Modeling effectiveness of broiler litter application method for reducing phosphorus and nitrogen losses

Palki Arora, Jasmeet Lamba, Puneet Srivastava and Latif Kalin

ABSTRACT

The linkages among the best management practices implemented at the field level and downstream water quality improvement at the watershed level are complex, because the processes that link management practices and watershed-level water quality span a range of scales. However, it is important to understand the effect of nutrient management strategies on watershed-level water quality because most of the water quality evaluation occurs at the watershed scale. The overall goal of this study was to quantify the effect of broiler litter application method (surface vs. subsurface application) on phosphorus (P) and nitrogen (N) losses in surface runoff using the Soil and Water Assessment Tool (SWAT) model. The research was conducted in the Big Creek watershed (8,024 ha) located in Mobile County, Alabama, USA. At the hydrological response unit level, the subsurface application of broiler litter to pastures reduced average annual (1991–2015) total P and N losses in surface runoff by 72% and 33%, respectively, compared to surface application of broiler litter. At the watershed outlet, subsurface application of broiler litter to pastures (covered 43% of the watershed area after the land use change scenario) reduced average annual (1991–2015) total P and N losses by 39% and 20%, respectively.

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INTRODUCTION

Increased levels of nutrients in surface waters result in water quality impairment. For example, excessive delivery of nitrogen (N) and phosphorus (P) to surface waters results in the growth of toxic algae and eutrophication (Carpenter et al. 1998). In the USA, about 10% (~181,856 km) of the assessed streams and rivers are impaired because of excessive levels of nutrients (USEPA 2014a). Similarly, in Alabama (AL), approximately 7% (~1,250 km) of stream impairment in assessed streams is due to excessive concentration of nutrients (USEPA 2014b). Agricultural runoff has been recognized as one of the major sources of nutrients in surface waters (USEPA 2009). Loss of nutrients via agricultural runoff to surface waters is substantial in areas of intensive animal production.

In AL, approximately 1.08 billion (12.4% of US production) meat birds are produced yearly, ranking it second behind Georgia (USDA 2016). Annually, approximately 1.25 million Mg of broiler litter is generated in AL (Aksoy et al. 2008). With the increasing production of broiler litter in AL, disposal of broiler litter is becoming a priority concern (Torbert & Watts 2014). Being an inexpensive option as compared to commercial fertilizers, broiler litter is commonly used to fertilize pastures (Lamba et al. 2013). Because of the expense and logistics of transporting broiler litter, it is typically surface-applied (broadcasted) onto pasture fields in close proximity to the production facilities. Broiler litter application to the same pasture fields (in close proximity to the production facilities) year after year, contributes to an increase in soil nutrient, especially P, levels. For example, Ranatunga et al. (2013) reported that in the Sand Mountain region of north AL, Mehlich-3 P levels are greater than 200 mg kg^{-1}, which is substantially greater than the agronomic optimum level of 50 mg kg^{-1}.

The high concentration of P in soils increases P (dissolved or particulate forms) losses in surface runoff (Lamba *et al.* 2012). Losses of P in dissolved form are dominant in surface runoff generated from grasses, forests, and uncultivated soils since soil erosion from these land uses is minimal (Elrashidi 2010).

Implementation of best management practices (BMPs) can help to reduce loss of N and P in surface runoff from agricultural landscapes (Arabi *et al.* 2006). To study the effectiveness of BMPs at a watershed level, long-term monitoring data are required. However, collection of long-term flow and water quality data is time-consuming, labor-intensive, and expensive. Therefore, typically, long-term data required to quantify the effectiveness of BMPs are not available (Arabi *et al.* 2006). Watershed-level models are commonly used to understand complex watershed level hydrological, sediment and nutrient transport processes, and assess the effectiveness of BMPs (Artita *et al.* 2013; Mirhosseini & Srivastava 2016). For example, watershed-level models, such as, Agricultural Policy/Environmental eXtender (APEX) and Soil and Water Assessment Tool (SWAT) have been successfully used by researchers to understand hydrological processes at the watershed level. SWAT is one of the prominent models, which has been used extensively to simulate the effectiveness of BMPs in controlling nutrient losses in agricultural watersheds (Lee *et al.* 2010; Panagopoulos *et al.* 2011; Artita *et al.* 2013; Dechmi & Skhiri 2013; Liu *et al.* 2014). For example, Lee *et al.* (2010) used the SWAT model to quantify the effectiveness of vegetative filter strips, riparian buffer systems, and fertilizer application rate on total P and N losses. Similarly, Panagopoulos *et al.* (2011) showed the effect of BMPs, such as contour farming with zero tillage, filter strips, and reduction of animal numbers in pastureland, on sediment, P, and N losses.

Nutrient management guidelines or tools (e.g., P Index) can help producers and conservation personnel to limit nutrient losses from fields (Kleinman *et al.* 2017). Effective nutrient management requires consideration of four independent factors, collectively referred to as '4R' factors: (a) right placement, (b) right time, (c) right rate, and (d) right form (Collick *et al.* 2016). The method of application of broiler litter to pastures can affect P and N loss in surface runoff (Randall & Hoeft 1988; Kleinman & Sharpley 2003; Roberts 2007; Pote *et al.* 2011; Lamba *et al.* 2012). For example,

field-based experiments conducted at the plot scale have shown that subsurface application of broiler litter can help to reduce P loss in surface runoff (Lamba *et al.* 2012). Similarly, N loss through ammonia (NH_3) volatilization is less from fields with subsurface-applied broiler litter compared to fields in which broiler litter is surface-applied (Pote *et al.* 2011). Additionally, as a result of increased availability of nutrients to crops, subsurface application of manure (e.g., cattle dung and farm yard manure) has been shown to increase crop yield compared to surface application of manure (Gana 2011; Otinga *et al.* 2013). Studies have been conducted to assess the effectiveness of subsurface application of broiler litter to reduce N and P losses in surface runoff. However, most of the previous studies have quantified the effectiveness of the subsurface application of broiler litter for individual storm events at a plot or field scale (Kanwar *et al.* 1985; Glæsner *et al.* 2011; Pote *et al.* 2011; Lamba *et al.* 2012; Torbert & Watts 2014). To our knowledge, no watershed-scale study (either monitoring or modeling) has been conducted to quantify the effectiveness of subsurface litter application in controlling nutrient losses on a long-term basis. Most of the watershed management occurs at the watershed scale for the long-term protection of water resources. A long-term monitoring study would be time-consuming and labor-intensive to conduct, thus, it is important to evaluate the long-term effect of subsurface application of broiler litter at the watershed level using a continuous simulation model such as SWAT. Therefore, the objectives of this study were to: (a) quantify the effectiveness of subsurface application of broiler litter on P and N losses using the SWAT model at different spatial scales on a long-term basis and (b) determine the effect of soil type and slope on N and P losses as a function of broiler litter application method. Data on the effectiveness of different management practices (e.g., manure application rate, tillage practices, vegetative filter strips) in controlling nutrient losses in surface runoff are available in the literature (e.g., Lee *et al.* 2010; Panagopoulos *et al.* 2011). As mentioned earlier in the paper, no data are available to assess the impact of broiler litter application method on watershed-level water quality. Therefore, data generated from this study will help conservation planners to develop and improve watershed-level management strategies aimed at reducing nutrient delivery to streams.

METHODOLGY

Study area

The study area for this research was 82 km^2 and is known as Big Creek watershed, located in Mobile County, AL (Figure 1). This watershed drains to the Converse Lake, which is the major source of drinking water for Mobile, AL. The mean annual (1990–2015) precipitation in the watershed is about 1,678 mm. Based on the National Land Cover Dataset (NLCD), in 2006 the dominant land uses in this watershed included 38% forest, 4% agricultural, 31% rangelands, 11% wetlands, and 12% pasture (Fry *et al.* 2011) on Coastal Plain soils (Figure 1). The soils in the study watershed are Troup-Bennadale (52.9%), Troup-Heidel (19.8%), Notcher (14.3%), Heidel (7.8%), Bama (2.9%), and Troup (2.3%). The texture of the majority of the soils in this watershed is sandy loam. Hydrological soil group (HSG) and slope information of the study watershed

are shown in Figure 2. The two major reasons for selecting this watershed for our study were: (a) this watershed consists of Coastal Plain soils, which are the dominant type of soils in southeastern AL, one of the major regions of broiler litter industry in AL and (b) availability of measured streamflow, P, and N data at the watershed outlet required for model calibration and validation.

