Spatial Resolution Effect of Precipitation Data on SWAT Calibration and Performance: Implications for CEAP

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Abstract. *Precipitation data sets representing four spatial resolutions were used to evaluate the performance of the Soil and Water Assessment Tool (SWAT) on the basis of reproducing measured streamflow, and to show differences in model parameters when different precipitation data sets are used to calibrate the model. The experiment was conducted on the 786 km² Ft. Cobb Reservoir experimental watershed (FCREW) in southwestern Oklahoma. Precipitation data sets included the National Weather Service (NWS) cooperative weather network (Co-op), NWS next-generation radar precipitation estimates (NEXRAD), the University of Oklahoma and Oklahoma State University's joint state-wide weather station network (Mesonet), and the USDA-ARS weather station network (Micronet) deployed in the FCREW. The FCREW was divided into three main subwatersheds (Cobb, Lake, and Willow Creeks), with SWAT calibrated for each subwatershed using each precipitation data set. Model simulations were generally "good" to "very good" at both the daily and monthly time steps for all precipitation data sets, except in the Willow Creek subwatershed, which scored "satisfactory" at the monthly time step and "unsatisfactory" at the daily time step when the Co-op data were used. Calibrated parameter values within the Cobb Creek subwatershed changed little across precipitation data sets. In the Lake Creek and Willow Creek subwatersheds, the deep recharge calibration parameter values varied greatly with respect to precipitation data source. Such variation could inappropriately affect, for example, model assessments of conservation practices designed to ameliorate the movement of agro-chemicals from the surface to lower positions in the soil profile and eventually into the groundwater.*

Keywords. *Model performance, Precipitation spatial resolution, SWAT, Watershed.*

The Conservation Effects Assessment Project (CEAP) is a USDA program designed to quantify the environmental benefits of conservation practices used by private landowners participating in selected USDA conservation programs. The environmental benefits are estimated by NRCS at a national scale through the National Assessment component of CEAP. Concurrent with the cropland National Assessment, 14 benchmark watershed assessment studies (WAS) are being conducted by the USDA Agricultural Research Service (ARS) to provide information needed to verify the accuracy of and/or suggest improvement to models used in the National Assessment. One primary model being used in the National Assessment, and thus in the WAS, is the Soil and Water Assessment Tool (SWAT) (Arnold et al., 1998; Arnold and Fohrer, 2005).

The SWAT model is a continuous simulation, daily time step, distributed parameter watershed model developed to simulate effects of various land management and climatic scenarios on hydrologic and water quality response of agricultural watersheds (Arnold et al., 1998). The model divides watersheds into subwatersheds and further into hydrologic response units (HRUs) based on land use and soil type information. All model outputs can be evaluated at heterogeneous spatial scales ranging from HRUs to watersheds. The SWAT model has been applied extensively in the U.S. and many other countries to make watershed management decisions (Arnold and Fohrer, 2005; Jayakrishnan et al., 2005; White and Chaubey, 2005; Gassman et al., 2007).

To a large degree, the accuracy of model output is dependent upon the quality of the input data sets, including their spatial and temporal resolutions (Zhang and Montgomery, 1994; Anderson et al., 2006; Borman, 2006, 2008). Of these input data sets, precipitation is one of the most important because of its influence on the hydrologic model's performance (defined as agreement between measured and simulated values) and its role in determining surface hydrologic processes (Haddeland et al., 2002; Beven, 2004; Bardossy and Das, 2008). Rainfall data are often obtained from rain gauge networks, and various researchers have investigated the effects of spatial variability of precipitation data from these networks on runoff timing and amounts (Singh, 1997; Syed et al., 2003), and the impact of precipitation sampling error on model simulations and model performance (Michaud and Sorooshian, 1994).

Of particular importance to the study described herein is the spatial variability of precipitation and its impact on SWAT simulations. More specifically, rainfall events are generated by convectional and frontal mechanisms producing storms of varying size, shape, direction of movement, and rainfall totals (e.g., Nicks, 1982; Singh, 1997; Syed et al.,

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2003; Hocker and Basara, 2008a, 2008b). These storm variables, coupled with the density of the gauge network used to measure precipitation, could influence the parameter values and performance (as described above) of SWAT simulations and inappropriately influence one's assessment of the effectiveness of a conservation practice. Bradley et al. (2002) investigated the effects of spatial variability of precipitation on rainfall estimation using data collected from low (1 observation/674 km^2) and high (1 observation/19 km^2) density rain gauge networks. They observed that errors in rainfall estimation increased with increasing spatial variability of the rainfall event, but much more so for the low gauge density configuration. Oudin et al. (2006) studied the impact of precipitation measurement errors on model performance and parameter estimation, and noted that the impact of input data measurement error on model parameters has largely been ignored by hydrologists. Using two lumped-parameter models on twelve U.S. watersheds, they observed that increasing random error in potential evapotranspiration (PE) data had little effect on the parameters in either model. However, increasing random error in the precipitation data translated into important modifications of most model parameters in both models, and decreased model performance. Increasing systematic errors in PE and precipitation data induced changes in parameter values in both models, resulting in moderate to large decreases in model performance, depending upon the model and watershed. Bardossy and Das (2008) demonstrated that spatial resolution of rainfall input affected parameter values in a semi-distributed conceptual rainfall-runoff model. These researchers noted that model performance decreased as rain gauge density decreased and that parameter values calibrated with the highest gauge densities were not transferable to the model when being applied at the lowest gauge density.

Moon et al. (2004) and Habib et al. (2008) note that rainfall data from rain gauge networks tend to be the main source of rainfall data used in hydrologic studies. Habib et al. (2008) further noted that the main limitations of rain gauges are often their low spatial resolution and their near-point sampling. The U.S. National Weather Service's cooperative weather network provides the most widely available rainfall data in the U.S. and has a density of about one rain gauge per 770 km^2 (Linsely, 1992).

