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Hydrologic calibration and validation of the Soil and Water Assessment Tool for the Leon River watershed

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Abstract: The Leon River watershed which drains into Lake Belton, a primary drinking water supply for central Texas residents, is being affected by high-density dairy production and manure management. Our objective was to apply the Soil and Water Assessment Tool (SWAT) model to evaluate its ability to simulate the hydrology of the Leon River watershed including water discharge from treatment facilities, reservoirs, and point sources. The 2005 version of SWAT (SWAT2005) was calibrated and verified using hydrologic data from the watershed. Runoff was simulated well ($0.65 < E_{NS} \leq 0.75$ [good]) to very well ($E_{NS} > 0.75$ [very good]) based on the Nash-Sutcliffe efficiency (E_{NS}) value. Average streamflow simulations agreed well with observed values during the calibration phase (PBIAS $< \pm 10$ [very good]), but the validation period agreement (PBIAS $\geq \pm 25$ [unsatisfactory]) was less than desired because one of the five validated stream gauges fell into the unsatisfactory range. These results demonstrate the rigor needed to calibrate and validate simulation models for the Conservation Effects Assessment Project, and although additional studies are needed, they also confirm that SWAT2005 can be an effective tool for evaluating the hydrology within the Leon River watershed.

Key words: Conservation Effects Assessment Project (CEAP)—hydrologic modeling—Soil and Water Assessment Tool (SWAT)—watershed modeling

The Leon River watershed (LRW) includes the Leon River, which flows 402 km (250 mi) through Texas Hill Country and drains into Lake Belton, and three reservoirs (Leon, Proctor, and Belton) with a total drainage area above Lake Belton of 9,145 km² (3,530 mi²). The northwestern (upper) half of the LRW has several confined animal feeding operations and is being impacted by intensive dairy production and manure management practices. The dominant land uses in the LRW are pastureland, hayland, and brushy rangeland (63%). Cropland comprises about 10% of the watershed area. The Lake Belton watershed contains 19 permitted domestic waste discharges, including 11 from municipal wastewater treatment plants. Geographically, the Leon River basin is adjacent to the Bosque River basin, where water quality has been degraded due to excessive nutrient loading. Therefore, according to the Texas Water Resources Institute, the LRW is an area of concern for water quality because the basin contains similar nutrient resources (dairies, manure application sites, urban runoff, etc.). Only the LRW hydrology is discussed in this paper.

The Conservation Effects Assessment Project (CEAP) watershed studies (Mausbach and Dedrick 2004) were initiated to help the USDA Natural Resources Conservation Service determine the effectiveness of various conservation practices within areas such as the LRW. Ideally, field studies and measurements would be made for all potential practices, but for an area such as the LRW, time requirements and cost would be prohibitive. Therefore, simulation models such as the Soil and Water Assessment Tool (SWAT) are being hydrologically calibrated and validated to prepare for best management practices evaluations. The 2005 version (SWAT2005) is an evolving product of the USDA Agricultural Research Service (Arnold et al. 1998; Arnold and Fohrer 2005) that has been shown to be an effective tool for evaluating nonpoint source water resource problems (i.e., flow, sediment, nutrients) for a large variety of applications nationally and internationally (Srinivasan et al. 1998; Santhi et al. 2001).

Barlund et al. (2007) used the SWAT model in a Finnish catchment to assess its usefulness to evaluate management impacts such as nutrient load reductions. While the model proved its worthiness, the exercise also demonstrated the need to adequately parameterize, calibrate and validate the model. These authors identified the need to include a sensitivity analysis to concentrate on the more influential parameters that impact calibration. Krysanova et al. (2007) and Rao et al. (2006) confirmed those results and concluded that powerful calibration and validation techniques were needed for hydrologic models. There is also a need to identify the criteria to achieve an adequate validation that is based on the sensitivity analyses to determine the most influential parameters. Miller et al. (2007) emphasizes the importance of the process used for parameter estimation; the higher the degree of spatial variability, the greater the complexity of correctly estimating parameter values.

The SWAT's hydrologic processes are continuing to be tested over a wide range of watersheds and conditions with both positive and negative results (Arnold et al. 1999; Chu and Shirmohammadi 2004; Rosenthal et al. 1995). Grayson et al. (1992) provided guidelines for analyzing any model, so in accordance with those guidelines, measured data were tested against SWAT2005 simulated data. Our primary objective was to evaluate the model's accuracy in simulating hydrologic balance within the LRW. However, including the reservoirs and point discharges significantly increased simulation complexity and required spatial calibration based on gauge location and soil type. This complexity led to a secondary objective of documenting the process required to calibrate and validate models such as SWAT2005 for CEAP applications.

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As such, errors associated with input data were assessed in accordance with the overall CEAP objective of quantifying conservation practices (Moriasi et al. 2007).

Methods and Materials

Model Background. The SWAT model is a continuous time simulation model that operates on a daily time step. It is physically based, uses readily available inputs, is computationally efficient for use in large watersheds, and is capable of simulating long-term yields for determining the impact of land management practices (Arnold and Allen 1996). Soil Water Assessment Tool components include hydrology, weather, sedimentation/erosion, soil temperature, plant growth, nutrients, pesticides, and agricultural management. The SWAT2005 model includes urban routines; an improved weather generator; the ability to read in solar radiation, relative humidity, wind speed, and potential evapotranspiration (Neitsch et al. 2002a, 2002b).