SWAT model description

SWAT is a watershed-scale model developed by the United States Department of Agriculture – Agricultural Research Service (USDA-ARS). It is a continuous time model that operates on a daily time step. The SWAT model is capable of simulating hydrological and nutrient transport processes and dynamics at a watershed level as a function of different management operations and practices. Major components of this model include hydrology, weather, erosion, soil temperature, crop growth, nutrients, pesticides, and agricultural
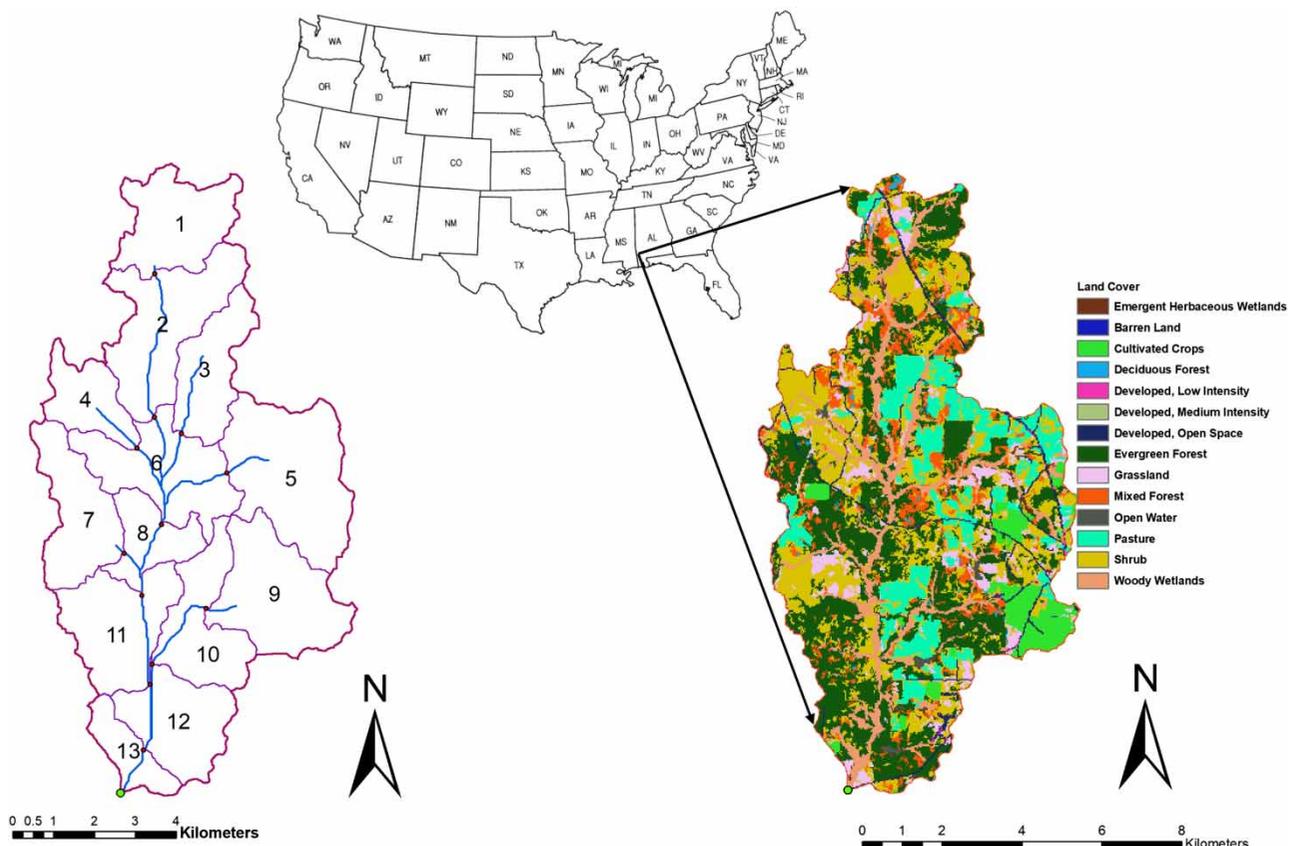
Figure 1 | Map showing individual subwatersheds and land use distribution in the Big Creek watershed, Alabama.
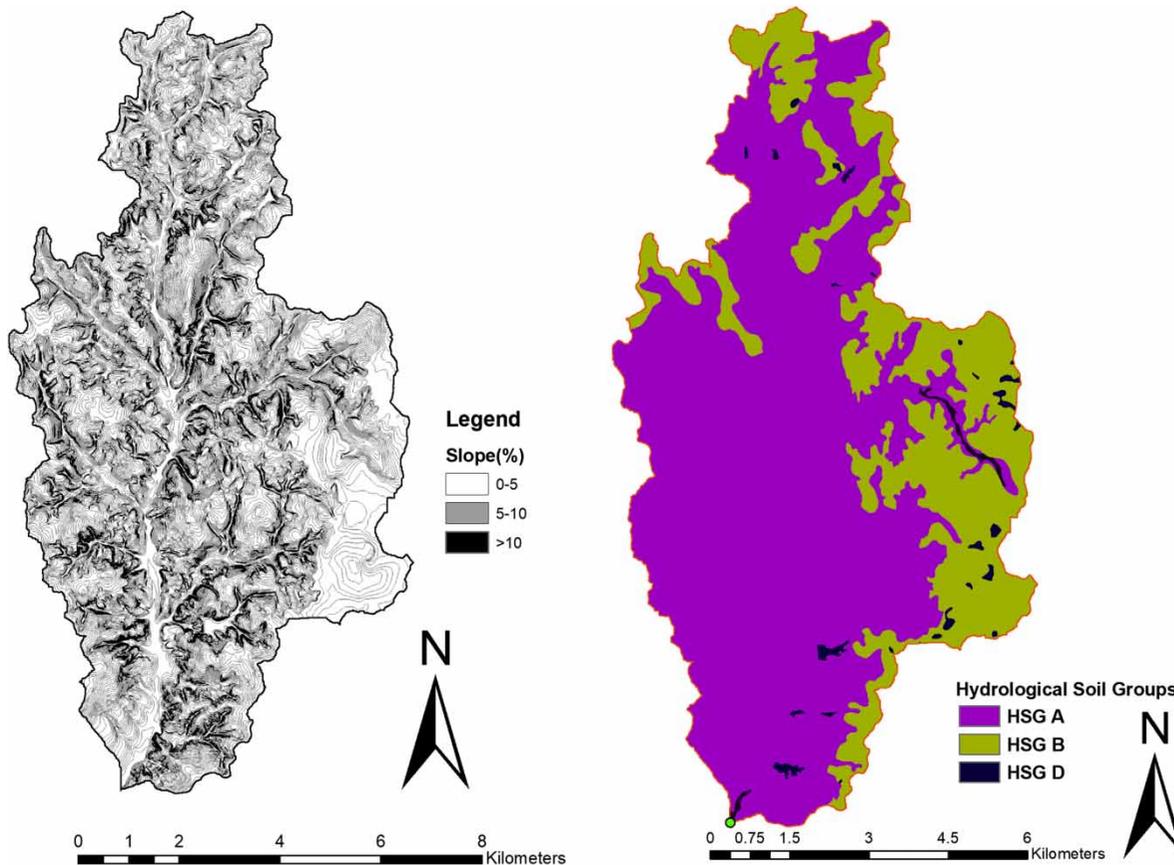
Figure 2 | Maps showing Hydrologic Soil Group (HSG) and slope classes in the study watershed.

management (Santhi *et al.* 2006). In SWAT, a watershed is divided into subwatersheds, which are further subdivided into hydrological response units (HRUs). The HRUs are lumped non-spatial areas with the same land use, slope, and soil type within a subwatershed (Mirhosseini & Srivastava 2016). For the HRU definition step, threshold levels for soil class, land use percentage, and slope were set to 0%, so that all land uses, soil type, and slope were represented within the watershed. For this study, the entire watershed was divided into 13 different subwatersheds and consisted of 1,808 HRUs. Surface runoff in SWAT can be calculated by using the USDA Soil Conservation Service (SCS) curve number method or the Green–Ampt infiltration equation (Neitsch *et al.* 2002). The SCS curve number method was used in this study. The methods available in SWAT to calculate potential evapotranspiration include Hargreaves method, Priestley–Taylor, and Penman–Monteith (Neitsch *et al.* 2002). The Penman–Monteith method was

used for this study. The modified universal soil loss equation was used to determine erosion and sediment yield for each HRU (Neitsch *et al.* 2002). Eroded sediment that enters the channel in SWAT was simulated by using the deposition and degradation technique (Neitsch *et al.* 2011). In addition to simulating sediment processes within a watershed, SWAT simulates the fate and transport of P and N. Phosphorus and N pools and processes which are modeled by SWAT are described in detail in the SWAT theoretical documentation (Neitsch *et al.* 2011). For this study, we used SWAT version 2016, revision 664.

