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Simulating sediment loading into the major reservoirs in Trinity River Basin

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Abstract: The Upper Trinity River Basin supplies water to about one-fourth of Texas's population. The anticipated rapid growth of North Central Texas will certainly increase regional demands for high-quality drinking water. This has increased concerns that sediment and nutrient loads received by drinking water reservoirs are reducing and will continue to reduce reservoir volumes and water quality. The objectives of this study are to calibrate and validate the Soil and Water Assessment Tool (SWAT) model for streamflow and sediment to assess current rates and sources of sediment loadings to 12 major reservoirs in the Upper Trinity River Basin (in 7 eight-digit watersheds) and to use the calibrated model for assessing the effects of upland ponds. SWAT performed well for streamflow, as evidenced by r^2 values ranging from 0.55 to 0.95. Nash-Sutcliffe efficiency values ranged from 0.5 to 0.9 based on monthly streamflow comparisons between simulated and observed values for calibration, and r^2 values ranged from 0.58 to 0.95 for validation. SWAT simulated sediment loads reasonably well, as evidenced by the percentage of errors within 11%. Streamflow and sediment loading were quite diverse across the Trinity River Basin, resulting in a multitude of parameter adjustments during calibration. Long-term predictions indicate that the Richland-Chambers, Ray Hubbard, and Lavon watersheds have significant channel contribution to sediment loading reaching the reservoirs. Pond removal scenario analysis shows a 4% to 48% reduction in sediment loadings to reservoirs via pond detention of overland flow. This wide range is mainly due to the vastly different proportion of land area draining to ponds, the locations of ponds, and the basin's erosion (upland and channel) characteristics within each study watershed. The results indicate that in addition to implementing conservation practices such as ponds in upland areas, it is also necessary to have conservation practices in channels to further reduce erosion and subsequent loss to reservoirs. One limitation of this study is the lack of site-specific management information, and it is known that poor management practices at the field level can dramatically elevate sediment loads from an area. In this study, reasonable management operations were applied mainly at the county conservation district level. Opportunity exists for further data collection, including detailed data of field management and channel dimensions, which will allow the model to provide greater insight in identifying sensitive areas and reaches for stabilization and restoration. Opportunity also exists for further evaluation of the effects of optimizing pond size and placement to minimize reservoir sediment loading.

Key words: erosion—model calibration—pond—sediment—Soil and Water Assessment Tool

The Trinity River Basin is the most populated river basin in Texas and is the primary water supply for both the Dallas–Fort Worth and Houston metropolitan areas. This river basin extends from northwest of Fort Worth to southeast, through the hearts of Fort Worth and Dallas, to the Gulf of Mexico, just east of Houston, Texas. The Upper Trinity Basin, which includes the Dallas–Fort Worth metroplex, supplies water to about one-fourth of Texas's population.

The Upper Trinity River Basin makes up most of Region C of the Texas water-planning program, although Region C also contains small parts of the Red, Brazos, Sulphur, and Sabine River basins. The region is heavily urbanized and growing rapidly. Over 90% of the water use in Region C is supplied by surface water, with most of this coming from major reservoirs both within and outside the boundaries of Region C. In 2010, the population of Region C was approximately 6.3 million, a 25% increase from the year 2000, and it is projected to grow to 9.1 million by 2030 and 13 million by 2060. Dallas and Tarrant counties currently contain 65% of the region's population, 81% of which is located in cities with populations greater than 20,000. Water use in Region C has increased significantly in recent years, primarily due to increasing population and municipal demand. Regional water use in 2006 was about 1,727 million m^3 (1.4 million ac ft), about 90% of which was for municipal supplies. Annual dry year demands are estimated to be 2,960 million m^3 (2.4 million ac ft) in 2030 and 4,070 million m^3 (3.3 million ac ft) in 2060. Normal year demands are expected to be 10% to 15% lower than dry year demands due to less lawn irrigation.

The anticipated rapid growth of North Central Texas during the next 20 to 50 years will almost certainly increase regional water demands. In recent years, sediment surveys of Texas reservoirs along with water quality monitoring have raised concerns that sediments and nutrients from these watersheds are reducing the capacity of reservoirs and degrading water quality in North Central Texas. Nonpoint source pollution in agricultural streams was identified as one of

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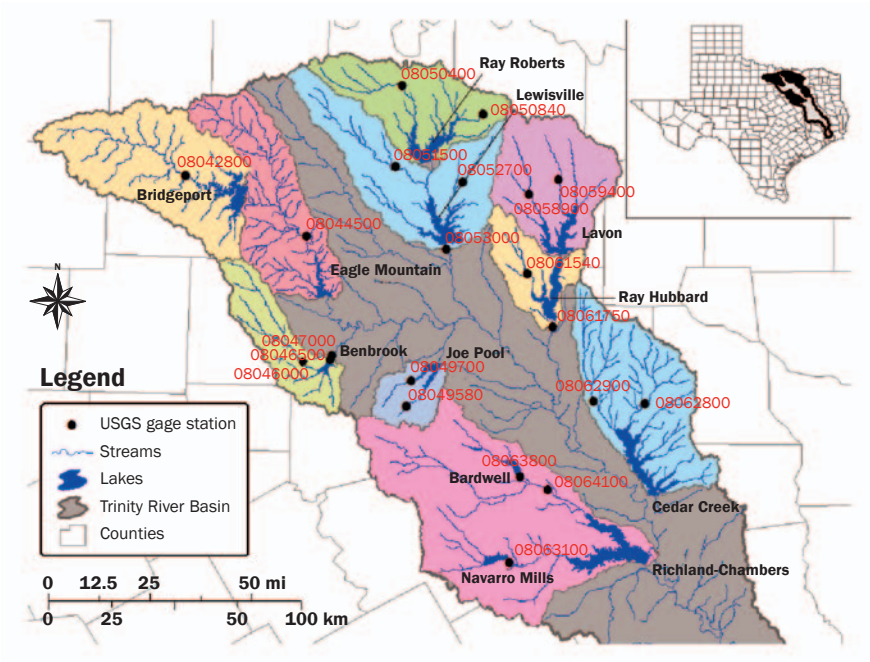
Figure 1

Locations of major reservoirs within the Trinity River Basin delineated for Soil and Water Assessment Tool (SWAT) simulations and US Geological Survey (USGS) gauging stations used for SWAT calibration and validation.



