STREAM FLOW ESTIMATION USING SPATIALLY DISTRIBUTED RAINFALL IN THE TRINITY RIVER BASIN, TEXAS

J. Moon, R. Srinivasan, J. H. Jacobs

ABSTRACT. *Rainfall is the driving force behind all hydrologic processes in a watershed, and therefore the driving force in hydrologic modeling. In the past, raingauge data has been used as the primary input for these models. However, raingauge networks are generally sparse and insufficient to capture the spatial variability across large watersheds. A relatively new alternative is high−resolution radar rainfall data from weather radar systems, such as the Next Generation Weather Radar (NEXRAD) of the National Weather Service (NWS). In this study, raingauge data were compared to NEXRAD data at each raingauge location to evaluate the accuracy and validity of rainfall data measured by radar. The main objective of this study was to evaluate the use of spatially distributed rainfall on stream flow estimation using radar rainfall inputs to a hydrologic model. SWAT, a distributed−parameter continuous−time hydrologic/water quality model, was used to estimate stream flow for a watershed in the Trinity River Basin of northeast Texas. Results obtained from simulations using NEXRAD rainfall inputs were compared to those obtained using traditional raingauge data as input to the same model. Estimation efficiency analysis was used to compare the storage volume for the Cedar Creek Reservoir with daily, ten−day, and monthly accumulated flow from SWAT simulations using raingauge and NEXRAD rainfall inputs. The efficiency for both models was similar; however, NEXRAD rainfall inputs seem to provide a better flow estimate. The accuracy of the model results suggest that NEXRAD is a good alternative to raingauge data, and can be extremely valuable in large watersheds without readily available raingauge data or sparse raingauge networks. In addition, NEXRAD can capture rainfall from localized events that may be missed by raingauge networks but that still contribute to overland runoff, thus contributing to stream flow.*

Keywords. *Hydrologic modeling, NEXRAD, Precipitation, Simulation, SWAT.*

Hydrologic modeling can provide information beneficial to natural resource managers for planning, flood and drought mitigation, reservoir operation, and other watershed and water resource management practices. In addition, models can provide a more cost−effective means of evaluating the best alternative management plan within a watershed. However, the accuracy of model results depends heavily on the accuracy of model inputs, especially rainfall, which is the driving function in the hydrologic process.

In the past, models have mainly used rainfall data derived from raingauge measurements due to its availability. The dense raingauge networks necessary to capture the spatial variability of rainfall in an area are often only available in experimental or research watersheds. However, a relatively new alternative to raingauge networks is high−resolution radar rainfall estimation from systems such as the Next Generation Weather Radar (NEXRAD) of the National Weather Service (NWS). Rainfall estimates from NEXRAD capture the spatial as well as temporal variability associated with rainfall, and do so in a near real−time fashion. Although this type of data can suffer from several sources of error, such as ground clutter contamination and incorrect calibration, the radar provides the most spatially distributed rainfall data available with current technologies.

NEXRAD data for this study were obtained from the West Gulf River Forecasting Center (WGRFC) of the National Weather Service (NWS). Twenty−three radar stations in Texas, Louisiana, New Mexico, and Colorado make up the Hourly Digital Precipitation (HDP) network utilized by the WGRFC. The raw data obtained from the HDP network are considered Stage I output, and are available in 4 × 4 km resolution grids, with cells identified by the Hydrologic Rainfall Analysis Project (HRAP) number. Stage I data are then corrected using a bias adjustment factor based on available one−hour raingauge reports. The resulting correction is available as Stage II data. Finally, Stage II data for all radars are combined into one map with ground truth data from gauge stations, and overlapping areas are averaged together. The result is multi−sensor Stage III adjusted data, which was used in this study. In this process, the combining and averaging of overlapping data, or mosaicking, helps to compensate for the overestimation or underestimation of individual radars (Jayakrishnan, 2001). More detailed information about NEXRAD products and processing algorithms can be found in Crum and Alberty (1993), Klazura and Imy (1993), Smith et al. (1996), and Fulton et al. (1998).