Input data

The input data required to set up a SWAT model include a digital elevation model (DEM), soil properties, land use information, management data (e.g., crop rotations, manure/fertilizer application rate), and weather (Mirhosseini

& Srivastava 2016). A 10-m DEM was used to delineate the watershed. The National Land Cover Database of 2006 was used to provide land cover information (Fry *et al.* 2011) and properties of soils in the study watershed were derived using a Soil Survey Geographical dataset (SSURGO) obtained from the USDA Natural Resources Conservation Service. It should be noted that the land cover within this watershed has not changed substantially (<10%) over the last two decades, therefore, the use of the 2006 National Land Cover Database to run the model on a long-term basis will not affect water quantity and quality results. The Mobile, AL airport weather station was used to obtain daily temperature (maximum and minimum temperature) and precipitation data. The SWAT built-in weather generator was used for the relative humidity, solar radiation, and wind speed data because these data were not available from the weather station. Management practices and operations substantially affect the hydrological and nutrient processes within a watershed. Therefore, it is important to incorporate management practices information in the SWAT model. Management information (e.g., crop rotation, tillage operation, fertilizer application rate) for the study watershed was obtained from the previous studies conducted in this watershed (Srivastava *et al.* 2010; Mirhosseini & Srivastava 2016). For cropland areas, a peanut–cotton rotation was used and bermudagrass for pasture land use. The management information for the peanut–cotton rotation is included in Table 1. Bermudagrass was planted at the beginning of March and then harvested in July every year (Ahring *et al.* 1975; Shaver *et al.* 2006) for a period of 25 years. In the final year of the SWAT model run, bermudagrass was harvested and killed for all HRUs under pasture land use.

Calibration and validation

To perform model calibration (streamflow and nutrients), sensitive parameters were identified from the previous studies conducted in this watershed (Mondal *et al.* 2011; Mirhosseini & Srivastava 2016) and scientific literature. SWAT model calibration and validation was performed at a monthly time step for streamflow (surface runoff and baseflow), total P, and total N. To minimize uncertain conditions (e.g., groundwater level, soil moisture content) in the SWAT model from the start of the calibration

Table 1 | Management operations incorporated in SWAT model for cropland HRUs

Plant type	Operation date	Operation type	Operation attributes
Peanut	15 May	Planting	
	21 Oct	Harvest and kill	
Cotton	25 Mar	Tillage	Generic conservation tillage
	15 Apr	Planting	
	15 Apr	Fertilization	50 kg ha^{-1} nitrogen
		Fertilization	45 kg ha^{-1} phosphorus
	1 Jun	Fertilization	50 kg ha^{-1} nitrogen
	1 Oct	Harvest and kill	

period, we used a warm-up period of 6 years (January 1985–December 1990). The model calibration and validation were performed separately for surface runoff and baseflow (Srivastava *et al.* 2010; Mirhosseini & Srivastava 2016). The Web-based Hydrograph Analysis Tool was used to separate total streamflow into surface runoff and baseflow (Lim *et al.* 2005). Surface runoff and baseflow calibration and validation periods were January 1991–December 2003 and January 2004–December 2015, respectively. The observed streamflow data required for model calibration and validation were obtained from the United States Geological Survey (USGS) gage (02479945) at the watershed outlet. Compared to streamflow data, observed data for P and N at the watershed outlet were limited. The P and N loading data at the watershed outlet were obtained from the USGS water resources investigation report (Journey & Gill 2001). The P and N calibration was performed January 1991–December 1995 and validation was performed January 1996–July 1998. The parameters used for surface runoff, baseflow, P and N calibration are listed in Table 2.

Model performance was assessed by using qualitative and quantitative methods. Qualitative methods involved plotting observed and simulated surface runoff, baseflow, streamflow, total P and N loading at a monthly time step. In quantitative methods, a wide variety of statistical techniques can be used to evaluate model performance. Coffey *et al.* (2004) and Moriasi *et al.* (2012) described over a dozen statistical tests and parameters (e.g., root mean square error, coefficient of determination (R^2), percent bias (PBIAS), Nash–Sutcliffe efficiency (NSE), cross correlation, non-parametric tests and t-test) that can be used to quantify model performance. In the literature, NSE, PBIAS, and R^2 proposed by Moriasi *et al.* (2007) are most commonly used (Strauch *et al.* 2012;

Table 2 | Parameters used for calibration of surface runoff, baseflow, P and N

Parameter description	Parameter	Default values	Final values	HRUs for which parameter is changed
Curve number	CN	Varies	15% decrease	All HRUs
Available water capacity of soil layer (mm H_2O/mm soil)	SOL_AWC	Varies	15% increase	All HRUs
Saturated hydraulic conductivity (mm/hr)	SOL_K	Varies	10% decrease	All HRUs
Biological mixing efficiency	BIOMIX	0.2	0.01	All HRUs
Baseflow alpha factor (1/days)	ALPHA_BF	0.048	0.50	All HRUs
Groundwater 'revap' coefficient	GW_REVAP	0.02	0.2	All HRUs
Deep aquifer percolation factor	RCHRG_DP	0.05	0.25	All HRUs
Groundwater delay time (days)	GW_DELAY	31	100	All HRUs
USLE equation support practice factor	USLE_P	1	15% decrease	All HRUs
Exponent parameter for calculating sediment re-entrained in channel sediment routing	SPEXP	1	1.5	All HRUs
Peak rate adjustment factor for sediment routing in the main channel	PRF	1	0.5	All HRUs
Peak rate adjustment factor for sediment routing in the subwatershed	ADJ_PKR	1	0.5	All HRUs
Manning's n value for overland flow	OV_N	0.1	0.4	FORESTED
Initial soluble P concentration in soil layer (mg P/kg soil)	SOL_LABP	5	3	All HRUs
Initial organic P concentration in soil layer (mg P/kg soil)	SOL_ORGP	0	0.01	All HRUs
Organic N in the baseflow (mg/L)	LAT_ORGN	0	2	All HRUs
Initial organic N concentration in the soil layer (mg N/kg soil)	SOL_ORGN	0	0.01	All HRUs

Niraula et al. 2013; Rahman et al. 2013; Mirhosseini & Srivastava 2016). Therefore, we used NSE, PBIAS, and R^2 to evaluate model performance. NSE, PBIAS, and R^2 were computed using Equations (1)–(3), respectively:

$$NSE = 1 - \frac{\sum_{i=1}^{n} (O_i - P_i)^2}{\sum_{i=1}^{n} (O_i - \bar{O})^2} \qquad (1)$$

$$PBIAS = \frac{\sum_{i=1}^{n} (O_i - P_i) * 100}{\sum_{i=1}^{n} O_i} \qquad (2)$$

$$R^2 = \left(\frac{\sum_{i=1}^{n} \left(O_i - \bar{O}\right)\left(P_i - \bar{P}\right)}{\left[\sum_{i=1}^{n} (O_i - \bar{O})^2\right]^{0.5} \left[\sum_{i=1}^{n} (P_i - \bar{P})^2\right]^{0.5}} \right)^2 \qquad (3)$$

where O_i is the ith observation for the constituent being evaluated; P_i is the ith simulated value for the constituent being evaluated; $\bar{O}$ is the mean of observed data for the constituent being evaluated; $\bar{P}$ is the mean of simulated data for the constituent being evaluated; and n is the total number of observations.

Method of application of broiler litter

Nutrient (N and P) losses in surface runoff were compared from all HRUs under pasture (number of HRUs under pasture = 182) land use in this watershed as a function of surface and subsurface application of broiler litter. The SWAT model considers a 10 mm deep soil surface layer. Below this surface layer, soil profile can be divided into individual soil layers with the maximum number of layers limited to ten. Fertilizer operations in SWAT allow the user to specify the fraction of fertilizer applied to the top soil surface layer (i.e., the top 10 mm of soil) (Neitsch et al. 2002). For the surface application of broiler litter, the fraction of fertilizer applied to the top 10 mm of soil was set to one (i.e., all the broiler litter was applied to the top soil surface layer) for all HRUs under pasture. This was done by setting the value of FRT_SURFACE parameter to one in the SWAT management file. Unlike the surface application of broiler litter, all the broiler litter was added to the first soil layer (below the 10 mm deep soil surface layer) for the subsurface application of broiler litter to all pasture

HRUs. It should be noted that the SWAT model cannot simulate the application of broiler litter in subsurface bands. In this study, broiler litter was uniformly distributed over the entire HRU area. Based on the typical application rate of broiler litter in the southeastern USA, an application rate of 13,400 kg ha^{-1} was used for both surface and subsurface application of broiler litter to pastures (Torbert & Watts 2014). The nutrient losses in surface runoff from pastures were compared on a long-term basis (1991–2015) at the HRU, subwatershed, and watershed level as a function of broiler litter application methods. To compare nutrient losses between surface and subsurface broiler litter application methods we used Mann–Whitney test and significance level of $\alpha = 0.05$ for all hypothesis testing.

