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# Using SWAT to enhance watershed-based plans to meet numeric water quality standards

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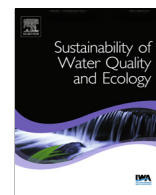
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## Using SWAT to enhance watershed-based plans to meet numeric water quality standards

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## ABSTRACT

The number of states that have adopted numeric nutrient water-quality standards has increased to 23, up from ten in 1998. One state with both stream and reservoir phosphorus (P) numeric water-quality standards is Oklahoma. There were two primary objectives of this research: (1) determine if Oklahoma was meeting the stream and reservoir numeric water-quality standards in the Illinois River and Eucha–Spavinaw watersheds, respectively and (2) identify various combinations of management practices required to meet the water-quality standards. A Soil and Water Assessment Tool (SWAT) model was developed for each watershed. After runoff and P calibration and validation, each model was used to determine if the numeric water-quality standards were exceeded. Due to recent land management changes in the Eucha–Spavinaw watershed, Oklahoma was meeting the established water quality standard,  $0.0168 \text{ mg L}^{-1}$  total P in Lake Eucha. Although extensive efforts to reduce P loads have been conducted in the last decade in the Illinois River watershed, a large quantity of P is still reaching the streams and Tenkiller Ferry Lake in the Illinois River watershed. The model was used to identify a combination of potential land management practices in Oklahoma to meet to meet the water-quality standard,  $0.037 \text{ mg L}^{-1}$  total P, in three of Oklahoma's designated Scenic Rivers: the Illinois River, Barren Fork Creek and Flint Creek. With recent reductions in poultry litter application and improvements in municipal waste water treatment plants, future conservation practices need to focus on cattle production and elevated soil test P. This research illustrated how a watershed model can provide critical information for watershed-based plans to address numeric water-quality standards.

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## 1. Introduction

Excessive nutrients are a major pollutant to many waterbodies worldwide. The United States (US) alone has 7765 waterbodies impaired due to nutrients with over a third on the States' Clean Water Act 303(d) list as a direct result of total phosphorus (P) (USEPA, 2015a). Major P sources include crop and livestock production, wastewater treatment plants (WWTPs) and urbanization. Dissolved and particulate P runoff and erode from overland sources such as agricultural fields, feed lots and urban lawns. Excess P entering streams, lakes and reservoirs can lead to eutrophication, resulting in algal blooms, oxygen depletion and the overall degradation of the water quality (Sims and Sharpley, 2005). Water quality degradation in

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streams and reservoirs has led to an increasing number of states to implement numeric water-quality standards, which can provide a remediation goal for state agencies to develop and implement effective watershed-based plans (USEPA, 2015b). The number of states adopting numeric water quality standards continues to increase; currently 23 states, which is over twice the number in 1998 (USEPA, 2015b).

Oklahoma has both stream, Illinois River watershed (IRW), and reservoir, Eucha–Spavinaw watershed (ESW), numeric water-quality standards. Both watersheds have a long history of poultry and cattle production leading to elevated soil test P, and elevated P in WWTP discharges. Major changes have occurred in the IRW and ESW during the last decade, including increased poultry litter export and upgrades to several WWTPs. Litigation induced changes, along with numerous technical assistance and agricultural cost share programs conducted by state and federal agencies, contributed to the decline in flow-adjusted total P concentrations in the Illinois River near the Oklahoma/Arkansas state line, at Tahlequah, Oklahoma and on the Barren Fork Creek near Eldon, Oklahoma (Scott et al., 2011; Haggard, 2010). In spite of the water-quality improvements in the watersheds, it is unknown if these are sufficient to meet Oklahoma water-quality standards.

The Soil and Water Assessment Tool (SWAT) (Arnold et al., 1998), a watershed-scale hydrological model, has been used worldwide to meet several different types of project needs such as the development of Total Maximum Daily Loads (TMDL) (Borah et al., 2006), modeling climate and land use change (Li et al., 2015) and the effects of conservation practices on water quality (Liu et al., 2014). However, to date the model has only been used by Storm et al. (2010) to aid in the development of a watershed-management plan to meet stream numeric water-quality standards. SWAT predictions have been used as input to reservoir models to evaluate if the water quality standard for a reservoir is exceeded (OWRB, 2008), but to date has not been used without a reservoir model.

The objectives of this research were to estimate P loads originating from the Oklahoma portion of these watersheds and to determine if those loads exceed existing water-quality standards. For this research, loads originating from Arkansas were not considered. If standards were not being met, new management practices were evaluated to reduce P loads. A variety of agricultural-management practices and land-use changes were simulated to determine the necessary changes required to meet the Oklahoma water-quality standards.



**Fig. 1.** Illinois River and Eucha–Spavinaw watersheds in northeast Oklahoma and northwest Arkansas showing counties (red), the Oklahoma/Arkansas state line (black) and the major streams and reservoirs. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

## 2. Methods and materials

### 2.1. Watershed descriptions

The IRW and ESW occupy over 4100 km<sup>2</sup> and 1100 km<sup>2</sup>, respectively (Fig. 1). Dominated by forest and pasture, the watersheds are located in the Ozark Highland Ecoregion. The area receives on average 1100 mm of precipitation annually. The headwaters of the Illinois River are in Benton County, Arkansas, and flow 230 km through Washington and Adair Counties before emptying into Tenkiller Ferry Lake (Lake Tenkiller) in Oklahoma. The two main tributaries are Barren Fork Creek and Flint Creek. Spavinaw Creek, also originating in Benton County, flows into eastern Oklahoma to Lake Eucha; its main tributary is Beaty Creek. The watersheds are characterized by well-drained cherty soils, dominated by Clarksville and Razort-gravelly loams. The gravel-bed streams are typically clear and support a variety of fish species. The average slope for pasture and forest is 4.5% and 17.7%, respectively. The main agricultural activities are pastured cow/calf operations and poultry production. Historically the largest sources of P from the upland areas were poultry litter, cattle and elevated soil test P (STP). The Illinois River and, to a lesser degree, Spavinaw Creek, are popular destinations for float trips, fishing and swimming. Lakes Tenkiller and Eucha are also popular recreational areas for fishing, boating and camping.

### 2.2. SWAT model description

SWAT is a basin-scale hydrological/water quality model used to predict streamflow and pollutant losses from watersheds with mixed land covers, soils and slopes. The model was developed to assist water resource managers assess water quantity and/or quality in large watersheds and as a tool to evaluate the impact on agricultural conservation practices implementation. The SWAT model, a product of over 30 years of model development by the US Department of Agriculture Agricultural Research Service, has been extensively used worldwide (Gassman et al., 2007, 2014). The model is process-based and can simulate several processes such as the hydrological cycle, soil erosion and nutrient transport.

This research used SWAT 2012 rev. 583 and the recently incorporated simplified in-stream P routine (White et al., 2014), which consists of two components. The first component represents the transformation of soluble P to particulate P (i.e. the uptake of soluble P by algae and P precipitation) and its interactions with sediment, which is based on an equilibrium P concentration (EPC). EPC is the concentration at which there is no net sorption or desorption from benthic sediments into the water column. If the EPC is greater than the concentration of soluble P in the water column, P moves from the streambed to the water column; the reverse occurs if the EPC is less than the soluble P. The second component represents the deposition and scour of particulate P (sediment-bound P and algal P) to/from the benthos. Based on the ratio of flow to bankfull discharge, P is either scoured or deposited.

### 2.3. SWAT model setup

Two SWAT models, one for each watershed, were created using the most detailed and accurate data available. Since land cover is one of the most important SWAT inputs and the latest available data was the 2006 National Land Cover Dataset (NLCD), a more recent land cover using Landsat 4–5 Thematic Mapper imagery was developed using ERDAS IMAGINE 9.3 and ArcGIS 10.0. Four Landsat 4–5 Thematic Mapper images from 2010 and 2011 were analyzed and the Normalized Difference Vegetation Index (NDVI) calculated in ERDAS IMAGINE using the equation:

$$\text{NDVI} = \frac{(\text{NIR} - \text{VIS})}{(\text{NIR} + \text{VIS})} \quad (1)$$

where VIS and NIR are the spectral reflectance measurements acquired in the visible (red) and near-infrared regions, respectively. The NDVI aided in the differentiation between vegetative land covers. An unsupervised land cover classification was conducted, and September 2011 ground truth data and 2010 NAIP (National Agricultural Imagery Program) aerial photographs were utilized to validate the 14 assigned land covers: water, wetlands, urban impermeable, urban grass, row crops, bare soil, shrub land, mixed hay, mixed well-managed, mixed overgrazed, warm season hay, warm season well-managed and warm season overgrazed. To simplify the SWAT model, the final land cover data layer was consolidated into nine categories with forest and pasture being the dominant land covers (Table 1; Fig. 2).

