Int. J. Environ. Res., 9(3):885-896, Summer 2015
ISSN: 1735-6865

Modifying and Validating the SWAT Model to Determine Landuse Effects on Watershed Water Quality: Using a Dual Level of Model Performance Based on Subbasin Size

Houser, J. B.[1*], Hauck, L. M.[2] and Saleh, A.[2]

[1]Appalachian State University, Boone, NC, USA

[2]Texas Institute for Applied Environmental Research (TIAER), Tarleton State University, Stephenville Texas, USA

Received 17 Aug. 2014; Revised 29 Dec. 2014; Accepted 1 Jan. 2015

ABSTRACT: The North Bosque River (NBR) was included in the Clean Water Act § 303(d) impaired list. The Texas Institute for Applied Environmental Research used the Soil Water Assessment Tool (SWAT) to develop a phosphorus (P) Total Maximum Daily Load. SWAT was modified to dynamically change manure application rates based on simulated annual soil P, change areas receiving manure, alter manure quantities each year, apply liquid and solid manure pools separately, move manure between subbasins, improve landscape P processes, model contributions of dairy lagoon discharges and improve in-stream water quality kinetics. Data was refined to increase spatial resolution of subbasins and include Public Law (PL)-566 flood retardation reservoirs. A dual level of model performance was established: one level for large drainage areas and a reduced performance level for all other sites. Main stem sites were to have streamflow, sediment, total nutrients achieve a "good" rating. For secondary sites and constituent parts of total nutrients besides PO4 a "satisfactory" rating was acceptable model performance. This dual level of model performance was developed in recognition of uncertainties in model input and measured data that resulted in better model calibration performance for larger (primary) drainage areas as compared to smaller drainage areas, and for total nutrients as opposed to their constituent parts. The refined SWAT model was satisfactorily calibrated for both historical long-term (30-year) base, surface and total streamflow data (Nash-Sutcliff Efficiency (NSE)> 0.71 and %Error < 12.7) and monthly streamflow and total nutrient loads (primary sites NSE >0.66 and %E <14). Average daily load and concentration were more problematic but satisfactorily predicted at three out of five sites and four out of five sites respectively.

Key words: Watershed Protection Plans, TMDL, SWAT, Phosphorus, Watershed models, Calibration

INTRODUCTION

Since the 1980's managing and protecting threatened or impaired waters has involved a watershed approach. Watershed water quality is protected through a watershed planning process that takes into account all stakeholders, appropriate technology and sound science (USEPA, 2008). The role of the scientist and environmental engineer is to provide a reliable method for determining how land use practices impact water quality (Pimentel *et al.*, 1997). One way this can be done is with comprehensive watershed models validated with measured data from the watershed. If properly validated these models can be used to estimate future watershed water quality conditions based on changing land use. To properly validate such a model there has to be an ample supply of measured data for adequate calibration and verification periods (Houser *et al.*, 2010). The North Bosque River (NBR) watershed in Central Texas is a well-monitored watershed with sufficient data to validate a complex watershed model. Through careful modification, validation (calibration and verification) and application, the Soil Water Assessment Tool (SWAT) was used to predict how land use changes within the watershed could affect overall watershed water quality.

If waters within a watershed are already recognized as impaired, part of the sound science involved in watershed planning is a Total Maximum Daily Load (TMDL) assessment. In 1998 the North Bosque River (NBR) was included in the Clean Water Act (CWA) § 303(d) List and assessed as impaired under narrative water quality standards related to nutrients and aquatic plant growth. Studies indicated that soluble reactive P (or orthophosphate P (PO_4)) was statistically better correlated to algal levels than total P (Kiesling *et al.*,

*Corresponding author E-mail: houserjb@appstate.edu.

2001), and that dairy waste application fields (WAFs) and municipal wastewater treatment plants (WWTPs) were the major controllable sources of P (Hutson *et al.*, 1998; Keplinger *et al.*, 2004; McFarland & Hauck, 1999). The Texas Institute for Applied Environmental Research (TIAER) made significant technical contributions to the Texas Commission on Environmental Quality (TCEQ) effort to establish a TMDL for the NBR. In September 2000, TCEQ released a TMDL for the NBR for public review. Based on stakeholder and public input it was ascertained that additional effort would be needed to address concerns regarding: 1) lack of spatial resolution in the definition of subbasins; 2) exclusion of the 40 Public Law (PL)-566 flood retardation reservoirs in the watershed; and 3) contributions of discharges associated with dairy lagoons and wastewater storage ponds. Improved simulation of in-stream water quality kinetics was also pursued in order to simulate algae growth and nutrient dynamics that have a profound effect on average daily nutrient concentration during low flow. A dynamic manure management component was also added to the SWAT model to simulate National Resources Conservation Service (NRCS) guidelines for manure management in the TMDL load allocation scenarios.

The NBR with a drainage area over 3000 km^2 flows into Lake Waco, the source of drinking water to Waco, Texas. The NBR watershed is typical of the Grand Prairie Region of Texas with medium-sized hills carved into the limestone plateau in the upper basin. Soils range from shallow, stony clay loams, especially in areas with moderate to steep slopes, to deep, cracking clays in valley bottoms. The watershed climate may be characterized as a subtropical, subhumid area with hot summers and dry winters. Average annual precipitation is approximately 660 mm. Rainfall generally follows a bimodal pattern with peaks in the spring and fall. Hydrologically, the river is described as having intermittent flow, especially in the upper basin, with a tendency toward flash-flooding during rainfall events. Base flow is usually minimal and diminishes quickly due to a combination of relatively impermeable soils and the limestone geology of the area. Range and pasture are by far the dominant land uses in the watershed. The primary forms of agriculture are dairies and grazed beef cattle in the northern section above Hico and grazed beef cattle and cropland in the south. Stephenville, Texas is the largest community in the watershed with a population of about 15,000 (Fig. 1).