The SWAT evolved through a long-term effort by the USDA Agricultural Research Service to model nonpoint source pollution. Its predecessors include the field-scale model Chemicals, Runoff, and Erosion from Agricultural Management Systems (Knisel 1980), Simulator for Water Resources in Rural Basins (Williams et al. 1985; Arnold et al. 1990), and Routing Outputs to the Outlet (Arnold et al. 1995). The SWAT contains several hydrologic components (surface runoff, ET, recharge, and stream flow) that have been developed and validated at smaller scales within the EPIC, GLEAMS and Simulator for Water Resources in Rural Basins models. Interactions between surface flow and subsurface flow in SWAT are based on a linked surface-subsurface flow model developed by Arnold et al. (1993). Characteristics of this flow model include non-empirical recharge estimates, accounting of percolation, and

Figure 1

Leon River and Cowhouse Creek subbasins including US Geological Survey stream gauges (08099100, 08099300, 08099500, 08100000, 08100500, 08101000, and 08102500).

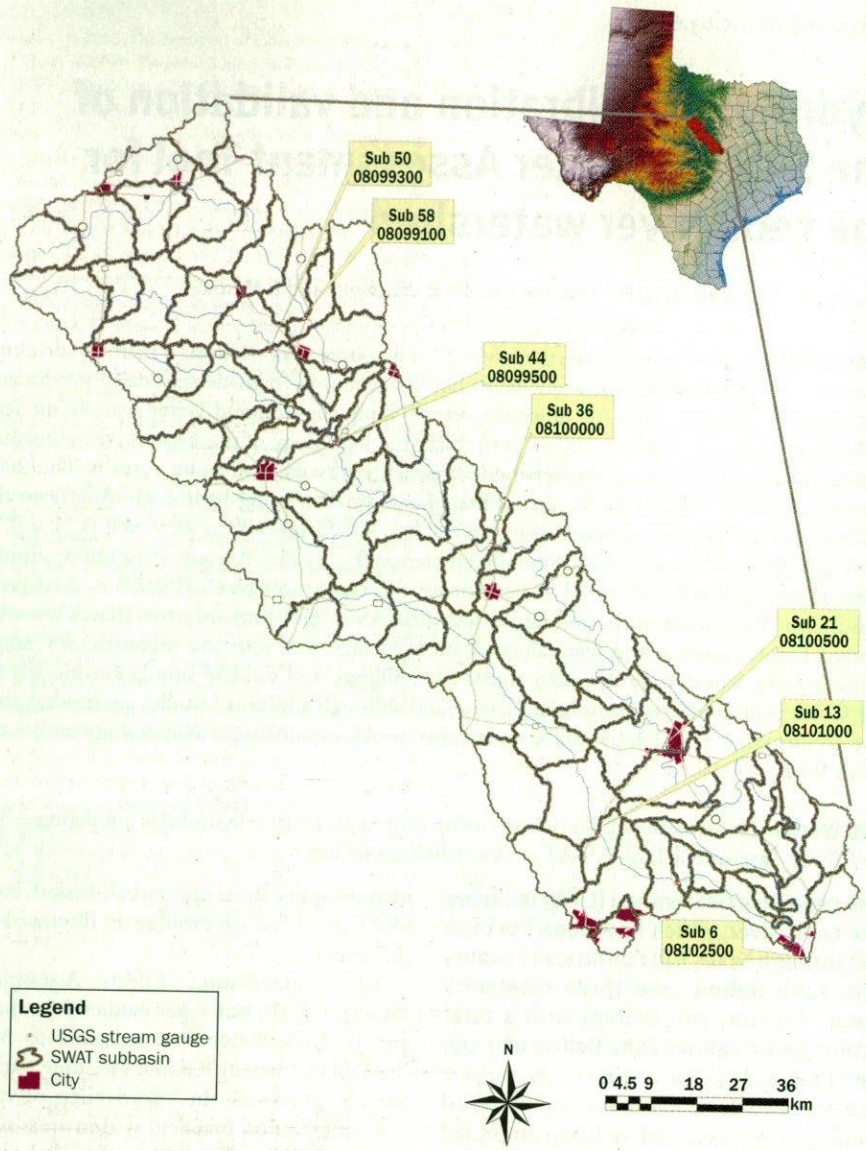
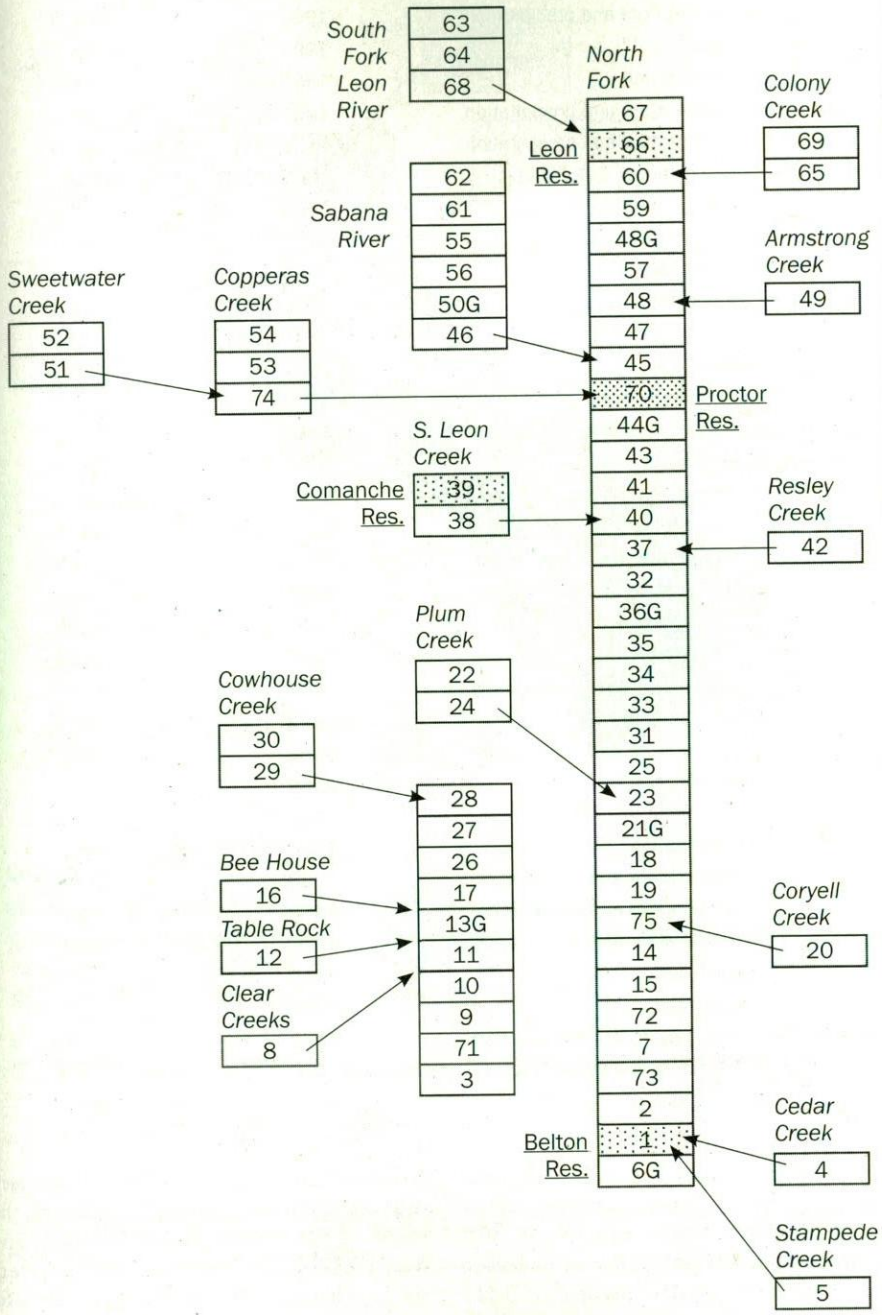