A number of previous studies have evaluated all stages of NEXRAD rainfall data in relation to raingauge data for corresponding areas. Lott and Sittel (1996) compared Stage III NEXRAD rainfall data with a network of 220 raingauges

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for rainfall events from 1994 to 1995. In 80% of the raingauge locations, radar underestimated rainfall totals. Anagnostou et al. (1998) compared Stage I data from the Tulsa, Oklahoma, radar with 240 raingauge stations. Their findings suggest that Stage III bias−adjusted data were a better comparison with raingauge data. Other studies found underestimation due to terrain blockage (Westrick et al., 1999) and extremely high rainfall events (Baeck and Smith, 1998). Legates (2000) derived a reflectivity−rainfall rate relationship (Z−R relationship) to address issues in radar calibration with the use of raingauge data. This relationship increased rainfall estimates, which more closely matched observed rainfall. Jayakrishnan (2001) compared NEXRAD and raingauge data in the Texas−Gulf basin. This study suggests that based on improved data processing algorithms and on−going developments, after 1998, NEXRAD was more accurate when compared to raingauge data. In addition, these data did not suffer from the underestimation seen in the past. The study states that raingauges with more than 20% underestimation dropped from 75% in 1995 to 6% in 1999.

These studies highlight the need for accurately calibrated radar data and suggest that there have been improvements in data processing over the history of this technology. Still, there is a need for comparison between NEXRAD and raingauge data in order to eliminate ground clutter or other sources of data contamination (Sauvageot, 1992; Legates, 2000). In this study, regression analysis was used to compare the NEXRAD rainfall estimates and the raingauge data at each raingauge location to evaluate the similarity of the two data sources and to avoid bias in the NEXRAD data before running the model.

The goal of this study was to evaluate the use of spatially distributed rainfall on stream flow estimation using a distributed parameter hydrologic model. NEXRAD rainfall was used as an input to the Soil and Water Assessment Tool (SWAT) to determine whether or not the spatial variability of rainfall captured by NEXRAD improves stream flow estimation in the Trinity River Basin of Texas.

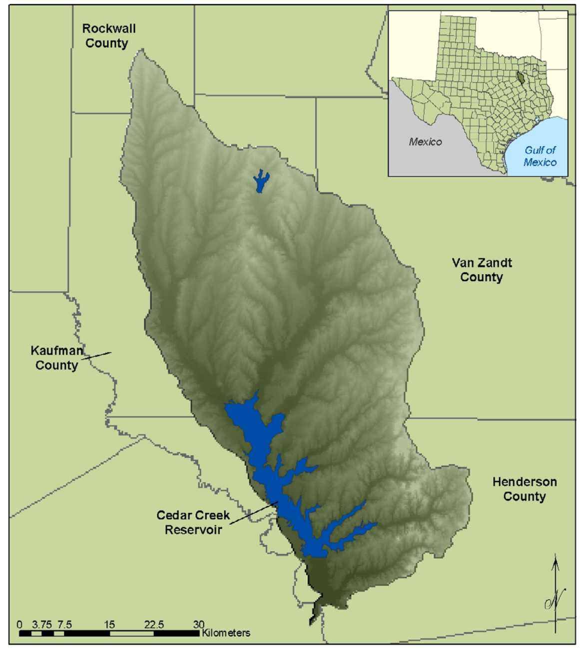

Figure 1. Cedar Creek watershed.

Materials and Methods

Study Area

Cedar Creek watershed, in the Trinity River Basin, is located within a four−county area in east−central Texas (Rockwall, Kaufman, Van Zandt, and Henderson counties) (fig. 1) and is composed of approximately 63% pasture. Kings Creek and Cedar Creek drain approximately 80% of the 2,608 km^2 area and feed into Cedar Creek Reservoir, which is located in the southwestern portion of the watershed. The reservoir is approximately 80 miles southeast of Fort Worth, Texas, and is managed by the Tarrant Regional Water District (TRWD). The surface area of the reservoir is 13,202 hectares, with conservation storage of approximately 78,595 hectare−meters of water, which provides a portion of the municipal drinking water to Tarrant County (TRWD, 2002).