The refined SWAT model was first calibrated to historical long-term (30-year) base, surface, and total streamflow data at three sites along the NBR. The model was then validated with hydrologic and water quality data collected by TIAER at over a dozen sites within the NBR watershed during the 1990s.

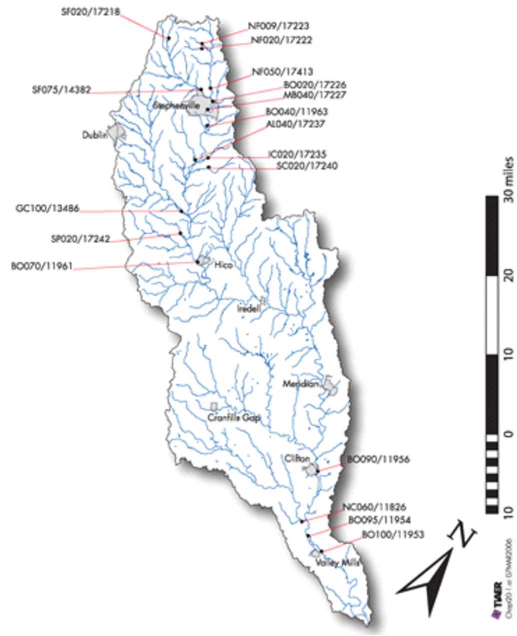

Fig. 1. TIAER flow and water quality sampling sites in the North Bosque River watershed used in model validation (TIAER ID/TCEQ ID)

MATERIALS & METHODS

SWAT (Arnold *et al.*, 1998), a watershed model, allows the user to specify multi-year management by application field. The SWAT model evaluates management effects on water quality, sediment, and agricultural chemical yield in large basins. The major components of SWAT include hydrology, weather, sedimentation, soil temperature, crop growth, nutrients, pesticides and agricultural management. SWAT divides a basin into a number of subbasins. Hydrologic, soil, and other processes are modeled within the subbasins through the use of hydrologic response units (HRUs). HRUs are lumped-parameter units based on unique combinations of soil and land use within the subbasin that have no spatial orientation within the subbasin.

Best management practices (BMPs) associated with manure application, that would be used in TMDL load allocation simulations, use STP to determine the correct amount of nutrients to be applied to a dairy WAF. Therefore, SWAT was refined to enable the manure application rate to a WAF to vary from year to year based on STP, and to move manure between subbasins as needed. The GIS land-use layer in the NBR differentiated between liquid and solid waste application fields; therefore, SWAT was made to split manure into a liquid and solid source and apply them separately. Algorithms developed in Lewis and McGechan (2002) to improve the landscape phosphorus processes within SWAT were included in the refined SWAT. Previous research had revealed that predictions from the current version of SWAT's in-stream kinetics were not matching results from proven analytical solutions, such as Streeter-Phelps equation, and proven steady-state models such as QUAL2E (Houser & Hauck, 2004). Therefore, modifications were made to the algorithms for in-stream kinetics to improve SWAT's capabilities to simulate nutrient kinetics and in-stream nutrient concentrations.

Spatial resolution of the NBR watershed was improved through a delineation process that defined additional subbasins within SWAT, particularly in the upper NBR watershed where the majority of dairy operations are located. PL-566 flood retardation reservoirs were included in the new TMDL simulation for hydrologic routing and water quality fate and transport. To allow proper hydrologic routing, relationships were determined of storage volume and spillway flows with water elevation for each reservoir. Also, historical monitored inflow and outflow data from two PL-566 reservoirs were used to estimate nutrient and suspended sediment removal efficiencies. An algorithm was developed to provide for simulation of unauthorized municipal WWTP discharges in the modeling system. TCEQ permit files were reviewed for information on unauthorized discharges. These data were gathered for use in estimating point source contributions as inputs into SWAT and to determine the occurrence of operational difficulties to provide a basis for quantifying unauthorized discharges and effluent quality outside of normal discharges. A water balance model was developed to simulate potential discharges or overflows from dairy waste storage ponds and waste treatment lagoons. Manure contributions from other sources besides dairy were incorporated into the new TMDL modeling effort. Manure from beef cattle was simulated in the model by assuming that 90 percent of range and pasture were being grazed. The SWAT grazing function was used to simulate the manure contribution based on established animal carrying capacities for range and pasture. In addition, there were 12 poultry facilities within the lower portion of the NBR watershed that used land application of turkey manure during the validation period (1993-1999).

The stream cross-section representation in the route files of SWAT were adjusted to conform with the measured cross-sectional areas at locations along the NBR. Time of travel studies were conducted on three reaches along the main stem of the NBR during low and moderate flow conditions. The combination of accurately measured cross-sectional areas with calibration of the model to time-of-travel studies permitted a highly refined simulation of the NBR stream hydrology and hydraulics, especially during periods of low flow when in-stream kinetics play a dominant role in determining nutrient concentrations. Efforts were taken to refine and improve the resolution of the precipitation input. Two data sources were used to provide precipitation data. The first source was TIAER data collected within the NBR watershed between January 1993 and December 2004. The second source was National Climatic Data Center (NCDC) data for 1960 through 2004 obtained from an on-line archive maintained by the Department of Commerce, National Oceanic and Atmospheric Administration (NOAA) and the National Environmental Satellite, Data and Information Service (NESDIS) for stations near and within the NBR watershed. Interpolation methods were used to estimate missing values at existing weather stations, fill in temporal gaps prior to the monitoring period at a station, and to estimate precipitation data for locations without a nearby gauging station to fill in gaps in spatial coverage.

