Buffalo River Watershed SWAT Modeling

Final Report

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Houston
Engineering Inc.

BUFFALO - RED RIVER
WATERSHED DISTRICT

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1. Summary

Watershed models were developed for the Buffalo River Watershed (BRW) for the purposes of simulating and evaluating hydrology and water quality (sediment, nutrients, and bacteria). The Soil and Water Assessment Tool (SWAT) 2009 model was used to develop separate models for the South Branch and Upper Mainstem of the Buffalo River (**Figure 1**). The models were developed to simulate conditions from 1995 through 2009; models were calibrated to data from 2001-2006 and validated with data from 1996-2000.

Key inputs to the SWAT models include: weather (i.e., precipitation, solar radiation, temperature, relative humidity, and wind speed) data, topography, soils data, and land cover, as well as land management information representative of typical practices in the region. In addition to the SWAT models, an HSPF (Hydrological Simulation Program – FORTRAN) model is also being developed for the BRW. A key goal in developing these models (both SWAT and HSPF) was to ensure consistency in model setup and data sources used, to allow for eventual comparison of the two models for use in water quality planning and management in the BRW and Red River Valley, in general. Local information sources, such as watershed delineations based on LiDAR (light detection and ranging) data and design details of impoundments, were used whenever possible.

The models performed well for hydrology for both simulated watersheds. For the Upper Mainstem and South Branch Models, respectively, mean daily flow values were within -3.7 and -31.5% of the observed mean values for the calibration period and within -6.0 and 3.4% of the observed mean values for the validation period. Additional model validation was performed for a downstream gauging station (near the watershed outlet) and predicted mean daily flow values were within -12.9% of observed data for the simulation period (1996-2006).

Because observed water quality data did not coincide with concomitant flow records, modeled flow values were used in conjunction with water quality monitoring data to generate pseudo-observed loads of sediment and phosphorus against which to compare model predictions. The SWAT models did a good to excellent job predicting sediment and total phosphorus loads at most monitoring points. A notable exception is model under-prediction of sediment at a monitoring point located near the watershed outlet. In contrast to generally good agreement at upland monitoring locations, under-prediction of sediment near the watershed outlet suggests that other sources of suspended solids such as re-worked channel sediments or in-stream primary productivity may be important in downstream reaches of the Buffalo River. Fecal coliform concentrations simulated with the SWAT models did not compare well against observed data and attempts to simulate bacteria in the BRW are considered unsuccessful.

2. Model Development

The SWAT model setup for the BRW was divided into two separate models (South Branch and Upper Mainstem) in order to simplify model development and reduce the time required to run the simulations (**Figure 1**). Outputs from the Upper Mainstem model were fed into the South Branch model as a point source, linking the two domains to simulate hydrology and water quality across the entire BRW.

The basic operational unit in the SWAT model is a polygon comprised of a unique combination of land use, slope, and soil type; these polygons are referred to as hydrologic response units, or HRUs. Depending on the size of the watershed, the complexity of the input data, and the goals of the model developer, a watershed can have from one up to several thousand HRUs. The main limitation with larger numbers of HRUs is the available detail/quality of input data and the time required for model simulations. More details on HRU development and key aspects of model parameterization and calibration values are provide below, along with a description of the setup of the two BRW SWAT models.

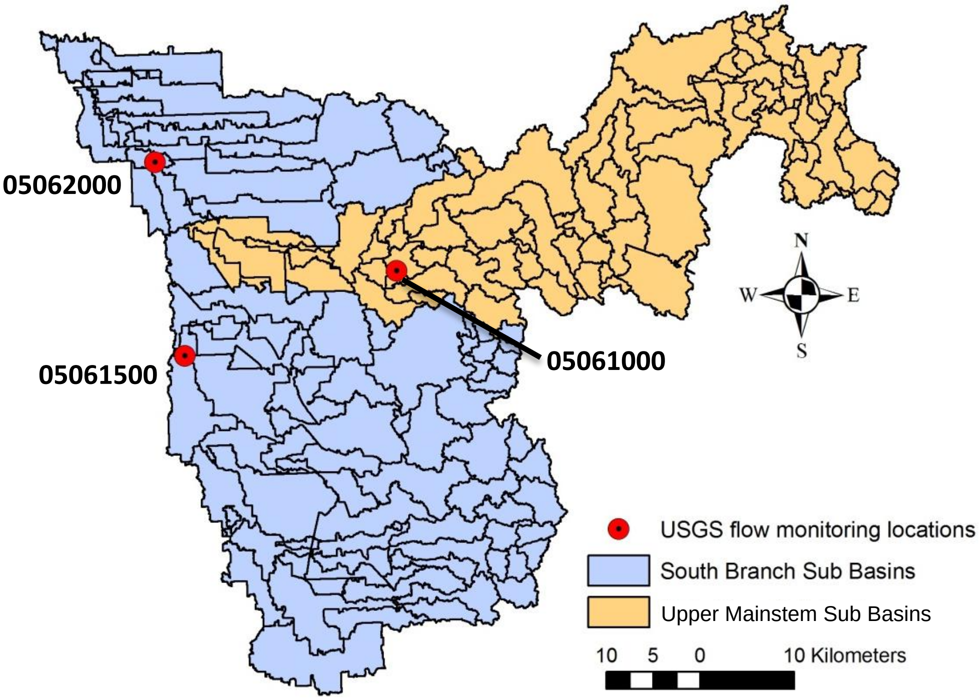


Figure 1. Buffalo River Watershed, highlighting the subbasins of the two SWAT models and the location of flow monitoring sites (numbers correspond to USGS site numbers).

2.1.Weather Data

The primary source of weather data for the BRW SWAT models were those data used in developing the HSPF model for the watershed. Given the importance of weather data in the performance of watershed models, matching these inputs between the SWAT and HSPF models was particularly important so modeling results can, eventually, be compared. Daily precipitation data was put into the SWAT model at thirteen state and federal weather stations, shown in **Figure 2**. These data covered the modeled time period through 2006 (since the HSPF model only extends this far). Non-precipitation weather data through 2006 were input at NOAA sites ND322859 and MN727457. More information on the weather data used in the BRW SWAT and HSPF models (through 2006) is available in a June 27, 2011 memorandum on the development of the HSPF model (HEI, 2011a).

To extend the SWAT model through 2009, additional weather data were appended to those data from the HSPF model. Precipitation and temperature records at the various stations were extended using data downloaded through a tool maintained by the Minnesota Climatology Working Group (http://climate.umn.edu/hidradius/radius.asp). Data was retrieved using the latitude/longitude of the stations shown in **Figure 2**; for days with missing data, the tool was allowed to substitute values from the nearest available station. Wind speed and relative humidity data were downloaded from the National Climate Data Center (http://www.ncdc.noaa.gov/cdo-web/search) for stations ND322859 and MN727457. Solar radiation data was filled by inputting no data values (-999) into the SWAT model and allowing the Weather Generator to substitute values.

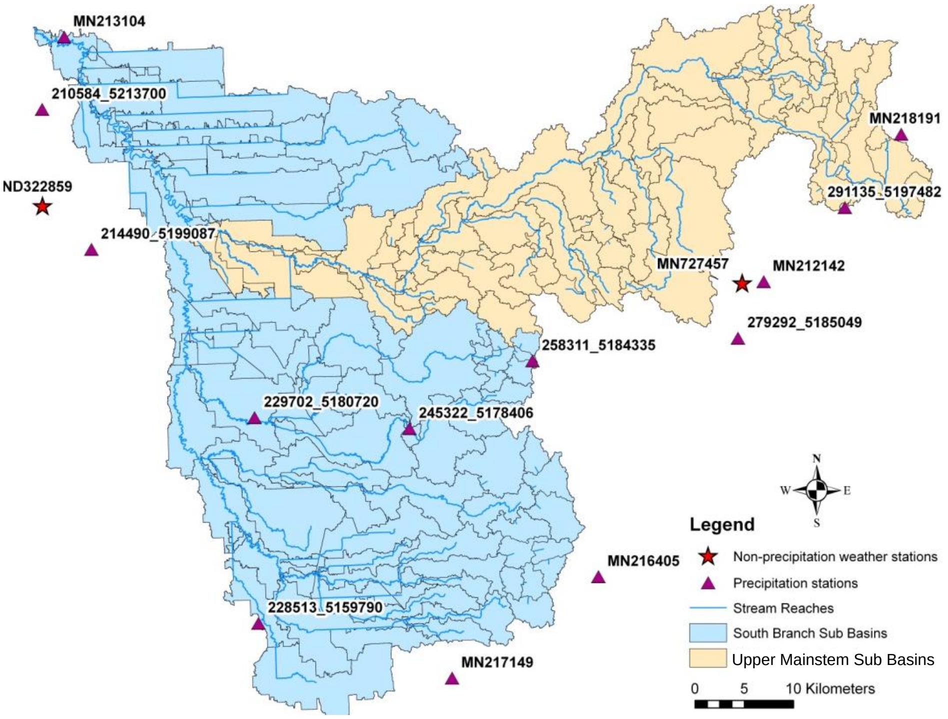


Figure 2. Weather stations used in the BRW SWAT models.

2.2.Land Cover

Land cover data for the BRW were derived from the 2006 National Land Cover Dataset (available from the United States Geological Survey (USGS) seamless data warehouse: http://seamless.usgs.gov/). In many cases, a land cover class represented a very small proportion of the total watershed area (usually 1% or less). In order to simplify the modeling process and reduce the overall number of HRUs, minor land cover classes were reclassified into the major classes. **Table 1** summarizes these changes, which reduced the number of land cover classes in the BRW from fifteen to six. **Figure 3** shows the newly classified data for the BRW.

Table 1. Original and modified land cover classifications used as input for SWAT model development.

Original Land Cover Dataset

Land Use Land Cover (LULC)	%	Reclassified As
Open Water	3.9%	no change
Developed, Open Space	4.0%	no change
Developed, Low Intensity	0.7%	Developed, Open Space
Developed, Medium Intensity	0.1%	Developed, Open Space
Developed, High Intensity	0.0%	Developed, Open Space
Barren Land (Rock/Sand/Clay)	0.0%	Developed, Open Space
Deciduous Forest	9.0%	no change
Evergreen Forest	0.5%	Deciduous Forest
Mixed Forest	0.0%	Deciduous Forest
Shrub/Scrub	0.1%	Pasture/Hay
Grassland/Herbaceous	2.2%	Pasture/Hay
Pasture/Hay	6.9%	no change
Cultivated Crops	65.7%	no change
Woody Wetlands	1.1%	Emergent Herbaceous Wetlands
Emergent Herbaceous Wetlands	5.7%	no change

Final Land Cover Dataset

Land Use Land Cover (LULC)	%
Open Water	3.9%
Developed, Open Space	4.9%
Deciduous Forest	9.5%
Pasture/Hay	9.2%
Cultivated Crops	65.7%
Emergent Herbaceous Wetlands	6.8%

2.3. Soils

Soils data were derived from county-level soil survey map units (SSURGO) downloaded from the web soil survey (http://websoilsurvey.nrcs.usda.gov/app/HomePage.htm). In some cases, digital map units did not have a corresponding record in the SWAT2009 database (the usersoil table for Minnesota provided by the SWAT development team). In these instances, the missing map unit was re-named as a nearby map unit with similar texture and drainage classes.

2.4. Overland Slope

Overland slopes within the BRW were determined from a 10m digital elevation model obtained from the national seamless data server (http://seamless.usgs.gov/). Three different slope classes were chosen to reflect different topographic regions in the watershed and used for HRU delineation:

- 0-3%
- 3-6%
- >6%

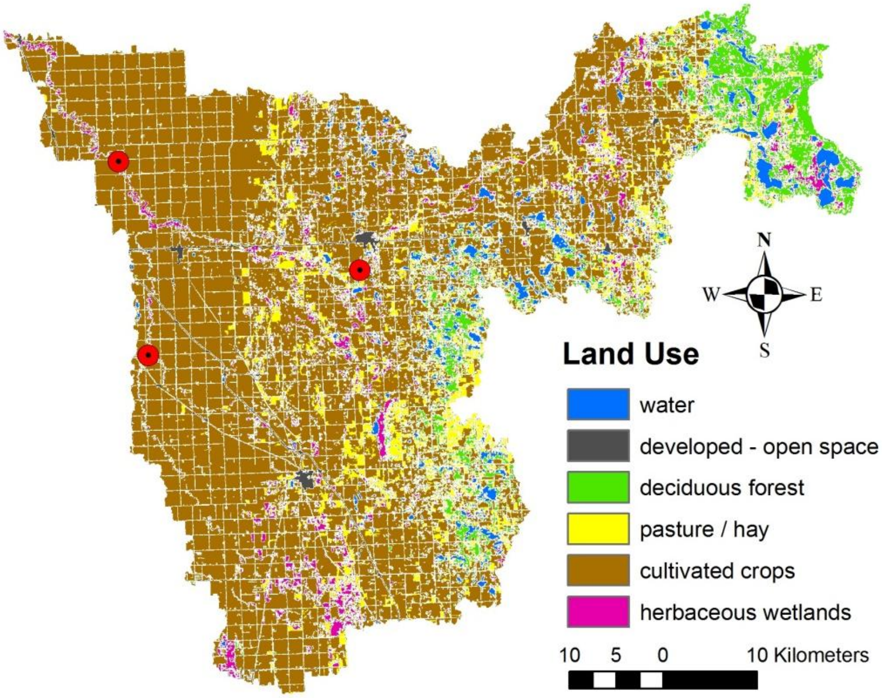


Figure 3. Land cover map developed from the 2006 NLCD and used for SWAT model development.