Land use change scenario

Land use under pastures in the study watershed was approximately 12%. Therefore, to quantify if the litter application method can reduce nutrient losses at the watershed level, we performed a land use change scenario. For this scenario, all the HRUs which were under rangelands (covered 31% of the total watershed area) within this watershed were converted to pastures. Conversion of rangelands to pastures increased the percentage of area under pastures to 43% in this watershed (number of HRUs under pastures after land use change = 298). The increase in land use under pastures helped to reduce the effect of unmanaged land uses on nutrient losses at the watershed level and therefore quantify the effect of litter application method on watershed-level water quality.

RESULTS AND DISCUSSION

SWAT model calibration and validation

The graphs showing time series of observed and simulated surface runoff, baseflow, and streamflow are shown in Figure 3. The SWAT model performed satisfactorily to simulate surface runoff, baseflow, and streamflow. The differences in average annual simulated and observed values of surface runoff, baseflow, and streamflow were less than 10% (Table 3). It should be noted that the time-series plot of observed vs. simulated baseflow (Figure 3) shows that the model captured the temporal trends in

baseflow well on a monthly time step. However, there were instances when the model underestimated or overestimated baseflow. These episodic contrasting trends in the simulated baseflow estimates balanced out on an average annual basis resulting in a perfect match of observed and simulated average baseflow values (Table 3). The NSE, PBIAS, and R^2 values for surface runoff, baseflow, and streamflow for the calibration and validation periods are included in Table 4. Based on the criteria specified by Moriasi *et al.* (2007), SWAT satisfactorily simulated streamflow. The observed vs. simulated total P and N loads at a monthly time step are shown in Figure 4. The total P and N loads predicted by the model followed the trends of observed total P and N loadings. The average monthly (January 1991–September 1998) observed and simulated P loading at the watershed outlet were 139 kg and 105 kg, respectively. Similarly, at the watershed outlet, the observed and simulated average monthly N loadings were 3,446 kg and 3,298 kg, respectively. Overall, the SWAT model adequately simulated the trends in observed monthly surface runoff, baseflow, total streamflow, total P, and total N. The model simulated results were comparable to the previous studies conducted in this watershed (Srivastava *et al.* 2010; Mirhosseini & Srivastava 2016). The SWAT model was not calibrated and validated for sediment at the watershed outlet because observed sediment data were not available. However, the average annual sediment yield values of various land uses estimated by SWAT model for the study watershed were similar to the sediment yield values reported by Niraula *et al.* (2012) for a watershed located nearby in south AL, indicating that the model captured sediment transport processes well.

Effect of broiler litter application method on P and N losses at the HRU level

At the HRU level, nutrient losses were significantly ($p < 0.05$) less in surface runoff when broiler litter was subsurface-applied compared to surface application of broiler litter. Subsurface application of broiler litter to pastures reduced average annual soluble P losses in surface runoff at the HRU level by 71.5% compared to surface application of broiler litter (Figure 5). Average annual total P losses were reduced by 71.7% in surface runoff at the HRU level
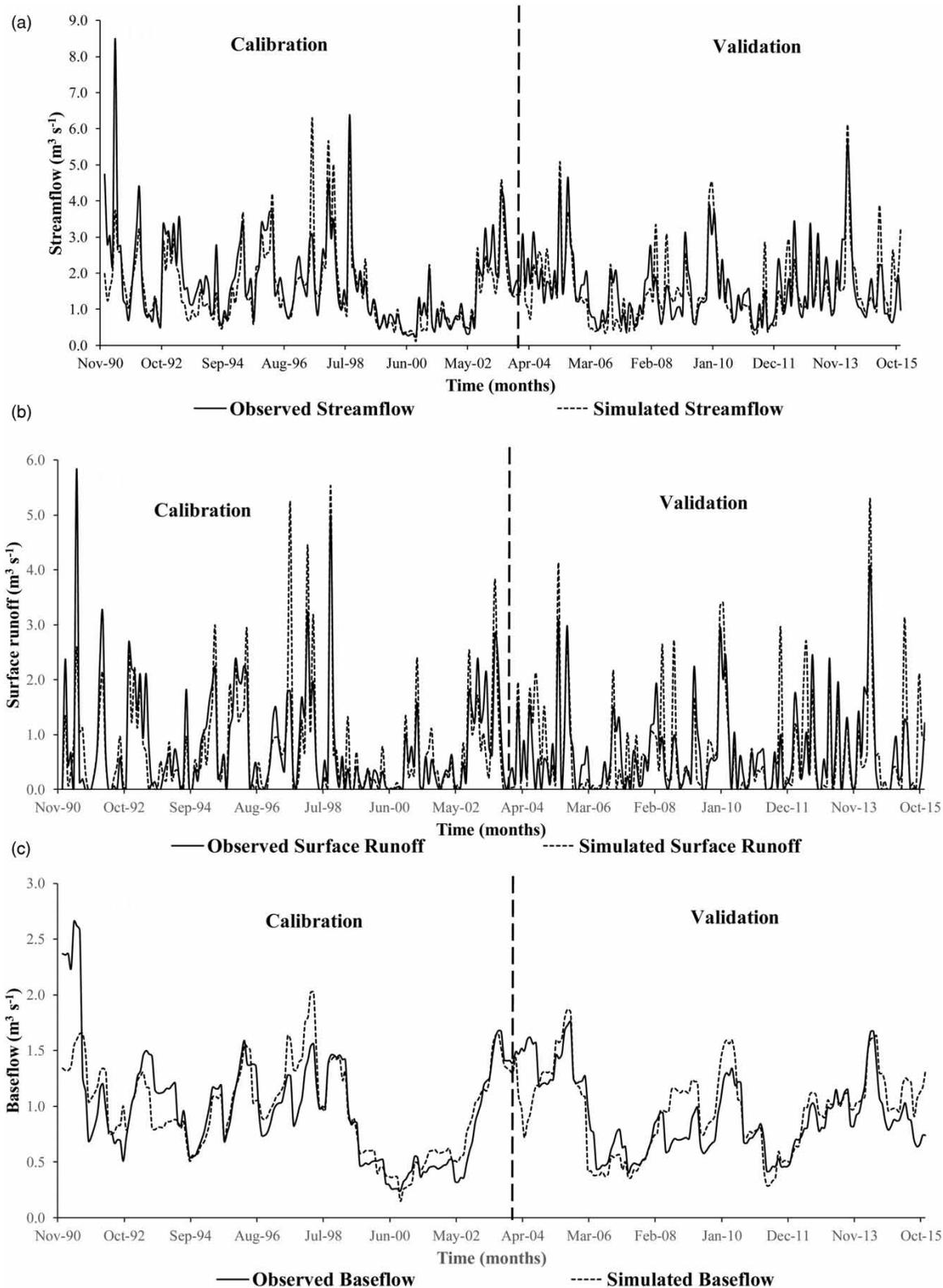
Figure 3 | Observed vs. simulated: (a) streamflow ($m^3 s^{-1}$), (b) surface runoff ($m^3 s^{-1}$), and (c) baseflow ($m^3 s^{-1}$).

Table 3 | Average annual observed and simulated streamflow ($m^3 s^{-1}$), surface runoff ($m^3 s^{-1}$) and baseflow ($m^3 s^{-1}$) for the time-period of January 1991–December 2015

Variable	Average annual value ($m^3 s^{-1}$)
Observed streamflow	1.67
Simulated streamflow	1.81
Estimated surface runoff	0.62
Simulated surface runoff	0.74
Estimated baseflow	1.05
Simulated baseflow	1.05

when broiler litter was subsurface-applied in comparison with the surface application of broiler litter to pastures (Figure 5). Since soluble P was the dominant part (around 72%) of total P in surface runoff from pastures (erosion rates from pastures are minimal), trends in reduction of soluble P and total P as a result of subsurface application of broiler litter were similar. Similarly, Lamba *et al.* (2013) reported that soluble P is the dominant form of total P in surface runoff from pastures. Compared to surface application of broiler litter, subsurface application of broiler litter reduced average annual total N losses in surface runoff at the HRU level by 33%. Similar trends were observed for nitrate losses in surface runoff between two broiler litter application methods (Figure 6). Unlike N, P is less mobile and binds to soil particles (Heathwaite *et al.* 2000), which likely resulted in greater reduction in P losses relative to N losses when broiler litter was subsurface-applied instead of broadcasting broiler litter on the soil surface.