SWAT Model

The Soil and Water Assessment Tool (SWAT) model is a physically based basin−scale continuous−time distributed−parameter hydrologic and water quality model. It is capable of predicting the impact of management on water, sediment, and agricultural chemical yields in large ungauged river basins for long periods. This model is also able to handle both spatially and temporally variable data as input for estimating stream flow through various comprehensive hydrologic processes (Arnold et al., 1998). Therefore, it was chosen for use in this study in order to capture the spatially variability of the NEXRAD rainfall input. A more detailed description of SWAT can be found in Neitsch et al. (2001). ESRI's ARC-VIEW 3. *x* interface (Di Luzio et al., 2002) for the SWAT model was used in this simulation as a means of extracting model inputs from various Geographic Information System (GIS) layers. SWAT uses spatially distributed inputs such as soils, land use and management, elevation, and daily rainfall to predict daily stream flow.

Input Data

The USDA−NRCS State Soil Geographic (STATSGO) database, at a 1:250,000 scale, was used as the soils input for the model. This dataset was created by generalizing more detailed soil survey maps or with the use of auxiliary data and Landsat imagery. The maps are delineated into map units of dominant soil type and may consist of up to 21 different components. This dataset is designed to support regional, multi−state, state, or river basin resource planning, management, and monitoring; however, it offers the most detailed statewide coverage available at the current time.

The landcover input was obtained from the 1992 U.S. Geological Survey (USGS) National Land Cover Data (NLCD). This dataset was derived from Landsat 5 Thematic Mapper (TM) imagery through a process of unsupervised clustering. Clusters were then placed into one of 21 thematic classes similar to the Anderson Level II land use classification scheme (Anderson et al., 1976). The accuracy assessment process has not been completed for Region 6, which includes Texas; however, this is the most detailed statewide coverage available at the current time. The scale for this dataset is 1:24,000.

The 1:24,000 scale USGS digital elevation model (DEM) was used as a topographic database for the study area. The resolution of the DEM is 30 m, allowing detailed delineation of subbasins within the watershed. For this study, 62 subbasins were delineated using the GIS interface developed for the SWAT model (Di Luzio et al., 2001). The average size of the subbasins was 4,081.8 ha, with a minimum of 9.6 ha and a maximum of 35,318.9 ha.

Unique combinations of soils and land use, or hydrologic response units (HRUs), were determined for each subbasin based on thresholds that were defined for minimum areas. This allows the user to eliminate minor soil classes or land use types from the HRU delineation (Di Luzio et al., 2001). For this study, the land use threshold was set for 5%, whereas the soil class threshold was set for 10% of the total area.

Daily precipitation totals were obtained from the National Oceanic and Atmospheric Administration's (NOAA) National Climatic Data Center (NCDC) for the six raingauge stations within and adjacent to Cedar Creek watershed (fig. 2). The time period for this data ranged from 1971 to 2002. Daily maximum and minimum temperatures were obtained from the only NCDC station with available temperature data (the Kaufman station). This data again covered the time period from 1971 to 2002. This was the only temperature data available for the study area; however, there should be little variation in temperature across this watershed due to its small size and a survey of nearby temperature stations. In addition, there is little effect of elevation on temperature and precipitation due to the small range of elevation (217 to 73 m). Therefore, this data is sufficient for the purposes of this study and was simply assigned to the nearest subbasin for modeling purposes.

NEXRAD data for the nearly two hundred 4 × 4 km grid cells within the study area (fig. 2) was obtained from the West Gulf River Forecasting Center (WGRFC) of the National Weather Service (NWS). Only data for the 1999 to 2001 time period was used in this study, based on findings by Jayakrishnan (2001) citing improved NEXRAD data quality and accuracy in recent years. To obtain daily NEXRAD data, hourly data were totaled from 7:00 a.m. one day to 7:00 a.m. the following day for each NEXRAD grid to correspond with raingauge data. In addition, because SWAT can accept only one weather input per subbasin, the daily NEXRAD rainfall was estimated through the use of a weighted average method for all grid cells within each subbasin for all of the 62 subbasin boundaries in the watershed (fig. 3).