Topography was defined by a United States Geological Survey (USGS) 10 m resolution Digital Elevation Model (DEM), which was used to calculate subbasin parameters, e.g. slope and slope length. The slopes were divided into three categories: 0–3%, 3–10% and >10%. The SWAT model for the IRW and ESW were delineated into 147 subbasins with 4,930 HRUs and 129 subbasins with 3629 HRUs, respectively. Additional outlets were added at the USGS gage stations and at the Arkansas/Oklahoma state line for all major streams. Soil characteristics were defined using SSURGO (Soil Survey Geographic Database) data. Significant time and effort was invested gathering and creating the weather files, one of the most important parameters for a hydrological model. Nine National Oceanic and Atmospheric Administration (NOAA) weather stations and three Oklahoma Mesonet stations were used in the models (Fig. 3). Monthly data for 12 WWTPs in the IRW and one at Decatur, Arkansas in the ESW were added to the SWAT models as point sources (USEPA, 2012) (Fig. 3). WWTP average annual flow and organic and mineral P from 1990 to 2010 used in the calibration and validation periods are in Table 2. The final data layer

**Table 1**

Land cover categories and area percentages used in the Illinois River and Eucha–Spavinaw watershed SWAT models based on the 2010 and 2011 Landsat 4 and 5 Thematic Mapper images.

Land cover	Watershed coverage (%)	
	Illinois River	Eucha–Spavinaw
Forest	47.2	48.6
Well-managed pasture	19.0	27.0
Overgrazed pasture	8.3	3.4
Hay	11.9	8.7
Rangeland	3.6	2.6
Row crops	0.2	1.1
Bare soil	0.2	0.1
Urban	8.5	2.4
Water	1.3	1.9

added to the models was ponds, which affected the hydrology by impounding water and trapping sediment and nutrients. The pond data layer was obtained from the National Hydrography Dataset, and the drainage area fraction of ponds for each subbasin was calculated and input into SWAT.

#### 2.4. SWAT land cover management

The most important management data for the two watersheds were cattle stocking rates, litter application rates and STP. Cattle density was calculated using the average population from 1987 to 2007 (USDA Census of Agriculture, 2012), which yielded 101,700 and 24,500 heads of cattle for the IRW and ESW, respectively. Well-managed pastures were assumed to be grazed at 0.60 animal units ha<sup>-1</sup> and overgrazed pastures at 1.25 animal units ha<sup>-1</sup> (Redfearn, D., personal communication, March 12, 2012).

In order to estimate the quantity of litter applied per subbasin, the location of poultry houses, the total quantity of litter applied and the STP were required. The most recent poultry house location data for the IRW were 2005, which included 1958 active houses (Fig. 4), 361 abandoned houses, 838 inactive houses, 110 removed houses and 294 unknown status houses (Fisher et al., 2009). Since poultry house data were not available for the ESW (ANRC, 2014; ODAFF, 2013), the poultry houses were manually digitized using 2010 NAIP images (Fig. 4). A total of 908 houses were digitized. The number of active and inactive houses for the ESW was also unknown; therefore, assuming 80,000 birds per house and the ratio of active to inactive houses in the Illinois River watershed (Fisher et al., 2009), 508 poultry houses were considered active.

Based on the average number of broilers, turkeys, hens and pullets in the watersheds and the quantity of waste produced per bird (NMP, 2007), a total of 316,000 and 81,000 Mg (dry weight basis) of litter were produced annually in the IRW and ESW, respectively, during the calibration and validation periods. Starting in 2003, the export of litter increased substantially over time in the two watersheds based on data obtained from the Oklahoma Poultry Waste Report and Arkansas 2013 Poultry Waste Report (ODAFF, 2013; ANRC, 2014). Using these data, regression equations for litter export vs time for the IRW (Eq. (2)) and the ESW (Eq. (3)) were developed:

$$\text{Litter export (\%)} = 0.512473 * X^{2.1214} \quad (2)$$

$$\text{Litter export (\%)} = (2.6107 * X) + 59.352 \quad (3)$$

where  $X$  is the year (1–10). For the IRW calibration period (2001–2010), Eq. (4) was integrated and divided by the total number of years (9 years) to estimate the average annual litter export used in the model, given as:

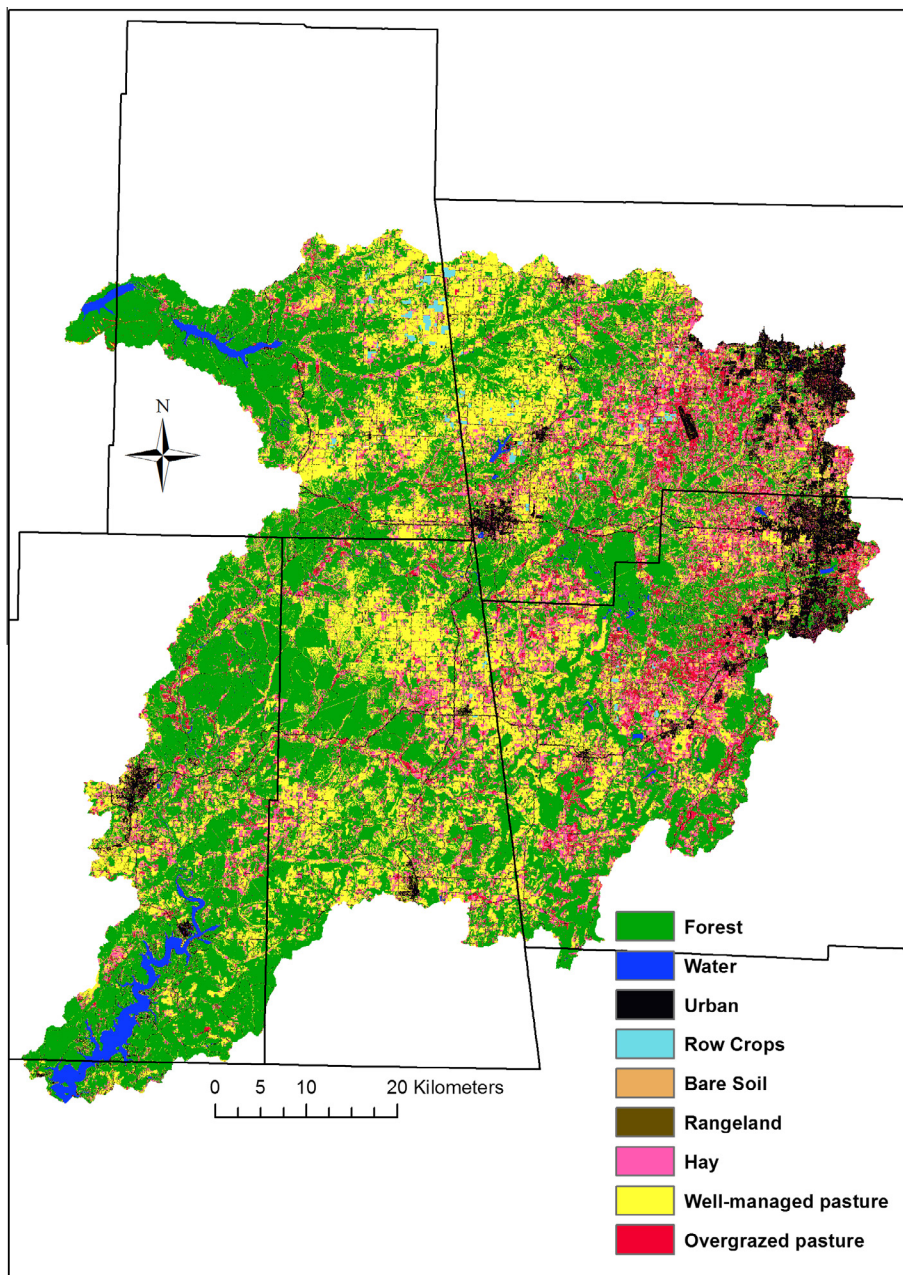
$$\text{IRW average annual litter export (\%)} = \frac{\int_1^{10} 0.512473 * X^{2.1214} dx}{9} = 24 \quad (4)$$

Twenty-four percent was subtracted from the total poultry litter produced in each county to obtain an average annual poultry litter application of 240,000 Mg. For the ESW calibration period (2002–2010), Eq. (5) was integrated and divided by the total number of years (8 years) to estimate the average annual litter export used in the model, given as:

$$\text{ESW average annual litter export (\%)} = \frac{\int_2^{10} (2.6107 * X + 59.352) dx}{8} = 75 \quad (5)$$

Seventy-five percent was subtracted from the total litter produced in each county to obtain an average annual litter application of 20,250 Mg.

