Original Research Paper

Application of Soil and Water Assessment Tool Model to Estimate Sediment Yield in Kaw Lake

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Abstract: Kaw Lake is one of the reservoirs built by the Army Corps of Engineers in 1976 for the purpose of flood control, recreation, water supply, navigation and fish and wildlife conservation. The Arkansas River flows from Colorado and Kansas before reaching Oklahoma. As it passes through these states, the water carries various kinds of pollutants such as metals from mine waste discharge, salinity from the geology of the area, nutrients, pesticides and sediment from the agricultural fields and the surrounding watersheds. Sediment and other dissolved particles flow with the water and are deposited at the bottom of the Kaw Lake. These sediments may impede fish migration and act as bedding for nuisance aquatic species, decreasing the water quantity and quality affecting future development of many cities that depend on the water supply of Kaw Lake. The objective of this study was to assess the amount of sediment inflow through the Ark City and Winfield gauging stations into the Kaw Lake using the Soil and Water Assessment Tool (SWAT) model. The study found that SWAT model predicted 691 M tones a year of sediment flow through the two gauging stations into Kaw Lake with an average annual sediment rate of 1.75 M tons per year. SWAT is a good predictor of sediment yield in that the observed and predicted sediment values matched very well. Since the Arkansas River is impaired for sediment because of runoff from the surrounding area, a Total Maximum Daily Load (TMDL) be developed and Best Management Practices (BMP) carried out to protect, preserve an improve the aquatic habitat and natural resources of the watershed.

Keywords: SWAT Model, Estimate Sediment Yield, Sediment, Kaw Lake

Introduction

The Arkansas River is a major tributary of the Mississippi River and the main source of water for Kaw Lake. The Arkansas River flows to the east and southeast as it traverses the U.S. states of Colorado, Kansas, Oklahoma and Arkansas (Fig. 1).

It is the sixth longest river in the United States and the second longest tributary in the Mississippi-Missouri System and the 45th longest river in the world (Kammerer, 1990) with a drainage basin of 195,000 miles. It enters Oklahoma near Arkansas City on the Kansas border above Kaw Lake in Kay County. The Arkansas River travels 327.9 miles before it enters the Mississippi River and discharges an average of 41,000 cfs (1,200 m^3/s) (Bolton, 1995).

The name "Arkansas" was first applied by Spanish, but later the French named it the Arkansas, referring to an American Indian tribe living in the region (Bolton, 1995).

Statement of the Problem

The water quality and quantity of the Arkansas River is impacted by sediment and nutrient runoff from the Arkansas River watershed. The Upper Arkansas River is one of the impaired rivers for turbidity and phosphorous under the Clean Water Act (CWA) Section 303 (d) list. According to the Army Corps of Engineers 1976 reportabout 500,000 ac/ft of sediment flows through the Kaw Lake every year. The Kansas USGS estimate, sediment loadings of the

Arkansas River into Kaw Lake have increased annually by an average of 5% over the last 20 years and 90% of the sediment entering Kaw Lake comes from the Arkansas River (Juracek, 2010). This excessive sediment loading from the Arkansas River has affected the water quality and quantity of Kaw Lake and the main cause of impairment for sediment, nutrient and turbidity.

Sediment in reservoirs is a concern for both physical and chemical characteristics of the water quality. Physically, sedimentation affects the useful life of reservoirs for various purposes and degrades the aesthetic quality. Chemically, sediments serve as a delivery mechanism for certain contaminants and a source for overlying water column and biota within a reservoir (Juracek and Stiles, 2010). Amount of sediment deposited in a reservoir is important because 95% of the phosphorous in streams tends to adhere to sediment particles (Hem, 1985; Juracek, 1998; Mittelstet *et al.*, 2012).

The objective of this study was to quantify the spatial and temporal patterns of sediment, nutrients (total nitrogen and phosphorous) and pesticides (atrazine) entering Kaw Lake using the Soil and Water Assessment Tool (SWAT) model.

SWAT Model

The Soil and Water Assessment Tool (SWAT) is an internationally recognized hydrology and water quality model that is being used by scientists, students, agricultural and environmental ministries, watershed and water supply authorities and environmental groups throughout the world to assess current and anticipated future water demands, supplies and quality in large and small watersheds, river basins, nations and continents. The model is physically based, computationally efficient and capable of continuous simulations over long periods of time, ranging from days to years to decades. The model is developed by the USDA Agricultural Research Service (ARS) in the early 1990 s and has undergone a continual review and expansion capabilities since it was created (Arnold *et al.*, 1998; Neitsch *et al.*, 2005). Major model components include weather, hydrology, erosion/sedimentation, soil temperature, plant growth, nutrients, pesticides, bacteria, agricultural management, stream routing and pond/reservoir routing (Gassman *et al.*, 2007). Over the past few decades, the SWAT model has been most widely used in a wide range of studies including hydrologic analyses, landuse changes, climate change impacts, pollutant load assessments and best management practices (Busteed *et al.*, 2009; Chattopadhyay and Jha, 2014; Douglas-Mankin *et al.*, 2013; Mittelstet *et al.*, 2012). SWAT divides a watershed into subbasins connected by a stream network and further delineates each subbasin into Hydrologic Response Units (HRUs), which consist of unique combinations of land cover, slope and soil type. SWAT is able to simulate surface and subsurface flow, sediment generation and deposit and nutrient movement and fate through the watershed system. For this report, only SWAT components concerned with runoff and sediment simulation are briefly introduced.

Fig. 1. Arkansas River and Kaw Lake Map (en.Wikipedia.org/wiki/Arkansas_River)

Hydrologic routines within SWAT account for snowfall and melt, vadose zone processes (i.e., infiltration, evaporation, plant uptake, lateral flows and percolation) and groundwater flows (Neitsch *et al.*, 2005). Surface runoff volume is estimated using a modified version of the Soil Conservation Service (SCS) Curve Number (CN) method (SCS, 1972). A kinematic storage model is used to predict lateral flow, whereas return flow is simulated by creating a shallow aquifer (Arnold *et al.*, 1998). The Muskingum method is used for channel flood routing. Outflow from a channel is adjusted for transmission losses, evaporation, diversions and return flow.

The SWAT model uses the Modified Universal Soil Loss Equation (MUSLE) (Williams, 1975) to estimate sediment yield at the HRU level. In-stream sediment transport was modeled using a modified Bagnold's equation, which is a function of peak channel velocity. Sediment is either deposited or re-entrained through channel erosion depending on the sediment load entering into the channel.

As a physically based hydrological model, SWAT requires a great deal of input data (Daggupati *et al.*, 2011; Hosseini *et al.*, 2011). Major input datasets include topography, soils, land use/land cover data and management practices, weather and hydrography. The methods used to develop Kaw Lake input data for SWAT are introduced in the model setup and data acquisition section below.

Methods and Materials

Kaw Lake Watershed

The study was conducted in one of the twelve major watersheds of the Arkansas River basin, the Kaw Lake Watershed (KLW), designated using an 8 digit Hydrologic Unit Code (HUC) of 11060001 (Fig. 2).

Kaw Lake is located in north central Oklahoma approximately 10 miles east of Ponca City, close to Kaw City, on the Arkansas River. It is within the Flint Hills Ecoregion, covering a total area of 280,607 acres. The Lake (Reservoir) covers approximately 17,040 surface acres (69 km2) and it is 33 miles away from Arkansas City along the shore line (www.swt.usace.army.mil). At normal levels, the Lake holds 428,600 acres feet (528,700, 000 m2) of water at pool elevation of 1012 feet (Fig. 3 and 4).