Sharpley (1985) reported that the surface runoff interacts with the top few centimeters of soil. In SWAT, the top soil surface layer (10 mm deep) interacts with the surface runoff. In the subsurface application of broiler litter method, broiler litter was added to the first soil layer, which is below the 10 mm deep soil surface layer. Therefore, P and N losses for the subsurface application of broiler litter method were less compared to surface application of broiler litter due to a lack of direct contact between surface runoff and broiler litter. Whereas in surface application of broiler litter, surface runoff was in direct contact with the broiler litter applied to the soil (broiler litter integrated within the top 10 mm soil surface layer), which resulted in greater losses of P and N in this method of litter application relative to subsurface application of broiler litter. Several field-based studies (Glæsner *et al.* 2011; Lamba *et al.* 2012) have reported that P and N losses are less in surface runoff when broiler litter is applied beneath the soil surface relative to surface application of broiler litter. For example, Pote *et al.* (2011) reported around 90% reduction in total P and N losses in surface runoff with subsurface band application of broiler litter compared to surface application of broiler litter. Similar results were reported by Glæsner *et al.* (2011) and Lamba *et al.* (2012). The results of this study showed that the SWAT model adequately predicted the effect of broiler litter application method on nutrient losses in surface runoff and results were similar to the field-based studies (conducted at plot or field scale for individual storm events). Importantly, SWAT modeling results show that subsurface application of broiler litter helped to reduce nutrient losses in surface runoff on a long-term basis, which has not been investigated in previous studies.

Effect of soil type and slope on P and N losses

A combination of different factors can influence P and N losses in surface runoff from pastures. For example, amount of surface runoff generated from an HRU, soil type, and slope can affect P and N losses in surface runoff. The

Table 4 | Streamflow, surface runoff, baseflow, total P, total N, NSE, R^2, and PBIAS (%) values for the calibration and validation time periods at the watershed outlet

|	Streamflow		Surface runoff		Baseflow		Total P		Total N	
	Calibration	Validation	Calibration	Validation	Calibration	Validation	Calibration	Validation	Calibration	Validation
NSE	0.593	0.651	0.527	0.557	0.557	0.574	0.215	0.125	0.624	0.605
R^2	0.604	0.689	0.682	0.563	0.627	0.611	0.565	0.456	0.728	0.776
PBIAS (%)	−6.034	3.477	6.277	−7.724	1.174	−4.847	20.5	24.05	10.15	−3.96
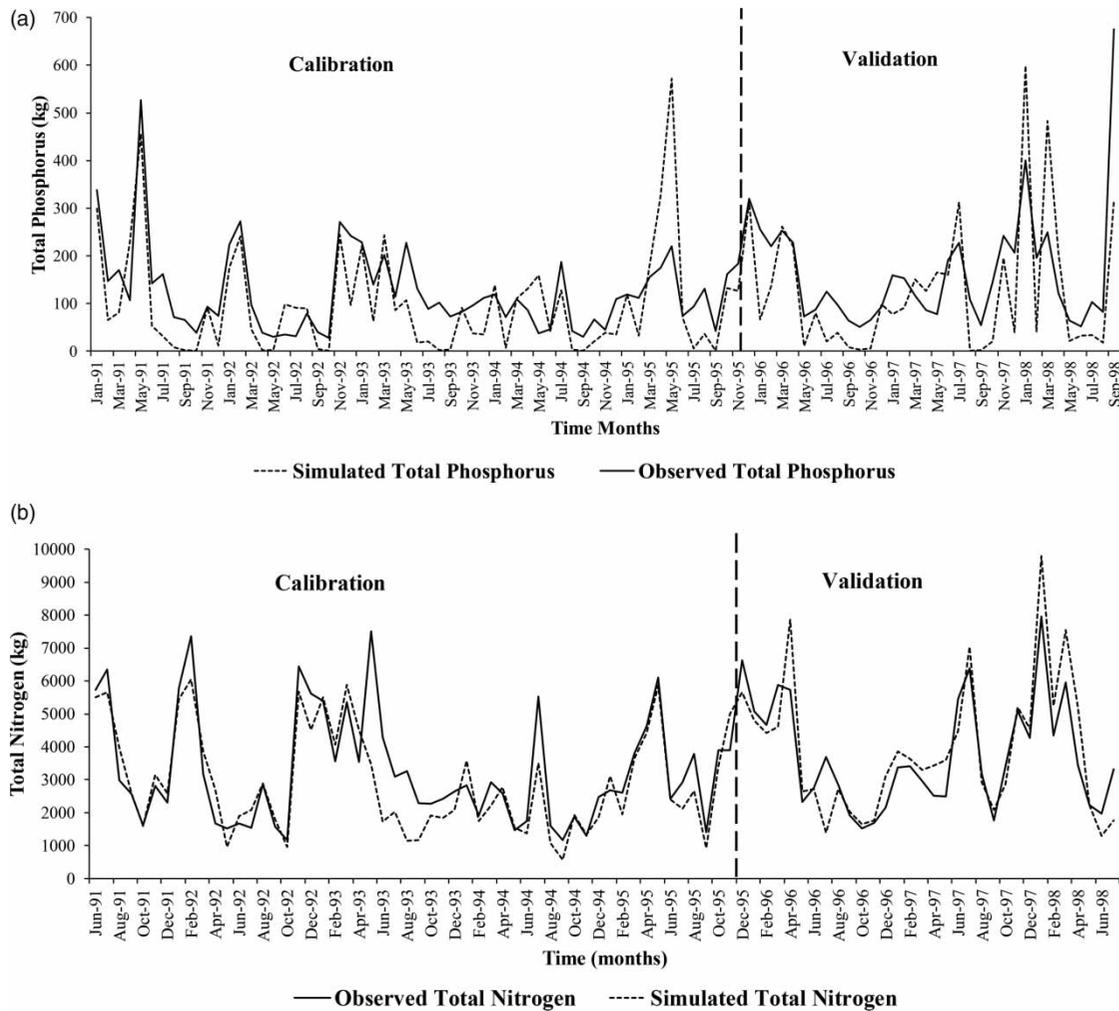
Figure 4 | Observed vs. simulated monthly: (a) P and (b) N loading (kg) at the watershed outlet.

amount of surface runoff generated from an HRU was affected by the HSG and slope (Table 5). The results show that the HSG D HRUs (mainly clayey soils) and HRUs at a slope greater than 10% generated a greater amount of surface runoff compared to HSG A or B soils on less steep (<10%) slopes. The P and N losses in surface runoff were greater from the HSG D soils and soils at a slope >10% (Figures 7–10). The HSG D soils have the potential to generate high surface runoff due to low infiltration rates compared to the HSG A and B soils (Edwards & Daniel 1993; Lamba et al. 2016). Soluble P losses increased as the amount of surface runoff generated from an HRU increased ($R^2 = 0.722$). Similar trends were observed between total P losses and amount of surface runoff generated from an HRU