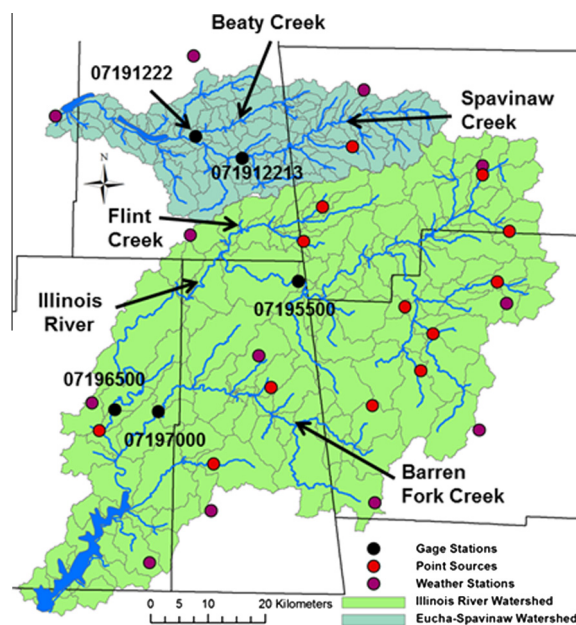




**Fig. 2.** Land cover for the Illinois River and Eucha–Spavinaw watershed SWAT models using 2010 and 2011 Landsat 4 and 5 Thematic Mapper images.

Reasonable estimates of the total poultry litter applied in the watersheds are given above; however, no data were available on the locations of poultry litter application. Litter was relatively expensive to transport and thus was typically only transported short distances; therefore, litter was assumed to be applied to pastures in close proximity to the point of production, i.e. within the same subbasin as the poultry houses. Pastures with the highest STP were assumed to receive more poultry litter over time. Oklahoma STP data for pastures were based on county level data from the Oklahoma State University (OSU) Soil, Water, and Forage Analytical Laboratory; data for Adair, Cherokee, Delaware and Sequoyah Counties were available from October 1994 to December 2008. Arkansas STP data were obtained from the University of Arkansas (UA) Soil Testing Laboratory for Benton and Washington Counties from 1999 to 2011.

The first step to determine poultry litter application rates by subbasin was to estimate the average pasture and hay meadow STP for each subbasin, which was assumed to have a minimum of  $15 \text{ mg kg}^{-1}$  (Engel et al., 2013). STP for each subbasin was calculated based on the ratio of poultry house numbers to pasture and hay meadow area. The more poultry houses per



**Fig. 3.** United States Geological Survey gage stations, weather stations and point sources used in the Illinois River and Eucha–Spavinaw watersheds SWAT models.

ha of pasture and hay meadow in a subbasin, the higher the STP assigned to the subbasin. Based on the county average observed STP for pasture and hay meadow, the subbasin STP values were uniformly adjusted to match the observed county average. This method was validated by comparing observed STP data for 529 samples on the Oklahoma side of the ESW (Storm and Mittelstet, 2015).

The quantity of poultry litter applied to each HRU was based on the average STP of the subbasin and the quantity of poultry litter produced in the county. Assuming all of the litter produced in a county was applied to all pasture and hay meadows within that county, the amount applied to each subbasin was estimated using an area weighted average of the subbasin STP values. As an example, assume a county had two subbasins, subbasin A and B, 2500 ha of pasture, 2500 ha of hay meadow, and STP of 100 and 300 mg kg<sup>-1</sup>, respectively. If the total litter produced in the county were 1,000 Mg, then subbasin A would receive  $1,000 * 300/400 = 250$  Mg of litter or 0.1 Mg ha<sup>-1</sup> and subbasin B would receive  $1,000 * 300/400 = 750$  Mg or 0.3 Mg ha<sup>-1</sup>. Since the litter was applied to all pasture and hay meadows, the application rate per ha was lower than reality since some fields do not receive litter each year.

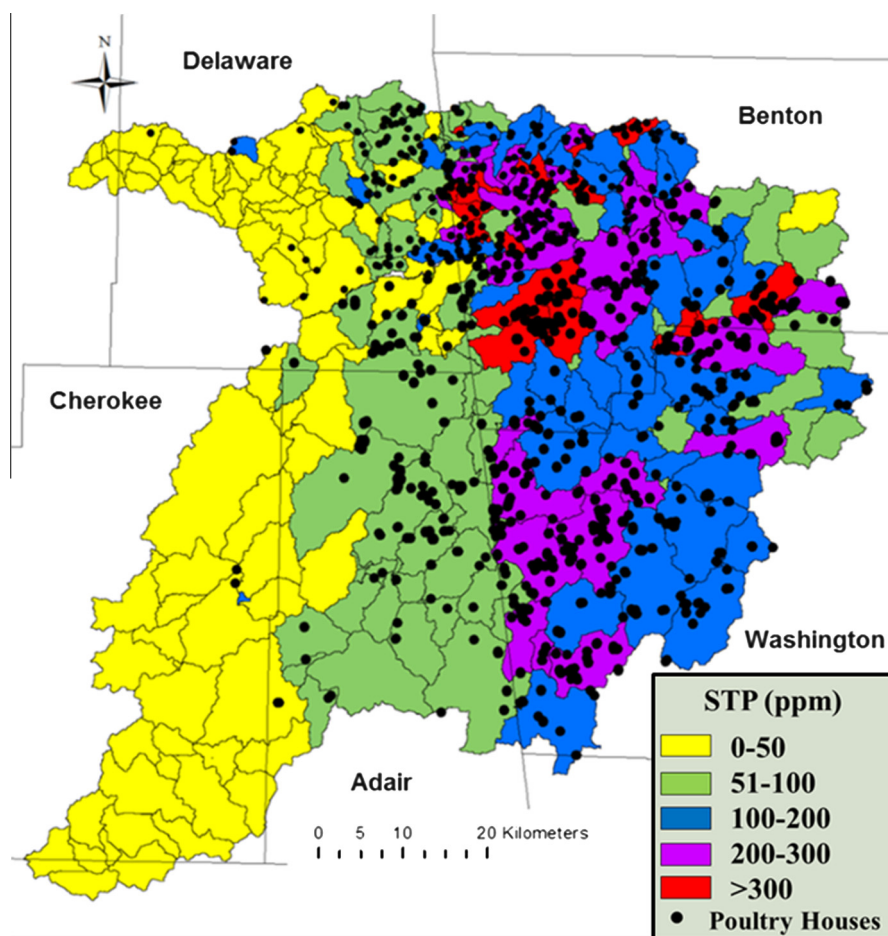
## 2.5. Model calibration and validation

Calibration is the process by which parameters are adjusted to make predictions agree with observations. Validation is similar to calibration except model parameters are not modified. Validation evaluates the calibrated model with observed data that are not used in the calibration process, and preferably under conditions outside the calibration period. For both the calibration and validation models, a five year warm-up was added to ensure that the model represents reasonable initial conditions at the beginning of each simulation, e.g. aquifer levels, soil water conditions, vegetative growth, etc.

**Table 2**

Average annual flow and organic and mineral phosphorus (P) load (1990–2010) from the wastewater treatment plants in the Illinois River and Eucha–Spavinaw watersheds used in the SWAT model for the calibration and validation periods (USEPA, 2012).

Point source	Flow (m <sup>3</sup> d <sup>-1</sup> )	Organic P (kg d <sup>-1</sup> )	Mineral P (kg d <sup>-1</sup> )
Town of Prairie Grove	1100	0.9	3.7
City of Fayetteville	16,000	1.4	5.7
Town of Lincoln	1800	0.7	2.8
City of Springdale	41,500	23	98
City of Rogers	20,200	7.7	33
Town of Gentry	1800	1.4	6.1
City of Siloam Springs	10,300	6.4	27
City of Tahlequah	10,200	1.5	6.5
Town of Westville	700	0.2	0.8
Stilwell Area Development	2500	0.8	3.5
Town of Decatur	4900	2.5	10.8



**Fig. 4.** Poultry house locations and average Mehlich III soil test phosphorus (STP) for pastures in the Illinois River and Eucha–Spavinaw watersheds based on 2005 data and a 2013 National Agricultural Imagery Program image.