2.5. Hydrologic Response Units

Hydrologic Response Units (HRUs) were formed by overlaying spatial layers of land use, soils, and slope. Spatial data (land use, SSURGO map units, slope classes) that comprised less than 5% of a subbasin were excluded from final HRU delineation. This resulted in 1193 and 948 HRUs in the Upper Mainstem and South Branch models, respectively.

2.6. Crop Management

The SWAT model is well-suited for simulating agricultural management practices and contains extensive input databases which allow for the creation of multiple different management schemes. This feature allows flexibility for initial model setup as well as generation and simulation of alternative management scenarios. Based on local stakeholder inputs, it was determined that typical management of row-crop lands in the BRW is a Corn-Wheat-Soybean 3-year rotation. Crop planting dates, tillage practices, and fertilizer application rates were based on local stakeholder input combined with data from Minnesota weekly crop reports and surveys of common agricultural practices in other Minnesota agricultural landscapes. It’s important to note that these rotations are not intended to be inclusive of all management practices in the BRW; rather, they reflect the most typical management scenario during the time period contained in the model and allow management inputs to be streamlined for model efficiency. More information on crop management practices simulated within the BRW is contained in **Appendix A**. In order to distribute each crop more evenly through time, three separate management files were developed:

- Corn-Wheat-Soybean
- Wheat-Soybean-Corn
- Soybean-Corn-Wheat

These management rotations were staggered amongst the model subbasins such that, in any given year, roughly 1/3 of the watershed was in each crop. This helped to dampen the effects of differences between any given crop and weather events in a given year. Generally, the tillage practices simulated in the model were fall chisel plow and spring field cultivator. In response to stakeholder input, half of the subbasins in the watershed did not receive fall tillage following soybeans. Spring fertilizer (at the time of planting) was applied for the corn and wheat phases of the rotation. Corn received nitrogen (as N) and phosphorus (as P) at rates of 141 and 25.5 kg/ha, respectively, while wheat received nitrogen (as N) at a rate of 67 kg/ha. Fertilizer application rates were based on typical practices for various Minnesota locations summarized in the MN Department of Agriculture FANMAP Surveys (Farm Nutrient Management Assessment Program; http://www.mda.state.mn.us/protecting/soilprotection/fanmap.aspx). Manure application rates were based on the estimated production of animal units reported for the BRW and summarized in a January 2013 memorandum (included as **Appendix B**). Nutrient content of various forms of manure was assumed to match that of manure records in the SWAT database. Manure application rates were set to roughly twice the agronomic rate for N described above to reflect stakeholder input that manure is applied to approximately 10% of the cropland in the watershed and is primarily managed as a method of manure disposal and not, necessarily, based on the crops' needs. Manure was assumed to be applied two times annually: in the spring at the time of planting and in the fall following crop harvest. Manure application was simulated to occur over a two-week period in order to reflect the fact that not all farmers in the watershed apply manure on the same day. Specific details about manure application rates, timing, and location are contained in **Appendix A**.

2.7. Point Sources

Point sources were accounted for in the SWAT models as summarized below (**Table 2**). Each point sources' discharged daily flow data were combined with monthly average concentration data (both obtained from the facilities' Discharge Monitoring Reports, provided by MPCA) to generate daily point source input files for: flow, total suspended solids, total phosphorus, and fecal coliforms. Daily modeled output from the Upper Mainstem SWAT model was input into subbasin 17 of the South Branch model as a point source file.

Table 2. Summary of SWAT model subbasins with water quality point sources.

Watershed	Subbasin	Description
South Branch	64	Barnesville WWTF
South Branch	21	Hitterdahl WWTF
South Branch	17	Output from Upper Mainstem Model
Upper Mainstem	47	Callaway WWTF
Upper Mainstem	41	Audubon WWTF
Upper Mainstem	31	Lake Park WWTF
Upper Mainstem	13	Hawley WWTF
Upper Mainstem	3	Glyndon WWTF

WWTF = wastewater treatment facility

2.8. Reservoirs

Reservoirs were placed in the following locations in both models and parameterized based on design data from engineering reports and synthesized by Houston Engineering, Inc. (HEI) (**Table 3**). Reservoir area and volume were determined from available data. For lakes, emergency surface area and volume were estimated to be 1.5 times the principle area and volume; principal areas and volumes were estimated based on the best available data in the watershed, as summarized in Appendix A of a 2011 report on the lakes of the BRW (HEI, 2011b).

Table 3. Summary of reservoirs simulated in the SWAT models and key model parameters.

SWAT Model	Subbasin	Reservoir/Lake	Surface Area (ha) [RES_PSA]	Volume (10^4 m^3) [RES_PVOL]	Emergency Surface Area (ha) [RES_ESA]	Emergency Volume (10^4 m^3) [RES_EVOL]
South Branch	45	Hay Creek	5.6	10	28	78
South Branch	58	Stony Creek	58	100	567	627
South Branch	42	Spring Creek	2	10	28	78
South Branch	63	Whiskey Creek	63	10	107	58
Upper Mainstem	31	Stinking Lake	263	469	319	740
Upper Mainstem	62	Big Sugar Bush Lake	184	1163	276	1,745
Upper Mainstem	33	Forget-me-Not-Lake	91	111	137	167
Upper Mainstem	81	Tamarack Lake (S.)	223	284	334	426
Upper Mainstem	79	Tamarack Lake (N.)	590	1570	884	2,356
Upper Mainstem	73	Rice Lake	91	324	137	486
Upper Mainstem	74	Rock Lake	486	1365	728	2,047
Upper Mainstem	68	Buffalo Lake	164	245	246	368

2.9. Non-contributing Subbasins

The BRW contains some areas that are not connected via surface water to the main river network under normal hydrologic conditions (i.e., non-extreme events). These closed basins are mainly in the upper portion of the watershed and typically drain into lakes. In order to represent these areas in the SWAT model, subbasins that are considered to be internally drained were simulated with a pond receiving surface runoff from the rest of the subbasin. The saturated hydraulic conductivity of the bottom of each pond was set to a high value such that water would infiltrate and ponds will not fill to reach their principal spillway. Pond calibration parameters are included below.

3. Model Calibration / Validation

SWAT is a long-term simulation model and, as such, its performance is best judged by comparing the model's ability to match monthly values of observed flow (i.e., monthly discharge volumes) and water quality parameters (in this case, total monthly loads of sediment and phosphorus and geometric means of bacteria concentrations). Comparisons can also be made to assess the model's ability to simulate hydrology and water quality on a daily time step; model performance, however, should be judged over a longer time period (Neitsch, S.L, et al., 2011). This is the approach that was used here.

In addition to comparing mean simulated and observed values for the calibration and validation periods, model performance was also evaluated using the Nash-Sutcliffe Efficiency metric (NSE; (Nash and Sutcliffe, 1970):

$$E = 1 - \frac{Y_o - Y_m\ ^2}{Y_o - Y_o\ ^2}$$

Where Y_o is the observed monthly value (discharge or load), Y_m is the modeled value of the same parameter, and Y_o is the mean value of the observed data. NSE values can range from -∞ to 1. Perfect agreement between predicted and observed data results in NSE = 1; an NSE value of 0 indicates that the mean of the observed data is as accurate as the model predictions. For watershed scale modeling, NSE values of 0.36 to 0.50 are generally considered fair, values from 0.50 to 0.75 are considered good, while values greater than 0.75 indicate excellent model performance (Moriasi, et al., 2009; Motovilov et al., 1999).

3.1. Hydrology

Primary model hydrology calibration and validation was performed for the Upper Mainstem model at the Buffalo River near Hawley (USGS gauge 05061000); and for the South Branch model at the Buffalo River at Sabin (USGS gauge 05061500). In most cases, the same calibration values were used for both models (differences are noted where appropriate). The models were calibrated to monthly hydrology values for the period from 2001-2006. Predicted flow generally agreed with observed data for the calibration period with NSE values of 0.70 and 0.75 for the South Branch and Upper Mainstem, respectively. For the validation period from 1996-2000, monthly NSE values were 0.87 and 0.70 for the South Branch and Upper Mainstem, respectively. Additional validation was performed for the entire simulation period (1996-2006) for a further downstream monitoring location on the Buffalo River near Dilworth (USGS gauge 05062000); NSE agreement for monthly flow was 0.81. Overall model hydrology performance statistics for the monthly time step are summarized in **Table 4**. Statistics for the daily time step are shown in **Table 5**; **Figures 4-6** show comparisons of observed and simulated daily flows. Model calibration was primarily focused on parameters pertaining to watershed-scale water balance and those that represented model outputs that could be verified against observed or published data (i.e., snow melt, evapotranspiration, groundwater recharge). The final model calibration parameters are contained in **Table 6**.

Table 4. Summary statistics for SWAT model performance for monthly stream flow.

		Mean Monthly Flow (AF)							
Site		**Observed**	**Predicted**	**Absolute Error**	**% Error**	**NSE**	**RMSE (acre-feet)**	**R**	**R^2**
BR Mainstem Near Hawley (05061000)	Calibration	6,948	6,689	-259	-3.7	0.75	4,288	0.87	0.76
	Validation	10,036	9,430	-605	-6.0	0.70	5,566	0.84	0.71
BR South Branch at Sabin (05061500)	Calibration	6,675	4,571	-2,104	-31.5	0.70	6,190	0.90	0.81
	Validation	7,728	7,994	266	3.4	0.87	5,078	0.94	0.88
BR Near Dilworth (05062000)	Validation (1996-2006)	19,028	16,566	-2,462	-12.9	0.81	12,138	0.91	0.83

AF = acre-feet

Table 5. Summary statistics for SWAT model performance for daily stream flow.

		Mean Daily Flow (cfs)							
Site		**Observed**	**Predicted**	**Absolute Error**	**% Error**	**NSE**	**RMSE (cfs)**	**R**	**R^2**
BR Mainstem Near Hawley (05061000)	Calibration	115.2	110.9	-4.3	-3.7	0.62	111.9	0.80	0.63
	Validation	166.1	156.1	-10.0	-6.0	0.31	190.4	0.65	0.43
BR South Branch at Sabin (05061500)	Calibration	110.6	75.7	-34.9	-31.5	0.61	190.2	0.82	0.66
	Validation	127.9	132.3	4.3	3.4	0.65	209.0	0.81	0.65
BR Near Dilworth (05062000)	Validation (1996-2006)	315.3	274.5	-40.8	-12.9	0.56	422.1	0.76	0.58

cfs = cubic feet per second

Table 6. Summary of key parameters used in model calibration.

