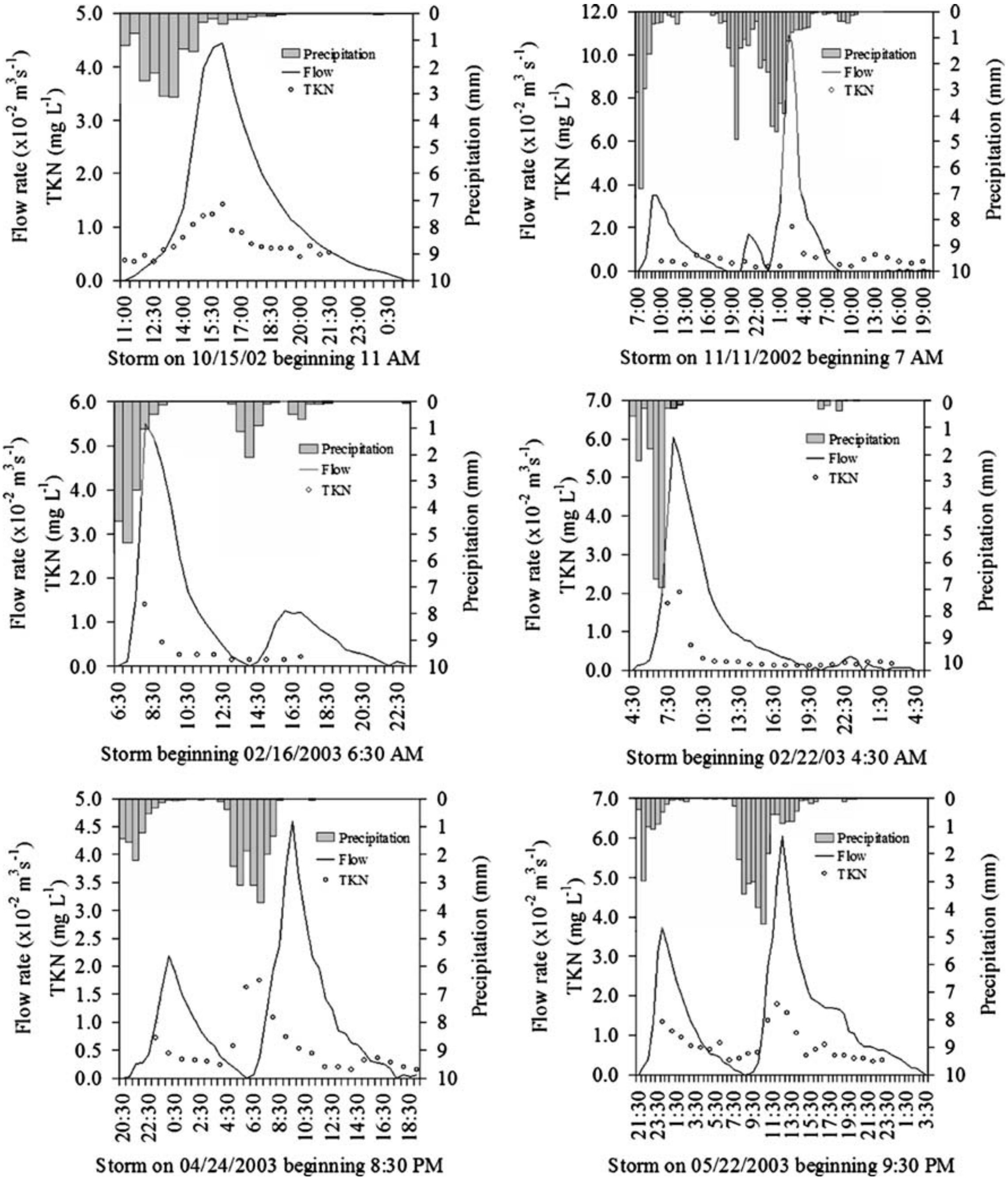

Fig. 3 Observed TKN concentrations during the storm events. Vertical bars represent precipitation, solid lines represent the stream flow, and the hollow circles represent the TKN concentrations

averaging 22%, interannual variations in precipitation controlled the stream flow volume. The majority of stream flow reflected primarily groundwater inputs (Fig. 5a). Modeled interception losses over the study period ranged from 123 mm/year to 247 mm/year with an average value of 170 mm/year corresponding to 23.2% of the precipitation over the study period. The modeled interception