To determine subbasin boundaries and slopes within subbasins, digital elevation models (DEMs) were obtained from the United States Geological Survey (USGS). The most refined elevation data available for the NBR watershed were in the form of 7.5-minute DEMs (1:24,000 scale) based on 30- by 30-meter data spacing with the Universal Transverse Mercator (UTM) projection. All files are in a UTM1927 zone 14 projection. Land use/land cover was based on Landsat Thematic Mapper imagery classification conducted by the NRCS Temple State Office for TIAER in the late 1990s. This land-use data layer was developed from a 1992 over-flight scene of Erath County and 1996 over-flight scenes of Bosque, Coryell, Erath, Hamilton, McLennan, and Somervell counties. The categories in this land use/land cover database are woodland, cropland, rangeland, improved pasture, water, and urban. TIAER constructed a GIS layer characterizing dairy WAF conditions as of May 2000 from information in dairy permits and dairy waste management plans on record with the TCEQ and supplementary, aggregated information from Texas State Soil and Water Conservation Board (TSSWCB) for non-permitted facilities. TIAER obtained soil information for the watershed from the Soil Survey Geographic (SSURGO) database maintained by the NRCS. SSURGO represents the most detailed level of soil mapping done by the NRCS and duplicates information provided in county level soil surveys. Map scales may vary by county but most represent 1:24,000.

The summarized yield goals and nutrient recommendations presented by Sweeten et al. (1991) were used extensively in dairy permits between 1990 and 1998 in determining land area needed for waste application. Total inspected dairy cow numbers associated with each SWAT subbasin were obtained from TCEQ inspection reports. Inspected cow numbers represent the total number of animals in confinement at the time of the inspection, including lactating cows, dry cows, heifers, and calves. Because specific cow numbers by animal type are not indicated in the inspection report, a consensus was reached at an advisory committee meeting that inspected numbers would be comprised of 64 percent lactating cows, 11 percent dry cows, 17.5 percent heifers, and 7.5 percent calves for the modeling effort. For inspected cow numbers, individual dairy operations were associated with SWAT subbasins to obtain dairy cow numbers by subbasin. For the model validation period, inspected values averaged for 1994-95, 1997-1999, and 1999-2000 were used. The average inspected cow number used in the modeling effort was 40,350. Dairy manure characteristics needed as input for the model include total solids (TS), nitrogen (N), and phosphorus (P) by animal type (lactating, dry, heifer, or calf). For the SWAT simulations, TIAER based dairy manure characteristics on work by Nennich et al. (2005). In order to simulate the effect of changing the P concentration in the dairy cow's diet as part of the future modeling scenarios, an equation that included the concentration of P in the diet (C_p) as a variable was used. To split the fresh manure into solid and liquid fractions, CDM (1998) and Osei et al. (1995) were reviewed. The CDM report provides an estimate of volume of solid material that would be available for collection and composting. Twenty-three percent of the total solids in fresh manure were determined to go into liquid fraction. The fresh dairy manure characteristics were then reduced by accepted losses associated with manure storage to determine characteristics of manure as would be applied to the land. Losses for TS and nutrients were based on a compilation of research reported by Osei et al. (1995) and in the Livestock Waste Facilities Handbook by MidWest Plan Service (MWPS, 1985). The nutrient losses created final nutrient values for solid and liquid applied dairy manure with N:P ratios of 3.2 and 2.9 respectively, which are similar to N:P ratios of the median for self-reported data from dairies in the NBR.

The validation process consists of model calibration and verification. During calibration model parameters are adjusted within allowable limits until model output for a given time period matches measured output within some predetermined measure of model performance. Verification refers to running the calibrated model (i.e., holding adjustment parameters constant) during a different time period and comparing model output to measured values. A long-term hydrologic calibration was performed for a 30-year period from 1965-1994 during which measured and predicted values for annual average daily streamflow were compared (there was no verification performed for the long-term hydrology). Data were assembled to assist with the long-term hydraulic validation of the model using at least 30 years of data from three USGS sites along the main stem of the NBR, located at Hico, Clifton and Valley Mills (Figure 1). Total streamflow is made up of base flow (e.g., groundwater contribution) and surface flow (direct rainfall runoff). A program extracted base and surface flow from both measured and simulated data so that the calibration entailed evaluating accuracy of predicted base and surface flow. The short-term validation period was from 1993-1999, with the calibration period being from 1993-1997 and the verification period being 1998-1999. The model was validated for streamflow, sediment, total P and its component parts (PO_4 and organic P), and total N and its component parts (nitrate, ammonia, and organic N). A shorter term of intensive water quality and flow data were available from TIAER for 17 sites that focused more closely on the model validation period of 1993-1999 (Fig. 1). These shorter term data were used to calculate daily and monthly flow values and daily and monthly concentrations and loadings of nutrient and total suspended solids for comparison with model output. In addition, to provide information to the modeling effort on algae as a sink or source of nutrients, grab samples were collected a few times each month during the period of 1993-1999 at water quality sampling locations within the NBR watershed and analyzed for chlorophyll-a (Chla). The SWAT in-stream water quality model simulated Chla, so data collected was used with the modeling effort to aid in the evaluation of in-stream kinetic calibrations.

For model validation, it was assumed that manure was applied at the N agronomic rate on all WAFs, the maximum rate allowed within TCEQ permits. Important assumptions in determining the allowable N agronomic rate as taken from NRCS (1996) were: (1) only 50 and 80 percent of the N in the solid and liquid manure, respectively, is plant-available the year of application, and (2) 20 percent of the N that is either surface-applied solid or liquid manure will be lost due to ammonia volatilization while 10 percent volatilization losses are assumed for incorporated solid manure applications. These assumptions imply that only 64 percent of the N in the liquid manure, 45 percent of the N in the incorporated solid manure, and 40 percent of the N in the surface-applied solid manure (manure is surface-applied on Coastal Bermuda grass and Coastal Bermuda grass/winter wheat rotations; the dominant cropping systems that receive manure) will be readily available to the plant. Soluble Soil P (SSP) is the SWAT simulated soil P component most similar to STP measurements collected for agronomic and regulatory purposes. SSP, as defined in SWAT, is generally less than STP. Specific TMDL load allocation scenarios will be based on STP conditions. Therefore, an algorithm relating SSP from SWAT to Mehlich3-P soil test results was developed. A start-up date was determined for the model validation by finding a start date which created an average simulated STP concentration in WAFs in the year 2001 comparable to the average measured STP from a special monitoring effort conducted in 2001 by TCEQ.