Parameter	Default Value	Calibrated Value (Upper Mainstem / South Branch models)	Notes
.bsn file			
SFTMP	1	-0.5	calibrated based on observed snow pack data
SMTMP	0.5	5	calibrated based on observed snow pack data
TIMP	1	0.2	calibrated based on observed snow pack data
SNOCOVMX	1	2	calibrated based on observed snow pack data
SNO50COV	0.5	1	calibrated based on observed snow pack data
ESCO	0.95	0.75	calibrated based on water budget and observed ET data
EPCO	1	0.25	calibrated based on water budget and observed ET data
FFCB	0	0.5	set to mid-point value to initialize (not sensitive)
SURLAG	4	0.5/2	calibrated based on daily hydrograph shape
ICN	0	1	calculate runoff based on plant ET
CNCOEF		1/0.5	calibrated to hydrograph shape
PET method	Penmen/ Monteith	Priestly-Taylor	requested by MPCA
PRF	1	0.2/0.5	calibrated to sediment data
SPCON	0.0001	0.0002/0.0005	based on observed TSS concentrations
SPEXP	1	1.5	calibrated to sediment data
WQDP	0	0.2	Persistent bacteria die-off factor
SDNCO	0	0.98	
.gw file			
SHALLST	0.5	1000	initialization value (not sensitive)
DEEPST	1000	2000	initialization value (not sensitive)
GW_DELAY	31	250/150	calibrated based on daily hydrograph shape
ALPHA_BF	0.048	0.4	calibrated based on daily hydrograph shape
GWQMN	0	1000	this value converges with SHALLST then becomes insensitive
RCHRG_DP	0.05	0.5	calibrated based on regional data about groundwater recharge
GWHT	1	5	initialization value (not sensitive)
.rte file			
CH_N2	0.014	0.03-0.06 (varies)	based on values measured in other watersheds with agricultural land use / and table values as well as calibrated to observed sediment loads
CH_K2	0	15	measured values from other sites - table values - calibration
.sub file			
CO2	0	380	atmospheric concentration from ~2000
.hru file			
OV_N	0.14	0.25	based on tables in SWAT documentation
CANMX	0	4	based on literature values
RSDIN	0	2500	initial value based on conservative estimate
ERORGP	0	0.6	calibrated to observed phosphorus data

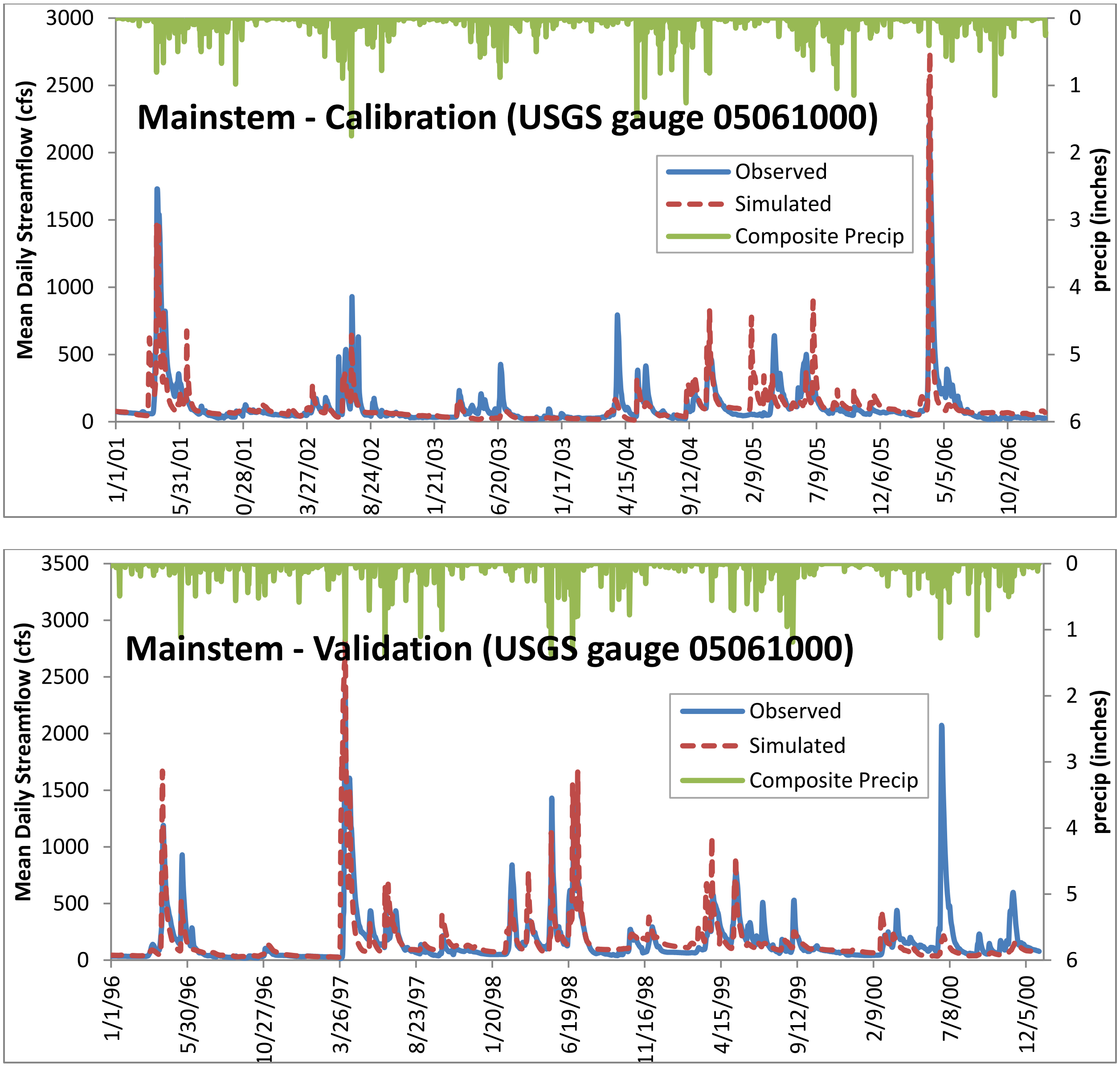
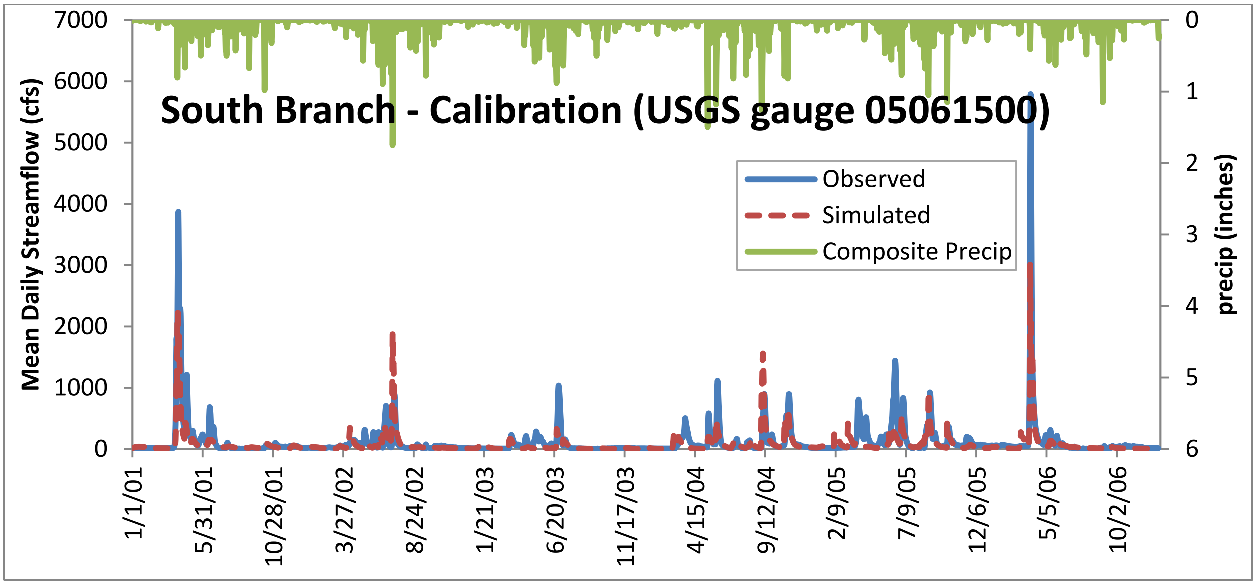


Figure 4. Observed and predicted mean daily stream flow for the Mainstem of the Buffalo River near Hawley, MN (USGS Gauge # 05061000).



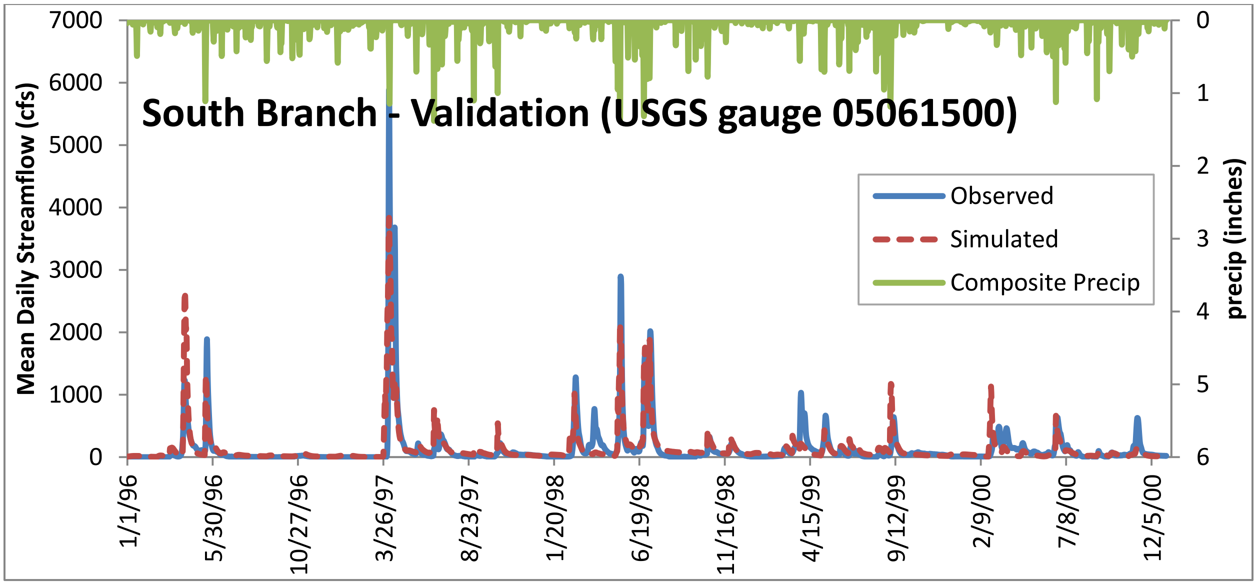


Figure 5. Observed and predicted mean daily stream flow for the South Branch of the Buffalo River at Sabin, MN (USGS Gauge # 05061500).

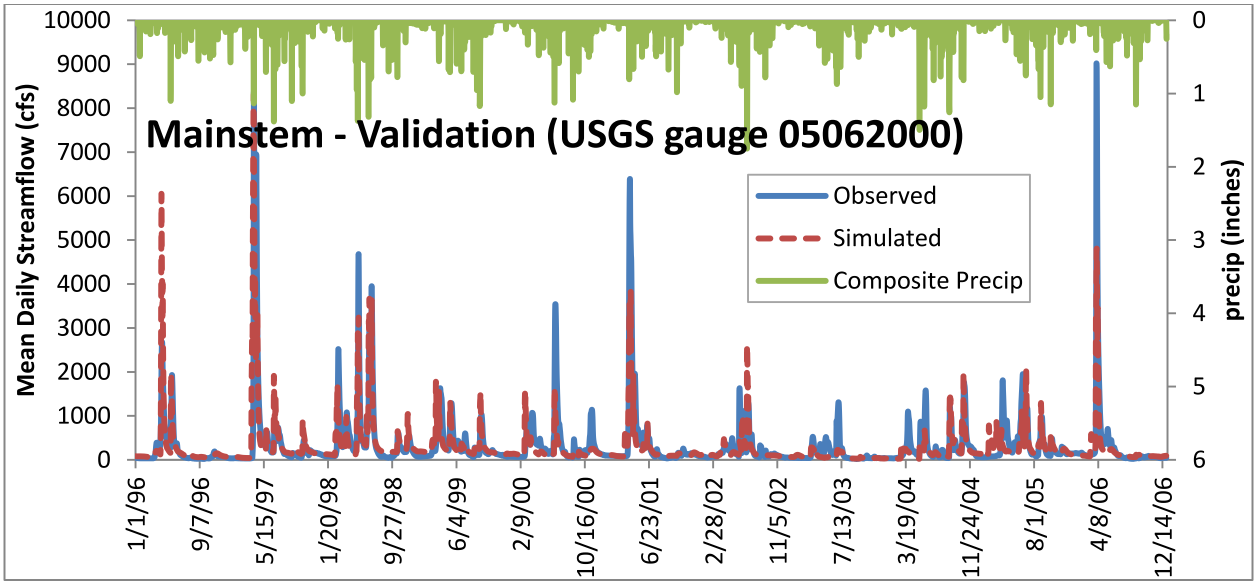


Figure 6. Observed and predicted mean daily stream flow for the Mainstem of the Buffalo River near Dilworth, MN (USGS Gauge # 05062000).