Radar-based precipitation products have been available for hydrologic applications for about the past 20 years (Krajewski and Smith, 2002). Because these products provide a higher spatial resolution than rain gauge networks and cover large regions, they are viewed as potentially useful in distributed hydrologic modeling. However, radar-based measurements of precipitation include measurement/estimation errors as well (Krajewski and Smith, 2002). Wang et al. (2008) and Guo et al. (2004) provide overviews of the development of these radar products and note some of the early problems with radar precipitation estimates.

Investigation of the use of radar precipitation products in hydrological models is an on-going research activity. Guo et al. (2004) used NEXRAD Stage III and a gridded rain gauge product in the VIC-3L model to assess the impacts of these rainfall data sets on runoff, evapotranspiration (ET), and soil moisture for the 1645 km^2 Illinois River watershed at Watts, Oklahoma. Both the NEXRAD Stage III and rain gauge products were resampled to represent a 1/8° grid spacing ($\approx$11 km $\times$ 14 km, yielding a density of 1 observation/154 km^2). For this mostly forested watershed, they found that realistic streamflows could be simulated from both precipitation products if the model parameters were first calibrated, and that runoff and evapotranspiration (ET) were more sensitive to the type of precipitation product than was soil moisture. Using the HEC-2000 model, Neary et al. (2004) evaluated the impact of precipitation data source on prediction of streamflow volume, magnitude, and time-to-peak for two watersheds (275 and 550 km^2 in size) in Tennessee. Rainfall data sets consisted of NEXRAD Stage III rainfall estimates and measurements from a rain gauge network located near, but not in, the study basins. The density of rain gauge observations for the study was reported to be 1 observation/556 km^2. The model was calibrated for each precipitation product. The study results indicated that the model was less accurate in predicting streamflow volume when the NEXRAD Stage III rainfall product was used, but that NEXRAD and rain gauge rainfall data were about equally useful when predicting streamflow magnitude and time-to-peak. Using SWAT, Moon et al. (2004) compared the effects of using NEXRAD Stage III rainfall estimates (1 observation/10 km^2) and rain gauge data (1 observation/345 km^2) on streamflow estimation in the 2080 km^2 Cedar Creek watershed in Texas, which consisted mostly of pastureland. Simulations were run for daily, ten-day, and monthly time steps for both input precipitation data sets. For the daily simulation, model runs incorporating the NEXRAD radar rainfall data exhibited a higher coefficient of determination (r^2) and greater model efficiency than simulations using the rain gauge data. For the ten-day simulation, the rain gauge data exhibited higher r^2 than the NEXRAD data, but the model efficiencies were nearly identical. Model efficiencies were slightly lower and r^2 slightly higher for the rain gauge data when model simulations were run at the monthly time step. Overall, the authors concluded that, for both rainfall data sets, model performance increased with longer time steps and that NEXRAD is a good alternative to rain gauge data.

The objectives of this study were: (1) to quantify the relationships between four independent rainfall data sets available for the study area, with particular emphasis on NEXRAD to determine if its indirect rainfall estimates are comparable to direct measurements of rainfall from the most dense measurement network deployed in the study area; (2) to compare differences in SWAT parameter values across four SWAT projects, each calibrated using the four precipitation data sets; and (3) to evaluate the performance of the SWAT projects, in terms of accurately reproducing average measured streamflow with respect to the density of the precipitation data sets. Results from the study will be interpreted with regard to possible impacts on CEAP-related studies.

Materials and Methods

Study Area

The Ft. Cobb Reservoir experimental watershed (FCREW) is located in southwestern Oklahoma (35° 11′ 43″ N, 98° 29′ 05″ W) (fig. 1) and is about 786 km^2 in size above the reservoir dam (Steiner et al., 2008). Four major streams feed the reservoir: Willow Creek, Lake Creek, Five Mile Creek, and Cobb Creek. USGS stream gauges are located at the lower ends of Willow and Lake Creeks, and below the confluence of Cobb and Five Mile Creeks (herein designated Cobb Creek) (fig. 1). The Cobb Creek subwatershed is about

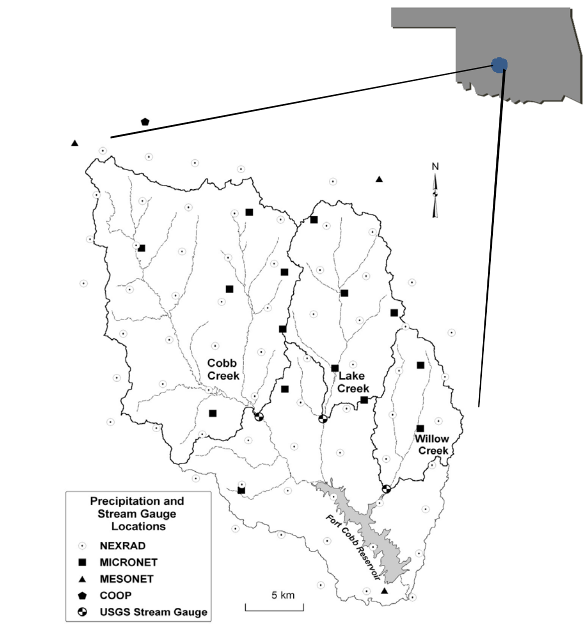

Figure 1. Precipitation and stream gauge measurement locations in the Cobb Creek, Lake Creek, and Willow Creek subwatersheds in Oklahoma.

twice as large as the Lake Creek subwatershed and about 4.5 times larger than the Willow Creek subwatershed (table 1). Although dissimilar in size, the three subwatersheds are comparable in their land use/land cover distributions (table 2) and in the type of soils found within them.

Weather and Stream Flow Data Sets

Daily weather data for precipitation, minimum and maximum air temperature, relative humidity, and solar radiation were obtained from weather stations shown in figure 1 for the time period July 2005 through June 2008. Four sources of rainfall data were available for this study. The first source derives from the National Weather Service (NWS) network of cooperative (herein referred to as Co-op) weather stations.