There are spatial differences between raingauge and NEXRAD rainfall data. In this study, NEXRAD overpredicted rainfall in 35% of the subbasins and underpredicted rainfall in the remaining 65% of the subbasins. Underprediction ranged from 274.8 mm to 46.9 mm, whereas overprediction ranged from 7.6 mm to 615.6 mm over the study period (September 1999 to December 2001). On average, when compared with raingauge data, NEXRAD underpredicted rainfall by 79.2 mm over the study period. The discrepancy between these two datasets could be explained by the location of raingauges. Raingauges are sparsely scattered throughout the watershed, whereas NEXRAD grid cells cover the entirety of the watershed in evenly spaced intervals. For this comparison, subbasins were assigned data from the nearest raingauge; therefore, rainfall from the raingauge might have been assigned to an area with negligible or no rainfall. In general in this area, rainfall is dominated by local thunderstorms, which are better characterized by NEXRAD than by the raingauges. Thus, the rainfall estimates may differ from the assigned raingauge rainfall totals, causing over− or underprediction.

The data period analyzed in this simulation was from September 1999 to December 2001. Any missing precipitation or temperature data (from the NCDC), and all solar radiation, relative humidity, and wind speed data were generated by the weather generator in the SWAT model (Neitsch et al., 2001). Because the goal of this study was only to evaluate rainfall inputs to predict stream flow, not the

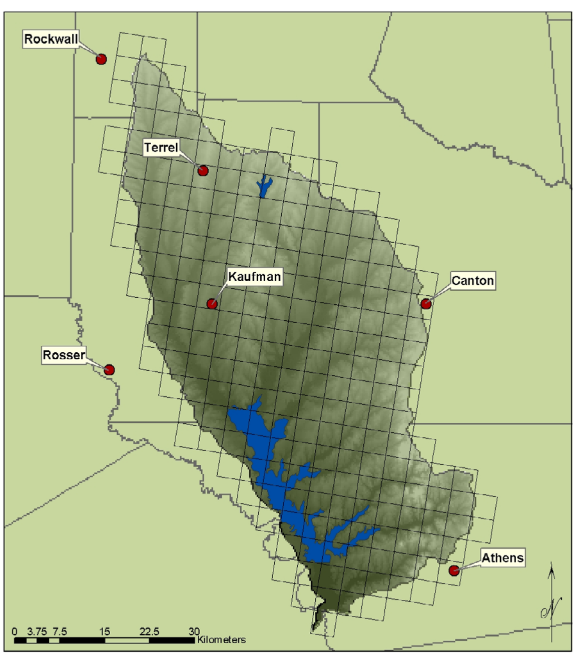

Figure 2. Raingauge and NEXRAD grid locations used in Cedar Creek SWAT simulations.

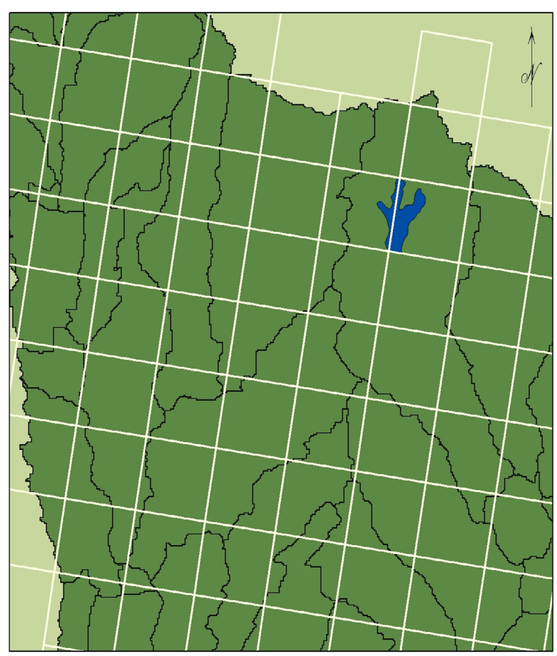

Figure 3. Portion of subbasin and NEXRAD grid overlay.

accuracy of the model, there were no calibrations or adjustments of parameters other than maintaining high and low flow periods.

Observed Data

Stage−storage relationship information and daily stage height data for 1993 to 2001 was acquired for Cedar Creek Reservoir from the TRWD authority (TRWD, 2002). This data, along with daily municipal water withdrawal information and lake evapotranspiration (ET), was used to establish daily inflow volumes to the lake. This flow data was composed of baseflow and runoff portions of total stream flow, which must be separated for proper estimation of high and low flow. Therefore, the data was passed through a baseflow filter algorithm to partition the baseflow and runoff portions of the flow to the reservoir. This process works much like the filtering of high−frequency signals in signal analysis. Low−frequency signals represent baseflow and high−frequency signals represent runoff (Arnold et al., 1995). After separation, baseflow was subtracted from total stream flow, providing the portion of flow that can be attributed to runoff.