the major water quality issues (Land 1997; TNRCC 1999). Watershed management through modeling and water conservation education and implementation are two of the most cost-effective practices for ensuring a safe and reliable public water supply. The hydrologic conditions in the Trinity River Basin vary considerably across the study unit, and the watersheds exhibit wide variations in the generation and transport of sediment. Not many published studies have focused on multiple basins at the same time. In the Hydrologic Unit Model for the United States project, Srinivasan et al. (1998) used the Soil and Water Assessment Tool (SWAT) watershed model (Arnold et al. 1998) to simulate 350 US Geological Survey (USGS) six-digit watersheds in 18 major river basins throughout the United States. Santhi et al. (2006) evaluated the impacts of water quality management plans (WQMPs) on nonpoint source pollution in the West Fork Watershed in the Upper Trinity River Basin using SWAT. Their study area included Bridgeport and part of Eagle Mountain watersheds (figure 1), about 20% of drainage area covered in this study. They focused on evaluating WQMPs' effects at the farm level and at two watershed locations (gauge stations 08042800 and 08044500, figure 1). Sediment loading to the reservoir was not a topic of their study. Their results revealed that the benefits of the WQMPs in reducing sediment and nutrient loadings were greater (up to 99%) at the farm level than at the watershed level (1% to 2%) because WQMP implementation area was very small compared to total watershed area. Debele et al. (2009) modified the Enhanced SWAT (ESWAT) model (Vandenberghe et al. 2001; Van Griensven et al. 2001; Van Griensven and Bauwens 2003) and applied it to two watersheds within the Trinity River Basin. The two watersheds are the upper stream of Cedar Creek Reservoir and the upper stream of Eagle Mountain Reservoir in the Trinity River Basin (figure 1); the total study area was about 10% of the drainage area covered in this study. The reservoirs' simulation and scenario analyses were not covered in Debele et al. (2009). Their work focused on incorporating hourly evapotranspiration and overland flow routing modules to the ESWAT model and evaluating the effects of these model enhancements on hydrological and water quality simulations. Their results indicate that the modified ESWAT model has reasonably reproduced observed runoff time series and commonly available water quality data. The objectives of this study are to calibrate and validate the SWAT model for streamflow and sediment to assess current rates and sources of sediment loadings to major reservoirs in the entire Upper Trinity River Basin and to attempt to predict the effects of upland ponds through a scenario analysis of pond removal.

The scenario without ponds involves departure from calibration conditions. It would be beneficial to have measured data to calibrate the model under the without-pond scenario condition. Unfortunately, conducting such field measurements is usually expensive and time consuming. There are also uncertainties or errors associated with the measured data and difficulty in repeating the measurement without additional resources when corrections are warranted (Santhi et al. 2006). In contrast, scenario analysis using a watershed simulation model is both fast and economical. This modeling approach has been utilized by many to evaluate the effects of conservation best management practices (BMPs) (Turpin et al. 2005; Zhang and Jørgensen 2005; Wang et al. 2009; Yin et al. 2009; Tuppad et al. 2010).

Materials and Methods

Model Description. The SWAT model is designed to help scientists and decision makers manage soil and water resources at the watershed and river basin scales. A team of the USDA Agricultural Research Service, USDA Natural Resources Conservation Service (NRCS), and Texas A&M University System engineers and scientists has been developing the model for the last 25 years (Gassman et al. 2007). In the last decade, the US Environmental Protection Agency and a large number of engineers and scientists in the United States and around the world have contributed substantial resources to the model, its databases, and interface development. For over a decade, SWAT has been used in numerous small- and large-scale projects in the United States and internationally.

SWAT is a continuous simulation model that operates on a daily time step and can be used for long-term simulations. The model was developed to overcome limitations of several previously developed models, such as Chemicals, Runoff, and Erosion from Agricultural Management Systems (CREAMS) model (Knisel 1980), Groundwater Loading Effects of Agricultural Management Systems (GLEAMS) model (Leonard et al. 1987), Erosion-Productivity

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Table 1
Major reservoirs and watershed delineations within the Trinity River Basin study area.

Reservoir	Year completed	Watershed area (km²)	Mean slope (% ± 95% confidence interval)	Total number of subbasins	Total number of hydrologic response units
Lavon	1953	1,993	3.33 ± 0.10	20	1,164
Lake Ray Hubbard	1969	907	2.62 ± 0.14	20	548
Ray Roberts	1986	1,790	3.00 ± 0.09	28	1,570
Lewisville	1954	2,520	3.01 ± 0.11	32	1,405
Joe Pool	1986	580	2.73 ± 0.15	7	461
Bridgeport	1931	2,849	5.04 ± 0.18	57	1,487
Benbrook	1951	1,100	5.11 ± 0.20	37	1,119
Eagle Mountain	1932	2,230	3.54 ± 0.22	150	1,516
Cedar Creek	1966	2,600	2.12 ± 0.11	106	1,516
Richland-Chambers*	1987	5,157	1.91 ± 0.04	156	3,687

*Reservoirs Bardwell and Navarro Mills drain to Richland-Chambers.

Impact Calculator (EPIC) model (Williams 1990), Routing Outputs to Outlets (ROTO) model (Arnold et al. 1995a) and Simulator for Water Resources in Rural Basins (SWRRB) model (Arnold and Williams 1987). By combining components of these models and developing new subroutines and functionality, SWAT allows the user to simultaneously simulate weather, hydrology, erosion sedimentation, crop production, nutrient and pesticide transformations and movement, and bacterial contamination in small or large watersheds. Major components of the SWAT model include weather, hydrology, soil temperature, plant growth, nutrients, pesticides, bacteria and pathogens, and land management. SWAT is a basin-scale, distributed hydrologic and water quality model in which a watershed is divided into multiple subwatersheds. The subwatersheds are further subdivided into hydrologic response units that consist of unique combinations of homogeneous land use, management, topographical, and soil characteristics.

SWAT uses daily weather data to simulate surface and subsurface hydrology. The model can read observed weather data such as daily precipitation, maximum/minimum air temperature, solar radiation, wind speed, and relative humidity directly from files or generate data from observed monthly statistics. Snow is simulated when temperatures are below freezing, and soil temperature is simulated because it impacts water movement and the decay rate of residue in the soil. Hydrologic processes simulated include canopy storage; surface runoff; infiltration; evapotranspiration; lateral flow; tile drainage; redistribution of water within the soil profile; return flow; and recharge by seepage from surface water bodies, ponds, and tributary channels. The plant growth module simulates all types of land covers and differentiates between annual and perennial plants. SWAT uses the Modified Universal Soil Loss Equation (Williams and Berndt 1977) to predict sediment yield from the landscape. The model simulates the movement and transformation of several forms of nitrogen (N), phosphorus (P), and pesticides. Users can define management practices for each hydrologic response unit. Loadings are routed through the streams and reservoirs within the watershed. The water balance for reservoirs includes inflow, outflow, rainfall on the surface, evaporation, seepage from the reservoir bottom, and diversions. Detailed model equations can be found in Arnold et al. (1998).

Study Area and Model Inputs. The Upper Trinity River Basin is located in North Central Texas. It has a total drainage area of about 29,500 km² (7,290,000 ac). It covers 7 USGS eight-digit watersheds (USGS 2011) and contains 12 major water supply reservoirs. We delineated the Trinity River Basin study area into 10 watersheds, encompassing the 12 major reservoirs (table 1 and figure 1).

Topography was defined by a 30 m (100 ft) digital elevation model from the National Elevation Dataset (table 2). The stream network and its characteristics, such as channel slope, length, and width, were derived from the digital elevation model through the ArcGIS SWAT (ArcSWAT) software (Olivera et al. 2006). The resulting stream network was then used to define the layout, number of subbasins, and their topographic parameters.

SWAT requires soil characteristics for each soil horizon (e.g., depth, texture, water holding capacity, etc.). The USDA NRCS Soil Data Mart provides Soil Survey Geographic (SSURGO) geographic information systems (GIS) data (table 2). SSURGO describes each soil mapping unit as a single soil series. This 1:24,000-scale soils dataset is available for many Texas counties but not all those in the study area. When SSURGO data were not available, we used State Soil Geographic (STATSGO) data instead. Despite STATSGO data having courser resolution than SSURGO data, they nonetheless provide adequate soil information in this large scale modeling study.