Table 1

The US Geological Survey stream gauge location and calibration and validation dates used for model simulation.

Stream gauge	Location	Calibration dates	Validation dates
08099100	On Leon River at subbasin 58 outlet	1/1/1967 to 12/31/1985	Gauge not in operation
08099300	On the Sabana River at subbasin 50 outlet	1/1/1967 to 12/31/1985	Gauge not in operation
08099500	On the Leon River at subbasin 44 outlet	1/1/1967 to 12/31/1985	1/1/1987 to 9/30/1991
08100000	On the Leon River at subbasin 36 outlet	1/1/1967 to 12/31/1985	1/1/1987 to 12/31/2000
08100500	On the Leon River at subbasin 21 outlet	1/1/1967 to 12/31/1985	1/1/1987 to 12/31/2000
08101000	On the Cowhouse Creek at subbasin 13 outlet	1/1/1967 to 12/31/1985	1/1/1987 to 12/31/2000
08102500	On the Leon River at subbasin 6 outlet	1/1/1967 to 12/31/1985	1/1/1987 to 9/30/2000

Figure 2
Subbasin flow diagram illustrating the inclusion of the locations of reservoirs (dotted boxes), tributaries, and USGS stream gauges (G).



applicability to basin-wide management assessments with a multi-component basin water budget. The surface runoff hydrologic component uses Manning's Formula to determine the watershed time of concentration and considers both overland and channel flow. As such, water can be transferred from one area to another within the basin (Arnold et al. 1994). Lateral subsurface flow can occur in the soil profile from 0 to 2 m (0 to 6 ft), and groundwater flow contribution to total streamflow is generated by simulating shallow aquifer storage (Arnold et al. 1993). Flow from the aquifer to the stream is lagged via a recession constant derived from daily streamflow records (Arnold and Allen 1996). Overall, SWAT simulates a basin by dividing it into subwatersheds that account for differences in soils and land use. The subbasins are further divided into hydrologic response units by overlaying soils and land uses.

Input Data. The SWAT requires input for bulk density, available water capacity, texture, organic matter, saturated conductivity, land use (crop and rotation), management (tillage, irrigation, nutrient and pesticide application), weather (daily precipitation, temperature, solar radiation, wind speed), channels (slope, length, bankfull width and depth), and shallow aquifer (specific yield, recession constant, and revap coefficient) characteristics (Arnold 1992). The USDA Natural Resource Conservation Service's Soil Survey Geographic database provides descriptions of the surface and upper subsurface of a watershed and is used to determine a water budget for the soil profile, daily runoff, and erosion. The SWAT uses information about each soil horizon (e.g., thickness, depth, texture, water holding capacity). Service's Soil Survey Geographic database data sets for the LRW included Bell, Bosque, Brown, Callahan, Comanche, Coryell, Eastland, Erath, Hamilton, Lampasas, McLennan, and Mills counties. Service's Soil Survey Geographic database polygons are associated with a soil series name used to link to the user soils database.