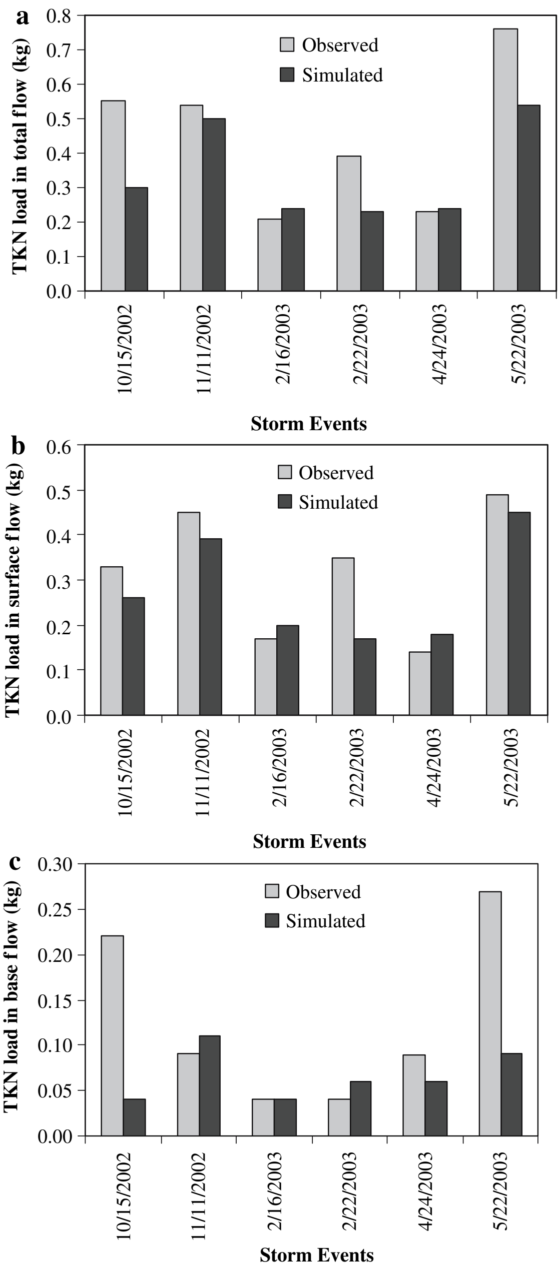

Fig. 4 (**a**) Comparison of the observed and simulated TKN loads in total flow during the storm events. (**b**) Comparison of the observed and simulated TKN loads in surface flow during the storm events. (**c**) Comparison of the observed and simulated TKN loads in subsurface flow during the storm events

losses in this study are relatively high as compared to previous studies. Bryant et al. (2005) reported an interception loss of 17.7% in the same watershed. For riparian forests located on coastal plain watersheds in Georgia, Inamdar et al. (1999a) reported average annual interception loss of 15%. This discrepancy in interception losses between this study and reported literatures is not expected. The study of Bryant et al. (2005) considered precipitation data from April 2001 to June 2002. Average precipitation during 2001–2002 was approximately 730 mm. The present study, conducted from 2000 to 2003, includes a drought year with only 475 mm of precipitation. Because relatively higher interception losses occur for small precipitation events, inclusion of the 2000 low precipitation period may have increased the relative interception losses.

Riparian Ecosystem Management Model's simulation indicated that the average annual TKN load is 0.04 kg/ha/year (Table 3). Annual values are less than previously reported dissolved nutrient loads in forested and agricultural watersheds. Burton et al. (1977) reported slightly higher nitrogen load of 0.15 kg/ha/year from forested watersheds in North Florida. In a hardwood forest in North Carolina, Swank and Douglas (1977) reported nitrogen load of 0.10 kg/ha/year. The nitrogen loads from southeastern coastal plain agricultural watersheds in Georgia, ranged from 0.40 kg/ha/year to 0.95 kg/ha/year as reported by Lowrance et al. (1985). A lower TKN load reported in this study is consistent with findings from earlier studies. For example, Bhat et al. (2006) reported relatively low TKN concentrations of 0.20 mg/l to 0.35 mg/l in stream water in the same watershed.

The study area produced variable TKN response to stormflow. For example the pattern of surface runoff TKN loads during storms were different from the baseflow TKN load patterns regardless of the precipitation intensity. Baseflow TKN loads during the storm events were less than that from the surface runoff. A potential explanation for this response is that the lower soil layers in this riparian area, where higher concentrations of dissolved nutrients are expected, was unaffected by the stormflow. An explanation for the pattern of consistently higher concentrations in the surface runoff and hence the load of TKN during the storms is that the intensity of a storm may affect the transport of TKN from near-stream soil and litter layer to the stream.