3.2. Water Quality

The water quality calibration and validation of these models was performed at the five locations shown in **Figure 7.** Only one of these sites (S003-152) had observed flow data also available at that location. For the other four sites, model-simulated flows had to be used in place of observed data to estimate “observed” sediment and nutrient loads. Model calibration for water quality is difficult when data are not accompanied by flow data collected at the same site. This is because model performance is judged by comparing observed and predicted loads of sediment and nutrients; loads cannot be computed without flow data. In cases such as this study, where observed flow data are not available for computing loads at observed monitoring locations, model performance can be evaluated by using model-predicted flow data as a substitute for observed flow data. Modeled flow data is coupled with observed water quality data to compute “pseudo-observed” monthly loads of sediment and phosphorus. It is important to note that this approach may impact the measures of model performance since any model disagreement in flow predictions is essentially ignored. Nonetheless, when model performance for flow is good (as is the case here), this approach provides an opportunity to determine if the model is simulating processes controlling sediment and nutrient export in a realistic manner.

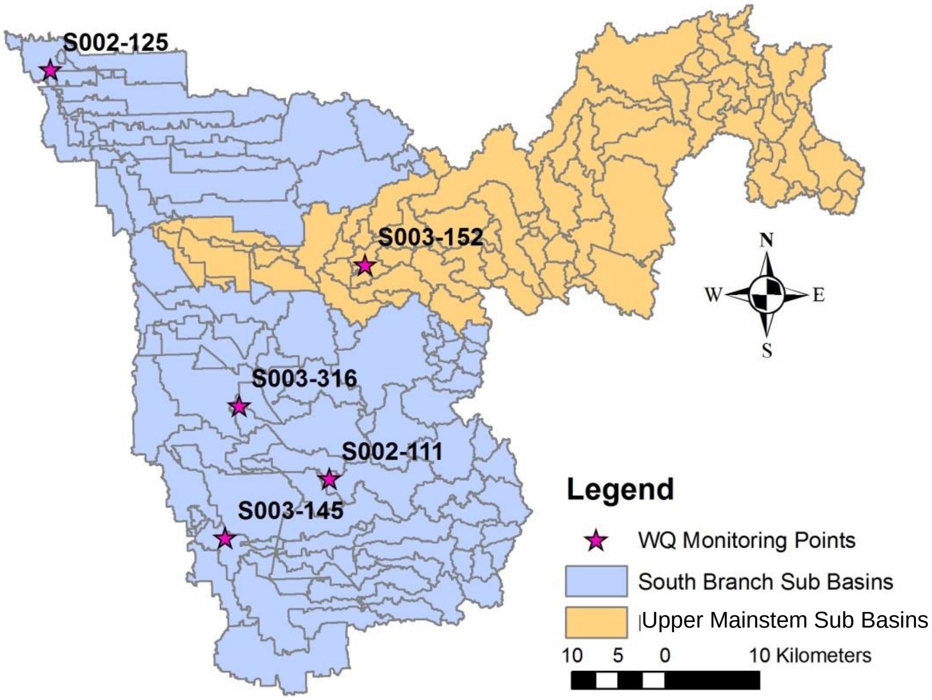


Figure 7. Locations of water quality monitoring stations used in this study (number corresponds to STORET database).

The ability of the BRW SWAT models to effectively predict sediment and nutrient loading was judged by comparing simulated and “observed” monthly and annual loads. The U.S. Army Corps of Engineers FLUX32 program (version 3.09) was used to estimate “observed” loads at the five water quality sites shown in **Figure 7**. Loads at site S003-152 were computed using mean daily flows from USGS site 05061000. Loads at the other four locations were computed using SWAT-simulated flows.

An additional challenge to judging the simulation of sediment loading in the BRW is the fact that none of the available water quality data in the BRW is actually associated with sediment, which is what the SWAT model simulates. A typical approach, in cases like this, is to assume that total suspended solids (TSS) data accurately represents sediment in the water column and to use observed TSS values to compare to simulated sediment to judge the model performance. Unfortunately, TSS data is also limited in the BRW. **Table 7** summarizes the amount of TSS data available at each of this study's water quality calibration locations. To extend the amount of TSS data available for use in estimating sediment loads, a relationship between all paired turbidity (which is widely available) and TSS data in the BRW was created. This relationship was then used to estimate TSS values at the calibration locations on days when turbidity was observed but TSS was not. **Table 7** shows the number of TSS values that were estimated from turbidity at each of the calibration sites, as well as the total number of TSS values (both observed and estimated) that were used in the FLUX runs to estimate "observed" monthly sediment loads. The turbidity-TSS relationship used for this work is shown in **Appendix C**.

Table 7. Summary of TSS data available at calibration points and used in FLUX estimates.

STORET ID	Number of Actual TSS Observations	Number of TSS Values Estimated from Turbidity	Total Number of TSS Values used in FLUX
S002-111	18	31	49
S003-145	5	20	25
S003-316	4	27	31
S002-125	81	0	81
S003-152	13	24	37

Comparisons of "observed" and predicted sediment and total phosphorus loads at the five water quality monitoring locations are presented in **Figure 8** through **Figure 17**; measures of model performance are summarized in **Table 8**. Validation statistics are shown in **Table 9**. Although validation statistics were computed for the models, it is notable that no water quality data is available at these monitoring locations during the validation period (the earliest available data is in 2002). Therefore, the "observed" loads presented in **Table 9** are based solely on the simulated/observed flows during this time period and the relationship estimated by FLUX for data from 2002 onward and extrapolated back to estimate loads pre-2002. As such, minimal weight should be given to these results and model performance will be judged solely by the calibration results (**Table 8**).

Table 8. Summary calibration statistics of annual and monthly loads of sediment and phosphorus.

Site	Parameter	Average Annual (2001-2006)			Average Monthly (2001-2006)				
		Mean “Observed” (tons/yr)	Mean Predicted (tons/yr)	r^2	Mean “Observed” (tons/month)	Mean Predicted (tons/month)	NSE	r^2	% error
S003-152	Sediment[1]	5,042	4,822	0.71	420	402	-0.50	0.75	-4.4%
	TP	40	45	0.98	3.3	3.7	0.87	0.93	11.2%
S002-111	Sediment[1]	195	149	0.83	16	12	0.86	0.89	-23.5%
	TP	1.0	1.0	0.82	0.085	0.082	0.68	0.93	-4.1%
S002-125	Sediment[1]	22,341	7,354	0.97	1,862	613	0.37	0.86	-67.1%
	TP	60	77	0.94	5.0	6.4	0.65	0.94	27.3%
S003-145	Sediment[1]	2,583	3,010	0.46	215	251	0.72	0.76	16.5%
S003-316	Sediment[1]	637	509	0.32	53	42	0.58	0.76	-20.2%

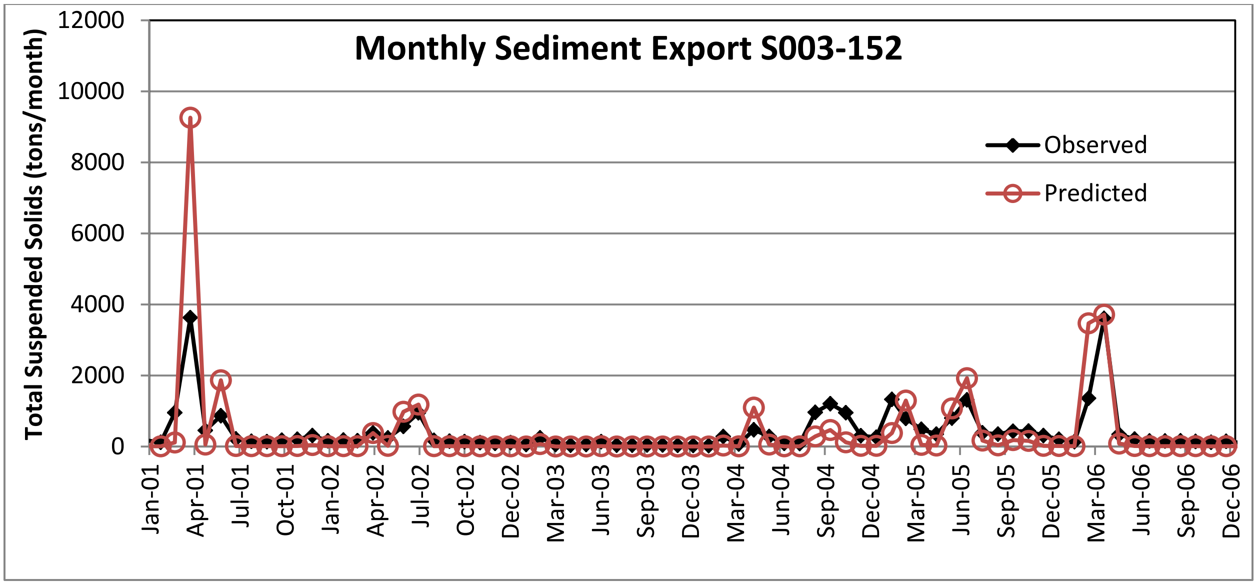
[1] “observed” sediment estimated as TSS.

Table 9. Summary validation statistics of annual and monthly loads of sediment and phosphorus.

Site	Parameter	Average Annual (1996-2000)			Average Monthly (1996-2000)				
		Mean “Observed” (tons/yr)	Mean Predicted (tons/yr)	r^2	Mean “Observed” (tons/month)	Mean Predicted (tons/month)	NSE	r^2	% error
S003-152	Sediment[1]	8,225	8,705	0.87	685	725	0.43	0.90	5.8
	TP	69	75	0.97	5.7	6.2	0.86	0.92	8.5
S002-111	Sediment[1]	455	621	0.93	38	52	-0.58	0.81	36.4
	TP	2.3	2.2	0.91	0.20	0.18	0.86	0.96	-7.6
S002-125	Sediment[1]	41,242	18,910	0.78	3,437	1,576	0.72	0.93	-54.1
	TP	115	149	0.78	9.6	12.4	0.53	0.85	29.0
S003-145	Sediment[1]	3,692	4,208	0.88	308	351	0.93	0.93	14.0
S003-316	Sediment[1]	1,218	973	0.83	101	81	0.83	0.87	-20.1

[1] “observed” sediment estimated as TSS.

The SWAT models generally did a good job of predicting mean monthly and annual loads and coefficient of determination (r^2) values show strong correlation between “observed” and predicted values (**Table 8**). With two exceptions, NSE values of monthly loads during the calibration period ranged from good (>0.5) to excellent (>0.75). For TSS loads at site S002-125 located near the watershed outlet, NSE agreement was fair (0.37) despite an r^2 value of 0.86. This reflects the fact that simulated TSS loads are consistently under-predicted at this site (**Figure 15**). The fact that TSS loads are in closer agreement for all other monitoring locations suggests that the model is simulating upland process realistically but is failing to capture something that is occurring in the downstream reaches of the watershed. This may be the result of other sources of TSS that are captured in measured samples but not predicted by the model such as re-worked channel and bed materials or in-stream primary productivity. At site S003-152, the monthly NSE value of -0.5 indicates that the model is failing to capture more variability than the mean monthly TSS load. This is primarily the result of poor model agreement during one month (April 2001) where the SWAT model is dramatically over-predicting observed loads. If this one data point is removed from the analysis, the NSE value increases to 0.36.