The Nash-Sutcliffe model efficiency (NSE) (Nash & Sutcliffe, 1970) and percent error (%E) of the monthly means were used as the indicators for the validation process when comparing the model output values to measured values. NSE represents how well the plot of observed versus simulated data fits the 1:1 line. A value of NSE = 1.0 indicates the pattern of model prediction perfectly matches the measured data. A negative NSE value indicates that the mean observed value is a better predictor than the simulated value, which indicates unacceptable performance (Moriasi *et al.*, 2007). A value of %E = 0 indicates the predicted total amount of flow or loads equals the measured value. The guidelines of Moriasi et al. (2007) were considered in the development of performance goals for the long-term hydrologic calibration, short-term calibration, and short-term verification of this reassessment modeling effort (Table 1). These goals represent desired, but not required, levels of performance of SWAT-TCEQ predictions during model validation. During this validation effort it was not required that the model predictions meet the goals at every monitoring site but it was recognized that a failure of the model to meet these goals at a majority of sites would constitute unacceptable model validation.

For the long-term hydrologic calibration the objective was to achieve the goal in Moriasi et al. (2007) for a "good" performance rating for streamflow (ENS > 0.65; %E ≤ ± 15 percent). For the short-term hydrologic and nutrient calibration, the guidelines of Moriasi et al. (2007) were again consulted (Table 1). A dual level of model performance was established: one level for NBR main stem sites with large drainage areas and a reduced performance level for all other secondary sites (Table 2). The goal of the calibration at the three primary sites (i.e., sites BO070, BO090, and BO100) was to have streamflow, sediment, total nutrients (total N and total P), and PO_4 achieve the "good" rating from Moriasi et al. (2007). For secondary sites and constituent parts of total nutrients besides PO_4 (i.e. organic N and P, NO_3 and NH_3) the "satisfactory" rating was the goal of acceptable model performance. This dual level of acceptable model performance was developed in recognition of uncertainties in model input and measured data that resulted in an anticipation of better model performance for larger drainage areas (primary sites) as compared to smaller drainage areas (secondary sites), and for total nutrients as opposed to their constituent parts.

Three important limitations of model input resulted in an anticipation of better model performance for large drainage areas. The first consequence anticipated, and generally observed, was that as the drainage area above a monitoring site increased, the number of producers increased, which made it more likely that the average management used for model input represented the average of management occurring in the drainage area, and the more likely that deviations from average management balanced out. In a similar manner, as the drainage area

Table 1. General performance ratings for recommended statistics from Moriasi et al. (2007)

	NSE Value	% E		
		Streamflow	Sediment	N,P
Very Good	0.75 < NSE ≤ 1.00	%E ≤ ±10	%E ≤ ±15	%E ≤ ±25
Good	0.65 < NSE ≤ 0.75	±10 ≤ %E < +15	±15 ≤ %E < +30	±25 ≤ %E < ±40
Satisfactory	0.50 < NSE ≤ 0.65	±15 ≤ %E < +25	±30 ≤ %E < +55	±40 ≤ %E < ±70
Unsatisfactory	NSE ≤ 0.50	%E ≥ ±25	%E ≥ ±55	%E ≥ ±70

Table 2. Statistical measures used in the validation process to define a rating of acceptable SWAT-TCEQ performance

Location[1]	Streamflow NSE	Streamflow %E	Sediment NSE	Sediment %E	Total Nutrients NSE	Total Nutrients %E	PO_4 NSE	PO_4 %E
Long-term calibration								
USGS Gauges	> 0.65	≥ ±15	-	-	-	-	-	-
Short-term calibration								
Primary Sites	> 0.65	< ±15	> 0.65	< ±30	> 0.65	< ±40	> 0.65	< ±40
Secondary Sites	> 0.5	< ±25	> 0.5	< ±55	> 0.5	< ±70	> 0.5	< ±70
Short-term verification								
Primary Sites	> 0.5	< ±25	> 0.5	< ±55	> 0.5	< ±70	> 0.5	< ±70
Secondary Sites	> 0.5	< ±25	> 0.5	< ±55	> 0.5	< ±70	> 0.5	< ±70

Primary sites = BO070, BO090, BO100; secondary sites = all other sites (NF009, NF020, NF050, SF020, SF075, BO040, IC020, AL040, SC020, GC100, SP020, & NC060)

above a monitoring station increased more model subbasins comprised the area above the site and it was anticipated that cumulative error in assignment of dairy cows to individual subbasins became less and "averaged out." The second consequence was that as the drainage area increased, inaccuracies of individual precipitation stations to represent rainfall for locations was also averaged out by the size of the area and the presence of several precipitation stations.

Increased accuracy was expected for model predictions of total nutrients as opposed to their constituent parts due to the fact that traditionally the SWAT model has performed better predicting total nutrients, than their constituent parts (particularly NO_3) (Saleh & Du, 2004). There are also unavoidable differences in how the model divides total nutrients into constituent parts as compared to how actual lab procedures define soluble, particulate, inorganic and organic components of total nutrients. These differences between model and laboratory separation of total nutrients into component parts create greater uncertainty with model predictions of the component parts than with the whole (or total), and an expectation of poorer model performance for these component parts (Harmel *et al.*, 2006). The validation results presented in this report emphasize total nutrients with the exception of PO_4, which is the primary nutrient for the TMDL. The same level of performance was set for PO_4 as the total nutrients (Table 2), because of its importance to the TMDL.