Table 3 Model simulated annual hydrologic and TKN budgets for the Bonham-South watershed

	Units	Year				4-year average
		2000	2001	2002	2003	
Precipitation	mm $year^{-1}$	475	736	731	1014	739
Surface flow*	mm $year^{-1}$	–	–	–	–	–
Subsurface flow**	mm $year^{-1}$	119	134	143	253	162
Observed stream flow (total)	mm $year^{-1}$	121	137	147	258	166
Simulated surface flow	mm $year^{-1}$	2	5	4	6	4
Simulated subsurface flow	mm $year^{-1}$	106	118	130	244	149
Simulated stream flow (total)	mm $year^{-1}$	109	124	133	250	154
Simulated throughfall	mm $year^{-1}$	352	599	558	767	569
Simulated interception losses	mm $year^{-1}$	123	137	173	247	170
Simulated % throughfall		74.1	81.4	76.3	75.4	76.8
Simulated % interception losses		25.9	18.6	23.7	24.6	23.2
Simulated TKN load (subsurface flow)	kg	2.8	2.9	2.8	3.4	3.0
Simulated TKN load (surface flow)	kg	3.1	5.9	5.2	7.5	5.4
Simulated TKN load (total flow)	kg	5.9	8.8	8.0	10.9	8.4
Simulated TKN load (total flow)	kg ha^{-1}	0.03	0.04	0.04	0.05	0.04

* and ** represents the surface and subsurface flow input to the zone 3 from uplands. Values are rounded off to nearest whole numbers

Even though the monthly water budget indicated the dominance of baseflow (Fig. 5a), TKN contributions from direct runoff were significantly greater than the loads from subsurface flow (Fig. 5b). On an average, 73% of the observed total TKN load was contributed by surface runoff during storm events; this would suggest surface runoff was flushing nitrogen from the forest floor and transporting it to the stream. This result is supported by a study conducted by Houser et al. (2006) in the same study area, in which the authors reported higher nitrogen levels in streams during storms and suggested that surface runoff or riparian zone soils were major sources of nitrogen during such events.

Our findings further supported by the current literature that contends that riparian areas are important contributors of nitrogen to streams during storms (Cirmo and McDonnell 1997).

Conclusions

Our study demonstrated that riparian areas are important contributors of nitrogen to streams during storm events. Even though the monthly water budget indicated the dominance of baseflow in this particular study, nitrogen loads from direct runoff were significantly greater than that from baseflow. The results also suggested that annual nitrogen loads to the stream from the riparian area depended on the precipitation amounts. The buildup of vegetation biomass in the riparian area and subsequent washoff of nutrients from the litter and soil layer during the storm events may have contributed to higher fluxes of nitrogen to the stream.

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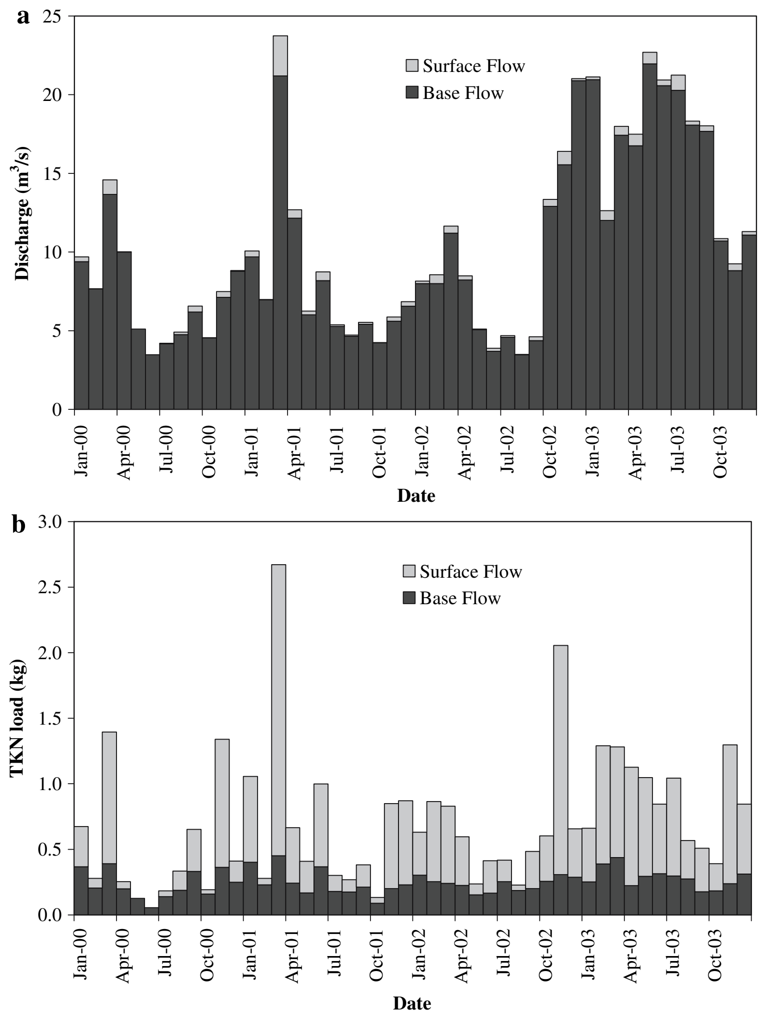

Fig. 5 (**a**) Simulated surface and subsurface flow in the Bonham-South watershed. (**b**) Simulated surface and subsurface TKN loads in the Bonham-South watershed

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