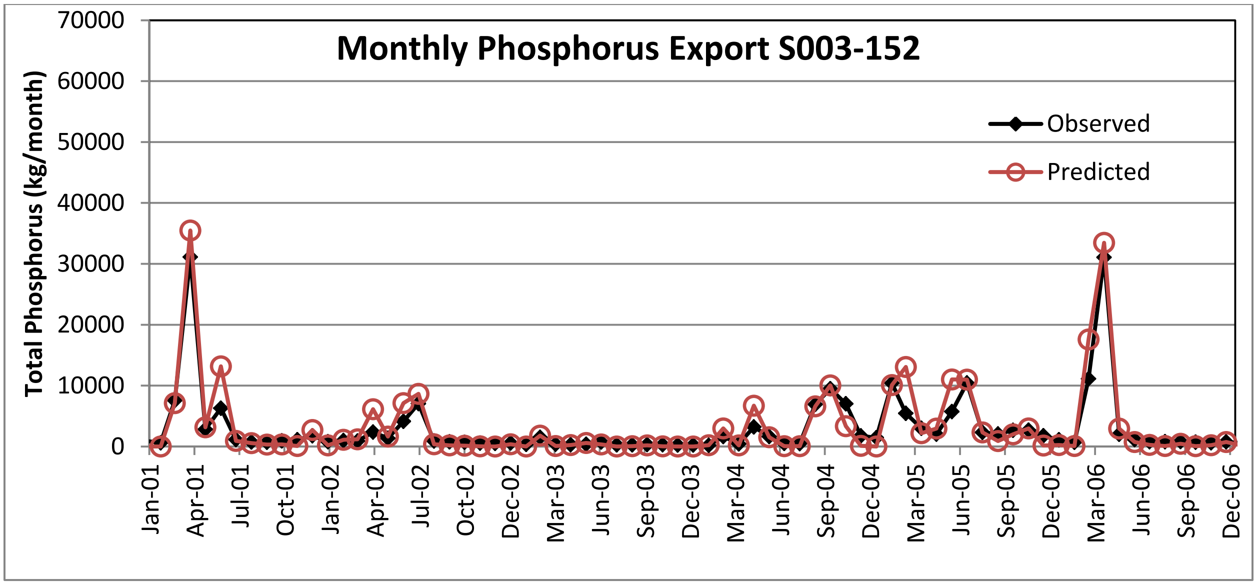
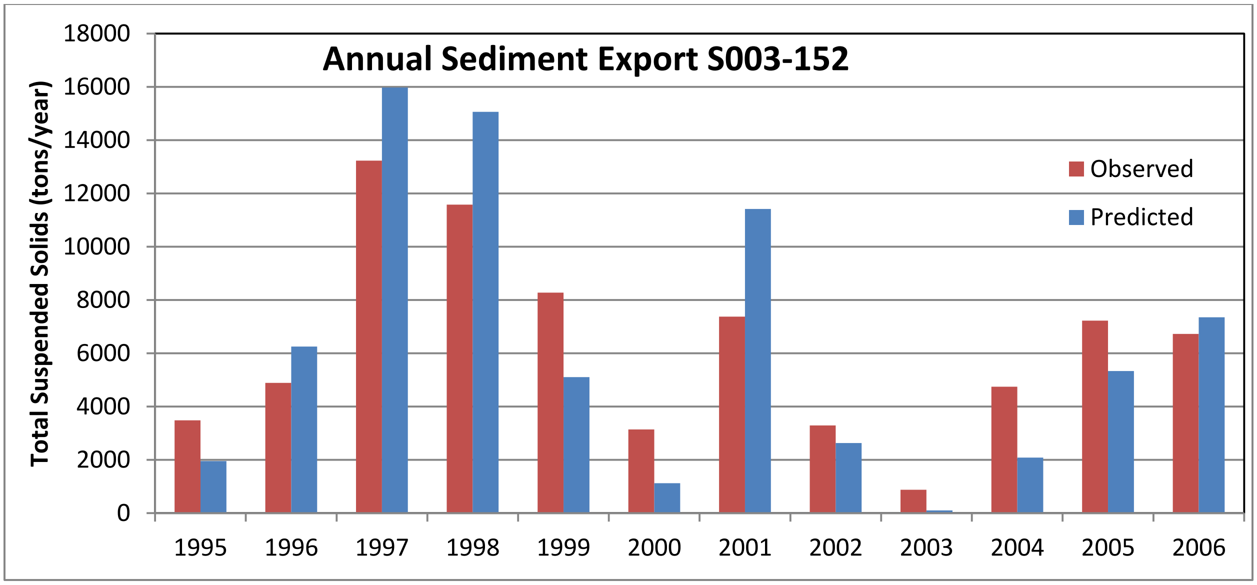


Figure 8. "Observed" and predicted monthly loads of sediment and phosphorus for monitoring point S003-152 (Buffalo River Mainstem) for the model calibration period from 2001-2006.



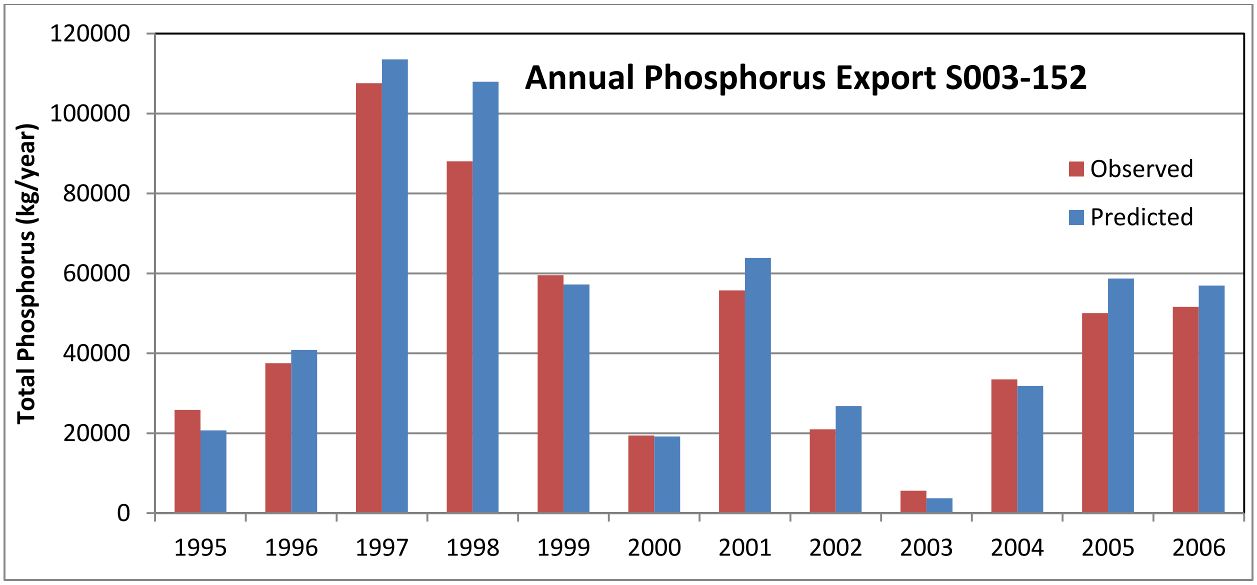
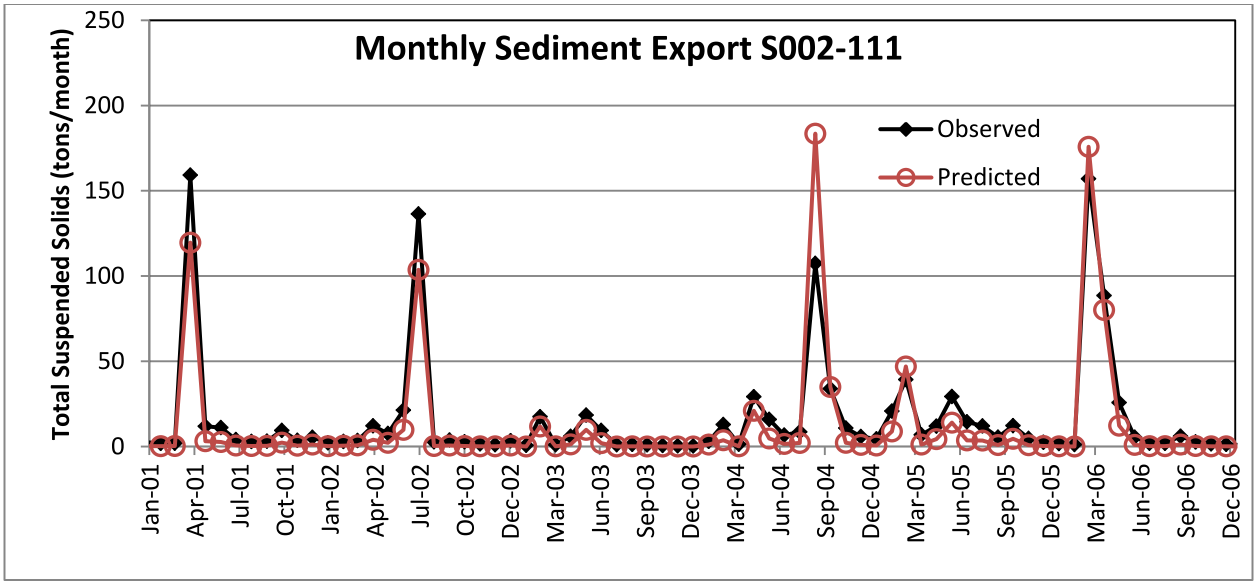


Figure 9. "Observed" and predicted annual loads of sediment and phosphorus at monitoring point S003-152 for the simulation period from 1995-2006 (water quality data were sparse or non-existent before 2001).



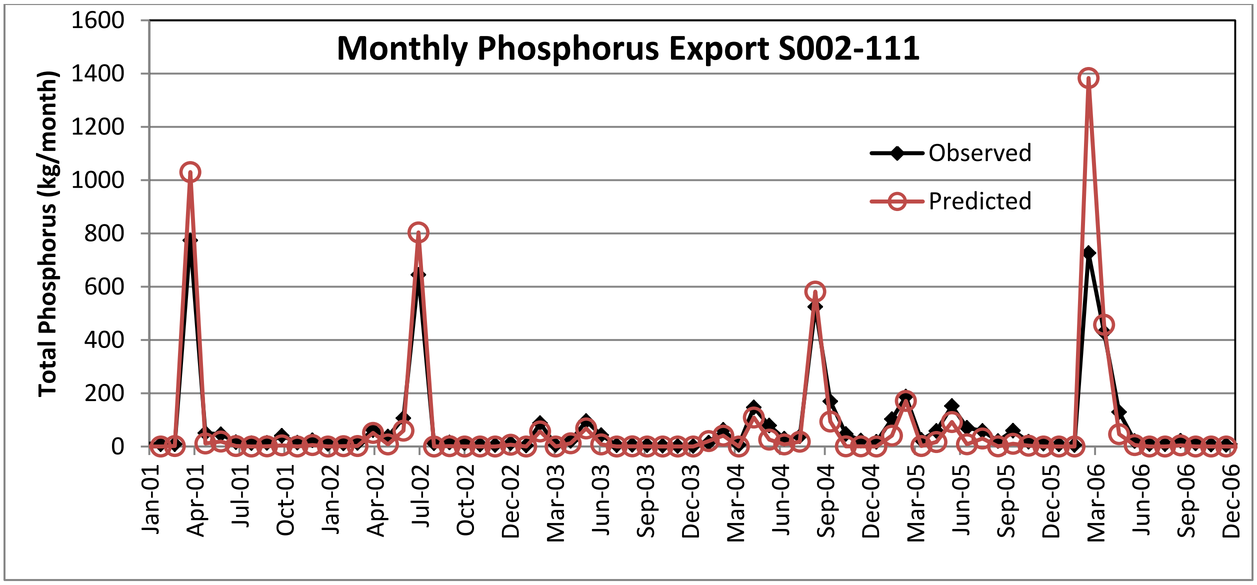
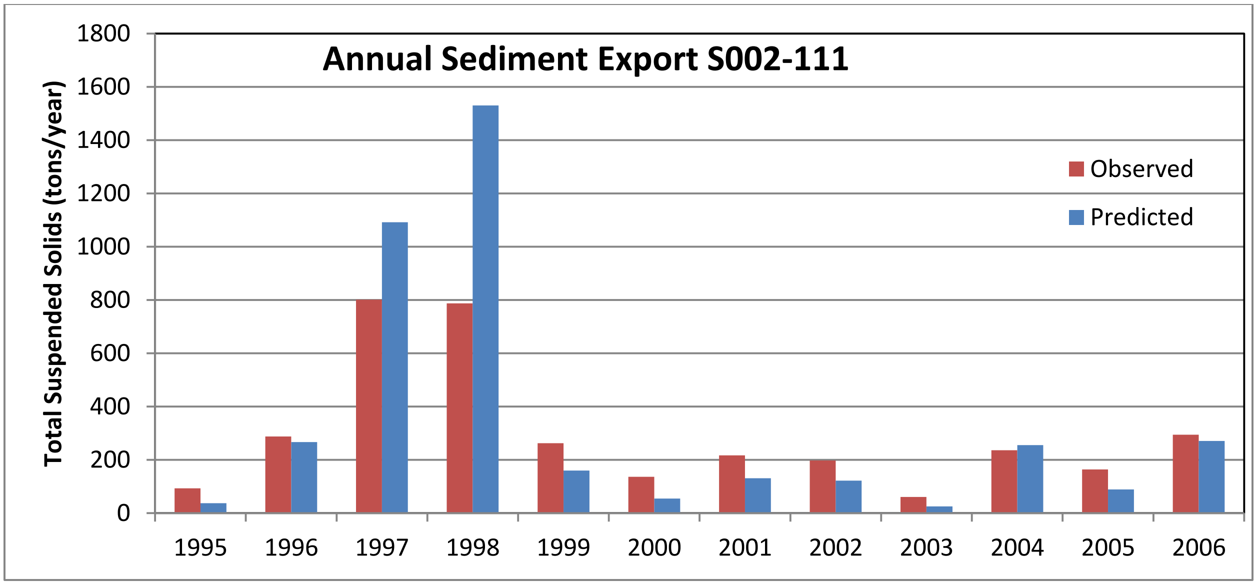


Figure 10. “Observed” and predicted monthly loads of sediment and phosphorus for monitoring point S002-111 (Buffalo River South Branch Model) for the model calibration period from 2001-2006.