Land cover is another important GIS data used in SWAT. It specifies the size and distribution of different type of land uses in the basin. Land uses such as pasture, row crop, and forest differ radically in terms of erosion and nutrient loss potential. During model setup, forested areas are assumed to contribute little to nutrient loading while pastures and row crops are thought to be primary sources of P. The Multi-Resolution Land Characteristics Consortium developed the National Land Cover Dataset (NLCD) from 1992 Landsat 5 Thematic Mapper satellite data (USGS 2002). NLCD 2001 is an enhanced dataset from 1992 comprised of three elements: land cover, impervious surface, and canopy density. NLCD data has a resolution of 30 m (100 ft) and represents the most current land cover information since the 1970s. We used this dataset to provide land use inputs for SWAT (tables 2 and 3). Telephone interviews with county conservation districts and NRCS personnel provided the information for most of the management operations used in the model. These included land use practices such as grazing rates, fertilization, and tillage.

The National Climatic Data Center's National Weather Service stations located in and around each watershed provided daily

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Table 2
General model input data for the Trinity River Basin modeling study.

Data type	Source
Topography (30 m resolution)	US Geological Survey National Elevation Dataset http://ned.usgs.gov
Landuse/landcover (30 m resolution)	US Geological Survey National Land Cover Dataset 2001 Multi-Resolution Land Characteristics Consortium www.mrlc.gov
Soils (30 m resolution)	Soil Survey Geographic (SSURGO) and Soil State Soil Geographic (STATSGO) databases, USDA National Resources Conservation Service Soil Data Mart http://soildatamart.nrcs.usda.gov
Reservoirs/dams	US Army Corps of Engineers, National Inventory of Dams (NID) https://nid.usace.army.mil
Weather (precipitation and temperature)	National Oceanic and Atmospheric Administration, National Climatic Data Center's National Weather Service (NCDC NWS) http://www.ncdc.noaa.gov/oa/climate/stationlocator.html
Point sources	US Geological Survey Water Resource database or the US Environmental Protection Agency's Permit Compliance System http://water.usgs.gov/data/

precipitation and temperature (minimum and maximum) (table 2). The original long-term precipitation and temperature data contain gaps that are filled with data from surrounding stations to arrive at a continuous daily record. Using its built-in weather data generator, the SWAT model simulated other weather parameters, including wind speed, solar radiation, and relative humidity. SWAT's weather generator (Nicks 1974; Sharpley and Williams 1990) uses monthly weather statistics from long-term, historical weather data. For example, mean daily wind speed is generated using average monthly wind speed and a random number between 0 and 1 in a modified exponential equation. It uses a method originally developed for the EPIC model (Sharpley and Williams 1990) to generate daily average relative humidity values from a triangular distribution using average monthly relative humidity statistics.

To simulate reservoirs, SWAT utilized available daily reservoir outflow data and reservoir characteristics from the National Inventory of Dams (NID) (USACE 1982) (table 2). The NID defined reservoir characteristics and the total number of small flood control reservoirs, most of which are known as PL-566 structures after the law authorizing their construction. For some basins, other sources, such as the NLCD and the Texas Commission on Environmental Quality, provided pond data as well. The PL-566 structures are represented as ponds in SWAT. In SWAT, ponds are water bodies located within a subbasin that receive overland flow from a fraction of the subbasin area. The surface area of a pond is used to calculate the direct intake of precipitation as well as the amount of evaporation and seepage. Storages at principal and emergency spillway thresholds are used to calculate pond outflow. In this study, the percentages of basins' areas drained into ponds range from 12% to 32% of the total area of their respective watersheds (table 3).

Table 3
Major land use for the Trinity River Basin modeling study.

Reservoir	Land use (%)						Area drain to ponds (%)
	Agricultural	Pasture	Range	Urban	Forest	Others	
Lavon	16.3	13.1	42.1	10.1	14.0	4.3	34.0
Lake Ray Hubbard	7.7	6.7	17.4	50.8	7.4	10.0	15.0
Ray Roberts	15.8	16.1	44.1	6.1	11.1	6.8	18.0
Lewisville	12.7	15.5	46.3	10.8	10.1	4.7	24.0
Joe Pool	12.8	10.7	36.3	17.2	18.3	4.8	12.0
Bridgeport	2.1	1.0	72.7	6.2	15.9	2.1	12.0
Benbrook	1.9	10.6	64.5	9.0	11.8	2.2	12.0
Eagle Mountain	3.2	9.1	58.5	9.6	17.4	2.2	13.2
Cedar Creek	3.2	60.9	1.3	7.1	15.8	11.7	20.4
Richland-Chambers	18.0	19.0	38.0	7.0	11.0	7.0	32.0

Model Calibration and Validation. Numerous SWAT studies have reported calibration parameters (Santhi et al. 2006; Douglas-Mankin et al. 2010; Tuppad et al. 2011; Arnold et al. 2012); many also provided tables with parameter ranges and final applied values. In this study, calibration is performed by adjusting model parameters that capture the spatial and temporal variations in model inputs (table 4). These parameters were adjusted within literature reported ranges (Santhi et al. 2001; Neitsch et al. 2002).

Streamflow. For each watershed, SWAT was calibrated and validated for flow using the measured annual and monthly streamflow at the USGS gauging stations (figure 1). The manual calibration aimed at matching observed with simulated flow while taking into consideration the proper split of simulated surface flow and baseflow. The Baseflow Filter Program (Arnold and Allen 1999; Arnold et al. 1995b) was used to analyze the streamflow records to determine the appropriate baseflow proportion. Statistical measures, including Nash-Sutcliffe efficiency (NSE) (Nash and Sutcliffe 1970) and r^2, were used to assess how well SWAT predicted streamflow compared with measured data. Moriasi et al. (2007) suggested that NSE should exceed 0.5 in order for model results to be judged as satisfactory for hydrologic evaluations performed on a monthly time step. Wang et al. (2012) suggested that an r^2 greater than 0.6 and NSE greater than 0.55 indicate satisfactory flow simulation. To date, no absolute criteria have been firmly established in the literature (Arnold et al. 2012) because the criteria for judgment of model performance should be tied to the intended use of the model (Engel et al. 2007). In this study, we adopted the metrics used by Wang et al. (2012) to gauge SWAT's streamflow simulation.

Surface runoff and base flow were calibrated simultaneously. Calibration parameters adjusted for surface runoff include curve number (CN2) and available water capacity of the soil layer (SOL_AWC1). The

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Table 4
Soil and Water Assessment Tool input parameters adjusted for calibration of flow and sediment (range and calibrated values).