Data on Total Suspended Sediment Concentration

Starting April, 2011, twelve (12) locations within the Kaw Lake Watershed were selected to determine the concentration of total suspended sediments using grab sampling and measurement of turbidity at the site using YSI Sonde. Grab sampling during storm events and non-storm periods was performed at each site to develop individual site specific turbidity vs. total suspended sediment relationships (Fig. 5 and 6).
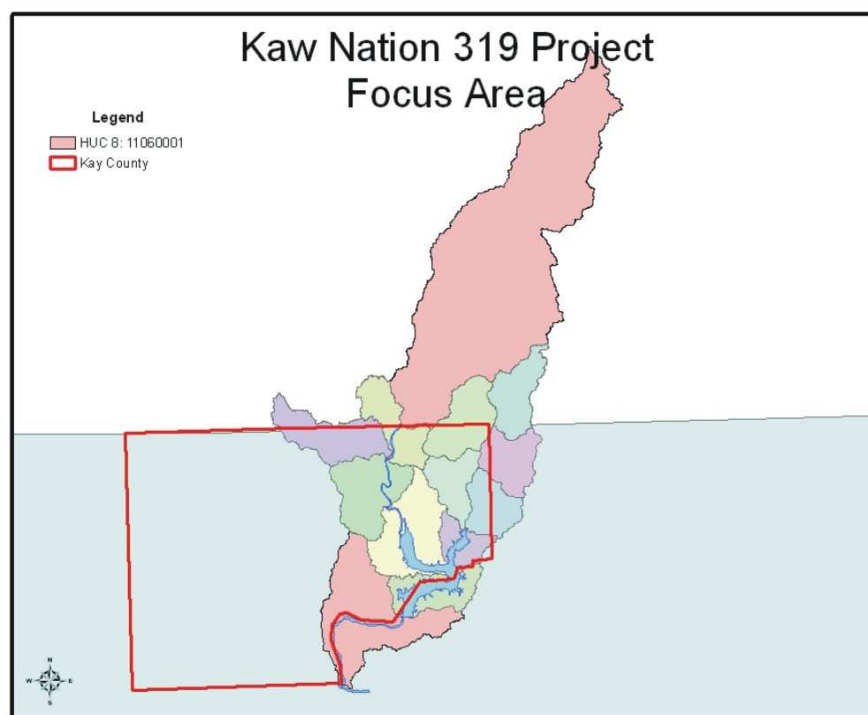

Fig. 2. Eight digit, hydrological unit codes (Kaw Nation)
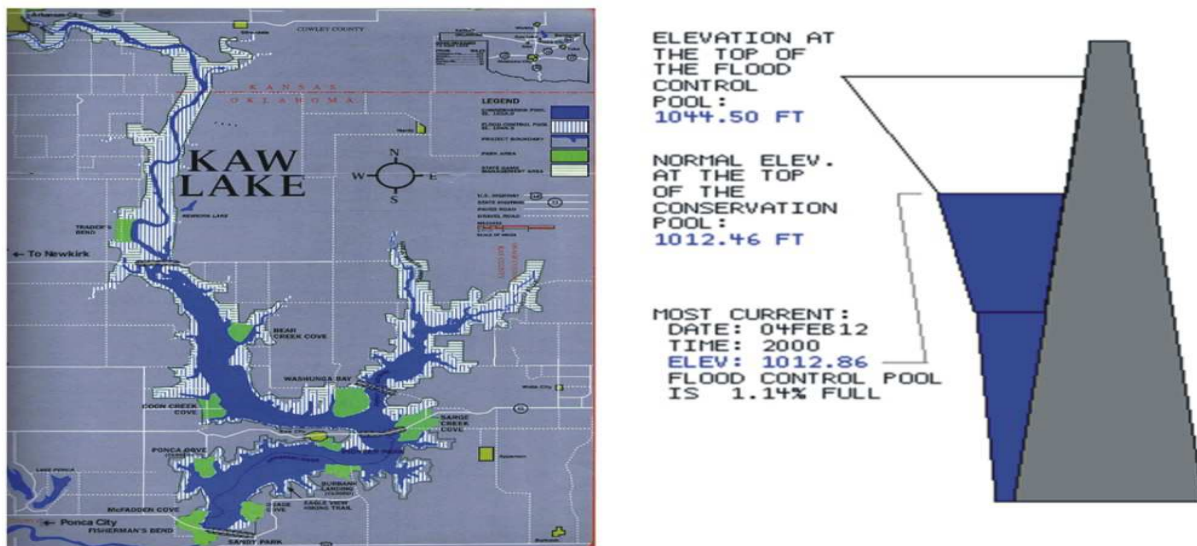
Fig. 3. Kaw Lake/Reservoir (Kaw Nation)

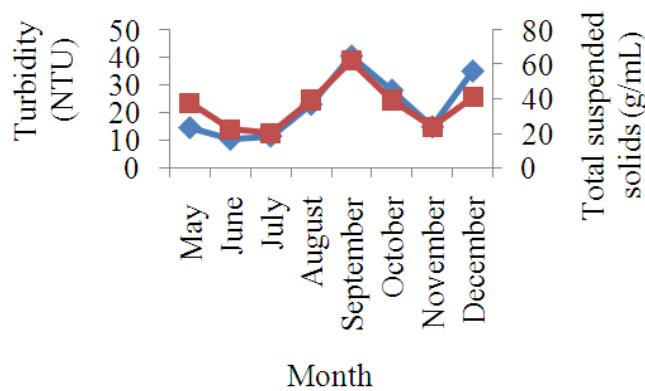Fig. 4. Kaw Lake-Location map and pool elevation (U.S. Army Corps of Engineers)

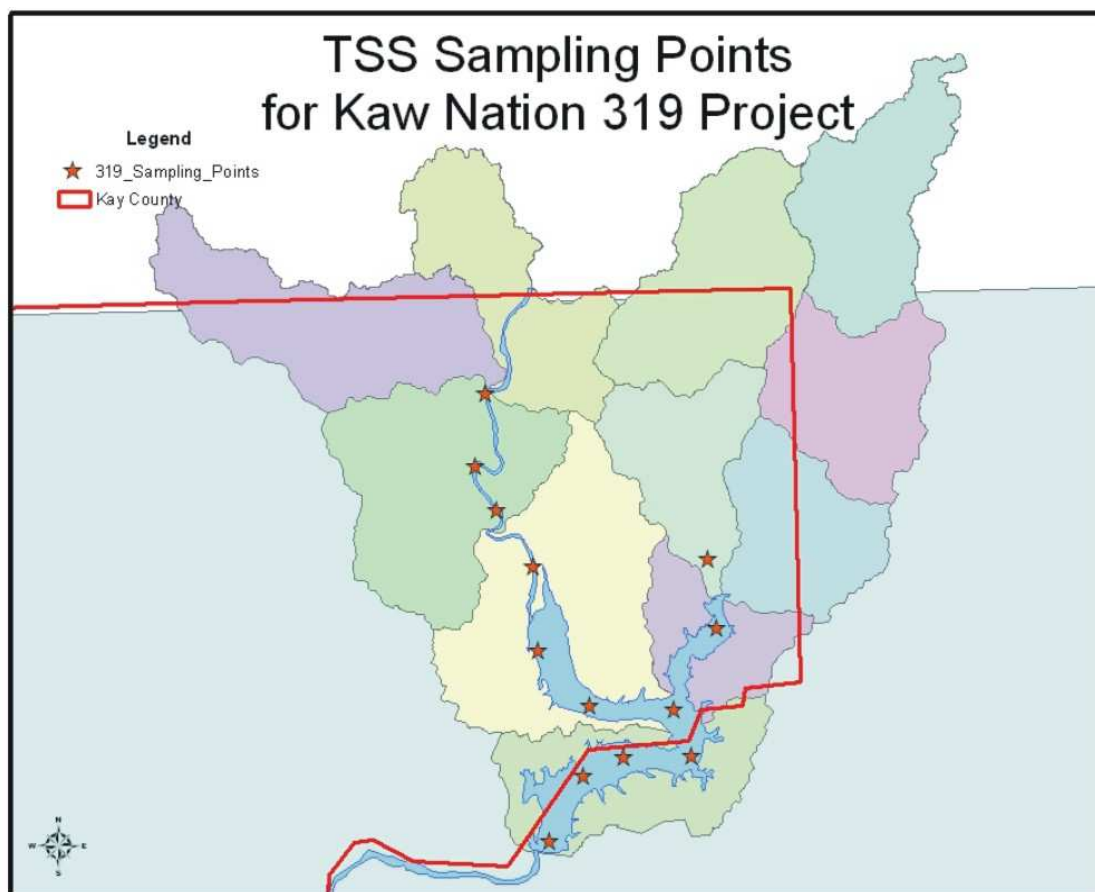Fig. 5. Relationship between turbidity and total suspended sediment