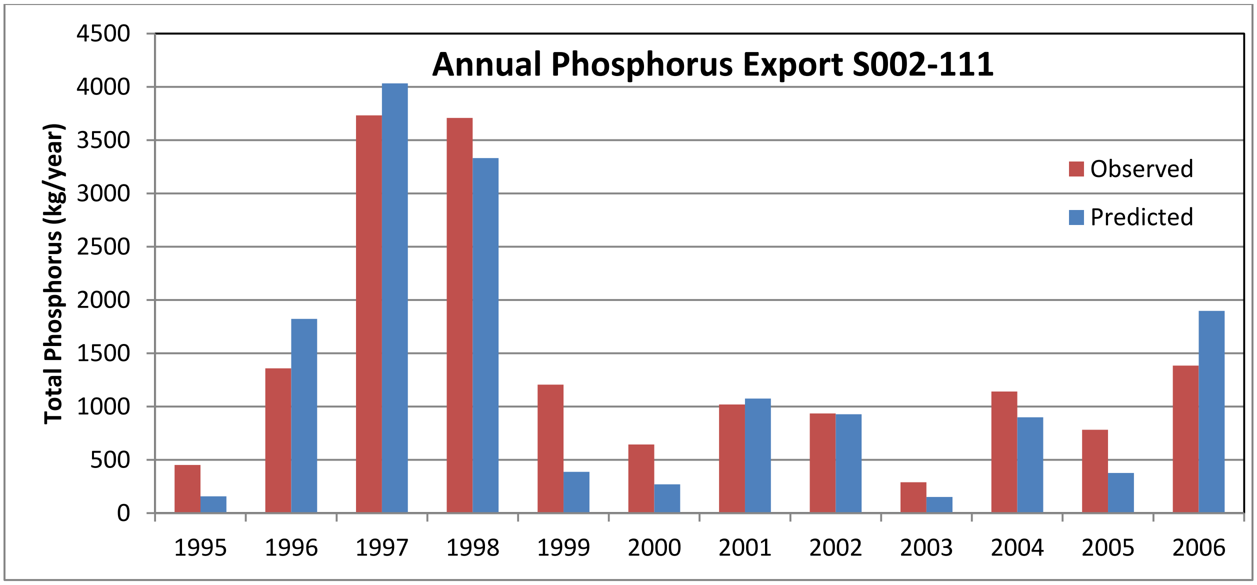


Figure 11. "Observed" and predicted annual loads of sediment and phosphorus at monitoring point S002-111 for the simulation period from 1995-2006 (water quality data were sparse or non-existent before 2001).

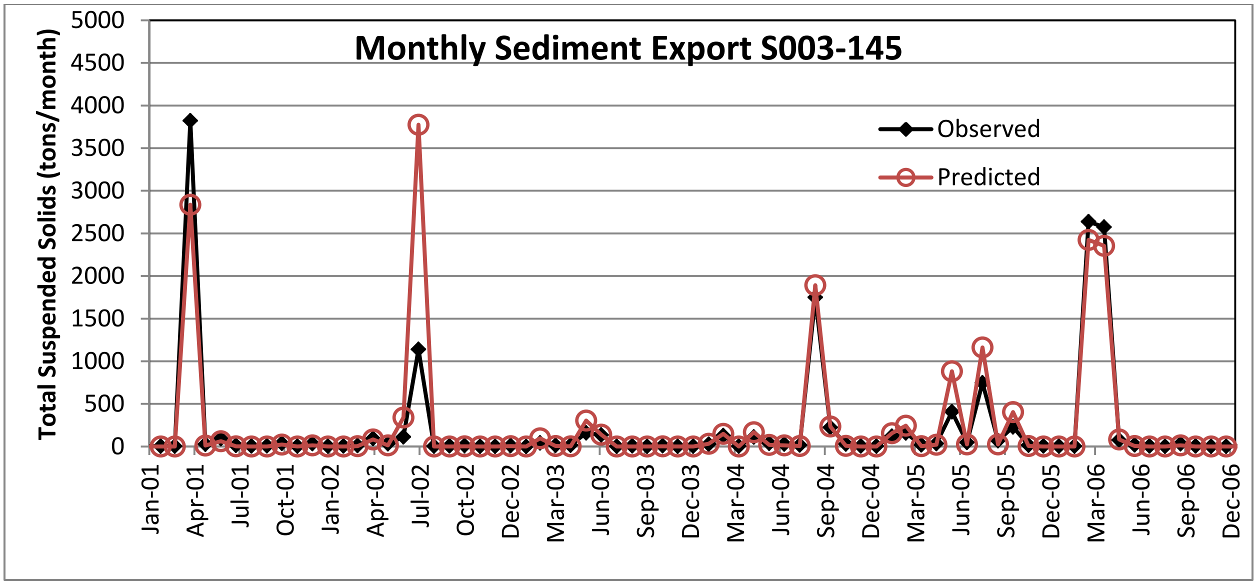


Figure 12. "Observed" and predicted monthly loads of sediment for monitoring point S003-145 (Buffalo River South Branch Model) for the model calibration period from 2001-2006.

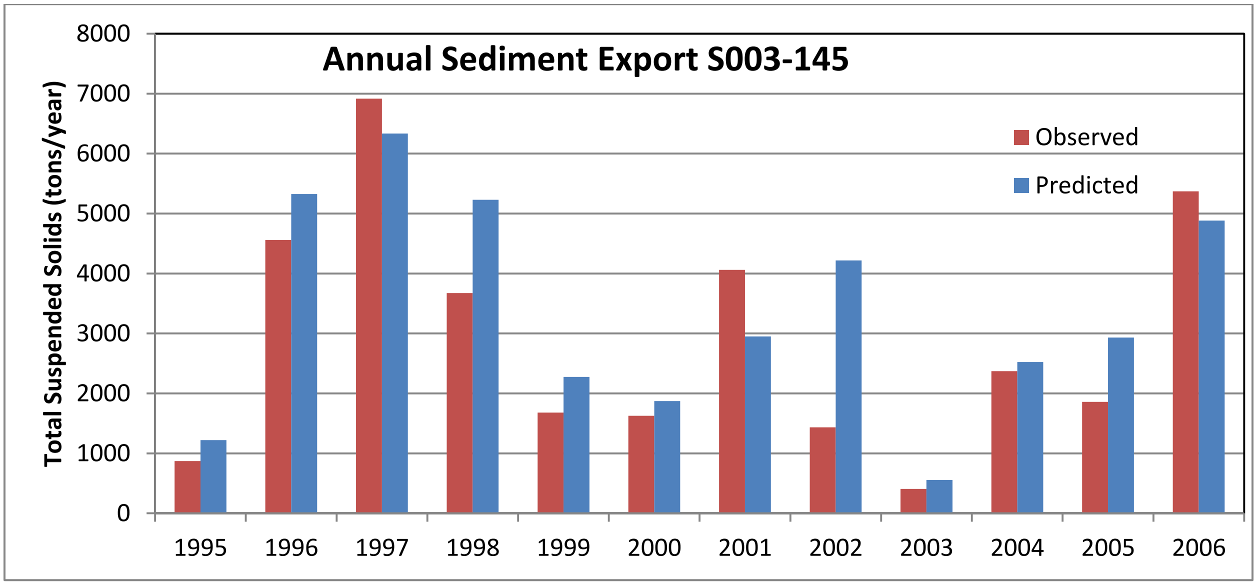


Figure 13. "Observed" and predicted annual loads of sediment at monitoring point S003-145 for the simulation period from 1995-2006 (water quality data were sparse or non-existent before 2001).

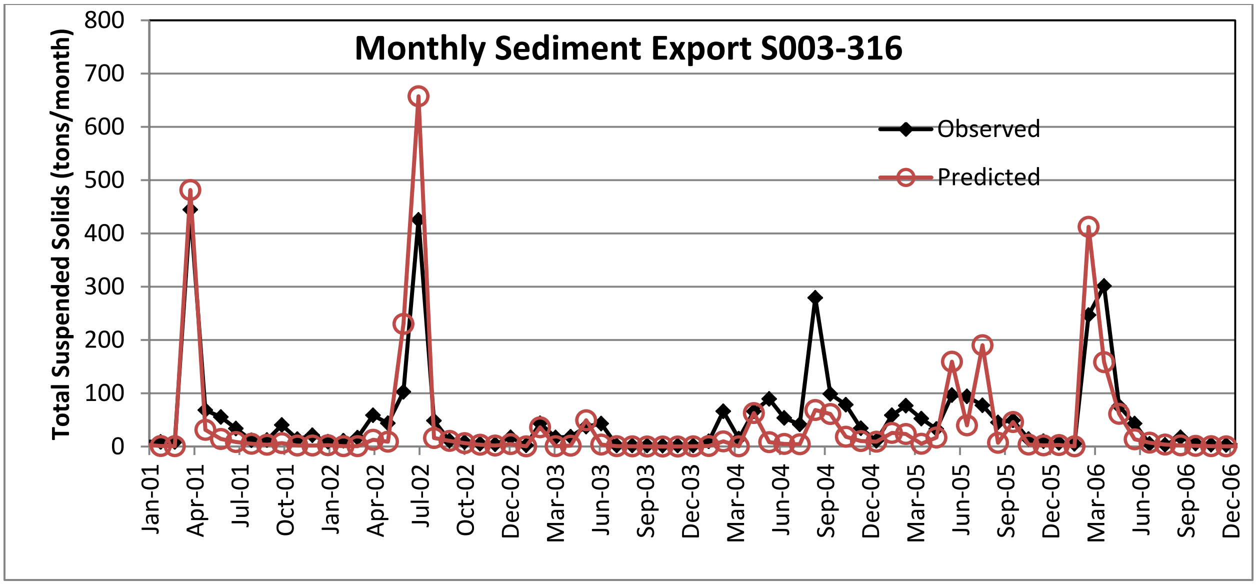


Figure 14. "Observed" and predicted monthly loads of sediment for monitoring point S003-316 (Buffalo River South Branch Model) for the model calibration period from 2001-2006.