#### 2.5.1. Streamflow

Manual calibration was used to calibrate the daily and monthly baseflow, peak flow and total flow at three USGS gage stations in the IRW (07195500, 07196500 and 07197000) and two in the ESW (07191222 and 071912213) (Fig. 3). Streamflow was calibrated and validated from 1990 to 2010 and 1980 to 1989, respectfully, for the IRW. For the ESW, flow was calibrated from 2005 to 2010 and validated from 1999 to 2004 for gage station 07191222 and 2006 to 2010 and 2002 to 2005 for gage station 071912213. Hydrograph separation program (HYSEP), a product of the USGS, was used to estimate baseflow (Sloto and Crouse, 1996).

A sensitivity analysis was conducted on eleven parameters based on previously used calibration parameters and SWAT documentation (Neitsch et al., 2011). Parameters were adjusted within the SWAT recommended range and the model sensitivity analyzed to determine the influence that each parameter had on peak flow and baseflow (Table 3).

The model performance was evaluated using the coefficient of determination ( $R^2$ ), Nash–Sutcliffe Efficiency (NSE). Model performance ratings for NSE for total monthly flow were the following: Very good  $>0.75$ , Good  $0.65–0.75$ , Satisfactory  $0.50–0.65$ , Unsatisfactory  $<0.50$  (Moriassi et al., 2007).

#### 2.5.2. Phosphorus

Overland sediment and particulate P were calibrated and validated simultaneously. Due to their uncertainty, cover factor and slope length were used in the calibration. Once the overland P was calibrated, the SWAT in-stream P model was calibrated and validated on a monthly time step from 2001 to 2010 and 1995 to 2000, respectfully, at the three USGS gage stations in the IRW. Due to limited P data, the two USGS gage stations in the ESW were calibrated from 2002 to 2010 with no validation. The five gages were calibrated for total P, dissolved P and particulate P. Similar to flow, the model was calibrated using the  $R^2$ , NSE and percent bias (PBIAS) simultaneously until the best fit was obtained. Details on model performance ratings for P on a monthly time can be found at Moriassi et al., 2007.



**Table 3**

Goodness-of-fit statistics for LOADEST total and dissolved phosphorus estimates for the Illinois River and Eucha–Spavinaw watersheds at five United States Geological Survey gage stations. NSE is Nash–Sutcliffe efficiency.

USGS gage station	Period of record	Goodness of fit parameter	Total phosphorus	Dissolved phosphorus
07196500	1990–2010	$R^2$	0.71	0.68
		NSE	0.69	0.65
07195500	1990–2010	$R^2$	0.45	0.38
		NSE	0.43	0.37
07197000	1990–2010	$R^2$	0.62	0.63
		NSE	0.58	0.60
071912213	2002–2010	$R^2$	0.55	0.55
		NSE	0.59	0.59
07191222	2002–2010	$R^2$	0.46	0.45
		NSE	0.42	0.31

Unlike flow data, daily observed P data were not available; therefore Load Estimator (LOADEST) was used to estimate daily loads (Runkel et al., 2004). The latest version estimates loads for a user defined time period from discrete water quality samples and measured daily flow using a formulated regression model (Runkel et al., 2004). Goodness-of-fit for LOADEST predictions at the five USGS gage stations are presented in Table 3.

## 2.6. Model update

After calibrating the two SWAT models, they were updated to represent current conditions. The major updates included poultry litter application rates (Table 4) (ODAFF, 2013; ANRC, 2014), point source discharges and weather. Although average discharge from the five largest point sources in the IRW increased over time (Table 5), the upgraded WWTPs resulted in average total P load and concentration reductions of 88% and 90%, respectively. The average total P concentration at Decatur, Arkansas also decreased from 1.8 to 0.22 mg L<sup>-1</sup> from 2002 to 2013, respectively.

Weather stations in the updated SWAT model added data from 2011 to 2013. Since the weather data from 2004 to 2013 represented drought and wet years, all SWAT scenario model runs were simulated with weather data from 2004 to 2013. The average rainfall over this period was 1150 mm yr<sup>-1</sup> at the Jay, Oklahoma Mesonet station with a range from 848 to 1720 mm yr<sup>-1</sup>. The purpose of using weather from this time period was not predict loads from 2004 to 2013, but to simulate loads using typical representative precipitation.

## 2.7. Meeting water quality standards

The Oklahoma Conservation Commission and the Oklahoma Department of Environmental Quality were interested in determining if the State of Oklahoma was meeting water-quality standards, and if not, what agricultural conservation practices could be adopted in order to do so. The updated SWAT model was used to estimate current P concentrations in the three subwatersheds: Barren Fork Creek, Flint Creek and the Illinois River; P loads entering Lake Eucha; and P loads and flows entering Oklahoma from Arkansas.

The total P criterion for the Oklahoma Scenic Rivers, which included the Illinois River, Barren Fork Creek and Flint Creek, is 0.037 mg L<sup>-1</sup> (Okla. Admin. Code § 785:46-15-10(h)). To meet the P standard, fewer than 25% of the daily geometric means, calculated using the present month and two previous months, must not exceed 0.037 mg L<sup>-1</sup> (Okla. Admin. Code § 785:46-15-10(h), 2014). These concentrations and loads were used to determine if Oklahoma was meeting the water-quality standards. When calculating the 90-day geometric means for total P, the daily total flow and P loads entering Oklahoma from Arkansas were removed from the three subwatersheds. This allowed the evaluation of P loads from only the Oklahoma portion of the watershed. The total P loads, geometric means and percent exceedances were then calculated for each subwatershed separately.

**Table 4**

Poultry litter applied (Mg yr<sup>-1</sup>) to pasture and hay meadow within each county in the Illinois River and Eucha–Spavinaw watersheds for the calibrated and updated (2013) SWAT models (ODAFF, 2013; ANRC, 2014).

Watershed	County					Total
	Cherokee	Adair	Delaware	Benton	Washington	
<i>Calibrated model</i>						
Illinois River	2,000	26,000	7,000	89,000	116,000	240,000
Eucha–Spavinaw	N/A	N/A	6,000	14,000	N/A	20,000
<i>Updated model</i>						
Illinois River	1,400	4,100	2,250	23,400	30,600	59,750
Eucha–Spavinaw	N/A	N/A	5,400	6,700	N/A	12,100

**Table 5**

Updated (2013) and historical discharge (1990–2010), total phosphorus (P) loads and concentration for the five largest point sources in the Illinois River watershed (USEPA, 2012).

Facility	Time period					
	2013			1990–2010		
	Discharge (m <sup>3</sup> )	Total P (kg d <sup>-1</sup> )	Total P (mg L <sup>-1</sup> )	Discharge (m <sup>3</sup> )	Total P (kg d <sup>-1</sup> )	Total P (mg L <sup>-1</sup> )
Fayetteville	24,000	2.7	0.11	16,000	7.0	0.44
Rogers	25,200	5.8	0.23	20,200	40.4	2.0
Springdale	50,600	11.9	0.25	41,500	121.4	3.9
Siloam Springs	9,500	3.8	0.40	10,300	33.2	3.2
Tahlequah	8,900	1.0	0.11	10,200	8.0	0.80
Total	118,200	25.2	Mean: 0.22	108,000	210	Mean: 2.1

The Oklahoma water-quality standard for Lake Eucha requires the long-term average total P concentration to not exceed 0.0168 mg L<sup>-1</sup> at 0.5 m below the water surface (Okla. Admin. Code § 785:45-5-10(8), 2014). The City of Tulsa maintains four water quality sampling sites on the reservoir (Fig. 5). Each site was sampled monthly 0.5 m below the surface and 0.5 m from the bottom of the reservoir bed. From 2004 to 2013 a combined 1,227 samples were taken at the four sites. The concentration in the reservoir was highest at sampling site EUC03 near the Spavinaw Creek confluence with the reservoir, 0.046 mg L<sup>-1</sup>, and lowest at sampling site EUC01 near the dam, 0.032 mg L<sup>-1</sup>, after P settled and was diluted by the forest-dominated tributaries around the reservoir.