($R^2 = 0.723$). The trends between surface runoff vs. soluble P losses and surface runoff vs. total P losses were similar because soluble P was the dominant component (~72%) of total P in surface runoff from pastures. Similarly, soluble P and total P losses from HRUs with slope >10% were greater compared to HRUs with slope 0–5% and 5–10% (Figure 8). The percentage reduction in soluble and total P losses per unit area as a result of subsurface application of broiler litter among HRUs on different HSG soils and slope classes was similar (Figures 7 and 8). The effect of HSG and slope was similar on N losses in surface runoff as a function of broiler litter application method (Figures 9 and 10). Overall, results show that subsurface application of broiler litter helped to reduce P and N losses substantially in surface
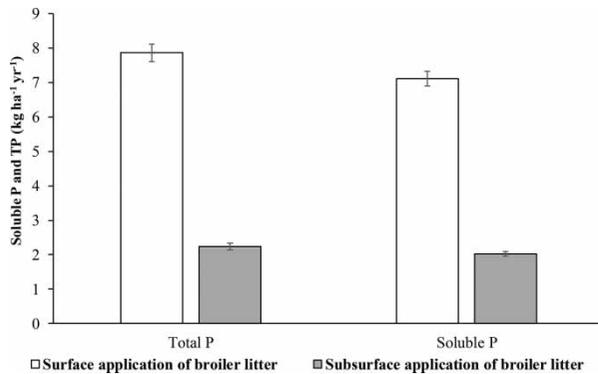
Figure 5 | Average annual (1991–2015) total and soluble P losses (kg ha^{-1} yr^{-1}) from pasture HRUs in surface runoff as a function of surface and subsurface application of broiler litter. Each half bar represents one standard error.
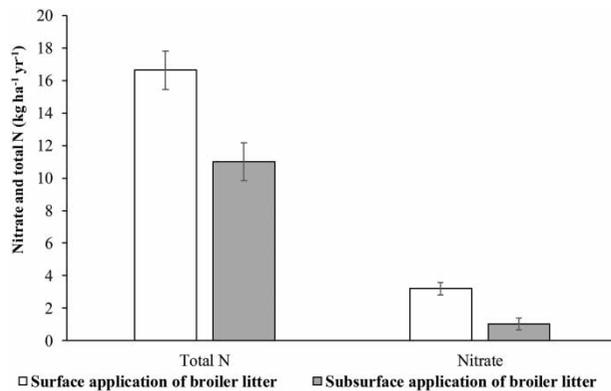
Figure 6 | Average annual (1991–2015) total N and nitrate losses (kg ha^{-1} yr^{-1}) from pasture HRUs in surface runoff as a function of surface and subsurface application of broiler litter. Each half bar represents one standard error.

Table 5 | Average annual (1991–2015) surface runoff values (mm) ± standard error for pasture HRUs as a function of HSG and slope classes

Soil/Slope	Surface runoff (mm)
A	50 ± 0.29
B	254 ± 0.31
D	598 ± 0.36
0–5%	136 ± 0.35
5–10%	167 ± 0.35
>10%	174 ± 0.48

runoff regardless of soil type and slope. The HRUs with HSG D and on slope >10% can help to reduce P and N losses substantially as a result of subsurface application of broiler litter relative to HRUs with slope 0–5% or 5–10% and on HSG A or B soils. Therefore, areas with steep slopes consisting of

HSG D soils should be prioritized for subsurface application of broiler litter.

## Nutrient losses at the subwatershed and watershed level

The reduction in N and P losses because of subsurface application of broiler litter varied as a function of spatial scale (e.g., HRU, subwatershed, and watershed level). The effectiveness of subsurface application of broiler litter in reducing nutrient losses diminished with the increase in the spatial scale. For example, the reductions in average annual total N and total P losses in surface runoff as a result of subsurface application of broiler litter at the subwatershed level ranged from 3% to 16% and 2% to 12%, respectively. Similarly, reductions in average annual soluble P and nitrate losses at the subwatershed level ranged from 3% to 16% and 1% to 10%, respectively. In contrast, subsurface application of broiler litter to pastures reduced average annual (1991–2015) total N and total P losses in surface runoff at the HRU level by 33% and 72%, respectively. The land use percentage under pastures within subwatersheds ranged from 12% to 43%. Since only a small fraction of area was under pastures within each subwatershed, the effect of subsurface application of broiler litter on nutrient losses at the subwatershed level was less compared to the HRU level. It should be noted that in addition to land use within a subwatershed, additional characteristics (e.g., soil type, slope, subwatershed size) can affect N and P losses within a subwatershed. For example, the amount of surface runoff generated within a subwatershed affected P and N losses at the subwatershed level. Subwatersheds generating a high amount of surface runoff per unit area contributed a greater amount of P and N to a stream ($R^2 = 0.99$). At the watershed level, subsurface application of broiler litter reduced average annual (1991–2015) P and N losses by 3% and 2%, respectively (Table 6). The effect of subsurface application of broiler litter on P and N losses at the watershed level was minimal because only 12% of the total watershed area was under pasture, whereas around 80% of the total watershed area was under unmanaged land uses (e.g., forests, rangelands). The P and N losses from the unmanaged land uses were minimal and likely masked the reduction in P and N at
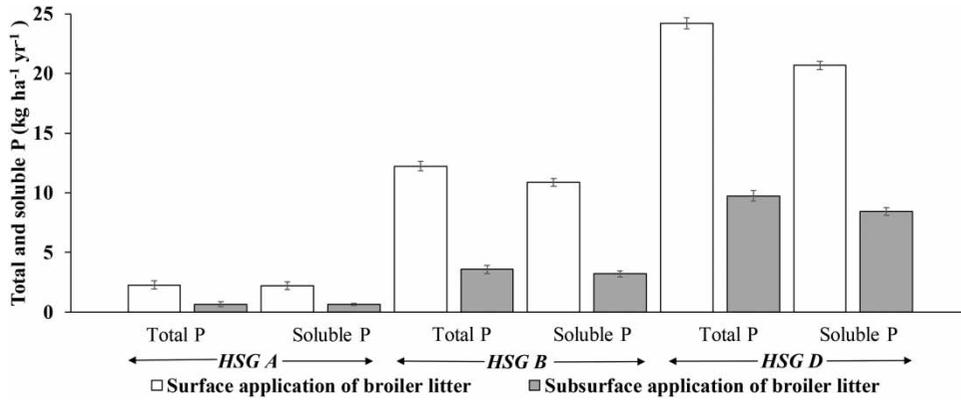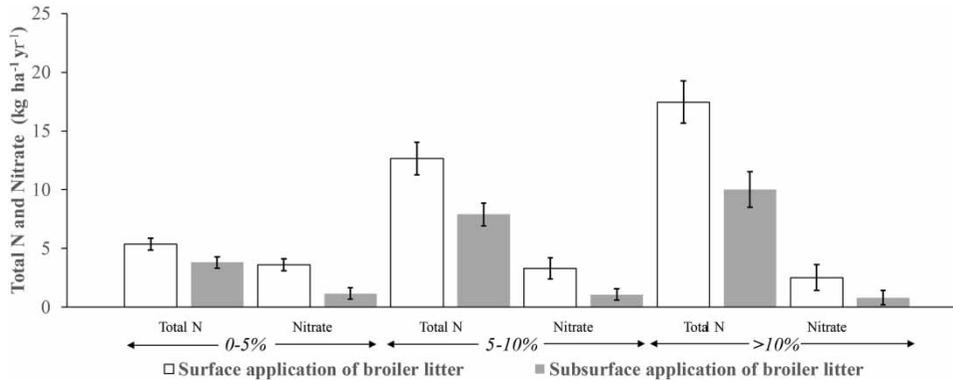
Figure 7 │ Average annual (1991–2015) total and soluble P losses (kg ha^{-1} yr^{-1}) in surface runoff from pastures at the HRU level from soils of different HSGs as a function of surface and subsurface application of broiler litter. Each half bar represents one standard error.
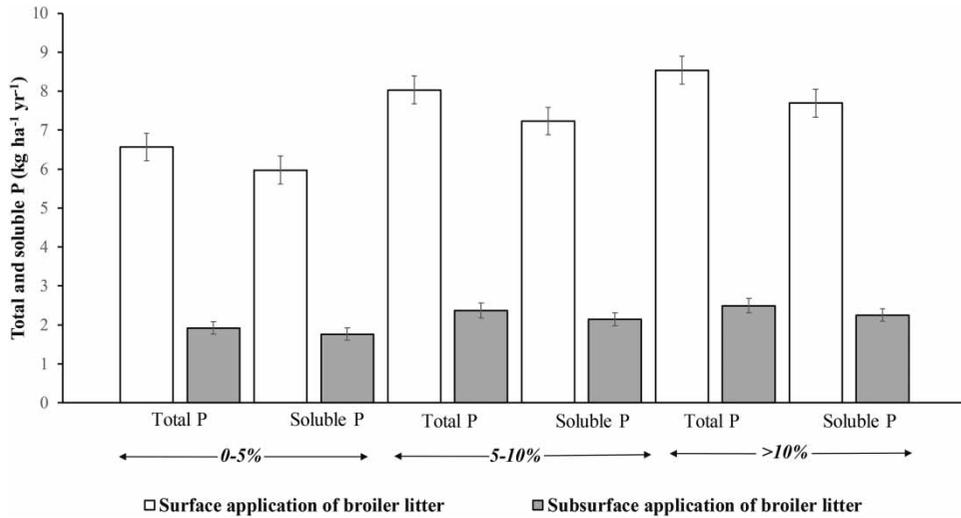
Figure 8 │ Average annual (1991–2015) total and soluble P losses (kg ha^{-1} yr^{-1}) in surface runoff from pastures at the HRU level from soils on different slope classes as a function of surface and subsurface application of broiler litter. Each half bar represents one standard error.
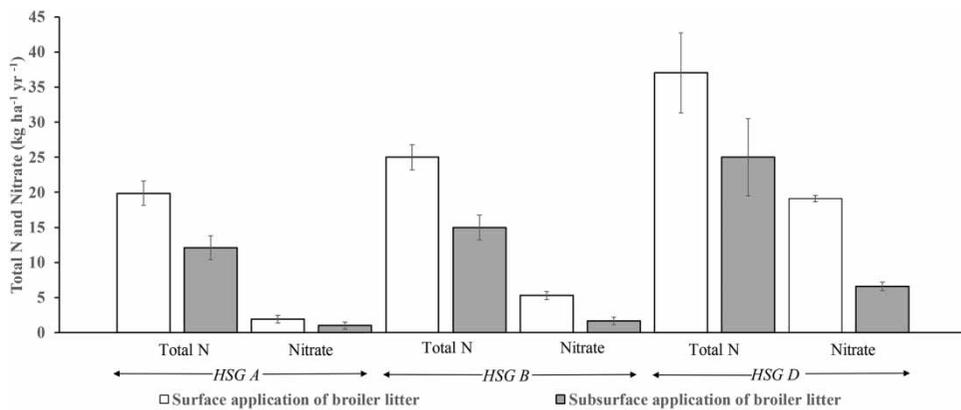
Figure 9 │ Average annual (1991–2015) total N and nitrate losses (kg ha^{-1} yr^{-1}) in surface runoff from pastures at the HRU level from soils of different HSG as a function of surface and subsurface application of broiler litter. Each half bar represents one standard error.