Table 1. Subwatershed area and number of precipitation observation points in each subwatershed as a function of precipitation data source. The values in parentheses represent the increase in density of observations as compared to the national average of one rain gauge per 770 km^2 (Linsely et al., 1992).

Subwatershed	Drainage Area (km^2)	Number of Precipitation Stations			
		NEXRAD	Micronet	Mesonet	Co-op
Cobb Creek	342	23 (52)	7 (16)	3 (7)	1 (2)
Lake Creek	154	10 (50)	7 (35)	2 (10)	1 (5)
Willow Creek	75	6 (62)	2 (21)	2 (21)	1 (10)

Table 2. Percentage of subwatershed area in a given land use/land cover category.

	Winter Wheat (%)	Grass (%)	Peanut and Cotton (%)	Dryland Summer Crops (%)	Forest (%)	Water (%)	Urban and Roads (%)
Cobb Creek	47.6	38.4	4.8	1.8	3.2	0.4	3.8
Lake Creek	38.5	38.0	9.3	4.7	5.2	0.1	4.2
Willow Creek	37.2	37.1	12.2	4.2	5.2	0.1	4.0

The Co-op data were acquired from the National Climate Data Center website (www.ncdc.noaa.gov/oa/ncdc.html). The Co-op measurement day (i.e., the "hydrologic day") is from 0600 h Central Standard Time (CST) from one day to 0600 h CST the next day. Only one Co-op station is located near the study area (fig. 1), and in relation to the size of the FCREW, yields a rain gauge density of 1 observation/786 km^2. It should be noted that in SWAT the rain gauge closest to the centroid of a subbasin provides the rainfall value for that subbasin. Thus, the Co-op rainfall values were identical for each subbasin since there was only one Co-op station used in the study.

The second source of precipitation data was obtained from the statewide Oklahoma Mesonet (McPherson et al., 2007). Of the over 110 stations distributed across the state, three were located near the study area (fig. 1). Rainfall is measured using a tipping bucket gauge and is reported to a central archive facility on a 5 min basis. Liquid precipitation is recorded as the number of bucket tips since 0000 UTC (McPherson et al., 2007).

In 2005, a network of 15 meteorological stations (herein referred to as the Micronet) were deployed in the FCREW (fig. 1) to measure air temperature, relative humidity, incoming solar radiation, rainfall (via tipping bucket), soil temperature, and volumetric soil water (Steiner et al., 2008). Measurements are made every 5 min for all variables except soil water content (which is measured every 30 min) and reported every 15 min to a central archiving and data quality control center. For rainfall, each 5 min period represents the amount of rainfall accumulated since the previous measurement. With the measurement day beginning at 0000 h (CST) and ending at 2355 h, daily accumulated rainfall is obtained from the 2355 h reading.

The National Weather Service NEXRAD Stage III radar-based precipitation product (herein referred to as NEXRAD) was used as the fourth source of rainfall data. NEXRAD data covering the study area are available from January 2005 to present and were obtained from the NWS Advanced Hydrologic Prediction Service web page (http://water.weather.gov/). The NEXRAD estimates of precipitation are given on a 4 km grid and coincide with the Co-op measurement time frame.

The finest time-scale common among the four precipitation data sources was the daily time step. Moreover, both the NWS Co-op and NEXRAD data are reported for the same "hydrologic day." Therefore, we recalculated daily rainfall for the Mesonet and Micronet from their subdaily files to match that of the Co-op and NEXRAD data sets. Putting the precipitation products on the same time frame allows the examination of the effects of gauge density relative to the precipitation events occurring on a given day.

Some studies have indicated that the indirect estimates of rainfall from NEXRAD and direct measurements from rain gauges sometimes do not correspond (e.g., Borga, 2002). An analysis of the correlation between NEXRAD and Micronet rainfall is conducted to determine the correspondence of the NEXRAD data with the most dense direct rainfall measurement network in the FCREW. In this analysis, a data set of daily rainfall values is constructed from the Micronet data and that from the NEXRAD observation nearest the Micronet station (fig. 1).

A second analysis is performed on the weighted, daily average precipitation calculated and used by SWAT during the model calibrations. This analysis is conducted at the subwatershed level and is designed to elucidate the relationships between the various rainfall data sets.

Observed daily stream flow data were obtained from the three USGS stream gauges deployed in the FCREW (fig. 1). The gauge on Cobb Creek was established in 1968 and has been continuously operated since that time. Stream gauges were established on Lake Creek in 2004 and on Willow Creek in 2005. The daily streamflow data were downloaded from the USGS web site (http://waterdata.usgs.gov/ok/nwis/rt). All three stream gauges are stage recorders of the same manufacture. The length of the streamflow data record at the Lake Creek and Willow Creek sites in combination with the deployment date of the Micronet in the FCREW limited the current study to the July 2005 through December 2007 time frame.

Input Data and Model Calibration

The 24-month data record for the study site was divided into an 18-month (July 2005 to December 2007) calibration period and a six-month (January 2008 to June 2008) validation period. Maps of digital elevation, soils, and land use, and measurements of daily precipitation, air temperature, relative humidity, solar radiation, and daily wind speed were supplied to SWAT using the ArcSWAT GIS interface. A 10 m digital elevation model (DEM) was obtained from the USGS Seamless Data Distribution System (http://seamless.usgs.gov/viewer.htm). The Arc SWAT GIS interface was used to determine subbasin parameters such as slope, slope length, and stream network parameters from the DEM. Soil characteristics were obtained from the 30 m NRCS STATSGO. Although the high spatial resolution SSURGO soils data set is available for the study area, there has been no consensus in the literature (Mednick et al., 2008) that its spatial resolution is advantageous, so it was not considered germane to this study. Land use/land cover information was obtained from a 30 m Landsat 5 TM land cover study conducted in the area in 2005.