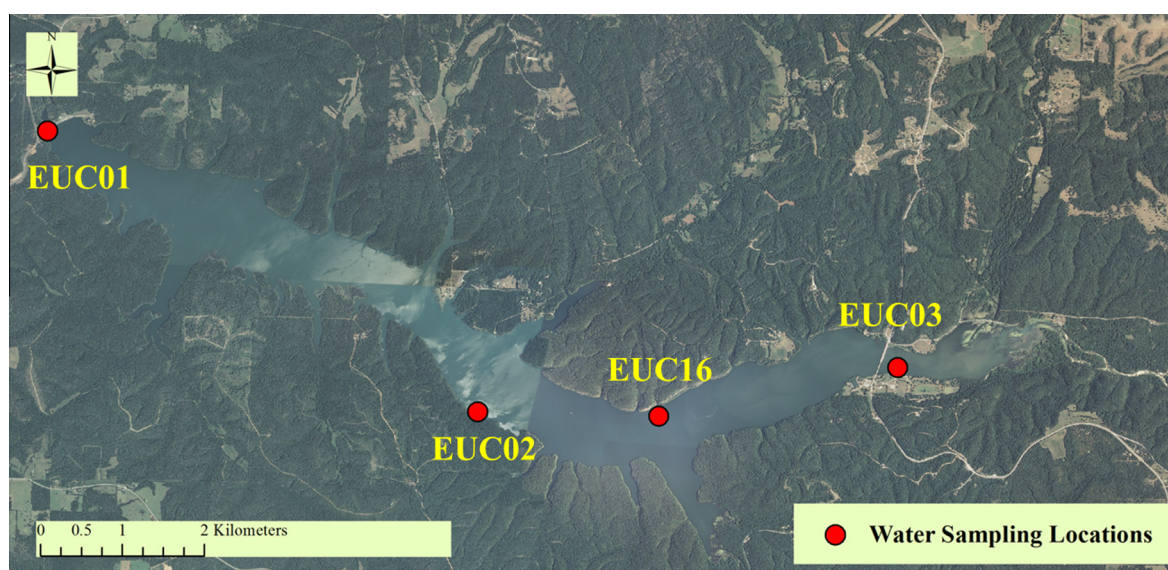
To determine if Oklahoma was meeting the water-quality standard in Lake Eucha, a method was needed to predict the P contribution from Oklahoma. There are three P load contributions to the reservoir: Oklahoma sources, Arkansas sources and internal loadings. First, the P load entering from Arkansas was subtracted from the P load entering Lake Eucha to obtain the P loads originating from Oklahoma. Second, Eq. (6) was used to determine the P contribution to the reservoir's water column originating from each of the three P sources:

$$TP_{res} = P_{OK} + P_{AR} + P_{IN} \quad (6)$$

where  $TP_{res}$  is the total P loading to Lake Eucha (Mg),  $P_{OK}$  is the P load contribution from Oklahoma (Mg),  $P_{AR}$  is the load contribution from Arkansas (Mg) and  $P_{IN}$  is the internal P loading from the reservoir (Mg). Third, Eq. (7) was applied to determine the P concentration in the reservoir if only P originating from Oklahoma was considered:

$$OK_{con} = \frac{P_{OK}}{TP_{res}} * Tot_{con} \quad (7)$$

where  $OK_{con}$  is the concentration in Lake Eucha if only Oklahoma's contribution was considered (mg L<sup>-1</sup>),  $P_{OK}$  is the P load originating from Oklahoma (Mg),  $TP_{res}$  is the total P loading to Lake Eucha (Mg) and  $TP_{con}$  is the average P concentration at sampling site EUC03 (mg L<sup>-1</sup>). Finally,  $OK_{con}$  was compared to the water-quality standard to determine if the standard was



**Fig. 5.** Lake Eucha and the four City of Tulsa water sampling locations.

being met. We chose to use sampling site EUC03 since it had the highest P concentration in the reservoir; therefore if the standard was met at the inlet, it would be met throughout the reservoir.

If Oklahoma was not meeting the water-quality standards, the following management practices were simulated to analyze the reduction in P concentration and loads for each watershed: (1) 100% of the poultry litter produced in the watersheds is exported outside the watersheds; (2) overgrazed pastures are converted to well-managed pastures; (3) 100% of the hay meadow in the watersheds are converted to forest; (4) 100% of the pasture is converted to hay meadow; (5) 100% pasture is converted to forest; (6) stocking rate is reduced from 1.25 AU ha<sup>-1</sup> to 0.60 AU ha<sup>-1</sup>; (7) STP is reduced to 33 mg kg<sup>-1</sup>; and (8) 100% of the crops are converted to forest. Exporting poultry litter and reducing STP will reduce P loss from overland areas while all other management changes will reduce runoff, sediment and P.

### 3. Results and discussion

#### 3.1. Flow calibration and validation

During the calibration process, parameters were manually adjusted to obtain the best goodness-of-fit statistics for each gage station. Ultimately seven parameters were modified in the final calibration (Table 6). The streambed hydraulic conductivity in both watersheds was very high due to the large gravel-bed streams. Each of the calibrated parameters were similar to previous modeling efforts in the watersheds (Storm et al., 2006, 2010). The total flow calibration results were all 'very good' with monthly NSEs all greater than 0.75 (Table 7). For the validation period, three of the five sites had NSEs greater than 0.75; the remaining two had NSEs of 0.69 and 0.65. Time series for the two gage stations furthest downstream in each watershed are given in Fig. 6. Daily calibration and validation NSEs ranged from 0.45 to 0.59, except for gage 07196500. Gage 07196500 was downstream of all 12 point sources and therefore received the cumulative error of the point source inputs, which were reported on a monthly basis. During summer months, the point source flow can be a large percent of the total flow. The average daily flow from 1990 to 2010 at gage 07196500 was 30 m<sup>3</sup> s<sup>-1</sup> compared to the average daily point source discharge of 1.5 m<sup>3</sup> s<sup>-1</sup>. Seven and 32 percent of the daily flows from 1990 to 2010 were less than 5 m<sup>3</sup> s<sup>-1</sup> and 10 m<sup>3</sup> s<sup>-1</sup>, respectively.

#### 3.2. Phosphorus calibration and validation

The average slope length and USLE C factor were reduced 0–60% for each subwatershed. The average calibrated sediment load ranged from 0.01 Mg ha<sup>-1</sup> (forest) to 0.48 Mg ha<sup>-1</sup> (bare soil) in the IRW. For the ESW, the average calibrated sediment ranged from 0.01 Mg ha<sup>-1</sup> (forest) to 0.66 Mg ha<sup>-1</sup> (crops). After the overland calibration, annual P loads were comparable to observed loads. The in-stream P model was then calibrated to improve monthly calibration results (Table 8). The calibrated values were similar for the two watersheds except for the period of influence (DI). DI is the number of days in the past that influence the P concentration for the current day. The difference in the calibrated values was attributed to the large number of point sources in the IRW (12) compared to the ESW (1). More information on the in-stream P parameters can be found at White et al. (2014). For the IRW, the monthly total P NSE was 0.79, 0.73 and 0.47 for the calibration period and 0.66, 0.73 and 0.65 for the validation periods for gage stations 07196500, 07195500 and 07197000, respectively. The ESW SWAT model produced similar results; the total P NSE for the calibration period was 0.72 and 0.50 for gage stations 071912213 and 07191222, respectfully. The PBIAS for each site ranged from –9.2% to 10.1%. Based on the performance ratings from Moriasi et al. (2007), calibration and validation for each site was 'very good'. The relative errors for total P were relatively small, as illustrated in Fig. 7.