For this study, from the filter analysis, the optimal SWAT input values for the baseflow recession constant and baseflow days, or the number of days required for the baseflow recession to complete one log cycle, were 0.0756 and 13.2, respectively. These values were used as model inputs to both NEXRAD and raingauge daily SWAT simulations (Arnold et al., 1995).

Statistical Methods

Estimation efficiency (Nash and Sutcliffe, 1970), which is commonly used in hydrologic model evaluation, was used to compare observed flow to SWAT−predicted flow using NEXRAD and raingauge weather data. The coefficient of efficiency (COE) is defined in equation 1:

$$COE = 1 - \frac{\sum_{i=1}^{n} (\beta_{mi} - \beta_{ci})^2}{\sum_{i=1}^{n} (\beta_{mi} - \overline{\beta}_m)^2} \quad (1)$$

where COE is the coefficient of efficiency for the modeled flow, n is the number of days of comparison, β_{mi} is the observed flow, β_{ci} is the predicted flow, and $\overline{\beta}_m$ is the mean flow over all days. COE can range from negative infinity to 1.0. An ideal case, where COE = 1, would indicate a one−to−one relationship between observed and predicted flow rates. COE values greater than 0 suggest a positive relationship between observed and predicted values, thus allowing for the use of predicted values in lieu of observed data. Negative COE values mean that the average of the observed values is a better model than the values used for prediction.

Linear regression and estimation efficiency analysis were computed for the comparison between NEXRAD and raingauge rainfall at each raingauge location. For the regression analysis, the regression line was forced through the origin. COE was calculated for the comparison between observed flow and the SWAT−raingauge simulated flow and again for the comparison between observed flow and the SWAT−NEXRAD simulated flow. The results were analyzed at daily, ten−day, and monthly aggregated intervals.

Table 1. Descriptive statistics for point−based comparison of raingauge and NEXRAD data.

Station	Raingauge No. of Rainy Days	Raingauge Max. Rainfall (mm)	NEXRAD No. of Rainy Days	NEXRAD Max. Rainfall (mm)	Volume Bias[a]
Athens	170	89.0	154	107.0	−0.1
Kaufman	154	115.6	138	135.0	−0.2
Terrel	134	181.4	148	181.0	−0.2
Rockwall	192	105.2	145	117.0	−0.3
Canton	190	109.1	167	109.0	−0.1
Rosser	149	175.0	147	210.0	−0.1

[a] (sum of NEXRAD rain − sum of raingauge rain)/sum of raingauge rain.

Results

Comparison of NEXRAD and Raingauge Data

Basic daily rainfall data provided a point−by−point comparison between NEXRAD and raingauge data at each raingauge location from September 1999 to December 2001. Descriptive statistics were developed for each of the raingauges and corresponding NEXRAD cell locations. These descriptive statistics include number of rainy days and maximum rainfall within the study period (September 1999 to December 2001) (table 1). Regression analysis was then used to compare daily raingauge and NEXRAD data on a point−by−point basis within the study area only at raingauge locations (table 2).

The Athens, Terrel, Rockwall, Canton, and Rosser stations had R^2 values between 0.43 and 0.80, with slopes above 0.68, and COE values between 0.50 and 0.77. The Canton station showed the highest R^2 (fig. 4) and COE values at 0.80 and 0.77, respectively. The Kaufman station showed the least similarities between the NEXRAD and raingauge point comparisons, with an R^2 value of 0.43 (fig. 5) and a COE value of 0.28. These results suggest that, in general, NEXRAD is very similar to raingauge data at each comparison point. However, in areas where the magnitude of rainfall differed, NEXRAD rainfall was slightly higher, and there were fewer rainy days for NEXRAD than for raingauge stations (table 1). On a volume basis, NEXRAD underpredicted rainfall by 10% to 30% for the entire study period.