Parameter	Description	Normal range	Value used
Flow			
CN2	Initial Natural Resources Conservation Service runoff curve number for moisture condition II	Default ± 6	Default ± 5
GWQMN	Threshold depth of water in the shallow aquifer required for return flow to occur (mm)	0.0 to 300	1.2 to 250
GW_REVAP	Groundwater revap coefficient	0.02 to 0.4	0.02 to 0.3
EPCO	Plant uptake compensation factor	0.01 to 1.0	0.5 to 1.0
ESCO	Soil evaporation compensation factor	0.01 to 1.0	0.50 to 0.95
REVAPMN	Threshold depth of water in the shallow aquifer for revap to occur (mm)	1.0 to 15.0	1.0 to 10
CH_K2	Hydraulic conductivity of channel alluvium (mm h^{-1})	0.025 to 127.0	0.1 to 5.0
PND_K	Hydraulic conductivity through bottom of ponds	0.001 to 0.5	0.5
GW_DELAY	Groundwater delay time (d)	31 to 135	31 or 135
ALPHA_BF	Baseflow alpha factor (d^{-1})	0.042 to 0.25	0.042 to 0.2006
RCHRG_DP	Deep aquifer percolation fraction	0.0 to 1.0	0.25
Sediment			
CH_N2	Mannings "n" roughness for channel flow	0.014 to 0.15	0.014 to 0.125
SOL_AWC1	Available water capacity of the soil layer	Default + 0.05	Default + 0.04
SPCON	Linear parameter for estimating the maximum amount of sediment that can be reentrained during channel sediment routing	0.0001 to 0.01	0.0006 to 0.01
CH_COV	Channel cover factor	0.0 to 1.0	0.02 to 0.95
CH_EROD	Channel erodibility factor	0.0 to 1.0	0.056 to 0.9
C-factor	Land surface cover factor	0.003 to 0.2	0.007 to 0.2
SPEXP	Exponent parameter for estimating the maximum amount of sediment that can be reentrained during channel sediment routing	0.65 to 1.5	0.67 to 1.4

parameters adjusted for base flow proportion include groundwater revap coefficient (GW_REVAP), plant uptake compensation factor (EPCO), soil evaporation compensation factor (ESCO), threshold depth of water in shallow aquifer required for return flow to occur (GWQMN) or for revap to occur (REVAPMN), baseflow alpha factor (ALPHA_BF), and deep aquifer percolation fraction (RCHRG_DP). These parameters were adjusted within the reported ranges (table 4). Streamflow was calibrated until r^2 becomes greater than 0.6 and NSE greater than 0.55 on both annual and monthly basis, if possible.

An iterative approach was used for the manual calibration, which follows the general calibration flowchart as provided in Arnold et al. (2012). Parameters were adjusted one at a time, and visual comparison of simulated versus observed time series in plots, along with the statistic measures of r^2 and NSE, are used to achieve best fit between simulated and observed data. Parameters' adjustments varied from watershed to watershed. For example, hydraulic conductivity through bottom of ponds (PND_K) was adjusted only for Benbrook and Bridgeport basins, and hydraulic conductivity of channel alluvium (CH_K2) was adjusted only for Cedar Creek and Eagle Mountain basins. For other watersheds, default values were used for these parameters. This is because either the r^2 and NSE metrics had reached the satisfactory thresholds without further adjusting these parameters or these parameters were not that influential to the watersheds' flow changes.

Sediment. In this study, there were a number of difficulties in the simulation and calibration of sediment loading. First, continuous records of measured data for sediment loading were not available. Only grab sample data (sediment concentration) were available from time to time (usually 2 to 10 samples per year, with missing years in between) at several monitoring sites within the study area. Second, some of the samples were taken on days with low flow or on days when streamflows were not recorded, which further limits the availability of quality sediment data since sediment loading is calculated as the product of streamflow and sediment concentration. Third, the SWAT model uses a relatively simplistic reservoir model that has limited representation of the otherwise complex sediment and nutrient retention dynamic of reservoirs. Hence, calibrating SWAT using measured data directly downstream of the reservoirs is problematic. For example, sites downstream of major reservoirs, such as Lake Weatherford in the Benbrook Watershed, were not used for sediment calibration.

Some additional sediment loading data were obtained from hydrographic surveys performed by the Texas Water Development Board (TWDB) and from the lake sediment surveys carried out by the Baylor University. Overall, water quality data are lacking, making it a challenging task to adequately calibrate each watershed simulation for the sediment component; with this limitation, some watershed models utilized SWAT-adjusted parameter setup from neighboring basins that have similar watershed characteristics. Therefore, efforts to collect these data for adequate validation of the model must continue. Nevertheless, careful considerations were given to the adjustment of parameter values reflecting various aspects of the sediment processes.

SWAT parameters related to sediment were applied based on expertise and experience obtained from previous studies (Neitsch et al. 2002; White et al. 2005; Santhi et al. 2006). Model parameters involved in both upland and channel sediment processes were adjusted. Specifically, for upland process, the Universal Soil Loss Equation's crop factor (C factor) was adjusted. For

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channel routing process, the channel cover factor (CH_COV), channel erodibility factor (CH_EROD), and the coefficients of the Bagnold equation (SPCON and SPEXP) (table 4) were adjusted.

For sediment calibration, percentage error was the preferred metric because available measured loads were generally scarce and often available only on an average annual basis. Typically, measured loading data are estimated based on grab sample concentrations, along with observed streamflow, by using a load estimator program (Runkel et al. 2004; Crawford 1998). Parameters were adjusted one at a time with continual assessment of the percentage error.

Pond Removal Scenario Analysis. Among the watersheds simulated, there was a wide range in the number of ponds and their contributing areas drained by small flood control structures. As mentioned previously, the SWAT model was set up to represent the many small flood control structures distributed across Trinity River Basin. Within each study watershed, they receive runoff from upstream overland area and trap sediment and nutrients, preventing their delivery to reservoirs. These structures are simulated as ponds in the SWAT model. The flow and sediment calibrations as described earlier were also performed for the SWAT model that includes pond representation. To assess their efficacy, we removed ponds from all study watersheds' SWAT models and then reran these SWAT models and compared the results between the preremoval and postremoval simulations.

Results and Discussion

Streamflow Calibration and Validation. The observed streamflow for the Trinity River Basin shows wide variations in temporal flow pattern across the USGS gauging stations. Daily flow rate values range from 0.34 to 22.2 $m^3\ s^{-1}$ (12 to 784 $ft^3\ s^{-1}$). Thus, the calibrations resulted in a range of parameter values as listed in table 4. Of the 22 USGS gauging stations, 4 are immediately downstream of reservoirs whose daily release schedules (used as input to SWAT) are the dominant flow data; therefore, the simulated streamflow results at these 4 USGS gauging stations were only used to validate the model. The mean simulated flow rates at various monitoring locations closely matched the mean observed flow rates for both the calibration and validation periods (table 5). The r^2 values ranged from 0.55 to 0.96, and NSE values ranged from 0.18 to 0.96 based on the monthly streamflow comparisons between observed and corresponding simulated values. The calibration results were comparable to the level of fit between observed and simulated values in previous works done by Santhi et al. (2006) using streamflow data from USGS gaging stations 08042800 and 08044500 and by Debele et al. (2009) using streamflow data from USGS gaging station 08062800.

In general, both simulated annual and monthly flows followed the temporal patterns of observed flows closely. In most of the study watersheds, SWAT performed well in its streamflow simulation as evidenced by their satisfactory r^2 and NSE statistics. This indicates that the calibrated SWAT models in large part captured the hydrologic dynamics in the diverse watersheds within the Trinity River Basin. However, there were both underpredicted and overpredicted flows on the annual and monthly basis. Noticeably, SWAT underpredicted flows for the years 1993 and 2001 at gauging station 08051500 (figure 2). This could be attributed to the underpredictions of flows for the months of February and March in those years as shown in the monthly hydrograph in figure 3. Conversely, the overpredictions of flow in the months of year 1986 and 1999 lead to slight overpredictions of annual flows for those two years (figure 2). Overall, monthly simulated and observed flows matched well, except for 4 out of 22 gauging stations, where the model performance statistics had NSE less than 0.55 and 2 of the 4 had r^2 less than 0.6 (table 5). These less than satisfactory simulation results occurred in Benbrook and Richland-Chambers watersheds.