Ideally, model predictions at all secondary sites could achieve the performance measure goals quantified in Table 2 to indicate acceptable model performance. The reality is, however, that at sites with smaller drainage areas and particularly for the simulation of sediment and nutrients, which are strongly affected by land management, the above mentioned limitations of model input result in the potential for very large discrepancies between model predictions and measured data. Conversely, precipitation could be specifically known if there was a rain gauge in the subwatershed, which often produced accurate streamflow predictions even in the smaller subwatersheds. Nevertheless, it was the goal of the validation process to achieve predictions at as many secondary sites as possible that met the established statistical performance measures without detrimentally affecting the measures at primary main stem sites. For the short-term verification period, the statistical measures of model performance were relaxed at the primary sites to those of the secondary sites (Table 2). The reason to reduce the acceptance standards from the "good" rating to the "satisfactory" rating in Moriasi et al. (2007) is twofold. First, the verification period was restricted to being only two years in duration and during that period the watershed experienced fairly intense drought conditions. Second, Moriasi et al. (2007) and Moriasi et al. (2012) recommends stricter performance ratings for model calibration than verification, because parameter values are adjusted during the model calibration period, but not adjusted for verification. To summarize, the accuracy of SWAT model predictions increases as the size of the watershed increases, since large watersheds better represent the "average" management used in the calibration simulations. In small subbasins (microwatersheds) management and precipitation information becomes more uncertain, and any divergence from "average" management has a greater impact on model predictions compared to measured data. In addition, the accuracy of predicting total nutrients is higher than predicting the constituent parts due to the inherent compounding errors of measured data (Harmel *et al.*, 2006). Therefore, the criterion outlined in Table 2 was used to evaluate the validation performance of the model.

RESULTS & DISCUSSION

The long-term hydrologic calibration had good or very good NSE values and %E at all three simulated sites (Table 3). In addition, the division of simulated streamflow into base and surface flow accurately reflected the measured ratio of base to surface flow at all three simulated sites (Table 3).

Table 3. Measured vs. predicted yearly average daily total, base, and surface streamflow during 1965-1994

		Stream flow (m^3/s)					
Total Streamflow		Total		Base		Surface	
NSE	% E	Meas	Pred	Meas	Pred	Meas	Pred
0.76	-12.7	1.7	1.5	0.49	0.50	1.2	1.0
0.74	0.20	6.2	6.2	1.8	2.0	4.4	4.2
0.71	4.7	7.5	7.9	2.4	2.8	5.0	5.1

The calibration of monthly stream flow was good to very good at all sites except SC020 and NC060 which have satisfactory %E values but unsatisfactory NSE values. Low flows are both difficult to measure and simulate which creates compounding errors. NSE values computed with low values are strongly influenced by one or two high values. NC060 is in a large tributary watershed in the southern end of the NBR watershed where the coverage of precipitation data was not as extensive as it was in the upper NBR watershed. Sediment calibrates satisfactorily at all main stem sites including the smaller main stem watershed outlet represented by BO040, but is often not satisfactory at smaller microwatersheds with low measured total sediment (Table 4).

The total P and total N calibration was good to very good at all main stem sites including BO040 (Table 5). Microwatersheds SC020 and NC060 were unsatisfactorily calibrated due to their unsatisfactory hydrologic calibration. Some small microwatersheds had unsatisfactory calibrations. Since the TMDL in the NBR watershed is based on annual daily average PO_4 load and concentration it was important that the PO_4 calibration be at least satisfactory at the main stem sites that correspond to the TMDL index stations. The monthly average calibration of PO_4 was satisfactory to very good at all main stem sites including BO040, as well as the outlet of the two major branches of the NBR the South Fork (SF075) and the North Fork (NF050) (Table 6; Fig. 1). In addition, the calibration of average daily PO_4 concentration was satisfactory, and was very good at the lower index stations representing the larger watersheds, and model performance of average daily load was assessed as very good at all sites except NF050 where it was good (Table 7).

As is often the case in validation efforts the model did not perform as well in the verification period compared to the calibration period (Moriasi *et al.*, 2007; Moriasi *et al.*, 2012). The lower performance was exacerbated by a short time period for the verification as well as an extended dry period, resulting in a long period of very low flow. Unfortunately, the availability of measured data dictated these particular calibration and verification periods. During the verification period at the main stem sites including BO040 the NSE values were good to very good; however, at BO070 the %E was only satisfactory for predicted monthly average streamflow. At many of the microwatershed sites that exhibited very low flows, the %E was often unsatisfactory, even though the NSE values were usually good. Sediment was assessed as satisfactory to very good at the main stem sites, and was only unsatisfactory at a few smaller microwatersheds (Table 8).

The NSE values for total P and N were all satisfactory at the main stem sites, and %E was very good at the main stem sites. For total P, all the %Es were satisfactory except at SP020 (Table 9). The NSE values for PO_4 were satisfactory at BO070 and BO090 but not satisfactory at BO100, and only at BO070 was the %E satisfactory. %E for PO_4 was satisfactory, except at the smaller watershed main stem sites in the upper NBR (BO020 and BO040) where the majority of dairies are located. At site BO100 the compounding errors of inaccurate streamflow prediction and low flows led to an unsatisfactory NSE value and an over prediction of PO_4 due to inaccurately high streamflow simulated between August 1998 and January 1999 (Table 10).

The NSE values for total P and N were all satisfactory at the main stem sites, and %E was very

Table 4. Monthly average streamflow and total sediment during calibration period (1993-1997): ENS, %E, performance measure (pm) (A – acceptable, U – unacceptable based on Table 2), measured and predicted value