Fig. 6. Water quality monitoring sites (Kaw Nation)

The water samples collected from each monitoring location, during storm events and non-storm periods were analyzed for suspended sediment (mg/L). The suspended sediment was determined by filtering the samples through 45 µm filters and then determining the oven dried weight of the filtered sediment. The suspended sediment values and corresponding turbidity values recorded by Sonde were plotted to develop the suspended sediment turbidity relationships.

Soil Erosion and Sedimentation Processes

Soil erosion and sedimentation are two separate, but interrelated processes at different stages in the loss of soil from the upland regions (Folle, 2010). Soil erosion is the removal of soil by water, wind, ice or gravity. Soil erosion by water involves the detachment; transport and deposition of soil particles by the erosive forces of rainfall and snow melt runoff. This can be in the form splash, sheet, rill or gully erosion (Klaghofer *et al*., 1998; Daggupati *et al*., 2013; 2014).

Detached soil particles are moved or transported by the intensity of rain drops hitting the soil surface inducing surface runoff of the dissolved or suspended soil particles, causing the process of sediment entrainment or transported to the outlet of the watershed (Julien, 2010).

Model Setup and Data Acquisition

Watershed Characterization and Hydrographs

In this study, ArcSWAT interface (Version 200.10.1) was used. The 30 m ((1/3-arc second) resolution Digital Elevation Model (DEM) datasets covering the whole watershed was downloaded from http://datagateway.nrcs.usda.gov/and was used as topographic input to the model. The GIS data layer of the stream network of the entire Kaw Lake watershed was obtained from the National Hydrography Dataset (NHD), produced by USGS and available on the web (http://nhd.usgs.gov). The DEM and NHD datasets together were used to delineate 65 subbasins in the watershed. During delineation, the Ark City and Winfield's USGS gauge stations and Kaw Lake dam were used as inlet and outlet of the watershed, respectively (Fig. 7).
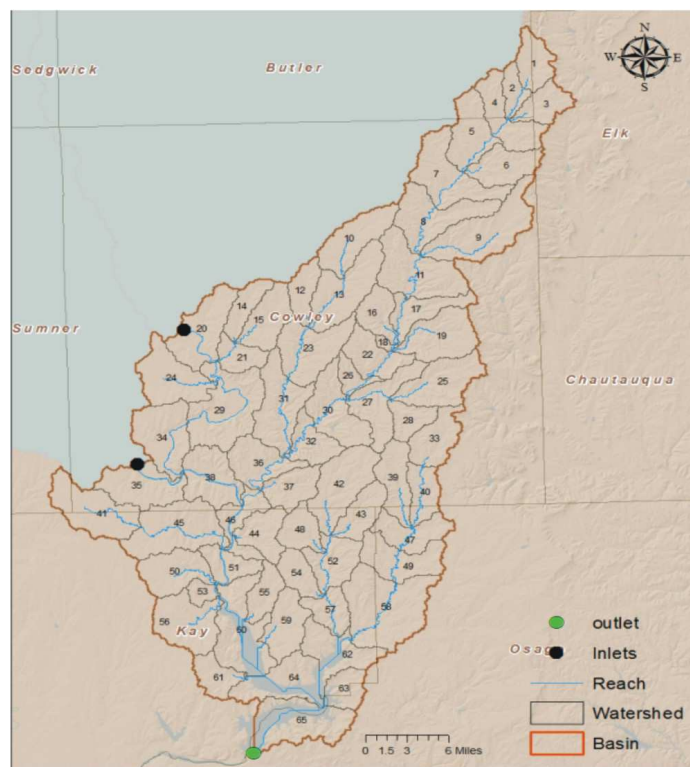
Fig. 7. Kaw Lake watershed with subbasins, inlets and outlet developed using SWAT model

Table 1. Kaw lake watershed landuse distribution

Landuse type	SWAT code	Area (ha)	% watershed area
Range-grasses	RNGE	55656	22.04
Corn	CORN	3015	1.19
Upland Cotton-harvested with	COTS	328	0.13
Grain Sorghum	GRSG	2543	1.01
Soybean	SOYB	13972	5.53
Sunflower	SUNF	45	0.02
Winter Barley	WBAR	0	0.00
Winter Wheat	WWHT	8985	3.56
Winter Wheat-Soybean	WWSB	3270	1.30
Rye	RYE	3	0.00
Oats	OATS	12	0.00
Pearl Millet	PMIL	2	0.00
Spring Canola-Polish	CANP	0	0.00
Alfalfa	ALFA	1224	0.48
Sweet Clover	CLVS	1	0.00
Carrot	CRRT	1290	0.51
Pasture	PAST	110647	43.82
Orchard	ORCD	2	0.00
Water	WATR	8979	3.56
Residential	URBN	9380	3.71
Residential-Low Density	URLD	2153	0.85
Residential-Medium Density	URMD	399	0.16
Residential-High Density	URHD	142	0.06
Forest-Deciduous	FRSD	22987	9.10
Forest-Evergreen	FRSE	24	0.01
Forest-Mixed	FRST	2	0.00
Range-Brush	RNGB	7	0.00
Wetlands-Forested	WETF	6557	2.60
Wetlands-Non-Forested	WETN	397	0.16
Winter Wheat-Corn	WWCO	1	0.00
Winter Wheat-Sorghum	WWSR	462	0.18
Winter Wheat-Cotton	WWCT	0	0.00

Landuse/Landcover

Landuse coverage is a very crucial input into the SWAT model. In this study the landuse/landcover was obtained from 2006 and 2008 NASS Cropland Data Layer (CDL) (www.datagateway.nrcs.usda.gov). The CDL contains crop specific digital data layers, suitable for use in Geographic Information Systems (GIS) applications. The CDL program focuses on classifying corn, soybean, rice and cotton agricultural regions in many Midwestern states using remote sensing imagery and on-the-ground monitoring programs through the USDA www.nass.usda.gov/research/Cropland/SARS1a.htm). In this study, 2006 and 2008 landuses were combined to develop a final landuse with crop rotations. The final

landuse map is shown in Fig. 8. Each landuse category is briefly explained in Table 1.