The LRW was divided into 75 subbasins (figures 1 and 2) based on a 30-m (100-ft) digital elevation model for the watershed (US Geological Survey [USGS] 2001). Soils in the upper portion of the watershed are mainly loamy fine sand with some fine sandy loam, while ranching and row cropping operations are predominantly on clay loam soils. Hydrologic discharge data was collected from United States Geological Survey (USGS 2001) stream gauges 08099100, 08099300, 08099500, 08100000, 08100500, 08101000, and 08102500 that were available for model stream flow calibration/validation (figure 2 and table 1). A baseflow filter (Arnold et al. 1995) was used to partition groundwater and surface flow, with approximately 31% being baseflow that was not influenced by the reservoirs. Pond data was taken from databases maintained by the State of Texas and USDA Natural Resources Conservation Service (National Engineering Manual Title 210 Section 520.21). When information (such as pond volumes and areas) was missing, it was estimated using information from the other ponds in the area. The "ponds" were classified as a, b, or c depending on size, with "a" dams

Table 2
Climate stations used in Leon River watershed simulations.

Station number	Station name	Data type	Start date	End date
03902	Robert Gray AAF	Temperature and precipitation	1950	1970
03933	Ft. Hood	Precip	1960	1970
480050	Adamsville	Precipitation	1963	1987
480665	Belton Dam	Temperature and precipitation	1951	1992
481138	Brownwood	Temperature and precipitation	1950	2003
481580	Center City	Precipitation	1963	2003
481914	Comanche	Precipitation	1960	2003
481984	Copperas Cove	Precipitation	1950	1983
481990	Copperas Cove 5 NW	Precipitation	1983	2003
482086	Cranfills Gap	Precipitation	1950	2003
482128	Cross Plains	Precipitation	1950	1959
482350	De Leon 6 NW	Precipitation	1992	2003
482598	Dublin	Temperature and precipitation	1950	2003
482715	Eastland	Temperature and precipitation	1960	2003
483171	Flat	Precipitation	1951	2003
483485	Gatesville	Temperature and precipitation	1950	2003
483646	Gorman 2 NNE	Precipitation	1951	1999
483884	Hamilton 1 NW	Temperature and precipitation	1950	2003
484137	Hico	Temperature and precipitation	1950	2003
484390	Hurst Springs	Precipitation	1950	2003
484440	Indian Gap	Precipitation	1960	1983
484792	Killeen Airport	Temperature and precipitation	1978	2003
485116	Leatherwood Ranch	Precipitation	1992	2003
485757	McGregor	Temperature and precipitation	1950	2003
486140	Mullin	Precipitation	1960	2001
487017	Pidcoke	Precipitation	1974	2003
487274	Priddy 1 NE	Precipitation	1984	1997
487300	Proctor Reservoir	Temperature and precipitation	1963	2003
487327	Putnam	Temperature and precipitation	1950	2003
487426	Ranger 1 W	Temperature and precipitation	1960	1975
487633	Rising Star	Precipitation	1950	2003
487637	Rising Star 5 NNE	Precipitation	1991	2002
488646	Stillhouse Hollow Dam	Temperature and precipitation	1963	2003
488910	Temple	Temperature and precipitation	1960	2003
489153	Troy	Precipitation	1950	2003