	Streamflow						Sediment					
Site	NSE	pm	%E	pm	Meas (m^3/s)	Pred (m^3/s)	NSE	pm	%E	pm	Meas (tons)	Pred (tons)
NF009	0.76	A	-3	A	0.024	0.024	0.03	U	-71	U	94	27
NF020	0.72	A	-13	A	0.038	0.033	0.34	U	-36	A	105	68
NF050	0.80	A	4	A	0.27	0.29	0.41	U	-37	A	445	280
SF020	0.63	A	-12	A	0.035	0.031	0.03	U	-82	U	30	5
SF075	0.59	A	11	A	0.29	0.32	0.15	U	-50	A	254	127
BO040	0.85	A	-5	A	0.97	0.93	0.67	A	-13	A	825	715
IC020	0.64	A	10	A	0.055	0.061	0.35	U	-54	A	81	37
AL040	0.67	A	-19	A	0.15	0.13	-0.28	U	-36	A	25	16
SC020	0.30	U	-29	U	0.11	0.077	0.57	A	-40	A	43	26
GC100	0.73	A	-19	A	1.21	0.98	0.84	A	-24	A	868	661
SP020	0.72	A	-6	A	0.087	0.082	-0.02	U	88	U	24	45
BO070	0.86	**A**	-9	**A**	3.45	3.16	0.88	**A**	8	**A**	3,917	4,237
BO090	0.70	**A**	-3	**A**	10.7	10.4	0.56	**U**	-2	**A**	21,480	21,075
NC060	0.36	U	-20	A	2.94	2.34	0.54	A	54	A	3,658	5,622
BO100	0.66	**A**	-12	**A**	14.43	12.68	0.74	**A**	2	**A**	30,724	31,227

Table 5. Monthly average total P and total N during calibration period (1993-1997): ENS, %E, performance measure (pm) (A – acceptable, U – unacceptable based on Table 2), measured and predicted value

	Total P						Total N					
Site	NSE	pm	%E	pm	Meas (kgs)	Pred (kgs)	NSE	pm	%E	pm	Meas (kgs)	Pred (kgs)
NF009	0.69	A	-37	A	59	37	0.58	A	-47	A	237	126
NF020	0.25	U	-30	A	258	182	0.25	U	-19	A	693	563
NF050	0.60	A	-32	A	642	439	0.14	U	-15	A	2,395	2,034
SF020	0.58	A	-36	A	20	13	0.54	A	-4	A	131	126
SF075	0.51	A	9	A	585	637	0.54	A	1	A	2,443	2,464
BO040	0.73	A	-22	A	2,677	2,091	0.62	A	-36	A	11,515	7,385
IC020	0.76	A	-22	A	165	128	0.13	U	-16	A	686	576
AL040	0.16	U	-76	U	239	58	0.53	A	-39	A	812	493
SC020	-9.2	U	205	U	88	269	-5.9	U	151	U	439	1,104
GC100	0.47	U	51	A	1,226	1,858	0.68	A	-3	A	8,171	7,902
SP020	0.76	A	11	A	42	46	0.69	A	36	A	244	332
BO070	0.71	**A**	-7	**A**	5,241	4,891	0.78	**A**	-7	**A**	22,822	21,212
BO090	0.66	**A**	12	**A**	12,999	14,591	0.67	**A**	12	**A**	64,217	72,242
NC060	0.36	U	64	A	1,793	2,939	0.02	U	-48	A	10,931	5,643
BO100	0.70	**A**	8	**A**	21,431	23,133	0.72	**A**	14	**A**	107,389	122,701

good at the main stem sites. For total P, all the %Es were satisfactory except at SP020 (Table 9). The NSE values for PO_4 were satisfactory at BO070 and BO090 but not satisfactory at BO100, and only at BO070 was the %E satisfactory. %E for PO_4 was satisfactory, except at the smaller watershed main stem sites in the upper NBR (BO020 and BO040) where the majority of dairies are located. At site BO100 the compounding errors of inaccurate streamflow prediction and low flows led to an unsatisfactory NSE value and an over prediction of PO_4 due to inaccurately high streamflow simulated between August 1998 and January 1999 (Table 10). Prediction of PO_4 average daily concentration was satisfactory during the verification period except at B0100 where it was unsatisfactorily over predicted. Average PO_4 daily loads were unsatisfactorily over predicted at BO090 and BO100 reflecting problems that appeared in monthly total load predictions (Table 11).

Table 6. Monthly average PO_4 load during calibration period (1993-1997): ENS, %E, performance measure (pm) (A – acceptable, U – unacceptable based on Table 2), measured and predicted values. Table 3-11Monthly average PO_4 load during calibration period (1993-1997)

Site	PO_4 NSE	pm	%E	pm	Meas (kgs)	Pred (kgs)
NF009	0.57	A	-27	A	25	18
NF020	0.27	U	-55	A	148	67
NF050	0.64	A	-13	A	308	268
SF020	0.15	U	-14	A	4	3
SF075	0.62	A	10	A	296	326
BO040	0.67	A	-18	A	1,648	1,359
IC020	0.70	A	-22	A	81	64
AL040	0.10	U	-81	U	151	29
SC020	-6.4	U	237	U	42	143
GC100	0.60	A	57	A	494	775
SP020	0.69	A	13	A	18	20
BO070	0.77	**A**	6	**A**	2,164	2,293
BO090	0.73	**A**	17	**A**	3,663	4,297
NC060	0.26	U	-31	A	383	265
BO100	0.66	**A**	3	**A**	5,815	5,998

Table 7. Average daily PO_4 concentration and load during calibration period (1993-1997): measured and predicted values, %E, performance measure (pm) (A – acceptable, U – unacceptable based on Table 2)Table 3-12Average daily PO_4 concentration and load during calibration period (1993-1997)

Site	PO_4 (mg/l) Meas	PO_4 (mg/l) Pred	%E	pm	PO_4 (kgs) Meas	PO_4 (kgs) Pred	%E	pm
NF050	0.335	0.168	-50	A	12.7	8.6	-32	A
SF075	0.247	0.272	10	A	10.1	11.6	14	A
BO040	1.17	0.767	-35	A	55.5	45.4	-18	A
BO070	0.214	0.225	5	A	79.0	80.6	2	A
BO090	0.046	0.051	11	A	134.2	158.9	18	A
BO100	0.044	0.052	18	A	167.5	172.6	3	A

Table 8. Monthly average streamflow and total sediment during verification period (1998-1999)Table 3-14 Monthly average streamflow and total sediment during verification period (1998-1999), ENS, %E, performance measure (pm) (A – acceptable, U – unacceptable based on Table 2), measured and predicted value