Soils

Along the hydrography and land use data, soils are another crucial input to the SWAT model. The Soil data was obtained from the U.S. Department of Agriculture, Natural Resource Conservation Soil Survey Geographic (SSURGO) database for Oklahoma and Kansas that contains soil maps at a 1:250,000 scale. All soil properties needed for the SWAT model were extracted from the SSURGO database and distributed them with Arc SWAT software. Soil map for entire watershed is shown in Fig. 9.
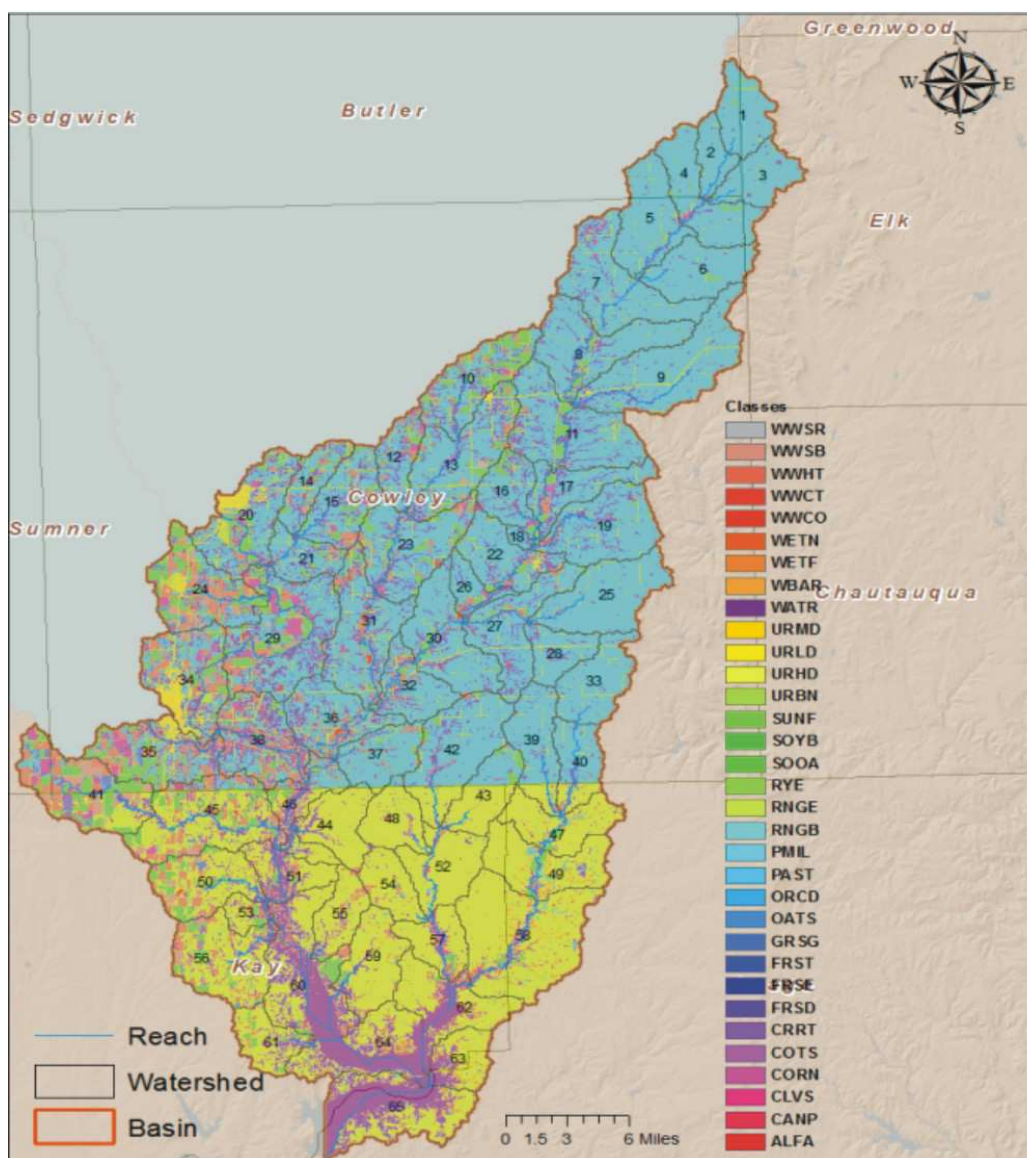
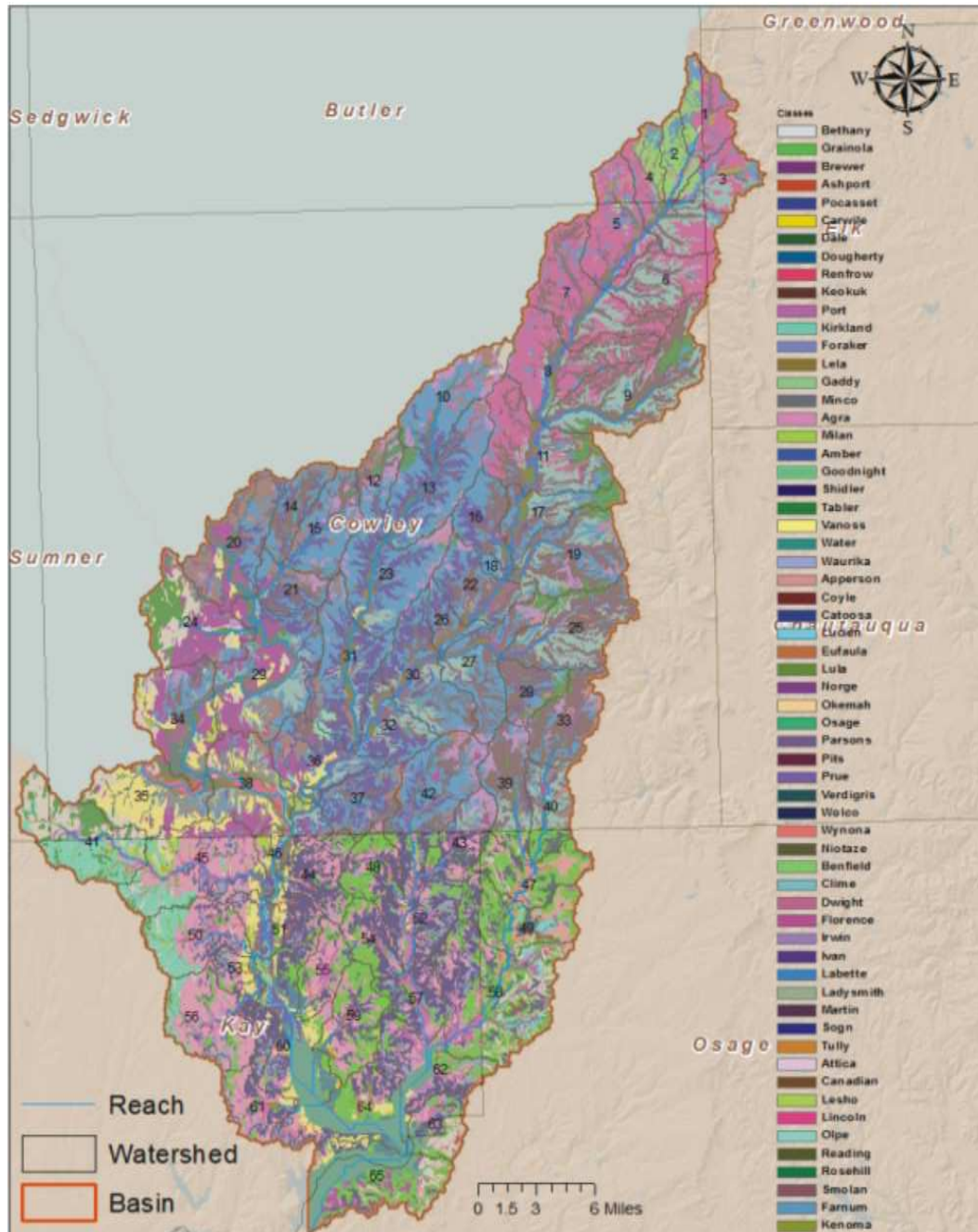

Fig. 8. Landuse map for entire watershed (Kaw Nation)

Fig. 9. Soils in Kaw Lake watershed (Kaw Nation)

Hydrologic Response Units (HRUs)

HRUs are the basic building blocks for the SWAT model where all landscape processes are computed. HRUs were formulated by finding unique combinations of sub-basin, land use, soil and slopes. Through the ArcSWAT interface, the land use, soil and slope layers were overlaid to create unique combinations of HRUs by sub-basin. The slope classes used for this process were 0-2, 2-4 and 8% and above. Overlaying these slope classes with the soils and land use layers described above and using a thresholds of 10/10/10 resulted in 3658 HRUs.