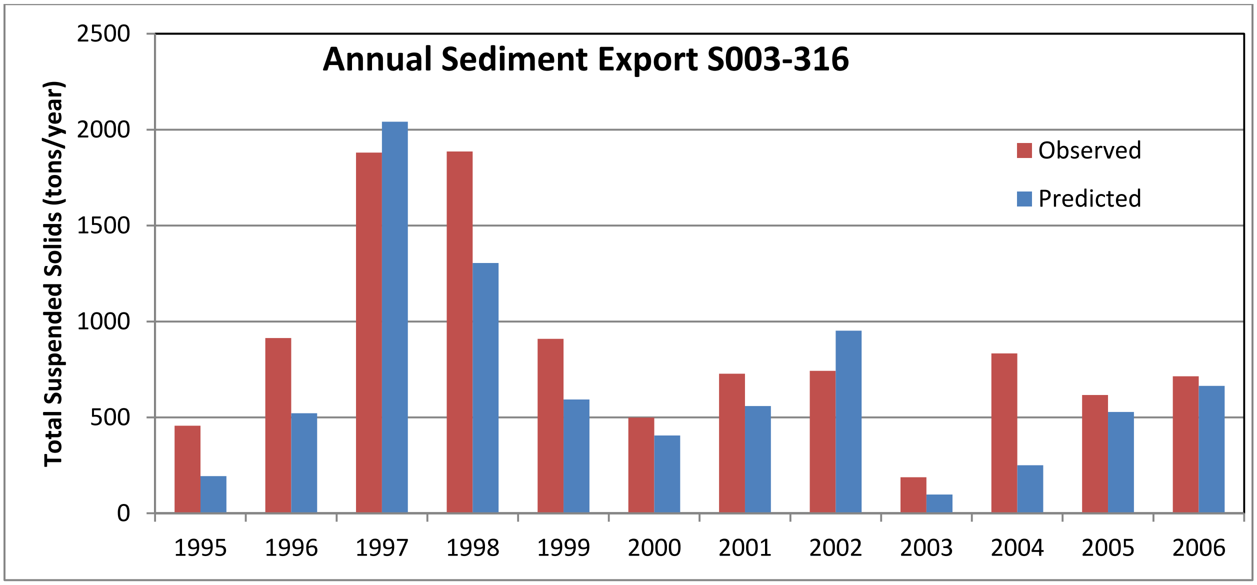
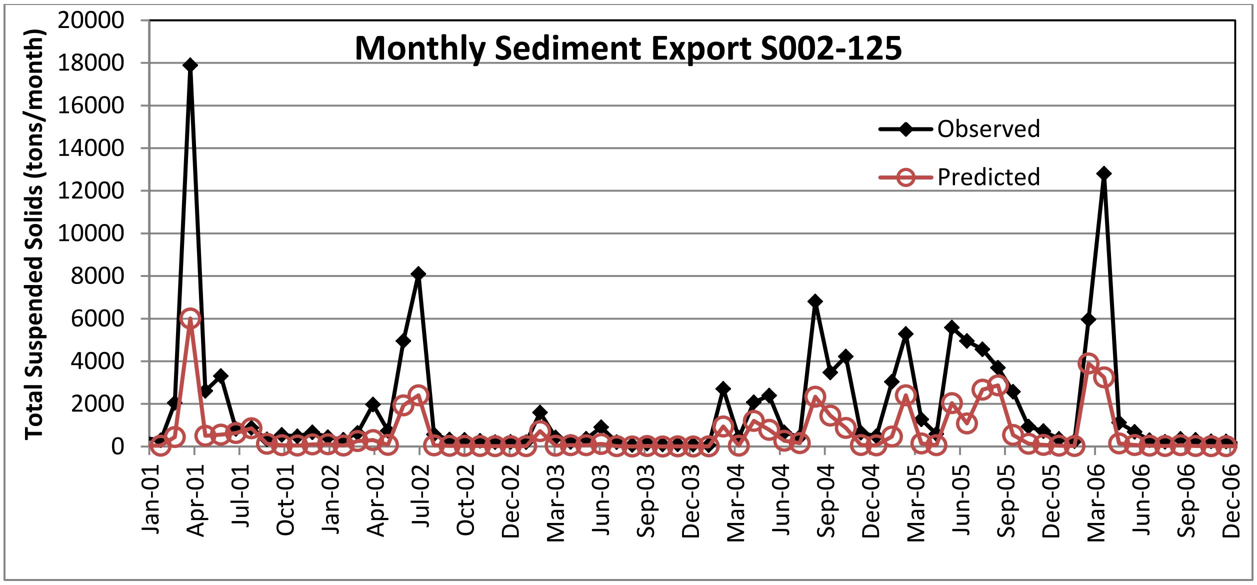


Figure 15. "Observed" and predicted annual loads of sediment at monitoring point S003-316 for the simulation period from 1995-2006 (water quality data were sparse or non-existent before 2001).



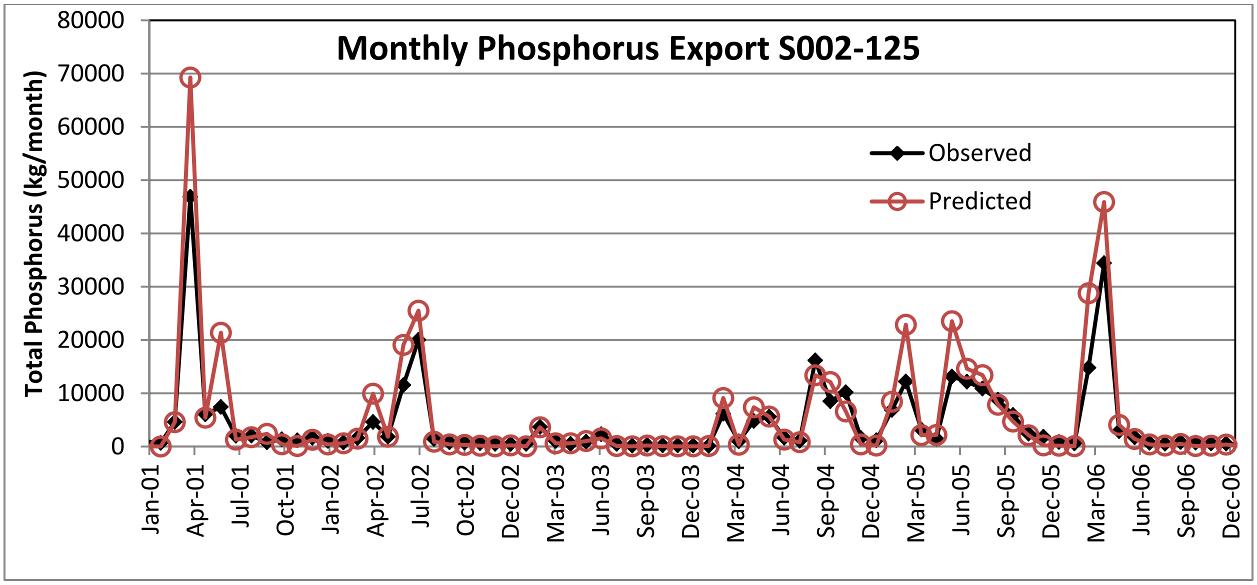
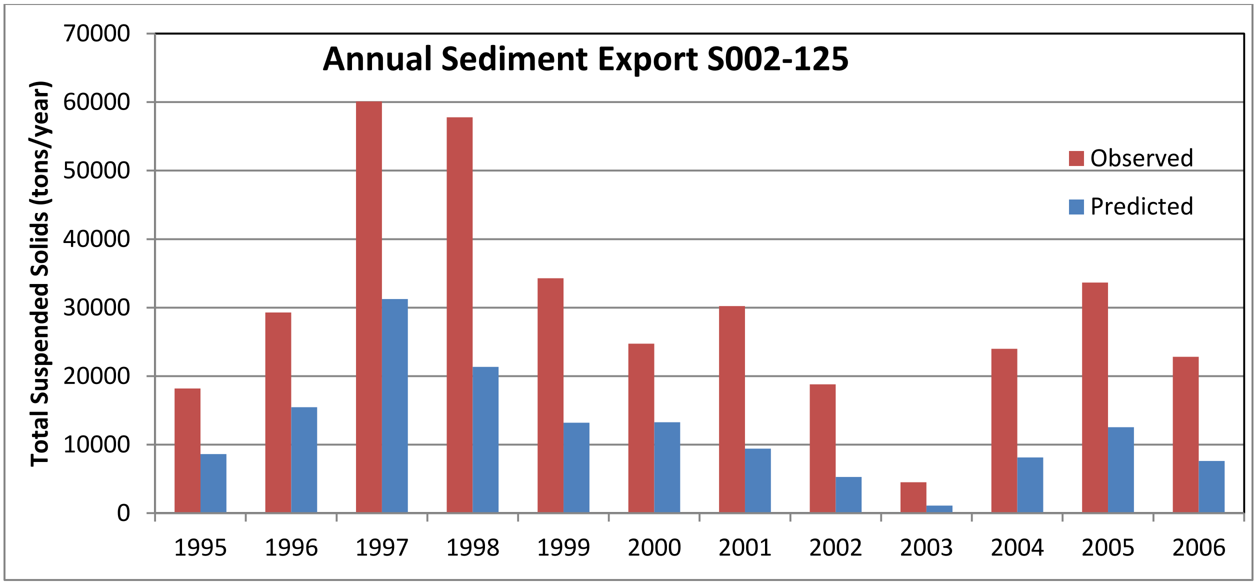


Figure 16 . "Observed" and predicted monthly loads of sediment and phosphorus for monitoring point S002-125 (Buffalo River South Branch Model) for the model calibration period from 2001-2006.



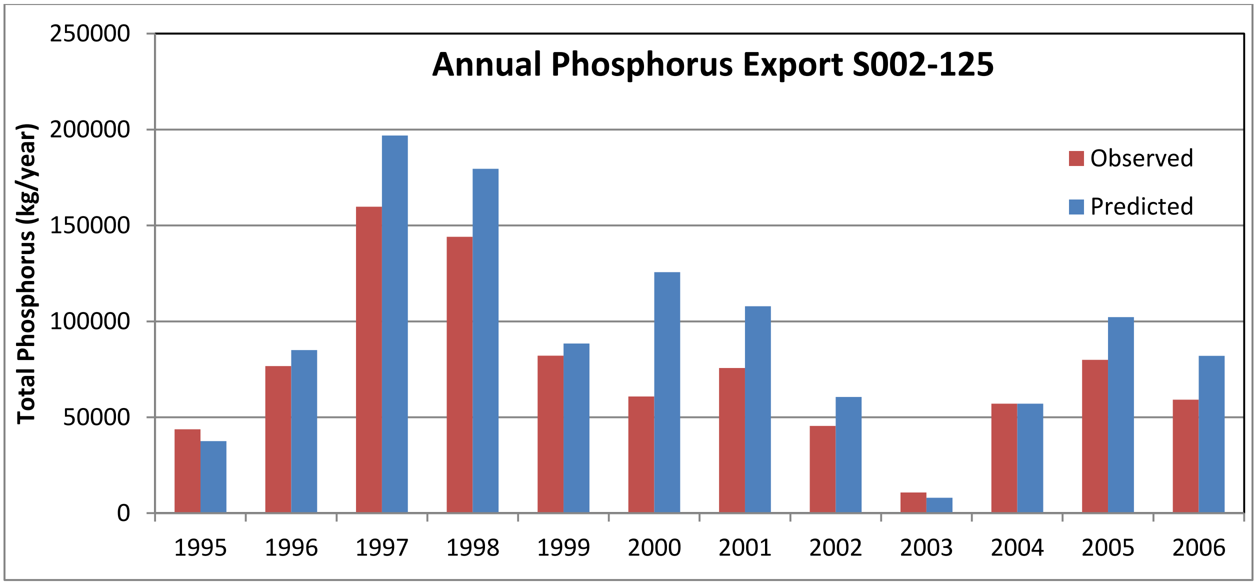


Figure 17. "Observed" and predicted annual loads of sediment and phosphorus at monitoring point S002-125 for the simulation period from 1995-2006 (water quality data were sparse or non-existent before 2001).

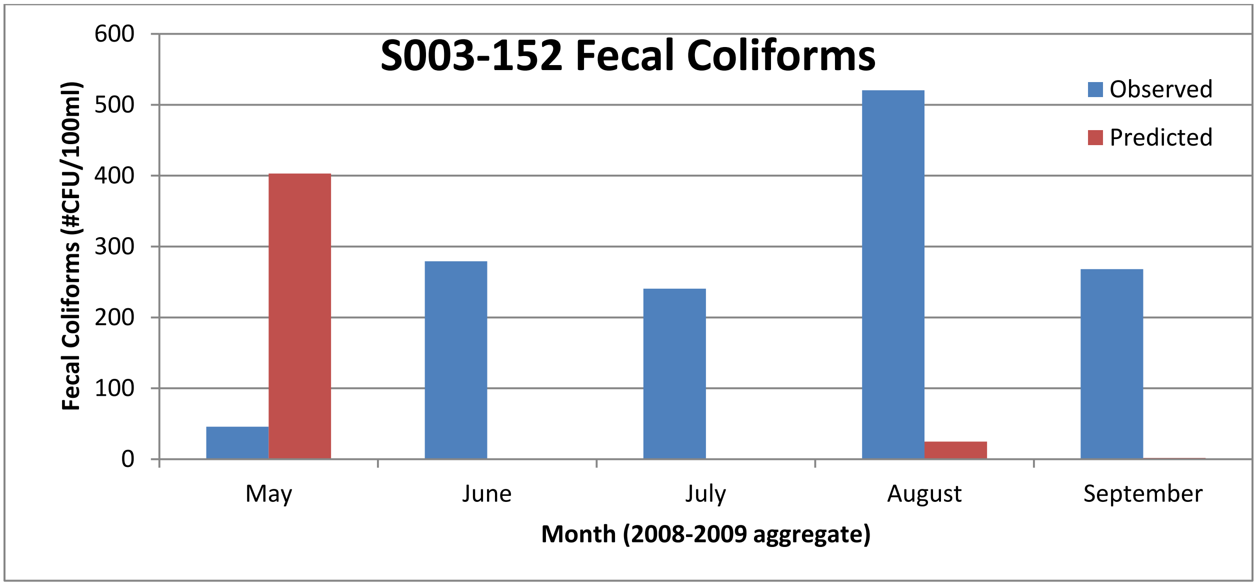
Sources of bacteria in the BRW SWAT models were simulated using data presented in a January 2013 memorandum in which BRW bacteria sources and methods of entry into the environment are discussed (HEI, 2013; included as **Appendix B**). Numerous conversations were had with local BRW resources managers to identify bacteria sources in the watershed, quantify these sources, and discuss their simulation in the SWAT models. Results of this work show that the primary sources of bacteria in the BRW are manure from beef cattle, dairy cattle, pigs, and waterfowl. As such, these are the sources that were simulated in the SWAT models. Dairy cattle manure, pig manure, and half of the beef cattle manure were simulated within the model by applying them to agricultural fields during a two-week window in the spring and fall (representing the disposal of manure from animals raised in confined feeding operations). The other half of the beef cattle manure was simulated in the model through application to haylands (representing grazing animals). This manure was applied from mid-March through mid-November, the presumed time that the animals would generally be grazing. Waterfowl manure was included in the SWAT model as duck manure applied every day from April through September, with increased application rates during the spring and fall migration. Duck manure in the Tamarac National Wildlife Refuge had increased application rates. Further details on manure applications within the model are included in **Appendix A**.