Site	Streamflow NSE	pm	%E	pm	Meas (m^3/s)	Pred (m^3/s)	Sediment NSE	pm	%E	pm	Meas (tons)	Pred (tons)
NF009	0.11	U	-66	U	0.020	0.0068	-13.70	U	176	U	4	11
NF020	0.71	A	-44	U	0.018	0.0097	-0.55	U	62	U	17	27
SF020	0.95	A	32	U	0.0092	0.012	0.63	A	-49	A	4	2
BO020	0.77	A	-19	A	0.27	0.21	0.45	U	-48	A	416	218
BO040	0.78	A	-26	U	0.46	0.34	0.83	A	-24	A	295	226
GC100	0.80	A	-5	A	0.36	0.34	0.91	A	-26	A	281	208
SP020	0.64	A	-30	U	0.076	0.053	-6.53	U	1888	U	3	57
BO070	0.89	**A**	16	**A**	1.11	1.29	0.83	**A**	-17	**A**	1,902	1,586
BO090	0.75	**A**	6	**A**	4.76	5.04	0.76	**A**	-13	**A**	11,122	9,664
NC060	0.08	U	30	U	1.06	1.38	0.25	U	157	U	1,093	2,814
BO100	0.70	**A**	12	**A**	6.06	6.77	0.53	**A**	-43	**A**	19,349	11,091

Table 9. Monthly average total P and total N during verification period (1998-1999), ENS, %E, performance measure (pm) (A – acceptable, U – unacceptable based on Table 2), measured and predicted valueTable 3-15 Monthly average total P and total N during verification period (1998-1999)

Site	Total P						Total N					
	NSE	pm	%E	pm	Meas (kgs)	Pred (kgs)	NSE	pm	%E	pm	Meas (kgs)	Pred (kgs)
NF009	-2.7	U	-27	A	17	12	-1.0	U	-56	A	93	41
NF020	0.50	U	-66	A	101	34	0.62	A	-59	A	263	108
SF020	0.86	A	24	A	4	5	-0.1	U	94	U	28	54
BO020	0.42	U	-57	A	779	332	0.11	U	-68	A	3,014	973
BO040	0.56	A	-42	A	1,590	925	0.66	A	-31	A	4,957	3,412
GC100	0.45	U	19	A	518	616	0.65	A	21	A	2,633	3,194
SP020	-1.4	U	97	U	18	35	-0.4	U	205	U	98	299
BO070	0.53	**A**	2	**A**	2,116	2,152	0.59	**A**	-15	**A**	12,558	10,691
BO090	0.72	**A**	-9	**A**	8,293	7,538	0.71	**A**	-2	**A**	40,751	39,931
NC060	0.31	U	-54	A	3,487	1,606	-0.1	U	150	U	4,517	11,309
BO100	0.75	**A**	-1	**A**	9,225	9,175	0.74	**A**	10	**A**	47,690	52,341

Table 10. Monthly average PO_4 load for verification period (1998-1999), ENS, %E, performance measure (pm) (A – acceptable, U – unacceptable based on Table 2), measured and predicted loadsTable 3-16Monthly average PO_4 load for verification period (1998-1999)65

Site	PO_4					
	NSE	pm	%E	pm	Meas (kgs)	Pr
NF009	-2.1	U	-17	A	7	
NF020	0.35	U	-76	U	62	
SF020	0.87	A	42	A	1	
BO020	0.75	A	-28	A	236	
BO040	0.40	U	-37	A	1,005	
GC100	0.59	A	-4	A	255	
SP020	-2.3	U	189	U	5	
BO070	0.61	**A**	43	**A**	650	
BO090	0.51	**A**	104	**U**	923	
NC060	-4.2	U	248	U	45	
BO100	0.34	**U**	118	**U**	946	

Table 11. Average daily PO_4 concentration and load during verification period (1998-1999), %E, performance measure (pm) (A – acceptable, U – unacceptable based on Table 2)Table 3-17 Average daily PO_4 concentration and load during verification period (1998-1999)65

Site	PO_4 (mg/l)		%E	pm	PO_4 (kgs)		%E	pm
	Meas	Pred			Meas	Pred		
BO020	0.200	0.140	-30	A	11.6	5.8	-50	A
BO040	1.618	1.231	-24	A	33.3	20.9	-37	A
BO070	0.230	0.155	-32	A	22.6	30.5	35	A
BO090	0.019	0.028	49	A	30.1	61.8	105	U
BO100	0.019	0.036	87	U	30.9	67.0	117	U

CONCLUSIONS

The refinements to the SWAT modeling effort based on public concerns regarding: 1) lack of spatial resolution in the definition of subbasins; 2) exclusion of the 40 PL-566 flood retardation reservoirs in the watershed; 3) contributions of discharges associated with dairy lagoons and wastewater storage ponds, were all successfully incorporated into the refined SWAT model. In addition, improved simulation of in-stream water quality kinetics was realized, and a dynamic fertilizer management component was added to the refined SWAT model. The refined SWAT model was satisfactorily calibrated for long-term annual average daily streamflow, and exhibited a correct ratio of base to surface flow compared to measured data. Based on measures of model performance from Moriasi et al. (2007), the refined SWAT model was satisfactorily calibrated for streamflow, sediment, and total nutrients, as well as PO_4, especially at the main stem sites on the NBR that correspond to index stations which will be used in the TMDL allocation scenarios. The refined SWAT model also calibrated well to average daily load and concentrations at sites which correspond to the index stations for the TMDL allocation scenarios, which is significant because the TMDL is based on annual average daily concentrations and load. The model also performed satisfactorily for streamflow, sediment and total nutrients at main stem sites during the verification period; however, at some sites unsatisfactory performance for PO_4 occurred during that period. The unsatisfactory performance for PO_4 at some main stem sites during the verification period was due in part to the occurrence of very low flows during a significant portion of the verification period. However, the calibration was good to very good at all main stem sites including BO040, as well as the outlet of the two major branches of the NBR the South Fork (SF075) and the North Fork (NF050) located in the northern section of the upper NBR watershed above BO040 where a majority of the dairies are located. Furthermore, the verification was mostly satisfactory during a period of extended low-flow. It was concluded that the refined SWAT model was validated for the NBR watershed and appropriate for applications to refine TMDL allocations from the previous TMDL, and estimate the impact of landuse scenarios on future water quality.