Comparison of Observed Flow to Estimated Flow

Observed flow volume for Cedar Creek Reservoir was compared to estimated flow from the SWAT simulations using raingauge and NEXRAD daily inputs (table 3). Because stage height observation time and municipal withdrawal may not coincide on a daily basis and withdrawal periods may continue for more than a day, outputs and flow data were aggregated for ten−day and monthly periods to minimize the effects of withdrawal timing in comparisons.

Table 2. Daily point−based regression and estimation efficiency analysis for NEXRAD vs. raingauge rainfall data.

Station	Regression Analysis R^2	Regression Analysis Slope	Regression Analysis Intercept	COE
Athens	0.67	0.80	0.32	0.63
Kaufman	0.43	0.63	0.53	0.28
Terrel	0.65	0.68	0.45	0.50
Rockwall	0.69	0.71	0.11	0.56
Canton	0.80	0.84	0.20	0.77
Rosser	0.74	0.82	0.12	0.70

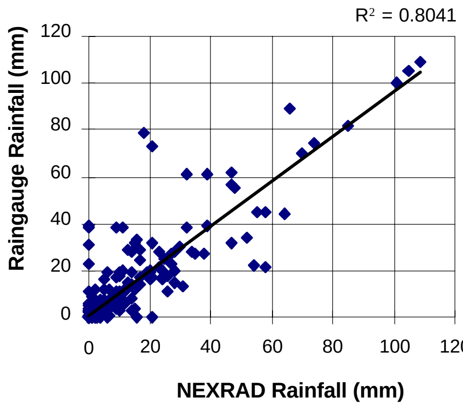

Figure 4. Daily raingauge vs. NEXRAD rainfall for the Canton site.

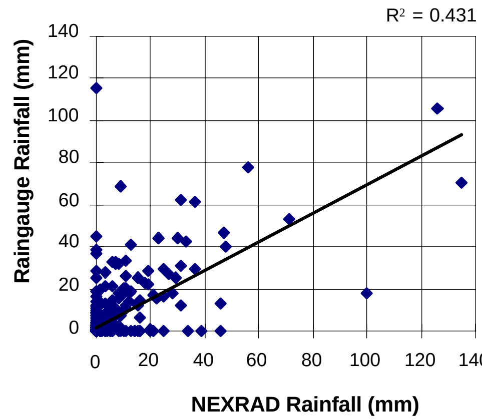

Figure 5. Daily raingauge vs. NEXRAD rainfall for the Kaufman site.

Table 3. Estimation efficiency for SWAT simulations using raingauge and NEXRAD rainfall inputs.

	Daily Simulation			Ten−Day Simulation			Monthly Simulation		
Rainfall Input	COE	R^2	Slope	COE	R^2	Slope	COE	R^2	Slope
Raingauge	0.48	0.53	0.77	0.75	0.85	1.13	0.78	0.86	1.13
NEXRAD	0.57	0.58	0.89	0.76	0.78	0.93	0.82	0.84	0.93

For daily, ten−day, and monthly time intervals, COE was greater for SWAT−NEXRAD than for SWAT−raingauge simulations. In addition, based on the regression analysis, the R^2 was greater for NEXRAD in the daily simulation and the slope was close to 1. The daily comparison provided the poorest COE values, with 0.48 for raingauge and 0.57 for NEXRAD (figs. 6 and 7). This time interval provided the poorest R^2 values as well, with 0.53 for raingauge simulations and 0.58 for NEXRAD (table 3). This was expected based on how the flow data was gathered and the lack of agreement in stage height observations and municipal withdrawal times. Again, aggregation of data for the ten−day and monthly time periods helped to alleviate this problem.

For the ten−day periods, little difference was found between COE values for the raingauge and NEXRAD−based simulations. COE for the raingauge simulation was 0.75 (fig. 8), whereas COE for the NEXRAD simulation was 0.76 (fig. 9). This could be the result of the variance of data at larger time steps being lower, which resulted from the aggregation functions.