General crop management operations were taken from various crop guides, information provided by farmers, agronomists, animal scientists, and other farming specialists either in or familiar with the study area. Grassland management included a 180-day grazing operation, typical for the area. Both grassland and winter wheat grazing operations included daily consumed and trampled biomass and manure deposition. The peanut/cotton land cover category was subdivided into 60% peanuts and 40% cotton, based upon Caddo County, Oklahoma, agricultural statistics. For the purposes of the simulations herein, the dry land summer crop category was defined to be grain sorghum, a typical crop found the FCREW. An auto-irrigation operation was applied only to the peanut and grain sorghum crops and was triggered when the plant-water stress factor reached 0.9 (Neitsch et al., 2002).

Each subwatershed was divided into a series of subbasins with outlet points representing a USGS stream gauge, water sampling sites, a reservoir, or a location on the stream channel in which the subbasins were comparable in area. The number of subbasins was 43, 24, and 9 for Cobb Creek, Lake Creek, and Willow Creek, respectively. The multiple HRU method was used with threshold levels of 5% and 0% for land use and soils, respectively. The number of hydrologic response units (HRUs) was 513, 311, and 99 for Cobb Creek, Lake Creek, and Willow Creek, respectively. Thus, the HRU density is comparable at 1.5, 2.0, and 1.3 HRUs/km^2 for the respective subwatersheds.

As suggested by Engel et al. (2007), a preliminary automated sensitivity analysis was conducted, which indicated that the curve number (CN2), soil evaporation compensation coefficient (ESCO), aquifer percolation coefficient (RCH_DP), plant uptake compensation factor (EPCO), effective hydraulic conductivity in tributary channel alluvium (CH_K1), and surface runoff lag coefficient (SURLAG) were the most sensitive parameters in SWAT for this study. The CN2 is a function of the soil's permeability, antecedent soil moisture conditions, and land use, with initial values (in the present study) ranging from the 40s (lower runoff) to the 70s (higher runoff). ESCO adjusts the depth distribution of soil evaporation to meet soil evaporative demand and varies between 0.01 and 1.0, inclusive. As the value of ESCO is reduced, the model is able to evaporate more water from deeper layers in the soil profile. EPCO adjusts plant water uptake and varies between 0.01 and 1.00, inclusive. As EPCO approaches 0.0, the model limits uptake of water by the plant to the upper portions of the root zone. RHC_DP describes the fraction of percolation from the root zone, which recharges the deep aquifer and varies between 0.0 (no percolation) and 1.0 (all the water percolating from the root zone reaches the deep aquifer). CH_K1 is the effective hydraulic conductivity (mm h^{-1}) of the channel alluvium and controls transmission losses from surface runoff as it flows through the tributary to the main channel in the subbasin. SURLAG is the surface runoff lag coefficient and provides a storage factor in the model that allows runoff to reach a subbasin outlet when the time of concentration is greater than one day. As SURLAG decreases, the amount of water reaching the outlet decreases.

Manual calibration was accomplished by increasing or reducing the calibration parameters, one parameter at a time, until the calibration standards described below were met; default values were used for the rest of the parameters. The calibrations were also constrained such that the simulated ET and biomass values were realistic and representative of the study area in order to minimize the potential for false positive outcomes (i.e., obtaining good statistics for the wrong reasons). According to Hanson (1991), the mean actual annual ET of this region during the study period was about 88%. A target range was set for ET of 80% to 96%. Ranges of total annual biomass production (in metric tons) were established using agricultural statistics, extension reports, scientific literature, and interviews with agronomic experts. Biomass production ranges (in metric tons) used in this study were: 1.8 to 2.7 for cotton, 4.4 to 6.6 for sorghum, 8.1 to 9.1 for peanuts, 4 to 6 for winter wheat, 3 to 7 for pasture/grassland, and 5 to 10 for forest. A wider range was given to the pasture/grass and forest categories due to large variation in species composition. The forest category is somewhat problematic because limited information is available for the study area. Actual biomass values could be very different from those indicated above. No other constraints were placed on the model during calibration.

Model Performance Evaluation

The American Society of Civil Engineers (ASCE Task Committee, 1993) suggested that model performance be evaluated through both graphical (e.g., hydrograph) and statistical techniques. Herein, daily and monthly hydrographs are used to identify model bias and differences in the timing and magnitude of peak flows.

Root mean square error (RMSE) is a common statistic used to evaluate model performance and is given by:

$$\text{RMSE} = \sqrt{\sum_{i=1}^{n} \left(y_i^{obs} - y_i^{sim}\right)^2 / n} \quad (1)$$

where y^{obs} is the ith observed (i.e., measured) value being evaluated, y^{sim} is the ith simulated (i.e., predicted) value being evaluated, and n is the total number of observations. RMSE is in the same units as y. Singh et al. (2004) stated that RMSE values less than one-half the standard deviation of the measured data may be considered low.

Additionally, two statistics suggested by Moriasi et al. (2007) are used to quantify model performance: percent bias (PBIAS) (Gupta et al., 1999) and Nash-Sutcliffe efficiency (NSE) (Nash and Sutcliffe, 1970). PBIAS is a measure of the simulated data's overall tendency to be larger or smaller than its measured counterpart, and is calculated in the following way:

$$\text{PBIAS} = \frac{\sum_{1}^{n} (y_i^{obs} - y_i^{sim})^2 \times 100}{\sum_{1}^{n} y_i^{obs}} \quad (2)$$

A PBIAS value of 0.0 is optimal, with low-magnitude values indicating precise model simulation. Positive values indicate a bias towards model underestimation, and negative values model overestimation.

The NSE indicates how well the plot of observed versus simulated data fits the 1:1 line and is computed as:

$$\text{NSE} = 1 - \frac{\sum_{1}^{n} (y_i^{obs} - y_i^{sim})^2}{\sum_{i}^{n} (y_i^{obs} - y^{mean})^2} \quad (3)$$

where y^{mean} is the mean of the observed data. NSE ranges between $-\infty$ and 1.0 (inclusive). An NSE value of 1 is optimal, while NSE values $\leq$0.0 indicate that the mean observed value is a better predictor than the simulated value.