ACKNOWLEDGEMENTS

Texas Institute for Applied Environmental Research, Tarleton State University, Stephenville, Texas.Texas Commission on Environmental Quality (TCEQ), 12100 Park 35 Circle, Austin, Texas.

REFERENCES

Arnold, J.G., Srinivasan, R., Muttiah, R.S., and Williams J.R. (1998). Large area hydrologic modeling and assessment. Part 1: Model development. Journal of the American Water Resources Association, **34(1),** 73-89.

CDM; Camp, Dresser & McKee. (1998). Brazos River Authority: Erath County Animal Waste Management Study. Camp Dresser & McKee Inc., Austin, Texas.

Harmel, R.D., Cooper, R.J., Slade, R.M., Haney, R.L., and Arnold, J.G. (2006). Cumulative Uncertainty in Measured Streamflow and Water Quality Data for Small Watersheds. Transactions of the ASABE **49(3),** 689-701.

Houser, J. B., and Hauck, L. M. (2004). Evaluating Performance of Environmental Models: Comparison of Three In-stream Water Quality Models (SWAT, QUAL2E, and HSPF). TIAER Report # TR0407. Stephenville, TX: Texas Institute for Applied Environmental Research, Tarleton State University.

Houser, J. B., Hauck, L.M., and Koenig, L. (2010). Refinement, Validation and Implementation of SWAT Model Central Texas TMDL. Proceedings of the 21st Century Watershed Technology: Improving Water Quality and Environment Conference, Universidad EARTH, Costa Rica, 21-24 February 2010. Sponsored by the American Association of Agricultural and Biological Engineers.

Keplinger, K.O., Houser, J. B., Hauck, L. M., Tanter, A. and Beran, L. (2004). Cost and Affordability of Phosphorus Removal at Small Wastewater Treatment Plants. Small Flows Quarterly, 5(4).

Kiesling, R., McFarland, A., and Hauck, L.M. (2001). Nutrient Targets for Lake Waco and the North Bosque River: Developing Ecosystem Restoration Criteria. TIAER Report # TR0107. Stephenville, TX: TIAER, TSU.

Lewis, D.R., and McGechan, M.B. (2002). Review of field scale phosphorus dynamics models. Biosystem Engineering, **82,** 359–380.

McFarland, A., and Hauck, L. (1999). Relating agricultural land uses to in-stream stormwater quality. Journal of Environmental Quality, **28,** 836-844.

Moriasi, D.N., Arnold, J.G., Van Liew, M.W., Bingner, R.L., Harmel, R.D., and Veith, T.L. (2007). Model evaluation guidelines for systematic quantification of accuracy in watershed simulations. Transactions of the ASABE, **50(3),** 885-900.

Moriasi, D.N., Wilson, B.N., Douglas-Mankin, K.R., Arnold, J.G., Gowda, P. (2012). Hydrologic and water quality models: Use, calibration, and validation. Transactions of the ASABE, **55(4),** 1-7.

MWPS, MidWest Plan Service. (1985). Livestock Waste Facilities Handbook (Second Edition). MWPS, Iowa State University, Ames, Iowa (MWPS-18).

Nash, J.E., and Sutcliff, J.E. (1970). River flow forecasting through conceptual models: Part 1. A discussion of principles. Journal of Hydrology, **10(3),** 262-272.

Nennich, T.D., Harrison, J.H., VanWieringen, L.M., Meyer, D., Heirichs, A.J., Weiss, W.P., St-Pierre, N.R., Kincaid, R.L., Davidson, D.L., and Block, E. (2005). Prediction of manure and nutrient excretion from dairy cows. Journal of Dairy Science, **88,** 3721-3733.

Osei, Edward, Lakshminarayan, P.G., Neibergs, S., Bouzaher, A., and Johnson, S.R. (1995). Livestock and the Environment: A National Pilot Project – The Policy Space, Economic Model, and Environmental Model Linkages. Livestock Series Report 4. Center for Agriculture and Rural Development (CARD), Iowa State University, Ames, Ia. (Staff Report 95).

Pimentel, D., Houser, J.B., Preiss, E., White, O., Fang, H., Mesnick, L., Barsky, T., Tariche, S., Schreck, J., and Alpert, S. (1997). Water Resources: Agriculture, the Environment, and Society. Bioscience, **47(2),** 97-106.

Hutson, J. L., Pitt, R. E., Koelsch, R. K., Houser, J. B., and Wagenet, R. J. (1998). Improving Dairy Farm Sustainability II: Environmental Losses and Nutrient Flows. Journal of Production Agriculture, **11(2),** 233-239.

NRCS, Natural Resources Conservation Service. (1996). National Engineering Handbook: Part 651, Agricultural Waste Management Field Handbook. United States Department of Agriculture, Washington, D.C. (revised).

Saleh, A., and Du, B. (2004). Evaluation of SWAT and HSPF within BASINS program for the Upper North Bosque River watershed in central Texas. Transactions of the ASAE, **47(4),** 1039-1049.

Sweeten, J.M., McFarland, M., Harris, B.L., Westmoreland, G., Baird, C., and Manning, L. (1991). Animal Waste Management. Texas Agricultural Extension Service, College Station, Texas, and Texas State Soil and Water Conservation Board, Temple, Texas. (L-5044).

USEPA, United States Environmental Protection Agency, Office of Water, Nonpoint Source Control Branch. (2008). Handbook for Developing Watershed Plans to Restore and Protect our Waters. EPA 841-B-08-002. Wash., D.C. GPO.