Figure 10 | Average annual (1991–2015) total N and nitrate losses (kg ha^{-1} yr^{-1}) in surface runoff from pastures at the HRU level from soils on different slope classes as a function of surface and subsurface application of broiler litter. Each half bar represents one standard error.

Table 6 | Percentage reduction in average annual (1991–2015) P and N losses before and after land use change scenario at the HRU, subwatershed, and watershed level

	Before land use change (%)				After land use change (%)			
Spatial scale	Soluble P	Total P	Nitrate	Total N	Soluble P	Total P	Nitrate	Total N
HRU level	72	72	68	33	65	65	69	33
Subwatershed level	11	12	8	8	46	48	22	25
Watershed level	2.5	3	2	2	35	39	17	20

the watershed outlet as a result of subsurface application of broiler litter. For example, at the HRU level, average annual (1991–2015) P and N losses in surface runoff from rangelands were 0.117 and 0.238 kg ha^{-1}, respectively. Similarly, for forested areas, average annual (1991–2015) P and N losses in surface runoff were 0.037 and 0.085 kg ha^{-1}, respectively. Therefore, dilution of P-enriched surface runoff from pastures with P-depleted surface runoff from unmanaged areas masked the downstream improvement in water quality at the watershed outlet. Additionally, baseflow is the dominant component (57%) of the total streamflow in the study watershed, which further masked the improvement in water quality at the watershed outlet. Results of this study show that it is important to evaluate the effectiveness of BMPs at various spatial scales (e.g., HRU, subwatershed, watershed level). This is because effectiveness of BMPs may vary as a function of spatial scale depending on the percentage of area targeted for BMPs, unmanaged land uses within a watershed, soil type, and slope.

As mentioned earlier, rangelands were converted into pasture land use to assess the effectiveness of subsurface application of broiler litter at the watershed level. The percentage of total watershed area under pastures was 43%

after converting rangelands to pastures. After the land use conversion of rangelands to pastures, subsurface application of broiler litter helped to reduce average annual (1991–2015) total P and N losses at the watershed level by 39% and 20%, respectively, compared to surface application of broiler litter (Table 6). Therefore, results of this study show that subsurface application of broiler litter can help to reduce P and N losses at the watershed level in agricultural watersheds.

CONCLUSIONS

This study used the SWAT model to test the effectiveness of subsurface application of broiler litter in reducing P and N losses from pastures. The SWAT model adequately predicted the effect of broiler litter application method on P and N losses in surface runoff. The results of this study show that at the HRU level, subsurface application of broiler litter helped to reduce average annual total P and N losses in surface runoff by 72% and 33%, respectively, compared to surface application of broiler litter. The reduction in P and N losses at the HRU level was greater compared to

subwatershed and watershed level. Soluble P was the dominant fraction of total P losses in surface runoff from pastures. The subsurface application of broiler litter on clayey soils at steep slopes can help to reduce P and N losses in surface runoff substantially. The land use change scenario (conversion of rangelands to pastures) showed that subsurface application of broiler litter can help to improve watershed level water quality in agricultural watersheds.

REFERENCES

Ahring, R. M., Huffine, W. W., Taliaferro, C. M. & Morrison, R. D. 1975 Stand establishment of bermudagrass from seed. *Agronomy Journal* **67** (2), 229–232.

Aksoy, B., Cullinan, H. T., Sammons Jr, N. E. & Eden, M. R. 2008 Identification of optimal poultry litter biorefinery location in Alabama through minimization of feedstock transportation cost. *Environmental Progress* **27** (4), 515–523.

Arabi, M., Govindaraju, R. S., Hantush, M. M. & Engel, B. A. 2006 Role of watershed subdivision on modeling the effectiveness of best management practices with SWAT. *JAWRA Journal of the American Water Resources Association* **42** (2), 513–528.

Artita, K. S., Kaini, P. & Nicklow, J. W. 2013 Examining the possibilities: generating alternative watershed-scale BMP designs with evolutionary algorithms. *Water Resources Management* **27** (11), 3849–3863.

Carpenter, S. R., Caraco, N. F., Correll, D. L., Howarth, R. W., Sharpley, A. N. & Smith, V. H. 1998 Nonpoint pollution of surface waters with phosphorus and nitrogen. *Ecological Applications* **8** (3), 559–568.

Coffey, M. E., Workman, S. R., Taraba, J. L. & Fogle, A. W. 2004 Statistical procedures for evaluating daily and monthly hydrologic model predictions. *Transactions of the American Society of Agricultural Engineers* **47** (1), 59–68.

Collick, A. S., Veith, T. L., Fuka, D. R., Kleinman, P. J. A., Buda, A. R., Weld, J. L., Bryant, R. B., Vadas, P. A., White, M. J., Harmel, R. D. & Easton, Z. M. 2016 Improved simulation of edaphic and manure phosphorus loss in SWAT. *Journal of Environmental Quality* **45** (4), 1215–1225.

Dechmi, F. & Skhiri, A. 2013 Evaluation of best management practices under intensive irrigation using SWAT model. *Agricultural Water Management* **123**, 55–64.

Edwards, D. R. & Daniel, T. C. 1993 Effects of poultry litter application rate and rainfall intensity on quality of runoff from fescuegrass plots. *Journal of Environmental Quality* **22** (2), 361–365.

Elrashidi, M. 2010 *Selection of an Appropriate Phosphorus Test for Soils. Testing Methods for Phosphorus and Organic Matter.* National Resources Conservation Service, USDA, Lincoln,

NE. https://www.nrcs.usda.gov/wps/portal/nrcs/detail/soils/research/guide/?cid=nrcs142p2_054264.

Fry, J., Xian, G. Z., Jin, S., Dewitz, J., Homer, C. G., Yang, L., Barnes, C. A., Herold, N. D. & Wickham, J. D. 2011 Completion of the 2006 national land cover database for the conterminous United States. *Photogrammetric Engineering and Remote Sensing* **77** (9), 858–864.

Gana, A. 2011 Appropriate method for organic manure application for higher sugarcane yield in Nigeria. *Journal of Agricultural Technology* **7** (6), 1549–1559.

Glæsner, N., Kjaergaard, C., Rubæk, G. H. & Magid, J. 2011 Interactions between soil texture and placement of dairy slurry application: II. Leaching of phosphorus forms. *Journal of Environmental Quality* **40** (2), 344–351.

Heathwaite, L., Sharpley, A. & Gburek, W. 2000 A conceptual approach for integrating phosphorus and nitrogen management at watershed scales. *Journal of Environmental Quality* **29** (1), 158–166.

Journey, C. A. & Gill, A. C. 2001 *Assessment of Water-Quality Conditions in the JB Converse Lake Watershed, Mobile County, Alabama, 1990–98.* US Department of the Interior, US Geological Survey, Montgomery, AL.