Moriasi et al. (2007) compiled ranges of values for PBIAS and NSE from the literature to provide guidance in interpreting model performance. The model performance guidelines of Moriasi et al. (2007) for streamflow at the monthly time step are summarized in table 3. The calibration process was considered complete when the performance criteria attained at least a satisfactory performance rating while ensuring that the simulated ET and biomass values were realistic and representative of the study area.

Table 3. Streamflow calibration performance rating statistics for the monthly time step (summarized from Moriasi et al., 2007).

Performance Rating	NSE	PBIAS (%)
Very good	$0.85 < \text{NSE} \leq 1.00$	$\text{PBIAS} < \pm 5$
Good	$0.75 < \text{NSE} \leq 0.85$	$\pm 5 \leq \text{PBIAS} < \pm 10$
Satisfactory	$0.65 < \text{NSE} \leq 0.75$	$\pm 10 \leq \text{PBIAS} < \pm 15$
Unsatisfactory	$\text{NSE} \leq 0.65$	$\text{PBIAS} \geq \pm 15$

Results

Precipitation Data Sources

Correspondence between NEXRAD and Micronet daily rainfall was analyzed using PROC GLM (SAS, 1997). The analysis indicated that measurement location did not contribute to variation in the data set, so a simple linear regression analysis was performed resulting in $r^2 = 0.75$. Given the spatial mismatch between the 4 km × 4 km NEXRAD estimates and the point measurements given by the Micronet tipping bucket gauges, the analysis indicates that NEXRAD data corresponded well to the direct rainfall measurements, sharing at least 75% of the variation with the Micronet data across the FCREW during the study period.

At the subwatershed level, linear regression analysis of the daily, weighted rainfall data used by SWAT during model calibration revealed that, in the Cobb Creek subwatershed, the Co-op data shared 74% of the variation with each of the other precipitation data sets. However, the NEXRAD and Mesonet data correlated best with the Micronet data ($r^2 = 0.83$ and 0.85, respectively). In the Lake Creek subwatershed, the Co-op data set shared 61%, 69%, and 64% of the variation in the NEXRAD, Micronet, and Mesonet data sets, respectively. As in the Cobb Creek subwatershed, the NEXRAD and Mesonet data correlated best with the Micronet data ($r^2 = 0.79$ and 0.87, respectively). In the Willow Creek subwatershed, the Co-op data shared about 59%, 59%, and 64% of the variation in the NEXRAD, Micronet, and Mesonet data sets, respectively, but the NEXRAD and Mesonet data correlated best with the Micronet data ($r^2 = 0.81$ and 0.85, respectively).

With the obvious exception of the Co-op data, total average annual precipitation within and between subwatersheds (fig. 2) differed by precipitation data source. The Co-op and Mesonet amounts tended to be higher than those from the Micronet and NEXRAD, with NEXRAD typically rendering the lowest value.

The difference between the Co-op total average annual precipitation values and those generated from the other precipitation data sources is shown in figure 2. Mesonet and Co-op precipitation amounts were about the same in the Cobb Creek subwatershed. However, the Mesonet values were 65 mm (2.6 in) larger and 51 mm (2.0 in) smaller than the Co-op values for the Lake Creek and Willow Creek subwatersheds, respectively. Micronet total annual average precipitation values were always less than the Co-op values, with differences increasing with distance of the subwatershed from the Co-op station. These differences ranged from 59 mm (2.3 in) in the Cobb Creek subwatershed to 121 mm (4.8 in) in the Willow Creek subwatershed. Similarly, NEXRAD precipitation amounts were always less than the Co-op amounts, with differences increasing with distance of the subwatershed from the Co-op station. These differences ranged from 148 mm (5.8 in) in the Cobb Creek subwatershed to 198 mm (7.8 in) in the Willow Creek subwatershed.

Model Calibration

The values for the most sensitive calibration parameters are given in table 4. No variation in CH_K1 and only small variations in CN2 and SURLAG occurred within and across subwatersheds with respect to the precipitation data set used to calibrate the model. Large variations in ESCO are observed within all subwatersheds except Cobb Creek. However, when the Micronet precipitation data is used in the Lake

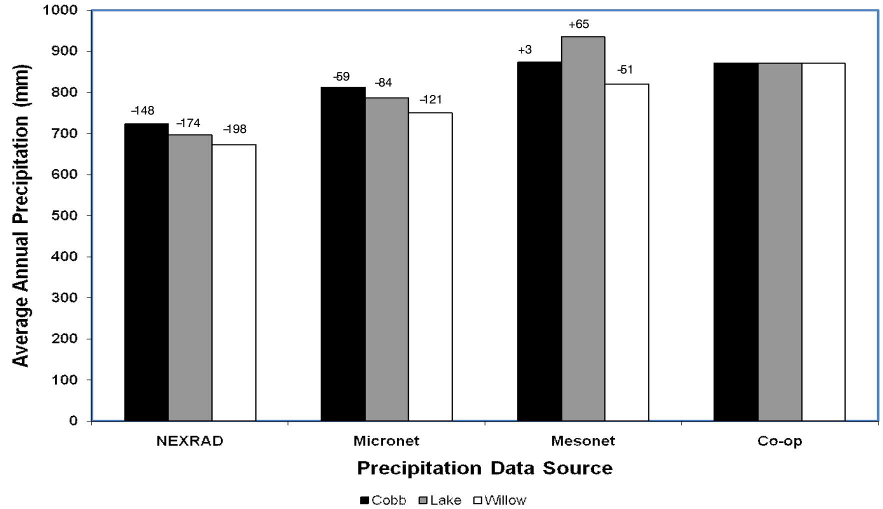

Figure 2. Average annual precipitation in each subwatershed shown as a function of precipitation data source. Values above each bar represent the amount of water (in mm) either underestimated (–) or overestimated (+) relative to the Co-op data.