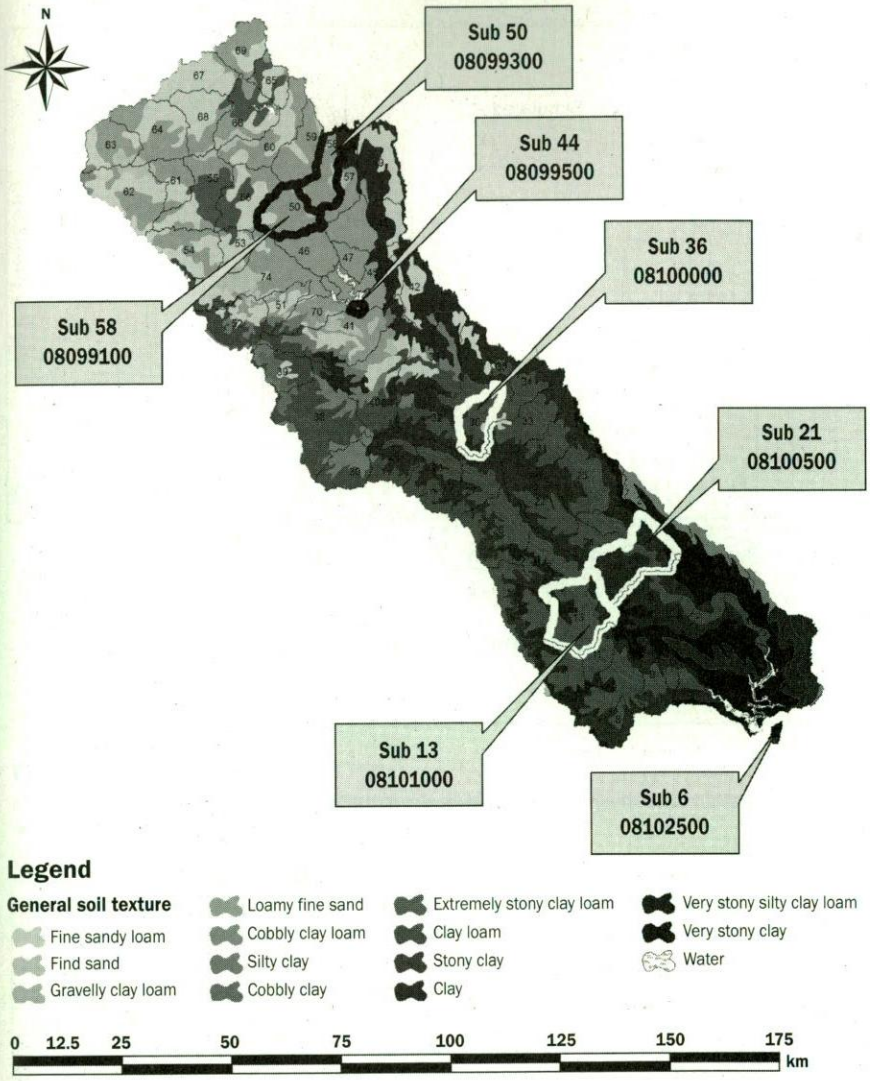
being more than 6 ft (1.8 m) in overall height and having a storage capacity of 61,674.5 m^3 (600 ac-in) or more. Inclusion of ponds in the model was essential because of their impact on watershed hydrology. Reservoir outlet data was also included as an input to the subbasin below the discharge point.

Daily precipitation and temperature (maximum and minimum, if available) were downloaded from the National Climatic Data Center and formatted for SWAT model use. Several climate stations were used (table 2) with gaps in the data being filled with information from adjoining stations. Land use data were obtained using the National Land Cover Dataset with recent changes for dairy use added to the data layer using information collected during the permitting process. Overall, cropland compromised about 10% of the LRW, and together, the combination of land use and soil type resulted in 3,117 hydrologic response units.

Calibration and Sensitivity Analysis. Whether the calibration is manual or automated, complex hydrologic models generally contain several parameters, but depending on the study, only a few or several parameters may be sensitive to the conditions being evaluated. The performance of SWAT was evaluated using the Nash-Sutcliffe efficiency value (E_{NS}) using a parameter sensitivity analysis tool embedded in the model (van Griensven et al. 2002). The E_{NS} values were used to compare predicted values to the mean of the average annual, monthly, and daily USGS-gauged discharge for the watershed, with a value of 1 indicating a perfect fit. The E_{NS} also describes the amount of variance for the observed values over time that is accounted for by the SWAT model. The difference between the E_{NS} and the R^2 is that the E_{NS} can interpret the model performance in replicating individually observed values while the R^2 does not.

The USGS gauge data from January 1, 1967, through December 31, 1985, were used to optimize the calibration parameters used for the January 1987 through

Figure 3
Leon River watershed gauge and soil type locations.



December 2000 validation phase (table 1). All of the USGS stream gauges were used in the calibration process (table 1). The model was initialized and calibrated with the LRW discharge data (table 1). Model defaults were used when values were not available.

Results and Discussion

Figure 3 illustrates why spatial calibration based on soil type and gauge location is necessary for effectively modeling the LRW. The upstream portion, represented by the lighter gray color, consists of sandier soils while the midstream portion had predominantly loam soils and the downstream section predominantly clay soils (indicated by the darkest gray colors).

Correctly simulating soil properties greatly influenced the LRW hydrologic balance (table 3). Those impacting runoff include the Soil Conservation Service runoff curve number for moisture condition II (CN2), the soil evaporation compensation factor, the initial soil water content expressed as a fraction of field capacity, and the ICN parameter, which is based on the SCS runoff curve number procedure and a soil moisture accounting technique and its related curve number coefficient. The ICN and curve number coefficient parameters are defined in Williams and LaSeuer (1976) and Green et al. (2006). The CN2 parameter was originally set to values recommended by the USDA SCS National Engineering Handbook (USDA SCS 1972) for these hydrologic groups. The final CN2 values were kept within reasonable ranges by limiting the change from the original value to ±10%. The ICN and curve number coefficient parameters were used to

Table 3
Calibrated values of adjusted parameters for discharge calibration of the SWAT2005 model for the Leon River watershed.

Parameter	Description	Range	Calibrated value
Soil evaporation compensation factor	Soil evaporation compensation factor	0.01 to 1.0	0.5
Fraction of field capacity	Initial soil water storage expressed as a fraction of field capacity water content	0 to 1.0	0.8
ICN*	Based on the SCS runoff curve number procedure and a soil moisture accounting technique	0 to 1	1
Curve number coefficient*	Curve number coefficient	0.5 to 2.0	0.75
CN2	Initial SCS runoff curve number to moisture condition II	30 to 100	55 to 89 (±10% from original CN)
GW_Revap	Groundwater "revap" coefficient	0.02 to 0.2	0.2
Sol_AWC	mm water/mm soil available water capacity of soil layer	0.1 to 0.80	0.1

* Williams and LaSeuer 1976.

account for the soil moisture in addition to the SCS runoff curve number.