Kanwar, R. S., Baker, J. L. & Laflen, M. J. 1985 Nitrate movement through the soil profile in relation to tillage system and fertilizer application method. *Transactions of the ASAE* **28** (6), 1802–1807.

Kleinman, P. J. A. & Sharpley, A. N. 2003 Effect of broadcast manure on runoff phosphorus concentrations over successive rainfall events. *Journal of Environmental Quality* **32** (3), 1072–1081.

Kleinman, P. J. A., Sharpley, A. N., Buda, A. R., Easton, Z. M., Lory, J. A., Osmond, D. L., Radcliffe, D. E., Nelson, N. O., Veith, T. L. & Doody, D. G. 2017 The promise, practice, and state of planning tools to assess site vulnerability to runoff phosphorus loss. *Journal of Environmental Quality* **46** (6), 1243–1249.

Lamba, J., Way, T. R., Srivastava, P., Sen, S., Wood, C. W. & Yoo, K. H. 2012 Surface transport of nutrients from surface-broadcast and subsurface-banded broiler litter. *Transactions of the ASABE* **55** (3), 995–1002.

Lamba, J., Srivastava, P., Way, T. R., Sen, S., Wood, C. W. & Yoo, K. H. 2013 Nutrient loss in leachate and surface runoff from surface-broadcast and subsurface-banded broiler litter. *Journal of Environmental Quality* **42** (5), 1574–1582.

Lamba, J., Thompson, A. M., Karthikeyan, K. G., Panuska, J. C. & Good, L. W. 2016 Effect of best management practice implementation on sediment and phosphorus load reductions at subwatershed and watershed scale using SWAT model. *International Journal of Sediment Research* **31** (4), 386–394.

Lee, M., Park, G., Park, M., Park, J., Lee, J. & Kim, S. 2010 Evaluation of non-point source pollution reduction by applying Best Management Practices using a SWAT model and QuickBird high resolution satellite imagery. *Journal of Environmental Sciences* **22** (6), 826–833.

Lim, K. J., Engel, B. A., Tang, Z., Choi, J., Kim, K. S., Muthukrishnan, S. & Tripathy, D. 2005 Automated web GIS based hydrograph analysis tool, WHAT. *JAWRA Journal of the American Water Resources Association* **41** (6), 1407–1416.

Liu, R., Zhang, P., Wang, X., Wang, J., Yu, W. & Shen, Z. 2014 Cost-effectiveness and cost-benefit analysis of BMPs in controlling agricultural nonpoint source pollution in China based on the SWAT model. *Environmental Monitoring and Assessment* **186** (12), 9011–9022.

Mirhosseini, G. & Srivastava, P. 2016 Effect of irrigation and climate variability on water quality of coastal watersheds: case study in Alabama. *Journal of Irrigation and Drainage Engineering* **142** (2), 05015010.

Mondal, P., Srivastava, P., Kalin, L. & Panda, S. N. 2011 Ecologically sustainable surface water withdrawal for cropland irrigation through incorporation of climate variability. *Journal of Soil and Water Conservation* **66** (4), 221–232.

Moriasi, D. N., Arnold, J. G., Van Liew, M. W., Bingner, R. L., Harmel, R. D. & Veith, T. L. 2007 Model evaluation guidelines for systematic quantification of accuracy in watershed simulations. *Transactions of the ASABE* **50** (3), 885–900.

Moriasi, D., Wilson, B. N., Douglas-Mankin, K. R., Arnold, J. G. & Gowda, P. H. 2012 Hydrologic and water quality models: use, calibration, and validation. *Transactions of the ASABE* **55** (4), 1241–1247.

Neitsch, S., Arnold, J. G., Kiniry, J. S. & Williams, J. R. 2011 *Soil & Water Assessment Tool Theoretical Documentation Version 2009*. Texas Water Resources Institute, College Station, TX, USA, pp. 1–647.

Neitsch, S. L., Arnold, J. G., Kiniry, J. R., Srinivasan, R. & Williams, J. R. 2002 *Soil and Water Assessment Tool User's Manual, Version 2000*. Texas Water Resources Institute, College Station, TX, USA.

Niraula, R., Kalin, L., Wang, R. & Srivastava, P. 2012 Determining nutrient and sediment critical source areas with SWAT: effect of lumped calibration. *Transactions of the ASABE* **55** (1), 137–147.

Niraula, R., Kalin, L., Srivastava, P. & Anderson, C. J. 2013 Identifying critical source areas of nonpoint source pollution with SWAT and GWLF. *Ecological Modelling* **268**, 123–133.

Otinga, A. N., Pypers, P., Okalebo, J. R., Njoroge, R., Emong'ole, M., Six, L., Vanlauwe, B. & Merckx, R. 2013 Partial substitution of phosphorus fertiliser by farmyard manure and its localised application increases agronomic efficiency and profitability of maize production. *Field Crops Research* **140**, 32–43.

Panagopoulos, Y., Makropoulos, C. & Mimikou, M. 2011 Reducing surface water pollution through the assessment of the cost-effectiveness of BMPs at different spatial scales. *Journal of Environmental Management* **92** (10), 2823–2835.

Pote, D. H., Way, T. R., Kleinman, P. J. A., Moore, P. A., Meisinger, J. J., Sistani, K. R., Saporito, L. S., Allen, A. L. & Feyereisen, G. W. 2011 Subsurface application of poultry litter in pasture and no-till soils. *Journal of Environmental Quality* **40** (2), 402–411.

Rahman, K., Maringanti, C., Beniston, M., Widmer, F., Abbaspour, K. & Lehmann, A. 2013 Streamflow modeling in a highly managed mountainous glacier watershed using SWAT: the Upper Rhone River watershed case in Switzerland. *Water Resources Management* **27** (2), 323–339.

Ranatunga, T. D., Reddy, S. S. & Taylor, R. W. 2013 Phosphorus distribution in soil aggregate size fractions in a poultry litter applied soil and potential environmental impacts. *Geoderma* **192**, 446–452.

Randall, G. W. & Hoeft, R. G. 1988 Placement methods for improved efficiency of P and K fertilizers: a review. *Journal of Production Agriculture* **1** (1), 70–79.

Roberts, T. L. 2007 Right product, right rate, right time and right place … the foundation of best management practices for fertilizer. In: *International Fertilizer Industry Association (IFA) Workshop on Fertilizer Best Management Practices*, March 7–9, 2007, Brussels, Belgium.

Santhi, C., Srinivasan, R., Arnold, J. G. & Williams, J. R. 2006 A modeling approach to evaluate the impacts of water quality management plans implemented in a watershed in Texas. *Environmental Modelling & Software* **21** (8), 1141–1157.

Sharpley, A. N. 1985 Depth of surface soil-runoff interaction as affected by rainfall, soil slope, and management. *Soil Science Society of America Journal* **49** (4), 1010–1015.

Shaver, B. R., Richardson, M. D., McCalla, J. H., Karcher, D. E. & Berger, P. J. 2006 Dormant seeding bermudagrass cultivars in a transition-zone environment. *Crop Science* **46** (4), 1787–1792.

Srivastava, P., Gupta, A. K. & Kalin, L. 2010 An ecologically-sustainable surface water withdrawal framework for cropland irrigation: a case study in Alabama. *Environmental Management* **46** (2), 302–313.

Strauch, M., Bernhofer, C., Koide, S., Volk, M., Lorz, C. & Makeschin, F. 2012 Using precipitation data ensemble for uncertainty analysis in SWAT streamflow simulation. *Journal of Hydrology* **414–415**, 413–424.

Torbert, H. A. & Watts, D. B. 2014 Impact of flue gas desulfurization gypsum application on water quality in a coastal plain soil. *Journal of Environmental Quality* **43** (1), 273–280.

USDA 2016 *Poultry: Production and Value*. USDA National Agricultural Statistics Service, Washington, DC, USA. http://usda.mannlib.cornell.edu/usda/current/PoulProdVa/PoulProdVa-04-28-2017.pdf.

USEPA 2009 *National Water Quality Inventory: Report to Congress, 2004 Reporting Cycle*. U.S. Environmental Protection Agency, Washington, DC, USA. EPA 841-R-08-001.

USEPA 2014a https://iaspub.epa.gov/waters10/attains_index.control#total_assessed_waters (accessed 9 May 2018).

USEPA 2014b https://iaspub.epa.gov/waters10/attains_state.control?p_state=AL (accessed 9 May 2018).