Creek and Willow Creek subwatersheds, the model evaporated more water from the upper soil profile, whereas when the other precipitation data sets were used in calibration, the model assumed water came from deeper in the soil profile. In terms of plant water uptake (EPCO), precipitation data sets showed no effect in the Cobb Creek subwatershed. In the Lake Creek and Willow Creek subwatersheds, the model assumed more water used by the plants in the lower parts of the root zone when the Micronet and Mesonet data sets were used, whereas when the NEXRAD and Co-op data sets were used, most of the water used by the plants appeared to come from the upper portions of the root zone. Little difference in deep recharge (RCH_DP) with respect to the precipitation data set was noticed in the Cobb Creek subwatershed. In the Lake Creek subwatershed, more water was allowed to recharge the deep aquifer when the Micronet and Mesonet data were used, but very little appeared to reach the aquifer when NEXRAD and Co-op data were used in the simulations. Conversely, in the Willow Creek subwatershed, more water appeared to reach the deep aquifer when the Mesonet and Co-op data were used, with lesser amounts reaching the aquifer when the Micronet and NEXRAD data were used.

The parameters developed during the daily calibration were applied in the monthly time step to facilitate comparison of model performances at the two time steps and to evaluate the robustness of the parameter set.

Model Calibration Performance

Figures 3, 4, and 5 are examples of daily (1 June 2007 to 31 August 2007) and monthly (June 2007 to December 2007) measured and simulated streamflow in the Cobb Creek, Lake Creek, and Willow Creek subwatersheds, respectively. The observed streamflows were integrated with time to compute the streamflow volume, which was divided by the respective watershed drainage area to compute streamflow depth. The time periods shown were chosen to display some of the larger runoff events and to avoid clutter on the graphs. Visual inspection of the daily and monthly hydrographs indicated that the precipitation input data sets yielded similar results, although there were some notable departures from measured hydrograph at both time steps. In Cobb Creek (fig. 3), the largest differences between measured and simulated streamflow depth were observed while using the Mesonet data both at the daily and monthly time scales. For Lake Creek (fig. 4), the greatest difference between the measured and simulated streamflow depth was obtained when using the Co-op data on a daily time step and NEXRAD on a monthly time step. In the Willow Creek subwatershed (fig. 5), the largest discrepancy between the measured and simulated streamflow depth, both

Table 4. Calibrated values of the selected model parameters for each subwatershed with respect to precipitation data source used in the modeling scenarios.

Subwatershed	Precipitation Data Source	CN2	ESCO	RCH_DP	EPCO	CH_K1 (mm h^{-1})	SURLAG
Cobb Creek	NEXRAD	47-69	0.96	0.01	0.01	0.5	1
	Micronet	44-64	0.90	0.05	0.01	0.5	1
	Mesonet	44-64	0.82	0.05	0.01	0.5	1
	CO-OP	47-69	0.86	0.01	0.01	0.5	1
Lake Creek	NEXRAD	52-76	0.65	0.01	0.10	0.5	4
	Micronet	49-71	0.85	0.50	1.00	0.5	4
	Mesonet	49-71	0.10	0.60	1.00	0.5	6
	CO-OP	52-76	0.10	0.12	0.30	0.5	6
Willow Creek	NEXRAD	48-70	0.20	0.53	0.30	0.5	4
	Micronet	46-67	0.60	0.50	0.90	0.5	1
	Mesonet	46-67	0.01	0.95	1.00	0.5	1
	CO-OP	46-67	0.30	0.90	0.60	0.5	4

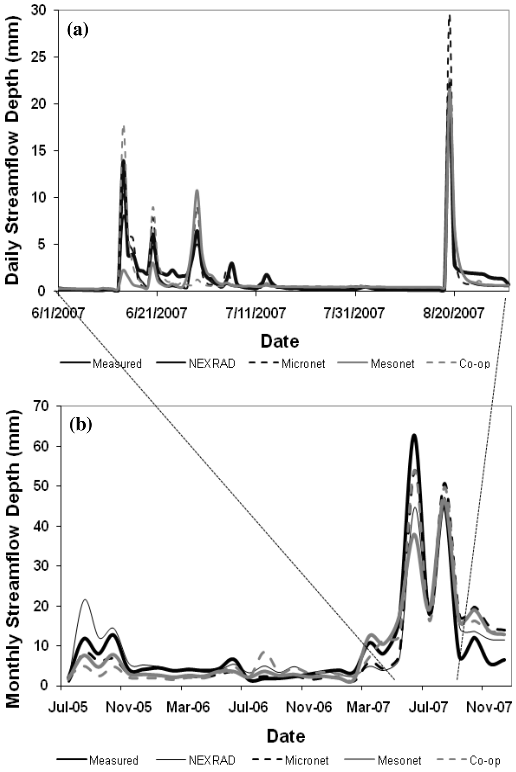

Figure 3. Measured and simulated (a) daily and (b) monthly streamflow depth in the Cobb Creek subwatershed. The daily time period shown in (a) was selected from the total calibration period to depict some of the larger runoff events and to make the graphs more readable.

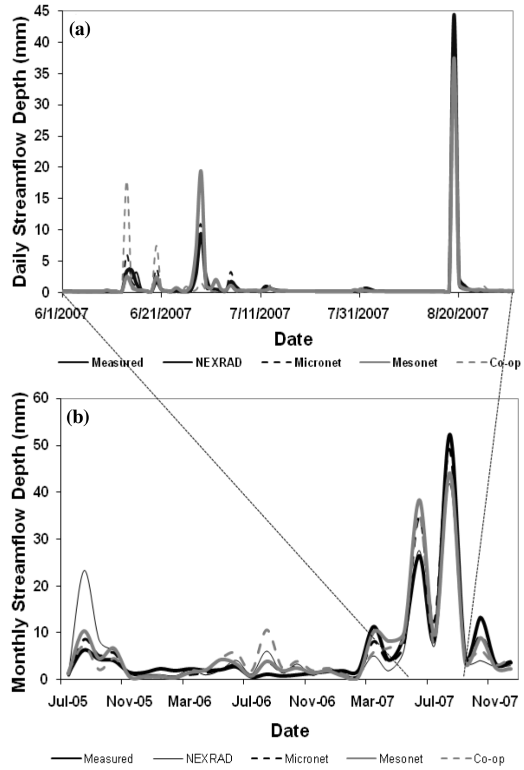

Figure 4. Measured and simulated (a) daily and (b) monthly streamflow depth in the Lake Creek subwatershed. The daily time period shown in (a) was selected from the total calibration period to depict some of the larger runoff events and to make the graphs more readable.

at the daily and monthly time step, occurred when using the Co-op data.