Water Balance. Only five of the seven gauges were used for validation because two were not operational during that period (table 1). Also because of the size of the LRW, only a few representative subbasins from the upper and lower regions are presented in detail. Subbasins 58 and 6 illustrate the calibration findings and subbasins 44 and 6 illustrate the validation results since the gauge for subbasin 58 was not operational during the validation period.

The annually averaged calibrated/validated hydrologic balance for the entire period that LRW data were available is as follows: precipitation 754/847 mm (30/33 in); surface runoff 48.0/82.0 mm (1.9/3.2 in); lateral soil runoff 6.6/7.5 mm (0.3/0.3 in); groundwater runoff in the shallow aquifer 13.7/17.9 mm (0.5/0.7 in); evapotranspiration 634/669 mm (25/26 in); and potential evapotranspiration 1463/1472 mm (58/58 in) (Hargreaves method). Figures 4 and 5 illustrate the calibrated measured and simulated runoff for subbasins 6 and 58. Figures 6 and 7 illustrate the validated measured and simulated runoff for subbasins 6 and 44. The figures illustrate the importance of representing the various land uses (table 4) as efficiently as possible due to their impact on the overall watershed hydrology.

According to tables 5 and 6, the calibration and validation (E_{NS}) values are very good; the PBIAS calibration and validation values are mostly good with one satisfactory value; and the root mean square error–standard deviation ratio calibration and validation values are good to very good. The one unsatisfactory PBIAS statistic (based on the criteria established in this study) occurred at a USGS gauge where all of the other statistical measures are good for both the calibration and validation simulations, and the root mean square error-standard deviation ratio calibration and validation values are good to very good. The statistical criteria results indicate the quality of the inputs and the calibrated parameter values. The SWAT model was able to achieve E_{NS} of 1.0 when reservoir output data were available for usage as an input for the downstream gauge. The overall trend of the simulations, as evidenced by the statistics, indicate that SWAT2005 was able to adequately model monthly runoff in the LRW. The statistics reflect data that included varied soils (loamy fine sand to clay loam), tributary

Figure 4
Monthly calibration of subbasin 6 discharge outlet below the Belton Reservoir in the lower region of the Leon River watershed.

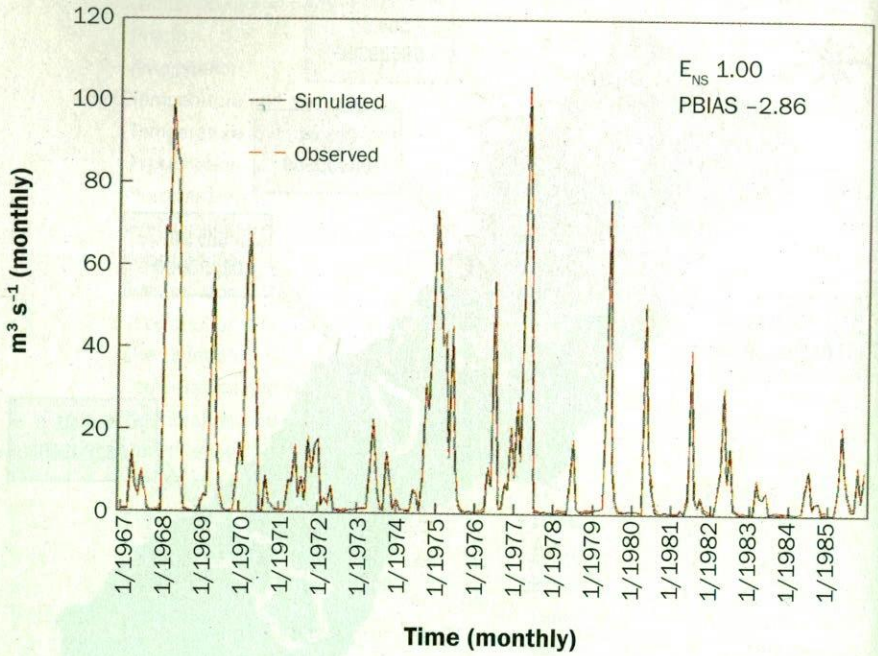


Figure 5
Monthly calibration of subbasin 58 discharge outlet in the upper region of the Leon River watershed.