Weather

The Kaw Lake watershed has a continental climate with cold winter and warm summer. The average monthly temperature ranges from 10°F, in January to

110°F, in July and August. The average annual precipitation ranges from 30 inches to 41 inches (USDA, 2009). Daily precipitation, minimum and maximum temperature were derived from weather stations located in Butler, Sumner, Cowley, Kay and Osage Counties. Missing daily weather data were adjusted internally using a stochastic weather generator embedded in SWAT. The locations of weather stations are shown in Fig. 10.

The KLW drainage network has four tributaries that drain into the Kaw Lake. These are the Chilocco, Bear, Little Beaver and Big Beaver Creeks. The Kaw Nation Environmental Department has established ten (10) ambient water quality monitoring stations to determine the concentration of nutrient, bacteria and pesticides as a result of runoff from the surrounding watersheds.
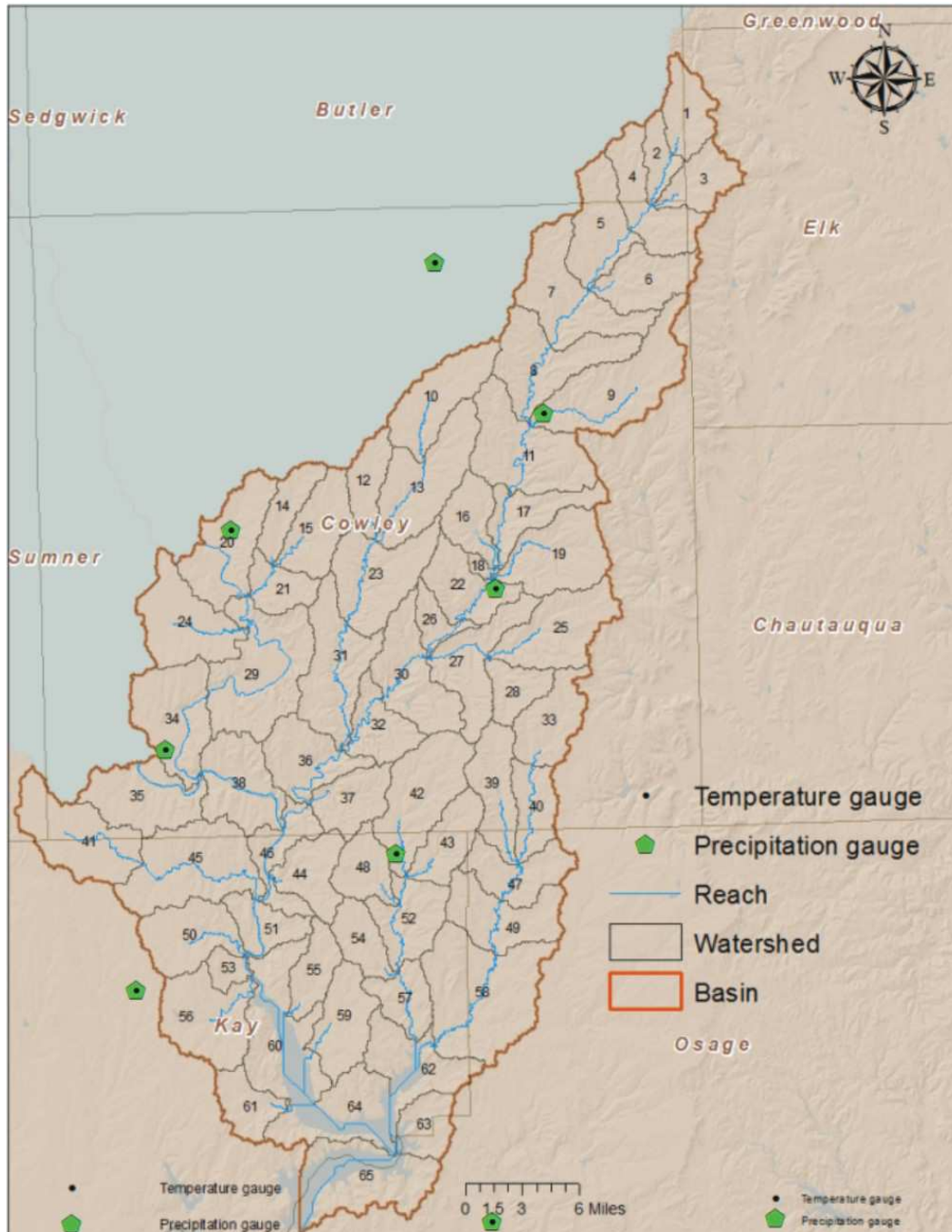

Fig. 10. Precipitation and temperature gauge locations in Kaw Lake watershed (Kaw Nation)

Results and Discussion

The Kaw Lake Watershed (KLW) was divided into five major land use categories. Rangeland is the primary land use in the watershed accounting for approximately 70%, cropland 20%, forestry 5%, wetlands-mixed with water 4% and urban and others l%. Fig. 11 shows the major crops grown are wheat (60%), Soybeans (20%) and Sorghum (10%) and others (10%).

The dominant soil series within the watershed were Shidler (45%), Pawhuska (21%), Tabler (9%), Sogn (5%), Labette and Wolco (3%) each and others (14%) (Fig. 12 and 2). In all the major soil types of the KLW, silt is the dominant soil texture that contributes for high benthic sediment concentration of Kaw Lake (Fig. 13).

Surface relief of the Kaw Lake Watershed drains from north and northwest into south and southeast with a descending elevation ranging from 210 to 150 m asl. The Arkansas River flows from Colorado to Kansas, Oklahoma and finally drains into Mississippi following the relief pattern (Fig. 1). About 95% of the Kaw Lake Watershed falls in the range of 0-11% land slope, 4% in the range of 11-22% and the remaining 1% is within greater than 33% slope class 95% of the watershed is flat and falls in the 0-11% slope class (Fig. 14).