The statistical model performance results for the three subwatersheds are presented in table 5. Using the guidelines in table 3, at the daily time step the Co-op data yielded "good" NSE in the Cobb Creek and Lake Creek subwatersheds, but was "unsatisfactory" in the Willow Creek subwatershed. The PBIAS values at the daily time step are ranked either as "good" or "very good" for all precipitation data sources. Except for the Co-op data in the Lake Creek and Willow Creek subwatersheds, the RMSE values tended to be less than half the standard deviation of the measured streamflow. The NEXRAD and Micronet RMSEs were lower than those for the Mesonet and Co-op in each subwatershed.

Model performance at the monthly time step generally reflects that of the daily time step: all PBIAS values ranked "very good," and Micronet NSE values are generally the highest in each watershed, agreeing with the graphical observations. Except for the Co-op data used in the Willow Creek subwatershed, the RMSE values are less than one-half the standard deviation of the measured streamflow. Although all data sets generally yielded at least "good" model performance, the Micronet data consistently yielded the best model performance in simulating streamflow; it is generally the most representative (spatial resolution and data quality) precipitation data set for watershed streamflow simulations. The NEXRAD data set also produced good model performance, but tended to be lower than that of the Micronet data set and much better than that of the Co-op data set at both time steps.

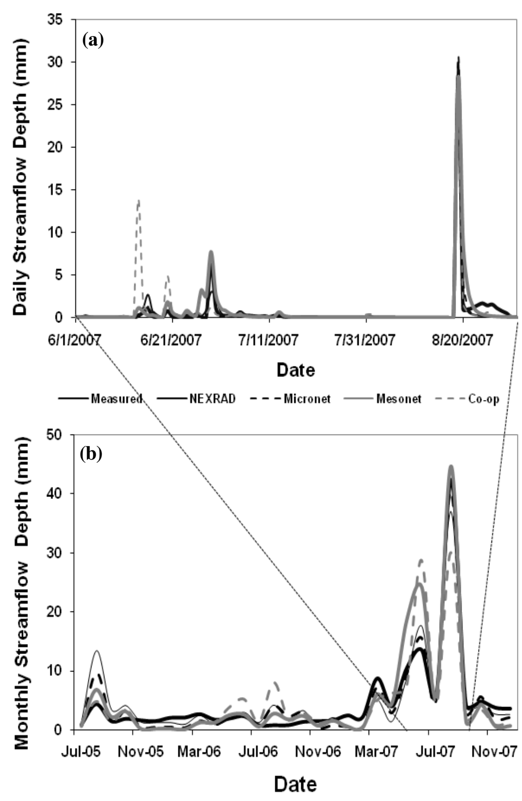

Figure 5. Measured and simulated (a) daily and (b) monthly streamflow depth in the Willow Creek subwatershed. The time daily period shown in (a) was selected from the total calibration period to depict some of the larger runoff events and to make the graphs more readable.

Table 5. Daily and monthly model calibration performance statistics for each subwatershed with respect to the precipitation data set used in each modeling scenario.

Subwatershed	Precipitation Data Source	Daily Time Step			Monthly Time Step		
		NSE	PBIAS (%)	RMSE (mm)	NSE	PBIAS (%)	RMSE (mm)
Cobb Creek	NEXRAD	0.81	-2.4	0.44 (15%)[a]	0.85	-2.3	4.9 (37%)
	Micronet	0.80	4.5	0.45 (16%)	0.88	4.6	4.5 (34%)
	Mesonet	0.68	5.1	0.57 (21%)	0.81	5.0	5.6 (43%)
	Co-op	0.77	3.1	0.48 (17%)	0.88	3.2	4.4 (34%)
Lake Creek	NEXRAD	0.85	1.8	0.61 (39%)	0.80	1.8	4.5 (44%)
	Micronet	0.96	−0.7	0.31 (20%)	0.95	-0.8	2.2 (21%)
	Mesonet	0.89	−4.3	0.52 (33%)	0.90	-4.2	3.2 (31%)
	Co-op	0.76	−4.5	0.77 (50%)	0.88	-4.4	3.5 (34%)
Willow Creek	NEXRAD	0.92	−1.2	0.28 (28%)	0.89	-1.3	2.5 (32%)
	Micronet	0.94	5.1	0.24 (24%)	0.95	4.8	1.7 (22%)
	Mesonet	0.86	−2.2	0.38 (38%)	0.85	-2.5	2.9 (37%)
	Co-op	0.65	4.0	0.59 (59%)	0.70	4.3	4.2 (53%)

[a] Values in parentheses are the RMSE's percentage of the standard deviation of the measured streamflow.

Table 6. Daily and monthly model validation performance statistics for each subbasin with respect to the precipitation data set used in each modeling scenario.