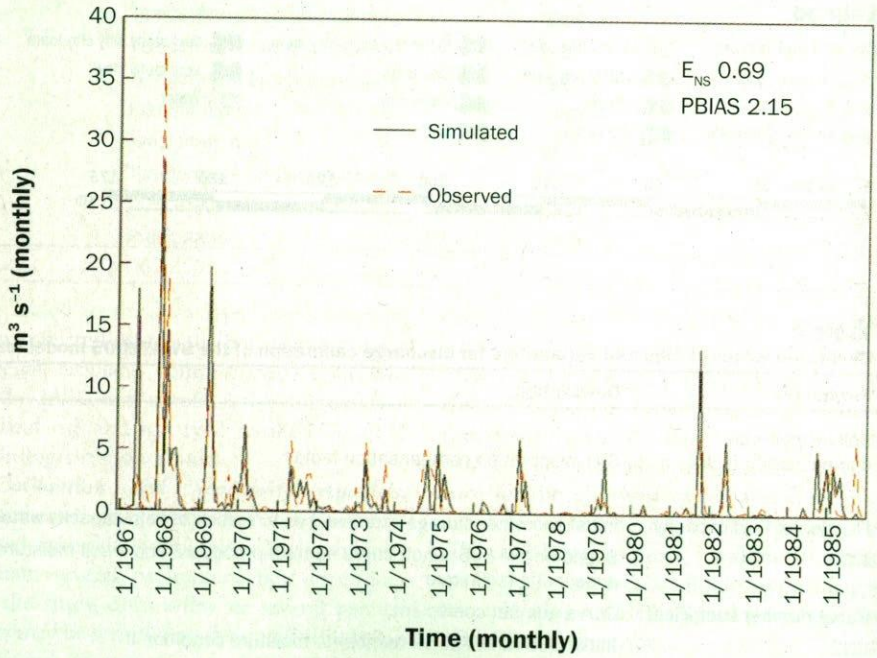


Figure 6
Monthly validation of subbasin 6 discharge outlet in the lower region of the Leon River watershed.

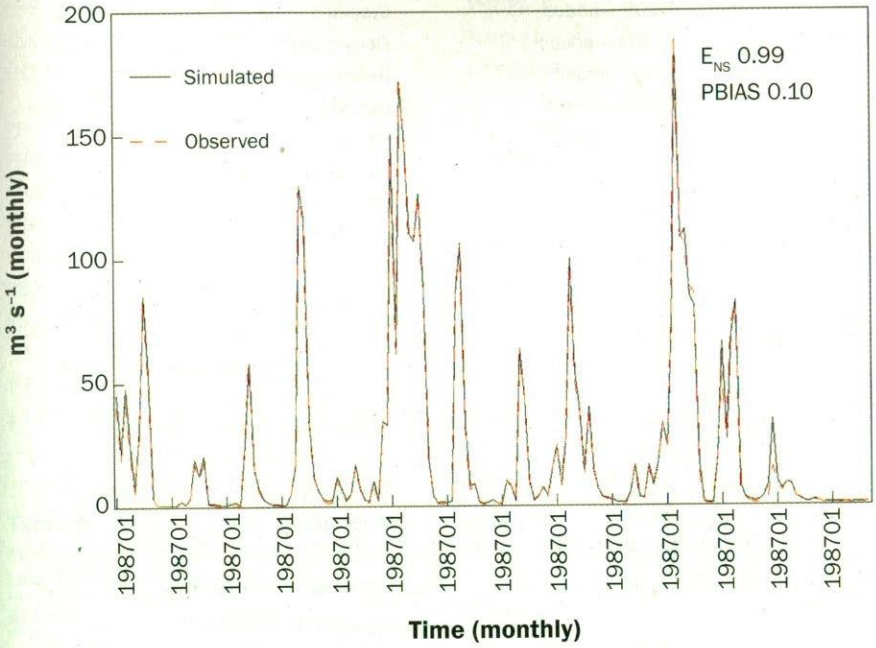
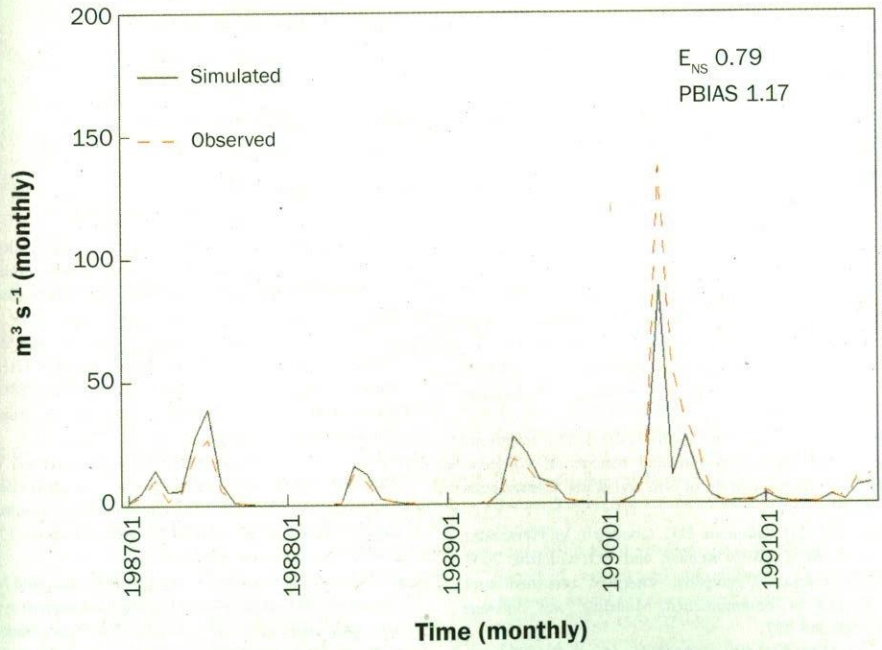


Figure 7
Monthly validation of subbasin 44 discharge outlet in the lower region of the Leon River watershed.



inputs, and reservoir impact, and are able to validate the USGS gauges measured data.

Using SWAT's parameter sensitivity analysis procedure resulted in a consistent relative parameter ranking from the most to least sensitive as follows: CN2, Sol_AWC, soil evaporation compensation factor, and Surlag, respectively. The CN2, soil evaporation compensation factor, and Surlag parameters are commonly considered among the most sensitive components in SWAT (Green and van Griensven 2008). However, the identification of the Sol_AWC as highly sensitive demonstrates the importance of having spatially calibrated the LRW by soil type since clay soils have a much different Sol_AWC than sandier soils.