A detailed monthly hydrograph of simulated versus observed streamflow at gaging station 08061540 is plotted in figure 3. It shows that while the SWAT model predicted some peak flows well (e.g., May of 1969, October of 1981, January of 1998, and February of 2001), it at times underpredicted (e.g., December of 1971, May of 1982, and December of 1991) or overpredicted (e.g., May of 1987, June of 1989, and May of 1990) the high peaks (figure 3). No consistent seasonal underprediction or overprediction by the SWAT model was identified.

Sediment Calibration. As previously described, the LOADEST2 program (Crawford, 1998) was used to calculate mean total suspended solid loads from sediment concentration grab sample data and measured streamflow data. These calculated loads were used to calibrate SWAT model sediment component. At the USGS gauging station on the Trinity River near Jacksboro (08042800) in the Bridgeport Watershed, the calculated mean sediment load is 24,900 Mg y^{-1} (27,400 tn yr^{-1}) from 1970 to 2007. After calibration, SWAT model simulated a mean of 24,800 Mg y^{-1} (27,300 tn yr^{-1}) sediment load for this period, i.e., with a percentage error of –0.4% (table 6).

For the Lavon, Lewisville, and Richland-Chambers watersheds, limited water quality samples are available. Hence, SWAT was calibrated to match average daily loads for days with available data. The percentage errors ranged from –6.1% to –3.1% (table 6).

Baylor University performed a lake sediment survey for Cedar Creek Reservoir and Eagle Mountain Reservoir, collecting sediment cores to estimate average density and thickness of sediment at the lake bottom (Allen et al. 2006). In addition, Allen et al. (2006) conducted a watershed survey to identify stream segments with channel erosion problems and to quantify channel erosion using NRCS field assessment techniques. Based on the lake sediment survey and the watershed survey, the total erosion rate within the Cedar Creek Basin is estimated at about 447,000 Mg y^{-1} (492,000 tn yr^{-1}). Out of the total rate, channel erosion contributed about 153,000 Mg y^{-1} (168,000 tn yr^{-1}) or 34.2% of the total erosion rate. The rest of the sediment output (294,000 Mg y^{-1} [324,000 tn yr^{-1}]) came from overland erosion (Allen et al. 2006). The SWAT model was calibrated until the predicted mean annual sediment loads from overland and channel erosion were approximately equal to measured data.

Allen et al. (2006) calculated sedimentation in the Eagle Mountain Reservoir by averaging three historical surveys. They concluded that the sedimentation rate of the lake was 376,000 Mg y^{-1} (414,000 tn yr^{-1}). Based on the lake sediment survey and the watershed survey, researchers estimated that the erosion rate within Eagle Mountain Basin was about 341,000 Mg y^{-1} (376,000 tn yr^{-1}). Out of this total, channel erosion contributed about 110,000 Mg y^{-1} (121,000 tn yr^{-1}) or 32%. The remaining sediment in the rate of 231,000 Mg y^{-1} (254,000 tn yr^{-1}) came from overland erosion (Allen et al. 2006). TWDB performed a study for the

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Table 5

Soil and Water Assessment Tool performance statistics at annual and monthly time step for the study watersheds. Low performance is identified as having Nash-Sutcliffe efficiencey less than 0.55 (corresponding r^2 ranged from 0.55 to 0.76) (bold text).

Gauge station ID (site name)		Period	Mean ($m^3 s^{-1}$) Measured	Mean ($m^3 s^{-1}$) Simulated	Yearly r^2	Yearly NSE	Monthly r^2	Monthly NSE
Joe Pool								
08049700 (Walnut Creek near Mansfield)	Calibration	1965 to 1986	0.47	0.48	0.76	0.75	0.73	0.72
	Validation	1987 to 2007	0.89	0.81	0.74	0.71	0.74	0.73
08049580 (East Fork Trinity River near Forney)	Validation	2002 to 2007	0.34	0.35	0.90	0.72	0.72	0.70
Lavon								
08058900 (East Fork Trinity River at McKinney)	Calibration	1976 to 1985	2.48	2.67	0.91	0.90	0.88	0.87
	Validation	1986 to 1995	4.39	3.81	0.81	0.70	0.83	0.80
08059400 (Sister Grove Creek near Blue Ridge)	Validation	1976 to 1995	1.83	1.59	0.81	0.75	0.77	0.76
Lewisville								
08052700 (Little Elm Creek near Aubrey)	Calibration	1970 to 1986	1.52	1.37	0.96	0.92	0.81	0.74
	Validation	1987 to 2006	1.54	1.55	0.84	0.84	0.74	0.74
08051500 (Clear Creek near Sanger)	Calibration	1970 to 1986	2.71	2.50	0.86	0.85	0.81	0.79
	Validation	1987 to 2000	3.66	3.14	0.87	0.83	0.80	0.79
08053000 (immediate downstream of reservoir)	Validation	1970 to 2007	22.21	21.99	0.97	0.97	0.99	0.99
Ray Roberts								
08050400 (Elm Fork Trinity River at Gainesville)	Calibration	1985 to 1995	3.66	3.42	0.91	0.88	0.85	0.82
	Validation	1996 to 2007	2.01	2.56	0.89	0.65	0.83	0.81
08050840 (Range Creek near Collinsville)	Calibration	1992 to 1999	0.56	0.50	0.76	0.67	0.73	0.72
	Validation	2000 to 2004	0.37	0.41	0.95	0.90	0.77	0.73
Ray Hubbard								
08061540 (Rowlett Creek near Sachse)	Calibration	1968 to 1987	2.82	3.06	0.67	0.64	0.74	0.73
	Validation	1988 to 2006	4.80	4.23	0.77	0.60	0.79	0.76
08061750 (immediate downstream of reservoir)	Validation	1973 to 2006	18.98	17.86	0.98	0.97	0.98	0.97
Benbrook								
08045850 (Trinity River near Weatherford)	Calibration	1980 to 1995	0.77	0.77	0.81	0.79	**0.55**	**0.50**
	Validation	1996 to 2005	0.51	0.86	**0.75**	**-0.21**	**0.76**	**0.18**
08046000 (Trinity River near Aldeo)	Validation	1970 to 1975	1.62	1.66	not enough points		**0.58**	**0.54**
08047000 (immediate downstream of reservoir)	Validation	1970 to 2005	3.36	2.93	0.96	0.92	0.97	0.97
Bridgeport								
08042800 (West Fork of Trinity River near Jacksboro)	Calibration	1985 to 2007	3.01	3.05	0.83	0.82	0.80	0.73
	Validation	1970 to 1984	2.32	1.86	0.74	0.67	0.77	0.73
Richland-Chambers								
08064100 (Chambers Creek near Rice)	Calibration	1984 to 1995	14.66	14.30	0.94	0.93	0.91	0.90
08063100 (immediate downstream of reservoir)	Validation	1984 to 1995	5.73	5.79	0.99	0.98	0.98	0.98
08063800 (Waxahachie Creek near Bardwell)	Validation	1984 to 1995	3.39	3.54	0.63	0.55	**0.67**	**0.44**
Cedar Creek								
08062800 (Cedar Creek near Kemp)	Calibration	1966 to 1987	3.48	3.61	0.85	0.84	0.82	0.81
08062900 (Kings Creek near Kaufman)	Calibration	1966 to 1987	4.72	4.77	0.92	0.90	0.89	0.83
Downstream of reservoir	Validation	1980 to 2002	18.37	19.16	0.82	0.80	0.80	0.76
Eagle Mountain								
08044500 (West Fork Trinity River near Boyd)	Calibration	1991 to 2005	7.14	7.04	0.96	0.96	0.96	0.95
	Validation	1971 to 1990	8.59	8.40	0.96	0.93	0.96	0.92