Model Calibration

The inflow of the Arkansas was inputted into SWAT model using the USGS Arkansas City and Winfield gauging stations from 1959-2010. Daily, monthly and yearly stream flow discharge measured at two USGS gauge stations in Arkansas City and Winfield were obtained from USGS web site at http://waterdata.usgs.gov/ks/current/?type=flow and discharge data for the period of 1959 through 2010 were downloaded. The SWAT model was simulated for the period from 1/1/1955 to 10/30/2009.
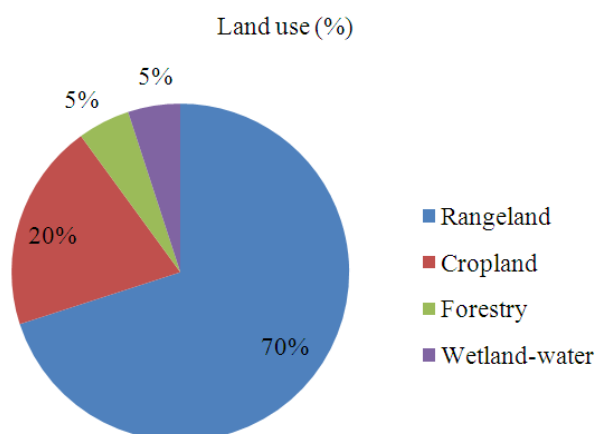

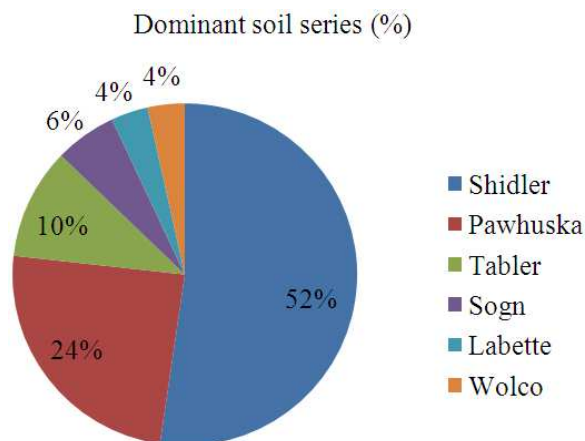Fig. 11. Landuse distribution in Kaw Lake watershed

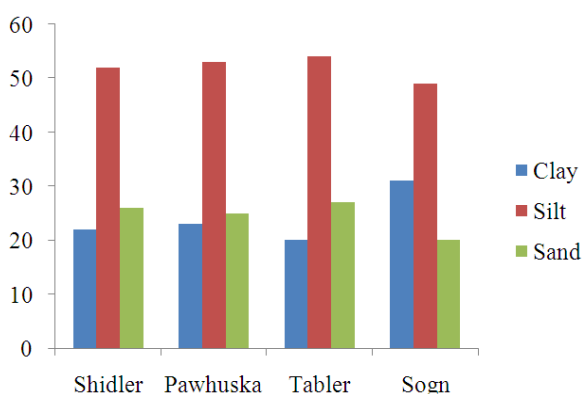Fig. 12. Soil distribution in Kaw Lake watershed

Fig. 13. Particle size distribution

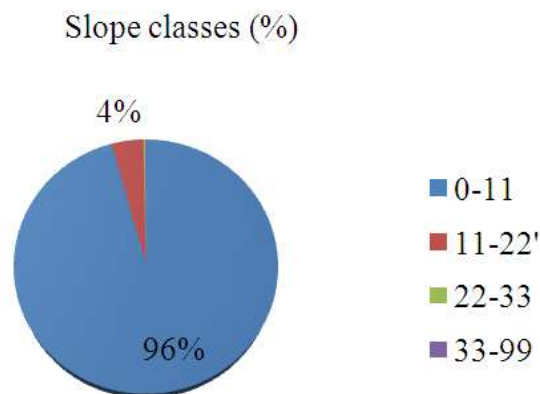Fig. 14. Slope classes in Kay Lake watershed

Table 2. Soil distribution by area

Soil types (soil series)	Area (acres)	% Watershed area
Pawhuska	59,266	21
Tabler	26,289	9
Bethany	3,323	1
Lincoln	4,158	2
Shidler	126,184	45
Sogn	11,642	4
Labette	8,368	3

SWAT simulated outflow was compared with lake levels converted into inflow by USCOE. The SWAT model was calibrated by adjusting selected parameter values till the simulated values of stream flow and base flow matched the observed values. The intent of calibration in the stream flow was to fit the model as closely as possible to the observed data (Table 2).

Sediment Yield

The total sediment load predicted by SWAT for a watershed is affected by subwatershed sediment loadings which are estimated by MUSLE equation and channel sediment routing which is based on stream velocity. The MUSLE equation has an implicit delivery ratio built into it that is a function of the peak runoff rate, which in turn is a function of the drainage area. The sediment routing in channel is a function of channel length and other channel dimensions that are affected by the watershed size. Both algorithms are nonlinear and will be affected differently by subwatershed size and channel lengths. Sediment load prediction is also affected by overland slope and slope length component used in the MUSLE equation. Slope and Length of Slope (LS-factor) in the MUSLE calculation greatly affect SWAT sediment yield prediction. However, slope and slope length variation across the watershed is minimal and sediment yield was not sensitive to these changes.

Sediment yield prediction in SWAT can be influenced by deposition and degradation components of sediment routing. As subwatershed size increases, drainage density (total channel length divided by drainage area) decreases because of simplifications in describing the watershed (Jha *et al.*, 2004). When drainage density is reduced, channels and their contributing areas are replaced by simplified overland flow elements that can affect the routing phenomena and decrease the accuracy of prediction (Jha *et al.*, 2004).

The sediment grab samples from USGS at the Arkansas and Winfield sites were extrapolated using daily stream flow to estimate monthly load and this load was included in the model as sediment input.

Figure 15 shows a frequency analysis of the monthly stream flow for the period of 1950-2010 at Arkansas, Winfield gauging station and SWAT simulated flow into Kaw Lake. From the Fig. 15, it is seen that the SWAT model simulated flow occurrences were in close agreement with the average of inflows from Arkansas and Winfield sites. This shows that roughly 95% of the flow that goes into the Kaw Lake originates from Arkansas and Winfield sites i.e., from the Arkansas River.

SWAT simulated monthly flow into Kaw Lake was compared with average of monthly inflow for the time period of 1/1995 to 10/2009 in Fig. 16. During low flow periods, the model simulated flows were in very good agreement with the observed flows. However, during the high flow periods, the model simulated stream flow resulted in higher peaks compared to observed flow

peaks. Overall, that there was a very close agreement between observed and simulated monthly flows.

Figure 17 shows regression relationship between observed and simulated stream flows. A very good linear relationship between observed and simulated stream flow of the Arkansas River with an R^2 of 0.97 is noticed. This further illustrates that the SWAT simulated stream flow and observed stream flow are in good agreement.

Flow and Load Duration Curve Analysis

The flow and load duration curves were developed using cumulative frequency of the flow and sediment load data over a long period of time ranging from 1955 to 2009. Five duration intervals are commonly defined based on the percentage of time a specific flow or load are met or exceeded. They are:

- 0-10% -- high flows
- 10-40% -- moist conditions
- 40-60% -- mid-range flows
- 60-90% -- dry conditions
- 90-100% lowest flows

Figure 18a and b shows the flow and load duration curves based on simulated SWAT outputs of flow and sediment in Kaw lake watershed. It can be seen from the Fig. 18a and b that most of the flow and sediment load entering the lake is during high flows (0-10%). During moist conditions (10-40%), flow still contributes to the lake, but the sediment contributions decreased. During mid-range flow condition (40-60%), dry conditions (60-90%) and low flows (90-100%), the contributions of both flow and sediment loads are substantially low.
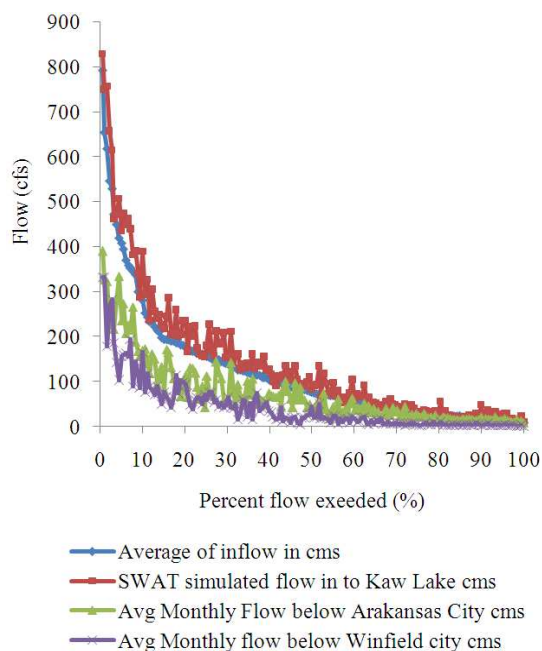