Subwatershed	Precipitation Data Source	Daily Time Step			Monthly Time Step		
		NSE	PBIAS (%)	RMSE (mm)	NSE	PBIAS (%)	RMSE (mm)
Cobb Creek	NEXRAD	0.65	8.9	0.55 (59%)[a]	0.65	8.9	3.54 (54%)
	Micronet	0.63	-14.7	0.56 (60%)	0.43	-14.7	4.56 (34%)
	Mesonet	0.38	6.6	0.73 (79%)	0.02	6.6	5.95 (90%)
	Co-op	0.39	-28.3	0.72 (78%)	-0.04	-28.3	6.13 (93%)
Lake Creek	NEXRAD	0.58	36.3	0.92 (64%)	0.28	36.3	6.18 (77%)
	Micronet	0.62	24.5	0.87 (61%)	0.46	24.5	5.36 (67%)
	Mesonet	0.28	55.1	1.21 (85%)	-0.81	55.1	9.81 (123%)
	Co-op	0.17	23.8	1.30 (91%)	0.18	23.8	6.63 (83%)
Willow Creek	NEXRAD	0.47	40.3	0.55 (73%)	0.30	40.3	4.44 (77%)
	Micronet	0.61	40.6	0.47 (63%)	0.09	40.6	5.08 (88%)
	Mesonet	0.39	61.8	0.59 (79%)	-0.84	61.8	7.21 (124%)
	Co-op	0.18	41.6	0.68 (90%)	-0.58	41.6	6.69 (115%)

[a] Values in parentheses are the RMSE's percentage of the standard deviation of the measured streamflow.

Model Validation Performance

The statistical model performance results for the three subwatersheds are presented in table 6. Perusal of table 6 indicates that the model performance measures are considerably poorer than those observed for the calibration period. This poor performance may be due in part to the rather short validation period. However, some general trends can be observed. For example, the NEXRAD and Micronet NSE values, for both the daily and monthly time steps, are higher than those for the Mesonet and Co-op data sets. The Co-op NSEs tend to be the lowest at the daily time step, and the Micronet NSEs tend to be the highest. The RMSEs for the Micronet and NEXRAD data sets are also smaller than those for the Co-op and Mesonet data sets. Moreover, in comparison to the other RMSEs, those for the Co-op data set, at both time steps, tend to be much larger than the standard deviation of the measured streamflow.

Discussion and Conclusions

The objectives of this article are : (1) to quantify the relationships between four independent rainfall data sets available for the study area, with particular emphasis on NEXRAD to determine if its indirect rainfall estimates are comparable to direct measurements of rainfall from the most dense measurement network deployed in the study area; (2) to compare differences in SWAT parameter values across four SWAT projects, each calibrated to a different precipitation data set; and (3) to evaluate the performance of the SWAT projects, in terms of accurately reproducing average measured streamflow with respect to the density of the precipitation data sets.

In relation to the first objective, four rainfall data sources were available for the study area: a low spatial resolution data set, represented by data from a National Weather Service co-operative weather station (Co-op), and increasingly higher spatial resolution data represented by, respectively, the Oklahoma Mesonet, the ARS Micronet, and NEXRAD data sources. A statistical analysis of the directly measured daily rainfall data from the 15 Micronets and the co-incident, indirect NEXRAD rainfall observations indicated a good correlation (r^2 = 0.75) between the data sets. This finding suggests that NEXRAD is a good high spatial resolution rainfall data set, suitable for hydrologic studies in watersheds where direct measurements of rainfall may not adequately represent rainfall patterns and distributions. Regression analysis of the daily, weighted rainfall data actually used by SWAT for subwatershed level model calibrations also indicated a good correlation between NEXRAD and Micronet. It is noted that as the distance of the centroid of the subwatershed increased from the Co-op station, that the correlation between the Co-op data and that of the other data sources decreased. This decreasing correlation suggests that a single Co-op station, depending upon its location, may not be representative of the precipitation patterns and amounts over the watershed of interest.

In regards to objective 2, the values of some of the most sensitive model parameters in this study were observed to change with respect to the rainfall data set used in model calibration (table 4). In some cases, the changes were small, but in other cases the range of values for a particular parameter reflected the upper and lower limits allowed by the model. For example, in the Lake Creek subwatershed, EPCO (the plant uptake compensation factor) varied from 0.1 with the NEXRAD data set to 1.00 with the Micronet and Mesonet data sets. In the case of the NEXRAD data, the value of EPCO restricted water use by the plant to the upper soil layers, but in the Micronet and Mesonet cases EPCO allowed the plants to extract water from deeper in the soil profile.

At the daily and monthly time step, the difference between estimates of rainfall such as that provided by the Co-op stations and estimates provided by a denser network of rain gauges may have important implications when evaluating the effectiveness of conservation practices in studies like CEAP. For example, from table 4 it was observed that the deep recharge parameter (RCH_DP) varied widely in the Lake Creek and Willow Creek subwatersheds. If the Co-op data were used in model simulations in the Willow Creek subwatershed to evaluate a conservation practice limiting the movement of agro-chemicals through the soil column to the groundwater, then 40 mm of water would be allowed to reach the groundwater (data not shown). If the Micronet or NEXRAD precipitation data were used, only 18 and 11 mm of water, respectively, would have reached the groundwater. Depending upon one's measure of effectiveness, the conservation practice under scrutiny could be mis-evaluated due to the precipitation data set used as the model input.

In terms of model performance, model simulation ratings, at the monthly time step, were ranked as "good" to "very good" in both the Cobb Creek and Lake Creek subwatersheds for all precipitation data sources. In the Willow Creek subwatershed, data from NEXRAD, the Micronet, and the Mesonet also yielded "good" to "very good" model performance ratings, whereas the Co-op data yielded only "satisfactory" model performance in the Willow Creek subwatershed. We hypothesize that this lower ranking is due to the distance that the Co-op station is from the subwatershed centroid, i.e., the Co-op data are not representative of precipitation actually received in the Willow Creek subwatershed. Similar findings were observed at the daily time step. The Micronet data provided better overall model performance as compared to the other rainfall data sets. The NEXRAD data set produced model simulations of streamflow as good as or better than those when the Co-op data were used. In terms of model performance, we conclude that any of the four precipitation data sets will yield satisfactory results for simulating streamflow. For evaluation of the effectiveness of conservation practices, such as in CEAP, other considerations may necessitate the use of more dense precipitation observations.

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