The lower NSEs for gage station 07197000 on the Barren Fork Creek near Eldon, Oklahoma was due to under predicting peak flows during large storm events, which was hypothesized to result from not accounting for streambank erosion. For example, the average observed and predicted flow for October 2009 was 37.2 and 35.9 m<sup>3</sup> s<sup>-1</sup>, respectively, yet the observed

**Table 6**

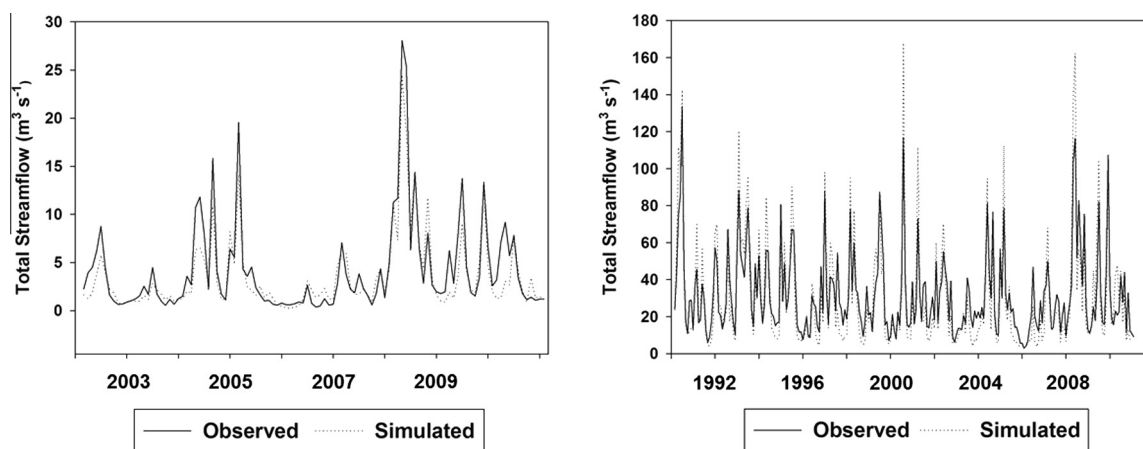
Original and calibrated parameter values used to calibrate the SWAT model for the Illinois River and Eucha–Spavinaw watersheds.

Parameter	Original value or range	Calibrated value or range		Description
		Illinois River watershed	Eucha–Spavinaw watershed	
ESCO	0.95	1.0	0.70	Soil evaporation compensation coefficient
RCHRG_DP	0.05	0.33–0.75	0.20–0.38	Aquifer percolation coefficient
ALPHA_BF	0.048	0.30–0.36	0.35	Baseflow Alpha Factor (days)
SOL_AWC	0.08–0.23	+0.10	+0.10	Soil available water capacity
CN2	39–94	–4 to +2	–6 to –2	SCS curve number adjustment
CH_K2	0	20–35	18–34	Effective hydraulic conductivity in main channel alluvium (mm h <sup>-1</sup> )
CH_K1	0.5	40–150	75–150	Effective hydraulic conductivity in tributary channel alluvium (mm h <sup>-1</sup> )

**Table 7**

SWAT model daily and monthly flow calibration and validation results for the Illinois River and Eucha–Spavinaw watersheds.

Time	Station ID	Coefficient of determination ( $R^2$ )	Nash–Sutcliffe (rating)	Coefficient of determination ( $R^2$ )	Nash–Sutcliffe (Rating)
<i>Illinois River watershed</i>		<i>Calibration</i>		<i>Validation</i>	
Daily	07196500	0.32	0.20	0.39	0.21
	07195500	0.57	0.50	0.65	0.57
	07197000	0.50	0.49	0.49	0.45
Monthly	07196500	0.82	0.81	0.80	0.79
	07195500	0.80	0.80	0.79	0.79
	07197000	0.80	0.77	0.66	0.65
<i>Eucha–Spavinaw watershed</i>		<i>Calibration</i>		<i>Validation</i>	
Daily	071912213	0.64	0.53	0.64	0.59
	07191222	0.59	0.59	0.47	0.47
Monthly	071912213	0.85	0.85	0.84	0.69
	07191222	0.81	0.80	0.80	0.75

**Fig. 6.** Total streamflow calibration results for monthly SWAT simulations at the United States Geological Survey gage stations 071912213 (left) and 07196500 (right).

and predicted P were 92,800 and 17,700 kg, respectively. Heeren et al. (2012) observed a large amount of streambank erosion during the October 2009 storm event and Miller et al. (2014) found that P derived from streambank erosion in the Barren Fork Creek watershed was significant; thus, supporting the hypothesis.

### 3.3. Current phosphorus sources

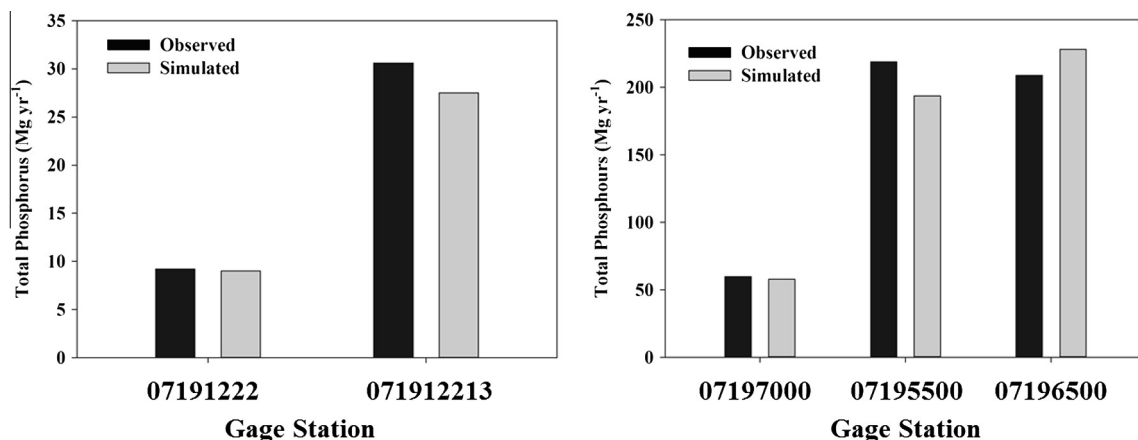
An average total P of 190 Mg yr<sup>−1</sup> entered Lake Tenkiller for the period 2004–2013, the watershed outlet for the IRW. Based on SWAT predictions, the major P sources reaching Lake Tenkiller were pasture, hay meadow and STP (Fig. 8), which contributed 65% of all P reaching the reservoir. The major sources in the watershed have changed in the last 10–20 years. Storm et al. (2010) found that these sources contributed only 35% from 1990 to 2006; with the major sources being point

**Table 8**

The parameters in the in-stream P model, the default values and the calibrated values for the Illinois River and Eucha–Spavinaw watersheds.

Parameter	Default value	Calibrated value	
		Illinois River watershed	Eucha–Spavinaw watershed
DI	250	500	100
$K_{in}$	0.10	0.10	0.06
$K_{out}$	0.10	0.10	0.07
$F_{eq}$	0.15	0.50	0.30
$F_{dep}$	0.01	0.01	0.01
$F_{scr}$	0.80	0.75	0.65
SPT	0.01	0.01	0.01





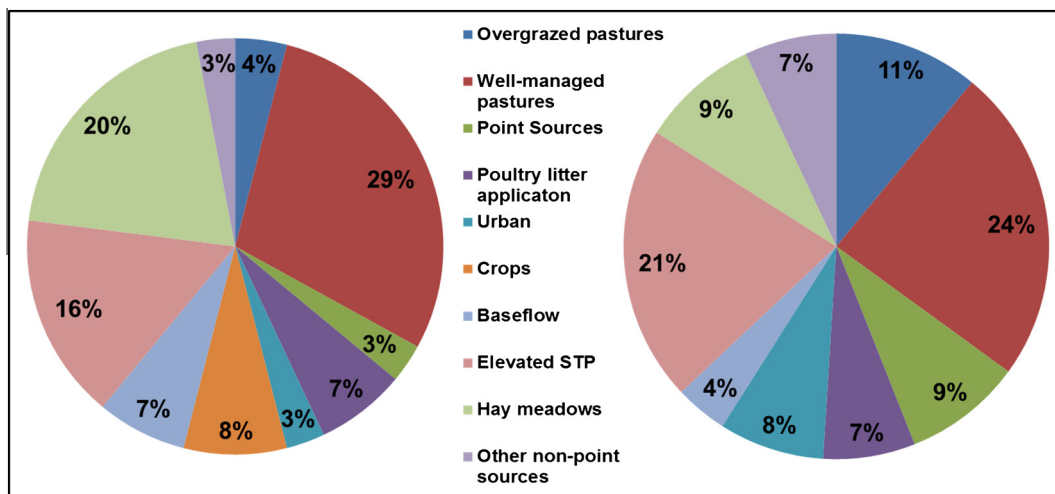
**Fig. 7.** Calibrated SWAT observed vs simulated total phosphorus (P) loads for the Eucha–Spavinaw (left) and Illinois River (right) United States Geological Survey gage stations.

sources (40%) and poultry litter (13%). Due to improvements to the WWTPs and the increase in poultry litter export, the poultry litter and point sources currently only contribute nine and seven percent, respectively. The increase in the fraction of P from pasture and STP was not due to an increase in their P loads, but rather an overall reduction in P from other sources. P concentrations and loads have been declining in recent years due to the significant changes in the watershed and the implementation of conservation practices (Scott et al., 2011; Haggard, 2010).