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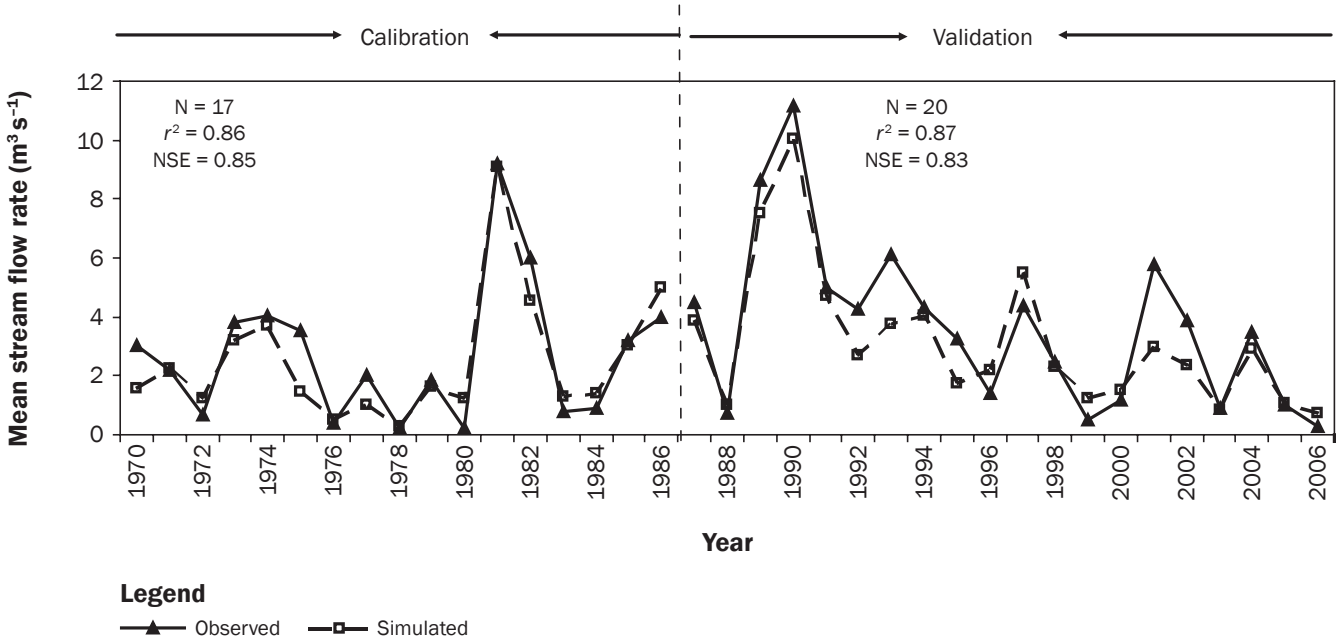
Figure 2

Measured and simulated mean annual streamflow rate at gauge 08051500, Clear Creek near Sanger, for calibration period (1970 to 1986) and validation period (1987 to 2006). NSE = Nash-Sutcliffe efficiency.



Eagle Mountain Reservoir in 2008 using a duel frequency method (TWDB 2008). Using this technique, they estimated the thickness of the reservoir's postimpoundment sediment. However, they could not measure shallow areas due to inaccessibility. This included shallow areas full of sediment near the mouth of major tributaries. Despite this drawback, this study used the most recent technology and measured with very fine resolution. Therefore, we adopted the measurements of this study and calibrated sediment based on TWDB estimates of total erosion rate. Because the TWDB survey did not estimate the contribution from overland and channel flow, we adopted the ratio of channel erosion sediment to overland sediment from Allen et al. (2006) for differentiation among the two sources. According to TWDB measurements, the reservoir sedimentation rate was 296,000 Mg y^{-1} (326,000 tn yr^{-1}), which is 45,000 Mg y^{-1} (50,000 tn yr^{-1}) less than reported in the study by Allen et al. (2006). Channel contribution was estimated at 98,600 Mg y^{-1} (108,600 tn yr^{-1}), or 33.3%, and overland erosion contribution was estimated at 197,000 Mg y^{-1} (217,500 tn yr^{-1}). SWAT was calibrated to match these annual average erosion rates with percentage error of −10.8% in the Eagle Mountain Watershed (table 6).

Model Prediction. The calibrated SWAT model was used to predict sediment losses from upland and sediment loading into reservoirs. The results are shown in figure 4. The study watersheds vary widely in their simulated sediment loss and transport, reflecting the variability among watersheds in land use/land cover, management, soils, slope, and climate conditions. For example, annual overland erosion rates ranged from 0.16 Mg ha^{-1} y^{-1} (0.07 tn ac^{-1} yr^{-1}) for the Bridgeport Basin to 1.59 Mg ha^{-1} y^{-1} (0.71 tn ac^{-1} yr^{-1}) for the Lewisville Basin; much of this difference was driven by cropland proportion, which was 2% in Bridgeport Basin and 13% in Lewisville Basin.

As simulated by the SWAT model, more sediment reached the reservoir than was generated from overland erosion in most watersheds (especially Richland-Chambers, Lavon, and Ray Hubbard) (figure 4). This indicates that eroding streambanks and beds were important sources of reservoir sedimentation. The lake sediment surveys (Allen et al. 2006) also indicated that the channel erosion contributes about 34.2% of the total sediment loading to the Cedar Creek Reservoir and about 32.3% of total sediment loading to the Eagle Mountain Reservoir. However, detailed studies of fluvial morphology and streambank and bed erosion would be necessary to confirm these results and identify sensitive reaches needing stabilization and restoration. In the mid-1990s, the Texas State Soil and Water Conservation Board (TSSWCB) provided incentives to landowners for installation of BMPs to control nonpoint pollution sources and protect water quality (TSSWCB 2001). As a result, BMPs such as nutrient management, brush management, pasture planting, critical area planting and grade stabilization structures, were implemented in the Eagle Mountain Watershed area. Later in the 1990s, in compliance with section 319(h) of the Clean Water Act, the US Environmental Protection Agency provided funding to TSSWCB for implementation of BMPs in Texas. Starting in 2000, BMPs, including forage harvest management, grade stabilization structure, critical area planting, residue management, range seeding, brush management, and contour terracing, were installed on farms located across Bridgeport and Eagle Mountain watersheds. The area of the BMPs installed in both projects is less than 1% of the watershed area (Santhi et al. 2006). Santhi et al. (2006) indicated that the benefit of the BMPs in reducing sediment loading was merely not significant (about 1%) at the watershed level due to the small percentage of total watershed area with BMP installa-

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Figure 3

Measured and simulated mean monthly streamflow rate at gauge 08061540, Rowlett Creek near Sachse, for the (a) calibration (March of 1968 to December of 1987) and (b) validation period (January of 1988 to December of 2006). NSE = Nash-Sutcliffe efficiency.