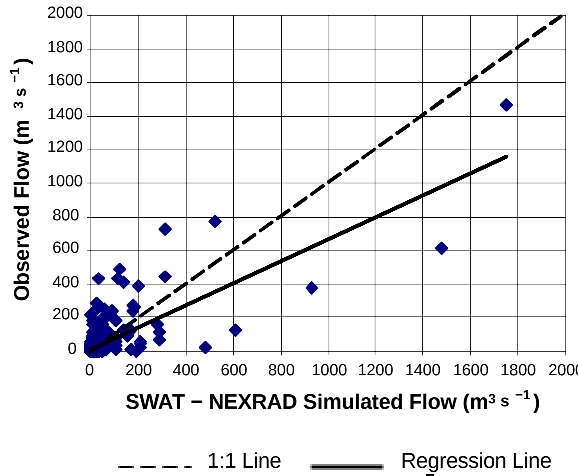

Figure 7. Daily SWAT−NEXRAD simulated vs. observed flow.

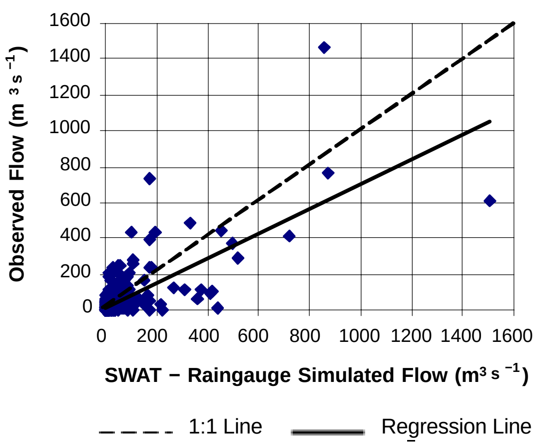

Figure 6. Daily SWAT−raingauge simulated vs. observed flow.

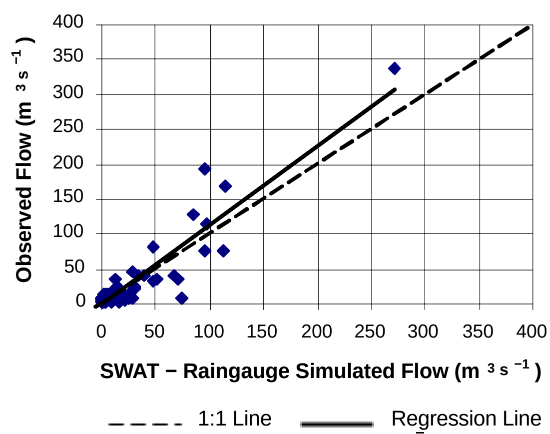

Figure 8. Ten−day SWAT−raingauge simulated vs. observed flow.

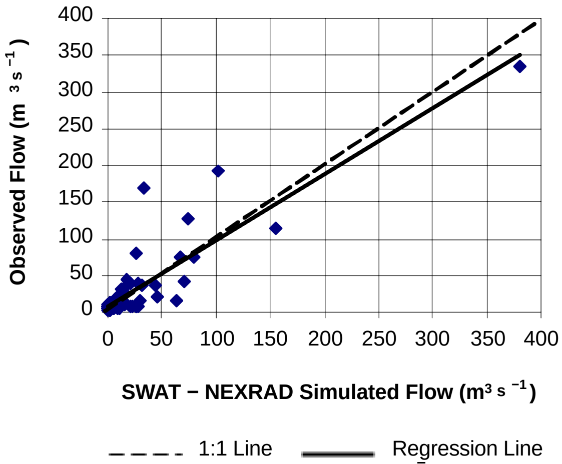

Figure 9. Ten−day SWAT−NEXRAD simulated vs. observed flow.

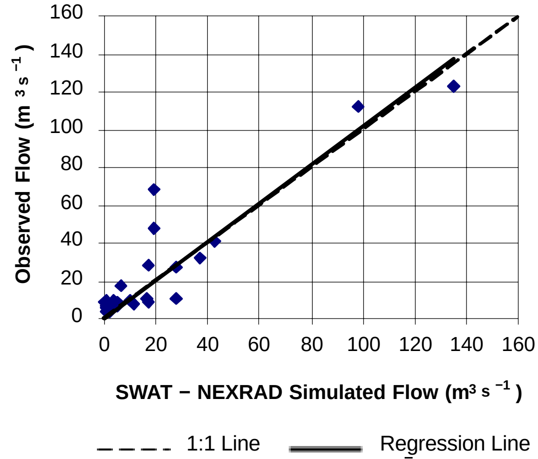

Figure 11. Monthly SWAT−NEXRAD simulated vs. observed flow.