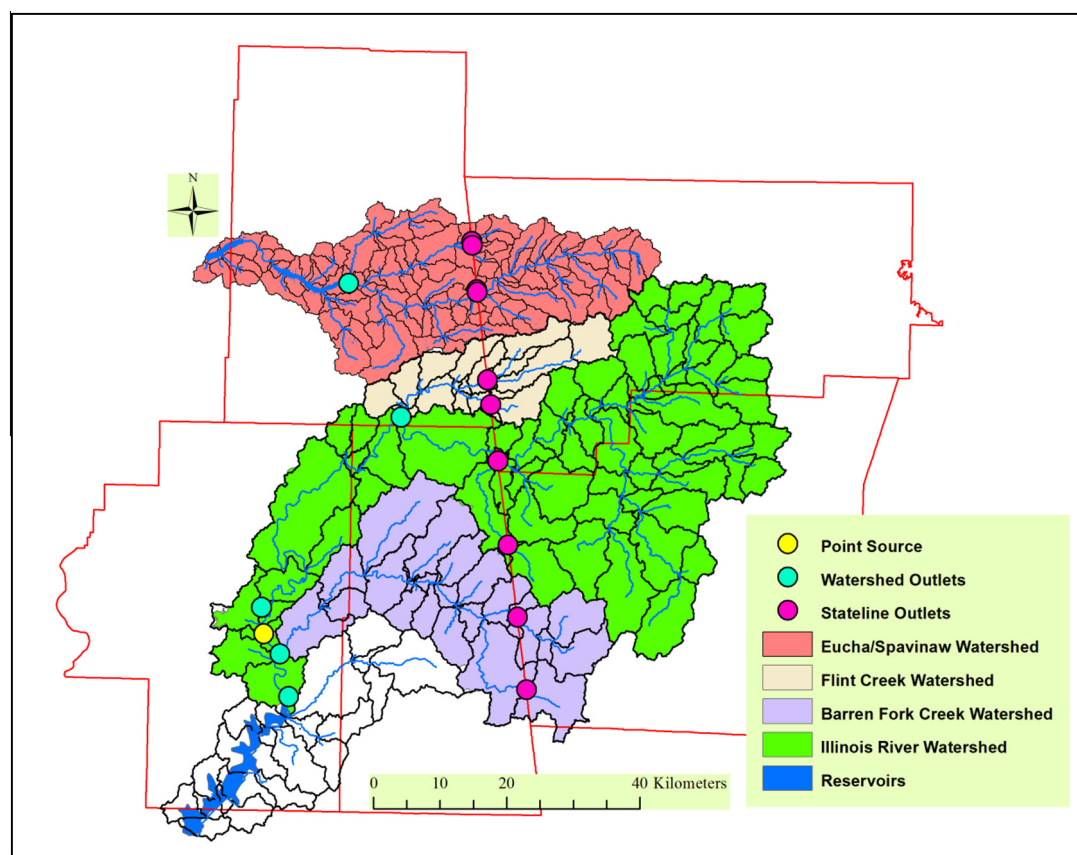
The total P reaching Lake Eucha was  $30 \text{ Mg yr}^{-1}$  for the period 2004–2013. The major sources of P were also well-managed pasture, hay meadow and STP (69%) (Fig. 8). In previous SWAT modeling efforts (Storm et al., 2001), STP, point sources and poultry litter were the main P sources. While STP is still a major source, point sources and poultry litter are not due to improvements at the Decatur, Arkansas WWTP and the increase in poultry litter export.

### 3.4. Meeting water-quality standards

In order to determine if Oklahoma was meeting the water-quality standards, all flow and P entering Oklahoma from Arkansas were removed (Fig. 9). Only the flow and P entering the waterbodies originating from Oklahoma were considered. For the water-quality standard to be met (Okla. Admin. Code § 785:46-15-10(h)), fewer than 25% of the daily flows can exceed  $0.037 \text{ mg L}^{-1}$ . The total P concentration was calculated by using the data from the current month and the two preceding calendar months. The 90-day geometric mean and the total number of days exceeding the Oklahoma Scenic River P



**Fig. 8.** SWAT predicted major phosphorus sources reaching Lakes Eucha (left) and Tenkiller (right), at the watershed outlets for the Eucha–Spavinaw and Illinois River and watersheds for the time period 2004–2013.



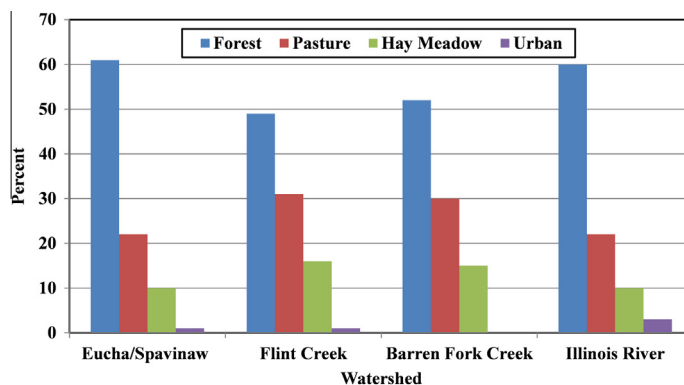
**Fig. 9.** Eucha–Spavinaw, Flint Creek, Illinois River and Barren Fork Creek watersheds and the reach outlets on the Arkansas/Oklahoma state line and at the subwatershed outlets, including above the point source on the Illinois River.

criterion  $0.037 \text{ mg L}^{-1}$  were calculated for each of the three subwatersheds in the IRW using daily SWAT predictions. At current conditions, only the Illinois River subwatershed above the point source discharge (Fig. 9) met the standard with only 12% exceedances. The percent exceedances for the Illinois River below the point source discharge was 33%, Flint Creek was 37%; and the Barren Fork Creek 44%.

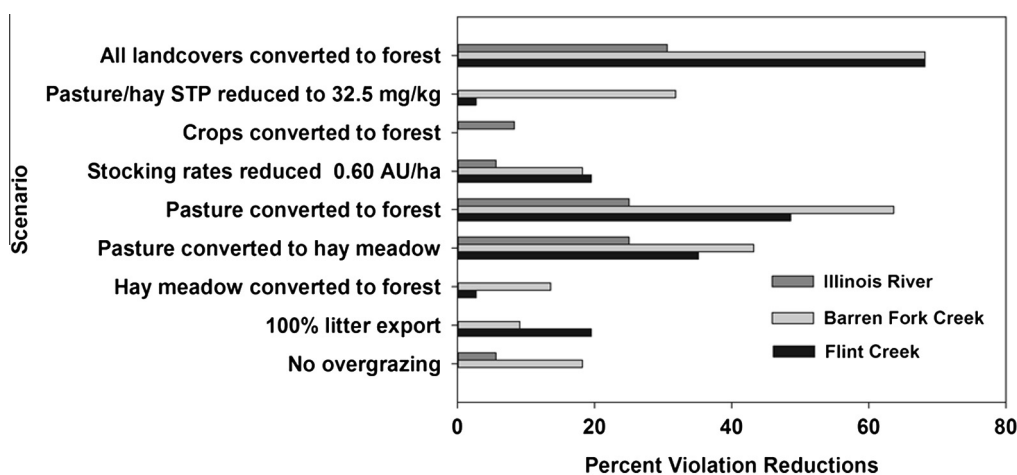
Based on the updated SWAT model, the total P load entering Lake Eucha from external sources was  $30 \text{ Mg yr}^{-1}$ ; 78% from Arkansas and 22% from Oklahoma. The internal P loading to the reservoir was  $12 \text{ Mg yr}^{-1}$  (Haggard et al., 2005); therefore the average total P loading to Lake Eucha was  $42 \text{ Mg yr}^{-1}$ . Applying Eq. (7), the average percent contribution and P loading originating from Oklahoma and Arkansas was  $6.6 \text{ Mg yr}^{-1}$  or 15.7% and  $23.4 \text{ Mg yr}^{-1}$  or 55.7%, respectively. Neglecting internal P loads and those originating in Arkansas, the P concentration in Lake Eucha was  $0.008 \text{ mg L}^{-1}$ . This concentration is less than  $0.0168 \text{ mg L}^{-1}$  and therefore Oklahoma meets the water quality standard. The average concentration considering only P loads from Arkansas or internal loads was  $0.021$  and  $0.014 \text{ mg L}^{-1}$ , respectively; therefore, Arkansas is not meeting the water-quality standard, but internal reservoir loadings do.