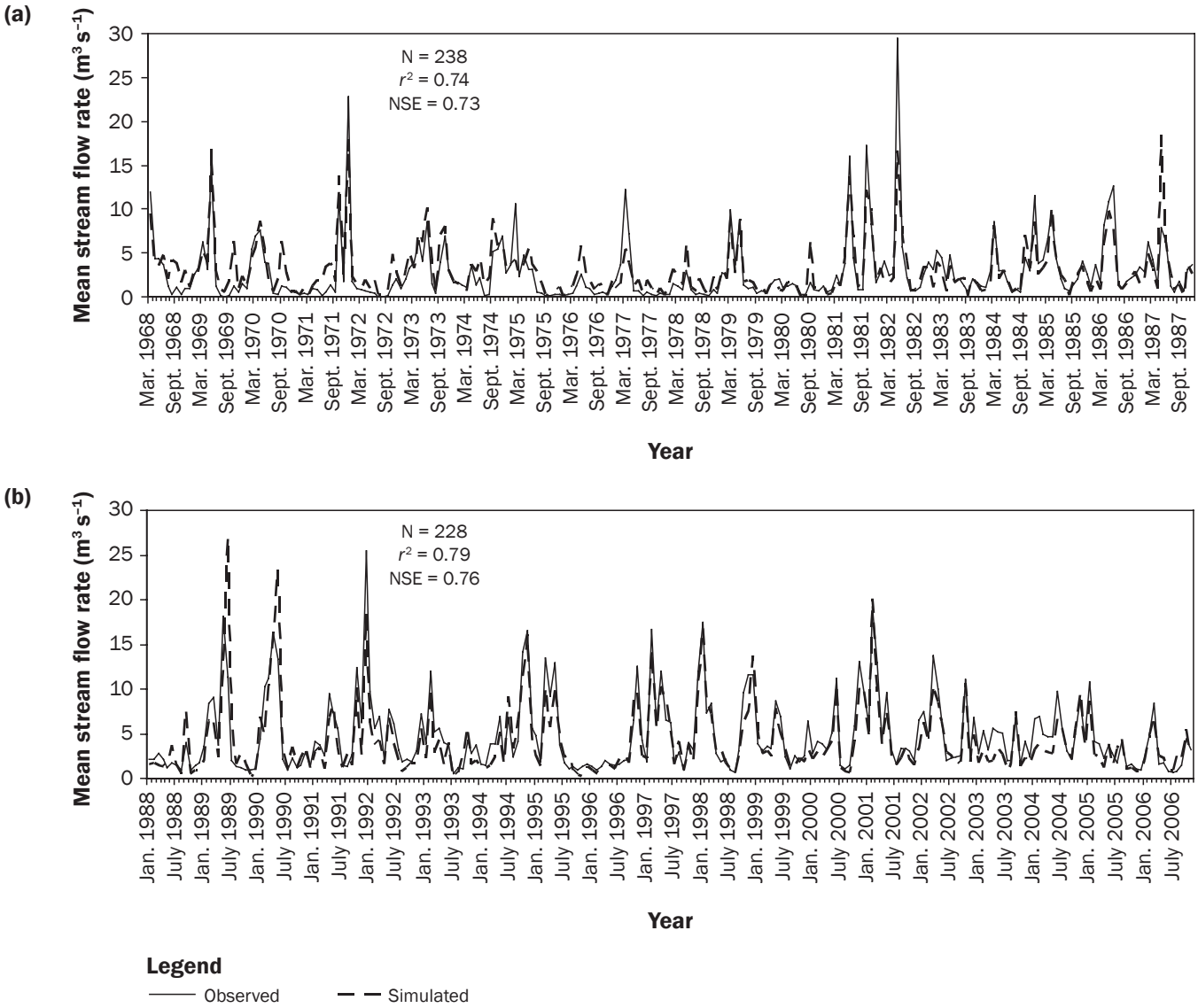

Table 6

Sediment calibration for the Trinity River Basin watersheds.

Watershed	Lavon*	Lewisville*	Bridgeport†	Eagle Mountain‡	Cedar Creek‡	Richland-Chambers*
Observed	227 Mg d^{-1}	1,764 Mg d^{-1}	24,886 Mg y^{-1}	295,822 Mg y^{-1}	446,558 Mg y^{-1}	1,542 Mg d^{-1}
Simulated	213 Mg d^{-1}	1,709 Mg d^{-1}	247,83 Mg y^{-1}	263,827 Mg y^{-1}	469,256 Mg y^{-1}	1,487 Mg d^{-1}
% error	−6.1	−3.1	−0.4	−10.8	5.0	−3.5

* Average daily loads for days with available data.

† Loadest2 (Crawford 1998) estimated mean as the observed value.

‡ Lake sediment survey and hydrographic surveys as the observed values.

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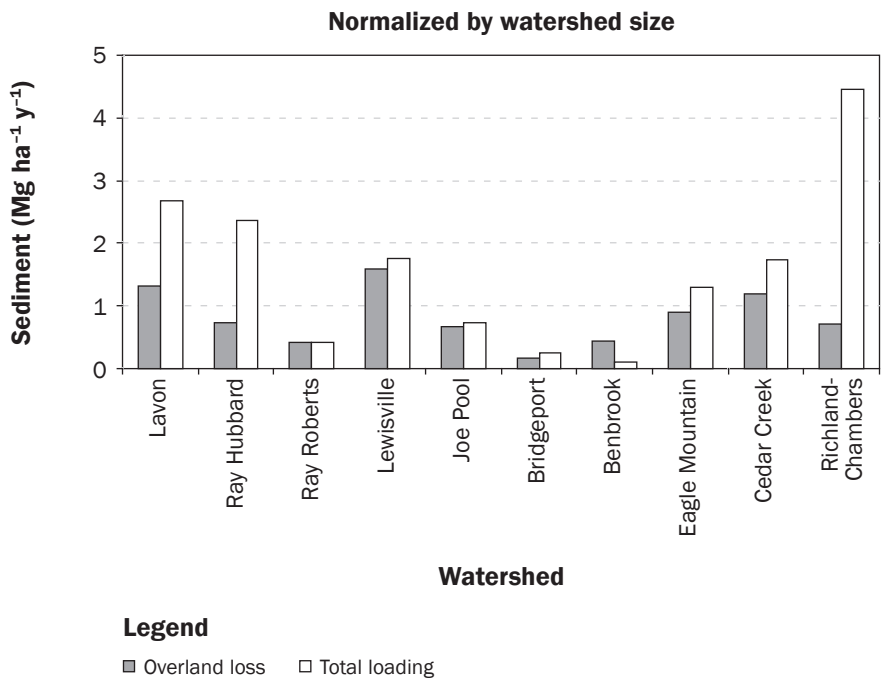
Figure 4
Sediment loss from overland and sediment loading to major reservoirs within the Trinity River Basin.



tions. Results from this study and from Santhi et al. (2006) indicate the need for continuous conservation management. For example, implementation of contour terracing, buffer strips along water courses, ponds, and grade stabilization structures would reduce sediment loadings to the receiving reservoirs.