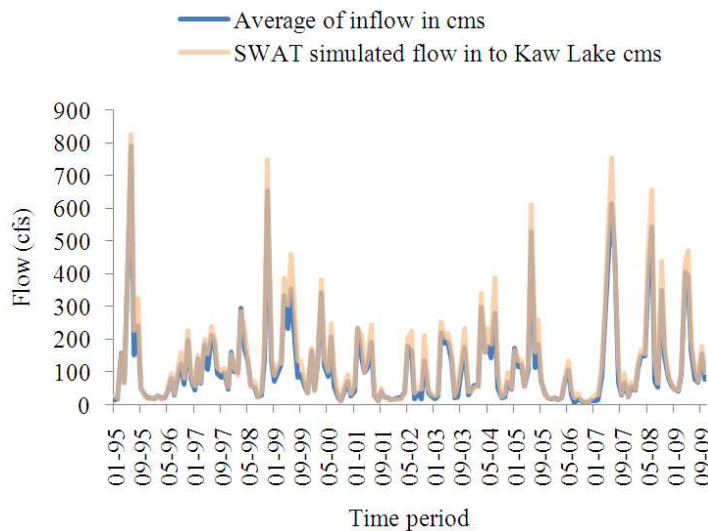Fig. 15. Flow duration curves for Arkansas River

Fig. 16. Simulated and observed flow for the time period of 1/1995 to 10/2009
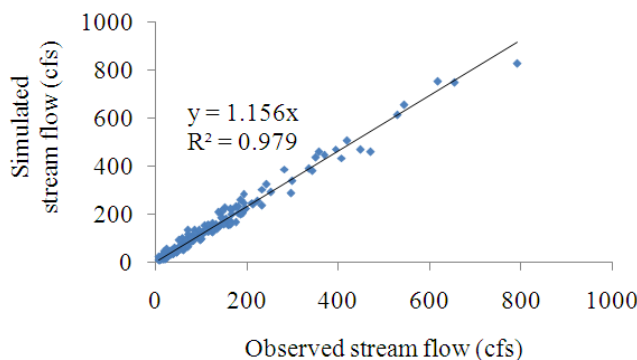

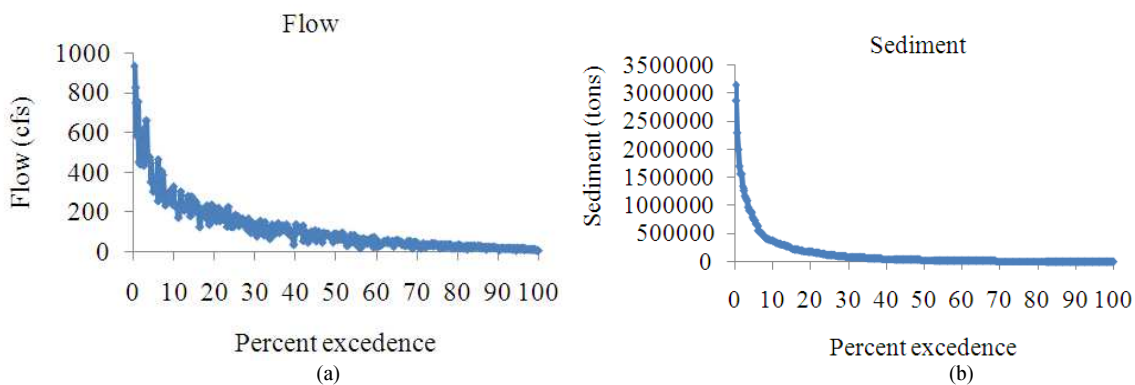Fig. 17. Relationship between observed and simulated stream flows

Fig. 18. Flow and load duration curves

From Fig. 19, it is seen that during high flow periods (at 10% exceedance), roughly 35% of flow resulted in 65% of sediment load entering Kaw lake watershed. This illustrates the fact that the more flow and sediment load is contributed to the lake only during higher flow/rain events and therefore appropriate BMPs have to be designed and implemented in order to reduce flow and sediment load originating from high flow/rain events.

Ground breaking ceremonies for Kaw Lake were held in May 1966 and impoundment of the reservoir occurred in 1976 Fig. 20 shows accumulated monthly sediment load entering Kay Lake from January 1977 to

October 2009. A gradual increase in sediment load entering into the lake over the years was observed. A total of 691 M tones of sediment entered into the lake after its inception with an average annual sediment rate of 1.75M tones/year.

Months that delivered highest sediment load into the lake were compared using monthly total sediment data extracted from USGS gauging station at Winfield, KS for a time period of 9/1961 to 9/1971. Figure 21 shows total contributions of sediment load for each month for the time period of 9/1961 to 9/1971. Months of June followed by April, September and October resulted in greater sediment load delivered into the lake. The lowest sediment contributing months were January, February, Auguest and December. Month of April, June is when farmers prepare the agricultural fields by tilling them to plant corn, soybean and sorghum and months of September and October is when the farmers preapre

agricultural fields to plant wheat in most of the upper regions of this Arkansas River.
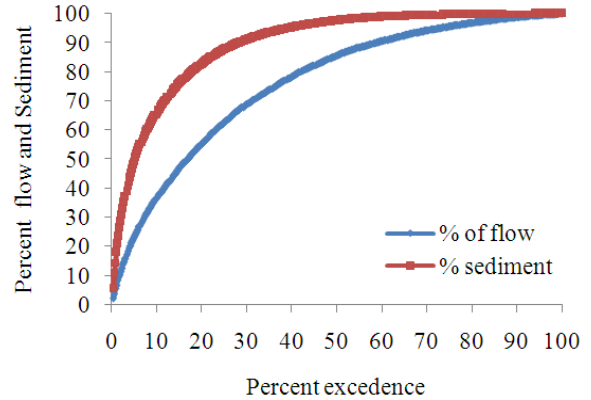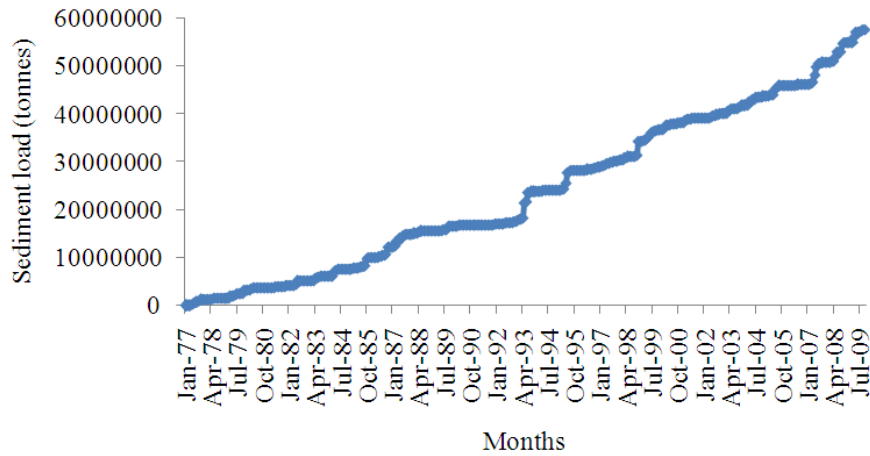