Based on these results, the standard is being met for the Illinois River above the point source and for the ESW. The reason these two watersheds meet the standard while Flint Creek and the Barren Fork Creek do not is due to a combination of land use (Fig. 9), STP and poultry house density. Note that these refer only to the Oklahoma portion of the watershed. Both the Illinois River subwatershed and ESW have a larger percent of forest and less pasture than Flint Creek and the Barren Fork Creek watersheds (Fig. 10). The Illinois River subwatershed and ESW both have lower STP, 40 and  $47 \text{ mg kg}^{-1}$ , respectively compared to  $52 \text{ mg kg}^{-1}$  for Flint Creek and  $65 \text{ mg kg}^{-1}$  for the Barren Fork Creek. While the poultry house density in the Illinois River subwatershed is only 0.0012 poultry houses per ha pasture, the density in the ESW was 0.0095 houses per hectare. This compares to 0.0092 and 0.0050 houses per ha pasture in the Flint Creek and Barren Fork Creek watersheds, respectively.

Since the water-quality standard is not being met in the three Illinois River subwatersheds, a sensitivity analysis was conducted to determine the percent reduction in standard violations based on several scenarios (Fig. 11). While most of the scenarios were impractical to implement, the predicted load reductions provide insight into influences that each of the management practices and land use changes have on P concentrations. The land use conversions that produced the largest reductions were the conversion of pastures and hay meadow to forest. Reducing STP to  $32.5 \text{ mg kg}^{-1}$  reduced the percent



**Fig. 10.** Percent forest, pasture, hay meadow and urban for the Eucha–Spavinaw watershed and the Flint Creek, Barren Fork Creek and Illinois River subwatersheds.

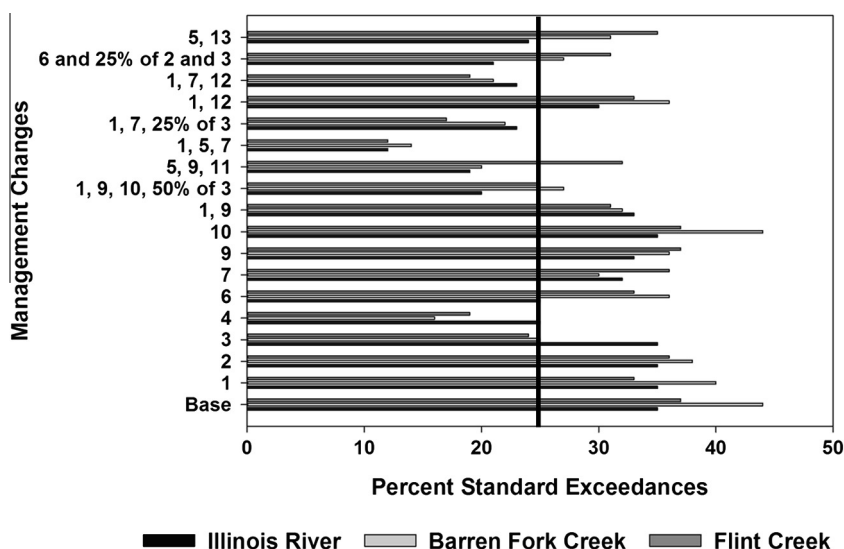


**Fig. 11.** SWAT predicted percent reduction in water quality violations for several alternative scenarios for the three subwatersheds in the Illinois River watershed. STP is soil test phosphorus; AU is animal units.

violation by nearly 40% in the Barren Fork Creek subwatershed while reducing cattle density reduced the percent violations by approximately 20% in the Illinois River and Flint Creek subwatersheds.

Guided by the results of the sensitivity analysis, a mixture of the scenarios was simulated for each subwatershed to determine the type and number of management and land use changes required to meet the water-quality standard in the Barren Fork Creek and Flint Creek subwatersheds and the Illinois River subwatershed below the point source. The following management changes were simulated individually and in various combinations:

- (1) 100% litter export
- (2) Hay meadow converted to forest
- (3) Pasture converted to hay meadow
- (4) Pasture converted to forest
- (5) Pastures with slope >3% converted to forest
- (6) Stocking rate reduced to 0.60 AU ha<sup>-1</sup>
- (7) STP reduced to 32.5 mg kg<sup>-1</sup>
- (8) Crops converted to forest
- (9) No overgrazing
- (10) No urban P fertilizer
- (11) No litter application on fields with slopes greater than 3%
- (12) Conversion of all pasture and hay meadow with slopes greater than 10% to forest
- (13) Hay meadow with slope >3% converted to forest



**Fig. 12.** Individual and a combination of management changes and the resulting percent standard exceedances for the three subwatersheds in the Illinois River watershed. The black line represents the standard (25% exceedances). The following scenarios were simulated: (1) 100% litter export; (2) hay converted to forest; (3) pasture converted to forest; (4) pasture with slope >3% converted to forest; (5) stocking rate reduced to 0.25AU ha<sup>-1</sup>; (6) STP reduced to 32.5 mg kg<sup>-1</sup>; (7) crops converted to forest; (8) no overgrazing; (9) no urban P fertilizer; (10) no litter application on fields with slopes greater than 3%; (11) convert all pasture and hay with slopes greater than 10% to forest; (12) hay with slope >3% converted to forest.

Fig. 12 shows the percent standard exceedances after the incorporation of several management and land use changes. The standard required fewer management changes to meet in the Illinois River subwatershed since forest made up 60% of the watershed compared to 49% and 52% for the Flint Creek and Barren Fork Creek watersheds, respectively. The standard was most challenging to meet in the Flint Creek watershed since pasture makes up over 30% of the watershed and it has a higher poultry house density.

The SWAT model adequately simulated P and a combination of several management changes required to meet the numeric water-quality standards. Converting pasture to either hay or forest yielded the largest P reductions. Reducing the stocking rate and elevated STP also yielded large reductions in total P. Due to the improved WWTPs and increases in poultry litter export in the last decade, most of the P entering the waterways is indirectly a result of cattle grazing. Increases in grazing intensities results in increases in runoff and sediment, and thus dissolved and particulate P. Other management changes, such as riparian buffers and cattle exclusion, would also result in large reductions in P loads reaching the stream systems. These management practices were not simulated due the limitations of the version of the SWAT model used in this study.

Note that the results of this research assume that in-stream P contributions are negligible, although P contributions from streambank erosion may be significant (Miller et al., 2014). It is also assumed that the flow and P data from the USGS is accurate, as well as the P estimates from LOADEST.

#### 4. Conclusions

The new in-stream P routine successfully calibrated the SWAT models for both the IRW and ESW. Poultry house density and county-level STP were used to characterize subbasin litter application rates and STP. The SWAT model proved to be a capable tool in the evaluation of various management changes and conservation practices required to meet numeric water-quality standards in the watersheds studied. Although there is not reservoir component to SWAT, a method was developed to determine if Oklahoma was meeting the water-quality standard in Lake Eucha. As the number of waterbodies in the US with numeric nutrient water-quality standards continues to increase, watershed models such as SWAT will be an invaluable tool to aid in the development of watershed-based plans. Due to recent land-management changes in the two watersheds, Oklahoma is now meeting the water-quality standard in Lake Eucha; however, more changes will be required in the IRW for the three designated Scenic Rivers to meet the 0.037 mg L<sup>-1</sup> water-quality standard. With the recent reduction in litter application rates and improvements in WWTPs, meeting the water-quality standard will require more focus on cattle and elevated STP. The largest reductions in percent standard exceedances were attributed to converting pasture to either forest or hay. Large reductions in P runoff were also obtained by reducing the stocking rate and STP in the soils. The SWAT model can aid watershed managers in identifying select fields where P load reductions will be maximized such as overgrazed pastures with elevated STP and slopes. Future modeling efforts should analyze P reductions obtained from implementing management practices such as riparian buffers and cattle exclusion. Future work also needs to quantify P stored in the flood-



plains, streambanks, ditches and other possible P sinks. The retention time of these sources and their transport through the stream system needs to be better understood in order to provide watershed managers and policy makers with the best location and most cost-efficient conservation practices to implement. This research illustrated how a watershed model can be used to provide critical information when developing watershed-based plans using water-quality standards in stream and reservoirs.

## Acknowledgments

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