Predicted Benefit of Ponds. Ponds affect hydrology by impounding water and trapping nutrients and sediment. Water in ponds is subject to evaporation and seepage, while nutrients and sediments settle and are retained. Some of the ponds have been surrounded by urban development, and many need to be renovated or removed. To simulate the effects of possible future removal of these structures on sediment and nutrient loading of water supply reservoirs, we modified the baseline model, which simulated all ponds, by removing these structures from model setup.

Pond efficiency is in part a function of detention time. Many small ponds discharge only a small fraction of the water they receive in a typical year and have very long detention times. Simulations with and without these ponds suggested that their effectiveness in reducing sedimentation of water supply reservoirs varied among watersheds. The percentages of basin area drained into ponds, locations of ponds, and basin's erosion characteristics all contribute to their overall effectiveness. In general, there is a positive relationship between the reductions of sediment loadings to the receiving reservoirs and contributing areas drained into ponds. For example, the percentages of basins' areas drained into ponds are approximately 12% for each of the Bridgeport, Joe Pool, and Benbrook basins, 18% for Ray Roberts, and 24% for Lewisville (table 3 and figure 5). Comparing modeling results between the with and without ponds scenarios shows that the percentage of sediment loadings to receiving reservoirs were reduced by 9.6%, 9.9%, 13.1%, 19.4%, and 48.3% in the above mentioned watersheds (figure 5), respectively. However, if the main contribution of sediment loadings to reservoirs are from streambanks, then one would not expect substantial reduction of total sediment loading to receiving reservoirs due to ponds alone. For example, the percentages of basins' areas drained into ponds are 34% for Lavon and 32% for Richland-Chambers, which are the highest among these study basins. Yet, the percentages of sediment loadings to receiving reservoirs were reduced by only 19% and 8% (figure 5) for these two basins, respectively. The Ray Hubbard basin has approximately 15% areas drained into ponds, but has only 4% reduction in sediment loading to the reservoir, the smallest reduction among these study basins. This is because the three watersheds (Lavon, Richland-Chambers, and Ray Hubbard) have the highest streambank/channel contribution of total sediment loadings to their receiving reservoirs (51%, 84%, and 69%, respectively; figure 5). While ponds are effective in settling sediment received from overland flow, vulnerable streambanks erosion can be another significant source for sediment to be carried on in the channel. Therefore, in addition to implementing conservation practices on upland areas, it is also necessary to apply conservation practices in stream channels for maximum reduction of sediment loading in receiving reservoirs

Summary and Conclusions

The 10 watersheds contributing to major reservoirs in the Trinity River Basin were simulated in this study. They vary in size ranging from 58,000 ha (143,321 ac) to 515,700 ha (1,274,322 ac). This study is focused mainly on assessing current rates and sources of sediment loading of major water supply reservoirs in the 10 watersheds of the Upper Trinity River Basin and the effectiveness of ponds in terms of sediment load reduction. The SWAT model hydrology component was calibrated and validated spatially and temporally. Although the SWAT model has been successfully applied in ungauged basins, model calibration and validation increases confidence in its prediction and application for BMP evaluation. In this modeling study of the Trinity River Basin, SWAT was calibrated for sediment for the watersheds with available monitoring data or survey data, while other watersheds lacking measured data adopted SWAT parameters from the neighboring watersheds' SWAT model setup.

Long-term predictions indicate that 8 out of the 10 watersheds had more sediment reaching the reservoir than was generated from overland erosion, especially for the Richland-Chambers, Ray Hubbard, and Lavon reservoirs. Eroding streambanks and/or beds in these watersheds are significant sources of sediment contributing to reservoir sedimentation. It would be beneficial to have detailed studies to identify sensitive reaches for stabilization and restoration treatment.

Simulations with and without ponds suggested that the ponds' effectiveness in

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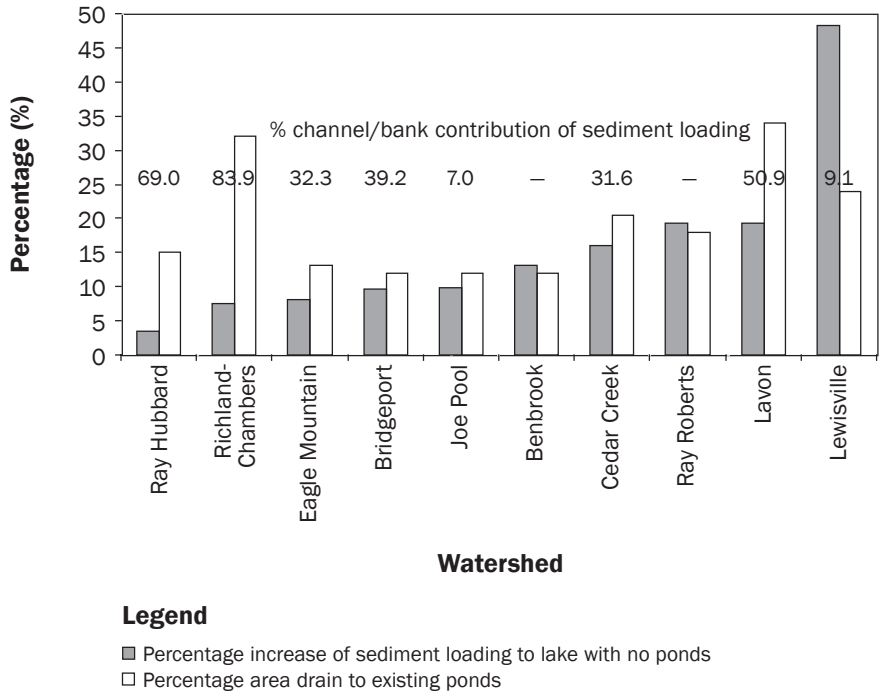
Figure 5

Benefit of upland ponds in reducing sediment loading to reservoirs in respect to percentage area drained to ponds and percentage streambank/channel contribution of sediment loading. Benbrook and Ray Roberts basins have more channel deposition than degradation.



reducing sediment loading to reservoirs varied among watersheds. The percentages of total watershed area drained into ponds ranged from 12% to 34% among the 10 watersheds. Without these ponds, sediment loadings to reservoirs would have increased by 4% to 48%. The ratios of the percentage sediment loading reduction to the percentage of pond controlled drainage area ranged from 0.23 to 2.01. Other factors such as the locations of ponds and basin's erosion characteristics all contributed to the different effectiveness. Future studies could evaluate the effects of optimizing pond size and placement to minimize reservoir sediment loading.

This study provides an overall estimate of the magnitude and spatial distribution of sediment generated by overland flow as well as the amount delivered to the major reservoirs within the Trinity River Basin. Opportunity exists for further data collection, including data for detailed field management and channel dimensions, which will enhance the SWAT models to provide greater insight into potential sediment sources and sinks. Implementation of contour terracing, buffer strips along water courses, ponds, and grade stabilization structures would reduce sediment loadings to the receiving reservoirs.

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