Fig. 19. Flow and load duration curves

Fig. 20. Accumulated sediment load entering Kay Lake from January 1977 to October 2009
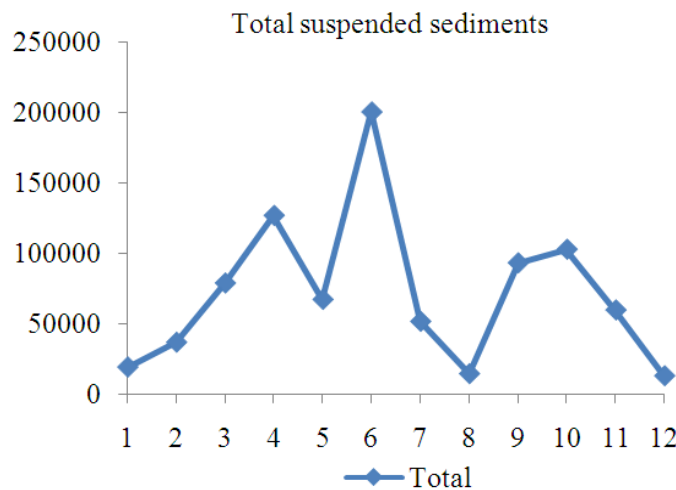

Fig. 21. Total montly sediment load

From Fig. 21, it is clearly seen that the months in which farmers prepare their agricultural fields resulted in greater sediment contributions. From the above discussion, we can deduce that agricultural fields and management practices implemented by farmers in agricultural fields is a greater contributor of sediment. Therefore, the importance of conservation management practices to reduce sediment leaving agricultural fields is well established.

Discharge or stream flow is the volume of water moving past a cross-section of a stream over a set period of time, measured in Cubic Feet per Seconds (CFS). Stream flow is affected by the amount of water within a watershed, increasing with rainstorms or snow melt and decreasing during dry periods. Of the total stream flow of the Arkansas River, 50% of the flow was contributed by the base flow. About 70% of the flow occurred March to June, which accounts to the biggest annual flow. The month of August has the smallest flow and April and May have the largest base flow.

Figure 22a and b shows relationship between annual and monthly rainfall and flow rate for the time period of January 1995 to December 2011. It is seen that rainfall directly affects the flow rate. 2006 recorded least rainfall and flow rate while the 2007 resulted in higher rainfall and flow rate (Fig. 22a). From Fig. 22b it is seen that the month of June constantly resulted in higher rainfalls and therefore higher flow rates. Also other months such as March, April, October and September also resulted in higher rainfalls and higher flow rates. Months of December, January, February resulted in low rainfalls and there by low flow rates.
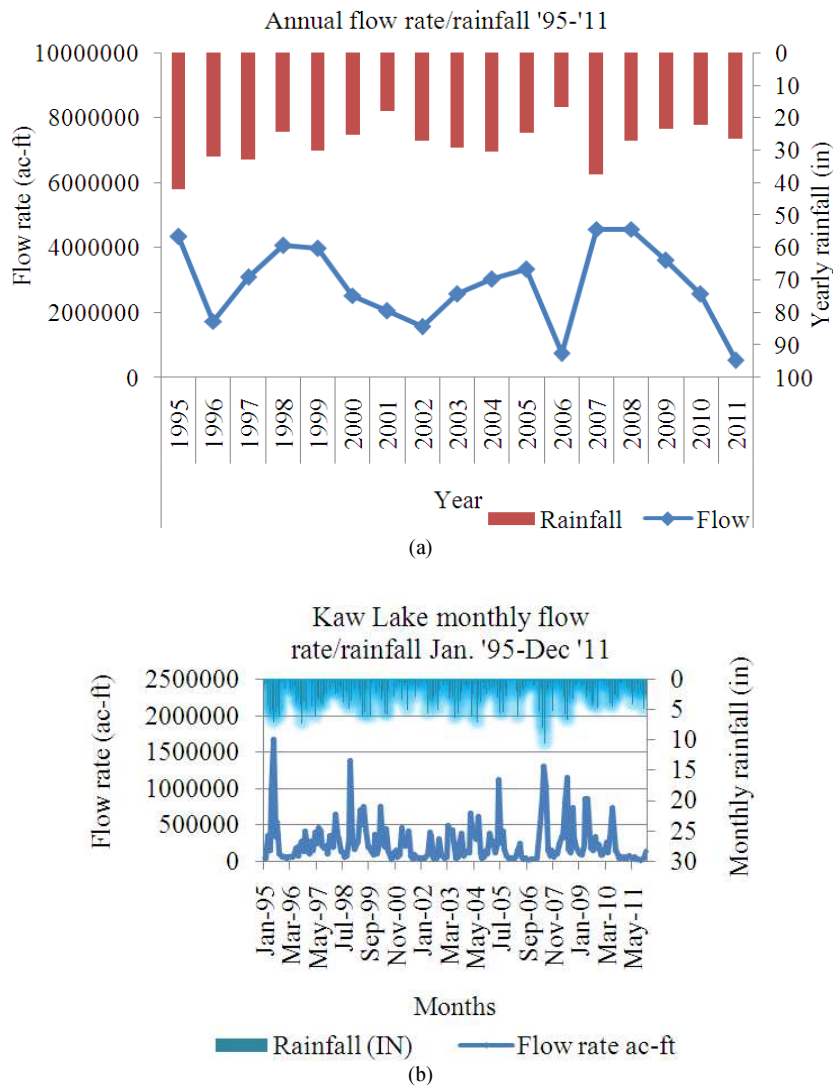

(a)

(b)

Fig. 22. Annual (a) and monthly (b) flow rate

It is evident that higher rainfall events results in higher flow rates and there by higher sediment loads into the Lake. Interestingly, most of the agricultural management practices such as tillage are practiced during high rainfall producing months which resulted in greater erosion and resulted in higher sediment loads into the Lake. Therefore, there is every need to implement conservation practices that target higher rainfall events to reduce the sediment leaving agricultural fields.

Conclusion

Non-Point Source Pollution of Rivers and Creeks into Reservoirs/Lakes is a major concern and critical problem in any sediment watershed studies. Because, sediment in Reservoir/Lakes not only damage the recreational and aesthetic values of water, but it is also decreases the quality and quantity of water.

The Arkansas River is the main source of water supply to Kaw Lake. It is also documented by USGS and Kaw Nation Environmental Department that a substantial accumulation of sediment is coming from the Arkansas River Watershed into Kaw Lake.

Application of SWAT in simulating the annual sediment yield of the Arkansas River into Kaw Lake was of high importance. SWAT was a good tool and predicted very well that the total observed and estimated sediment loads are concomitantly close in values. A total of 691 M tons of sediment entered into Kaw Lake after its inception with an average annual sediment rate of 1.75 M tones per year. SWAT model was also calibrated in this study and found to be a good predictor of sediment loads into the watershed.

According to this study 20% of the Kaw Lake sediment originated from agricultural fields while 40% is from river flows. Since the Arkansas River watershed is impaired for turbidity/sediment, a Total Maximum Daily Load (TMDL) should be developed and Best Management Practices (BMP) be carried to Protect, Preserve and Improve (PPI) the aquatic habitat and natural resources of the watershed.

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Author's Contributions

All authors equally contributed in this work.

Ethics

This article is original and contains unpublished materials. The corresponding author confirms that all of the other authors have read and approved the manuscript and no ethical issues involved.

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