The monthly time period seemed to provide the best flow simulation results based on efficiency analysis, with COE values of 0.78 for raingauge and 0.82 for NEXRAD (figs. 10 and 11). The R^2 values were higher for the raingauge than for the NEXRAD simulations, but the slopes for the NEXRAD simulations were close to 1 at the ten−day and monthly intervals.

The R^2 values for the raingauge simulations were slightly higher than those of the NEXRAD simulations for both ten−day and monthly intervals; however, the slope remained the same for both simulations (table 3).

For all time periods, COE values for NEXRAD simulations were greater than 0.57, which suggests a good relationship between observed and predicted values without any calibration of the model. The regression analysis shows that R^2 values between NEXRAD and raingauge simulations were similar; however, the slope of the NEXRAD simulation was close to 1, suggesting a better prediction from NEXRAD than from raingauge simulations.

In general, the SWAT−NEXRAD simulation was able to predict high flows better than the SWAT−raingauge simulation, in spite of overpredictions. For example, daily flow comparisons (figs. 6 and 7) show that for one of the major rainfall events, SWAT−raingauge simulated flow was only 830 $m^3\ s^{-1}$, whereas SWAT−NEXRAD simulated flow was 1750 $m^3\ s^{-1}$. The observed flow for the same event was 1440 $m^3\ s^{-1}$. To validate the daily high−flow events, the top 10 % of high−flow days were ranked and additional regression and COE analysis were done. The results showed that COE for the SWAT−raingauge simulations was 0.39 with an R^2 of 0.45, whereas for SWAT−NEXRAD simulations COE was 0.55 with an R^2 of 0.58, thus supporting the use of NEXRAD as an input for peak−flow hydrologic simulations. The daily analysis shows that, for small rainfall events, SWAT−raingauge simulations tend to overpredict daily flow, whereas SWAT−NEXRAD simulations tend to underpredict daily flow.

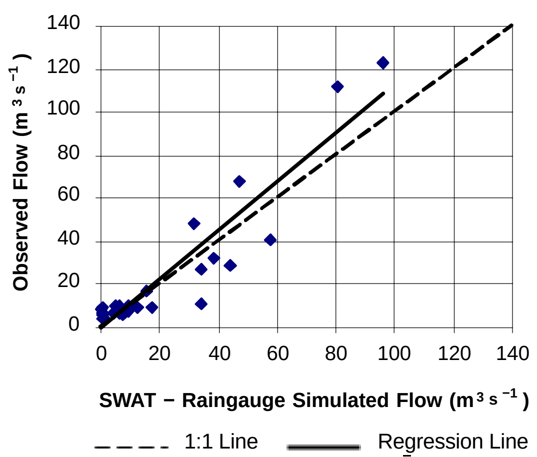

Figure 10. Monthly SWAT−raingauge simulated vs. observed flow.

CONCLUSIONS

In this study, observed flow to Cedar Creek Reservoir was compared with hydrologic model (SWAT) simulated flow using raingauge and NEXRAD data as rainfall inputs to the model.

Regression analysis of rainfall measured by raingauges and NEXRAD at each raingauge location suggests that, in general, NEXRAD is as good an estimate of rainfall as raingauge stations at these locations. At five out of the six stations used in the daily rainfall data point comparison, the R^2 value was greater than 0.65, and the coefficient of efficiency (COE) was greater than 0.50.

Estimation efficiency analysis was used to compare observed flow with estimated flow from the two SWAT simulations. COE values for the SWAT−raingauge simulation ranged from 0.48 to 0.78, whereas COE values for the SWAT−NEXRAD simulation ranged from 0.57 to 0.82. In both simulations, efficiency increased with longer time interval aggregations. The efficiency for both models was similar.

In general, SWAT−NEXRAD simulations overpredict high−flow events and underpredict low−flow events. However, the accuracy of the model results suggests that NEXRAD is a good alternative to raingauge data. This can be extremely valuable in watersheds without readily available raingauge data or with sparse raingauge networks.

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