Having calibrated and validated the SWAT2005 hydrology for the LRW, the next step will be to add the sediment and nutrient loading information. This tool will then assist in the simulation of multiple management scenarios including managing water, land resources, fertility programs, cropping sequences, and dairy waste application to local fields. The information obtained will be distributed to landowners, and the appropriate BMPs will be selected based on local needs and their ability to minimize nutrient loading within the watershed due to agricultural management.

Summary and Conclusions

Use of a spatially calibrated model based on gauge location and soil type has allowed for a relevant and useful hydrologic study that can be used as a basis for multiple land management and water quality scenarios in the future. This study establishes a baseline for the LRW that can be used to distinguish its characteristics from those of the Bosque watershed. It also illustrates the complexity of calibrating and validating simulation models to answer the types of questions being posed to natural resource managers.

The SWAT2005-simulated streamflow trends well ($0.65 < E_{NS} < 0.75$ [good]) to very well ($E_{NS} > 0.75$ [very good]) as shown by the graphical and statistical results during both the calibration and validation simulations. However, the average magnitude of the simulated streamflow was much closer to the observed streamflow during calibration (PBIAS $<\pm 10$ [very good]) than during validation (PBIAS $\geq \pm 25$ [unsatisfactory]). Of the five validated stream gauges, only one fell into the unsatisfactory range. The majority of

the validation values were in the very good category. The most significant impact of this CEAP study is that through these efforts both rural and metropolitan areas that depend on the Leon River water should benefit from the changes made to protect their drinking water resources.

Table 4
Leon River watershed land use categories and adjustments made.

Value	Land use SWAT	Land use
1	DCOP - added	Cropland
2	DCOM - added	Dairy complex
3	DHQ - added	Headquarters
4	DOTH - added	Other land
5	DPAS - added	Pasture
6	DRNG - added	Rangeland
7	DWAT - added	Water
8	DWLF - added	Wildlife land
11	WATR	Open water
21	URLD	Low intensity residential
22	URHD	High intensity residential
23	UTRN	Commercial/industrial/transportation
31	SWRN	Bare rock/sand/clay
32	SWRN	Quarries/strip mines/gravel pits
41	FRSD	Deciduous forest
42	FRSE	Evergreen forest
43	FRST	Mixed forest
51	RNGB	Shrubland
61	ORCD	Orchards/vineyards/other
71	RNGE	Grasslands/herbaceous
81	PAST	Pasture/hay
82	AGRR	Row crops
83	AGRC	Small grains
84	AGRL	Fallow
85	PAST	Urban/recreational grasses
91	WETF	Woody wetlands
92	WETL	Emergent herbaceous wetlands
94	R2CP	Cropland inside 2 mi radius
95	R2PS	Pasture inside 2 mi radius
96	R4CP	Cropland inside 4 mi radius
97	R4PS	Pasture inside 4 mi radius
98	R6CP	Cropland inside 6 mi radius
99	R6PS	Pasture inside 6 mi radius

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Table 5
General reported performance ratings for ENS, PBIAS, and RSR (adapted from Moriasi et al. 2007).

Criteria	Value	Rating	Modeling phase	Reference
ENS*	>0.65	Very good	Calibration and validation	Saleh et al. (2000)
ENS*	0.54 to 0.65	Adequate	Calibration and validation	Saleh et al. (2000)
ENS*	≥0.50	Satisfactory	Calibration and validation	Santhi et al. (2001); adopted by Bracmort et al. (2005)
PBIAS†	<±20%	Good	Calibration and validation	Van Liew et al. (2006)
PBIAS†	±20% to ±40%	Satisfactory	Calibration and validation	Van Liew et al. (2006)
PBIAS†	>± 40%	Unsatisfactory	Calibration and validation	Van Liew et al. (2006)
RSR‡	0.00 ≤ RSR ≤ 0.50	Very good	Calibration and validation	Harmel et al. (2006)
RSR‡	0.50 < RSR ≤ 0.60	Good	Calibration and validation	Harmel et al. (2006)
RSR‡	0.60 < RSR ≤ 0.70	Satisfactory	Calibration and validation	Harmel et al. (2006)
RSR‡	RSR > 0.70	Unsatisfactory	Calibration and validation	Harmel et al. (2006)

* Nash-Sutcliffe efficiency value.

† Percent bias.

‡ Root mean square error-standard deviation ratio.

Table 6
Monthly summary streamflow statistics for the calibration and validation simulations for the Leon River watershed.

Criteria	Statistic	Calibration*	Validation†
E_{NS}	Minimum	0.66	1.00
	Maximum	0.81	0.69
	Median	1.00	0.84
RSR‡	Minimum	0.03	0.58
	Maximum	0.43	0.06
	Median	0.56	0.40
PBIAS (%)	Minimum	-4.89	2.15
	Maximum	-1.58	-29.04
	Median	12.31	-2.94
R^2	Minimum	0.64	1.00
	Maximum	0.84	0.81
	Median	1.00	0.87

* Calibration values were based on seven US Geological Survey stream gauges.

† Validation values were based on five US Geological Survey stream gauges.

‡ Root mean square error-standard deviation ratio.

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