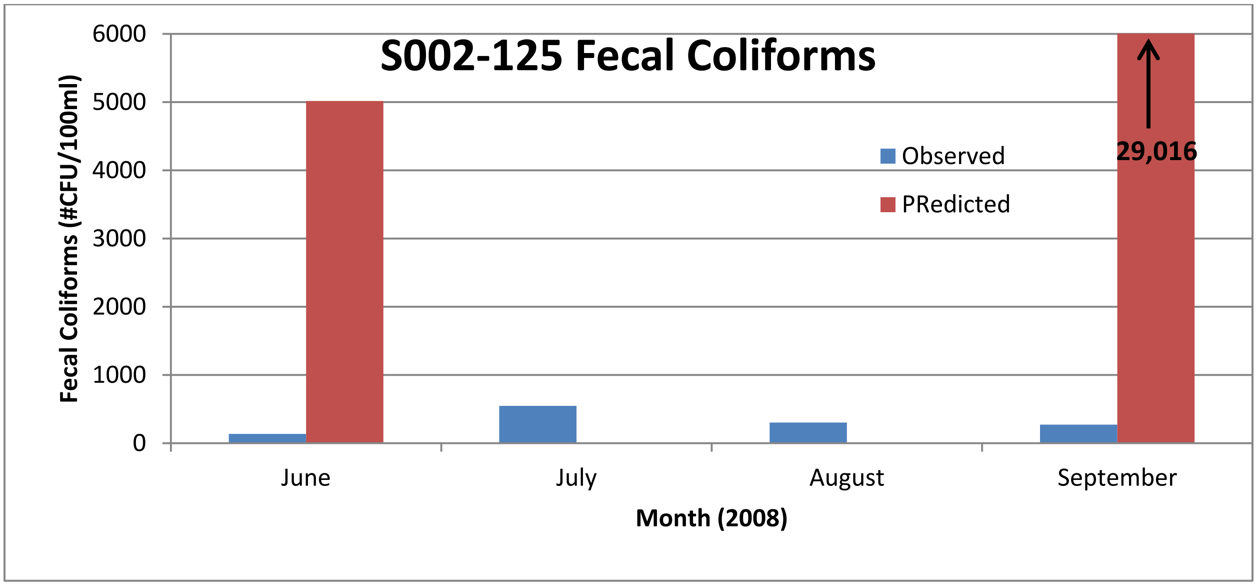
The largest source of bacteria in the BRW SWAT models is associated with manure applications to agricultural fields and haylands. Once these bacteria are in the soil, they are transported to receiving water bodies during runoff events. Also, once on the landscape, simulated bacteria die-off according to established relationships (i.e., first-order decay). The rate of die-off is the primary bacteria calibration parameter in the SWAT model. SWAT does not currently have sophisticated methods for simulating bacterial persistence, regrowth, or resuspension in the channel.

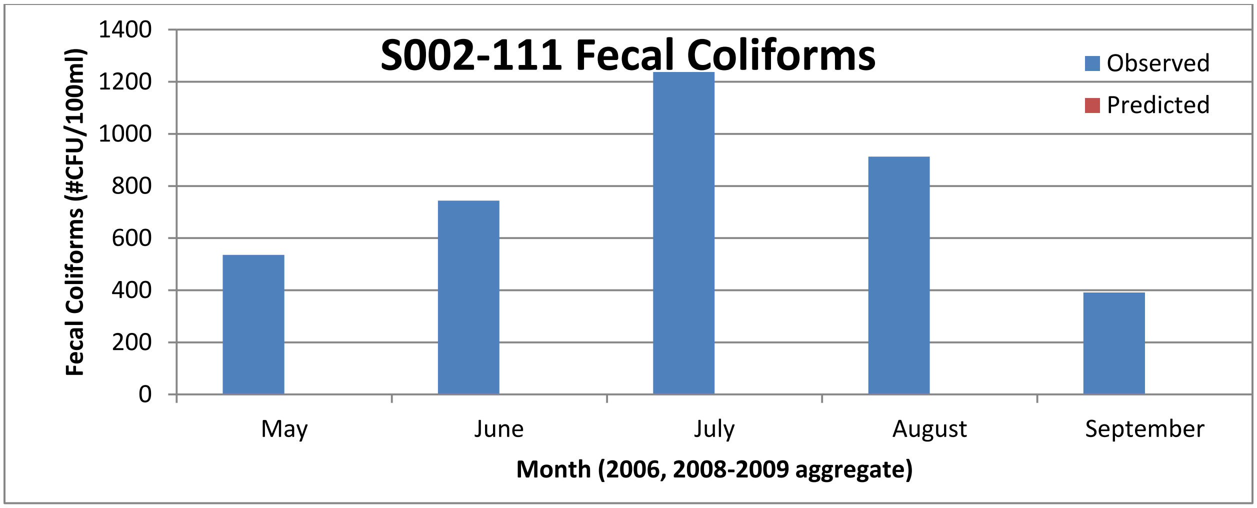
Figure 18 shows a comparison of simulated and observed bacteria concentrations in the BRW. Results are presented as monthly geometric mean values, which is how the water quality standard is written for this parameter. Results are presented only for those months when observed data were available, typically May – September with one station having no data in May. Also of note is the fact that bacteria data in the BRW are only available post-2006, with most stations only having data since 2008. This time period is inconsistent with the other calibration time periods that were used in this work, but was employed to allow for the judgment of the SWAT bacterial simulations.

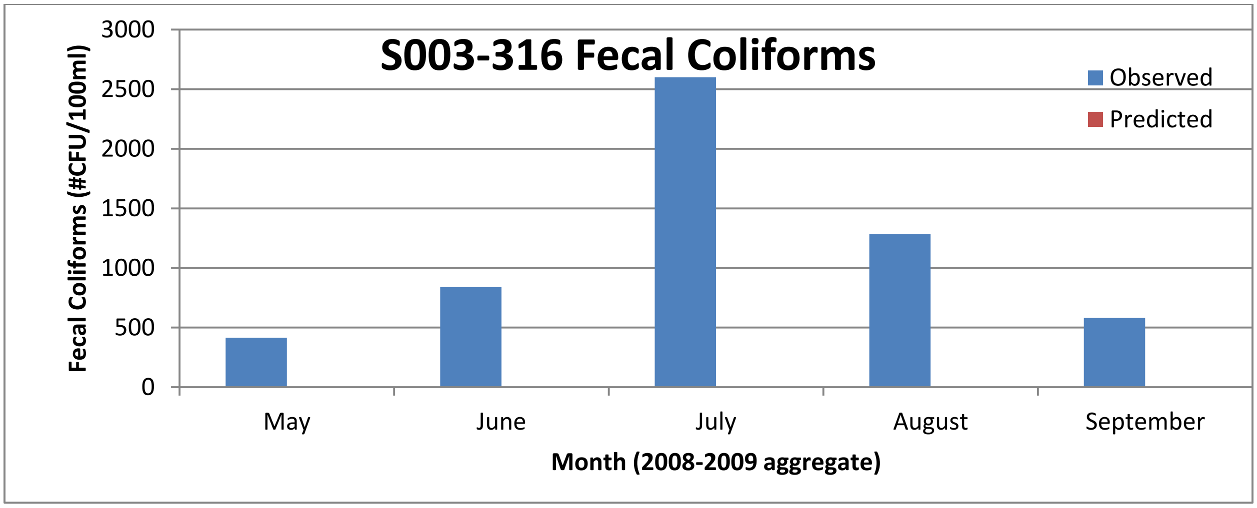
As seen in **Figure 18**, the developed SWAT models are not accurately simulating bacterial concentrations in the BRW. Simulated bacterial concentrations during the summer months are extremely low, while observed data show high values. Simulated bacterial concentrations during the spring and fall months (not included in **Figure 18** due to a lack of observed data) are very high; unfortunately no observed data are available during these time periods for comparison, but it is assumed that observed values would be substantially lower than the model is predicting.

Results of this analysis suggest that there is a more persistent source of bacteria in the BRW than is currently being simulated in the SWAT model. Some of the data or assumptions agreed upon by the project team (i.e., HEI, state representatives, and local managers) and discussed in the January 2013 memorandum may not reflect actual conditions in the study area. Limitations in the SWAT model's ability to simulate persistence, regrowth, or resuspension of bacteria may also contribute to the poor performance. Based on the results presented here, it is not recommended that the SWAT model be employed to evaluate fecal coliform water quality problems in the BRW at this time, but rather that empirical methods be used to evaluate the issue. It is recommended that additional work be done to refine the identification of bacterial sources and pathways in the BRW, potentially including the performance of a microbial tracking study. Given this recommendation, fecal coliform will not be included in the discussion of the effectiveness of various BMP/management scenarios at improving water quality in the BRW.









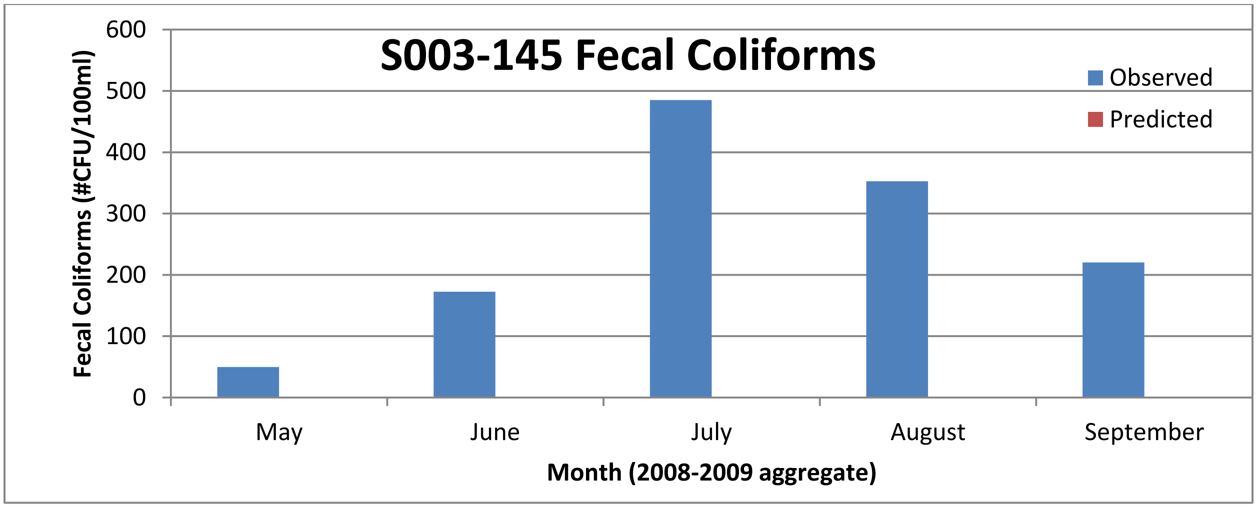


Figure 18. Comparison of observed and model-predicted fecal coliform for sites in the BRW. Values represent the geometric means of available data aggregated by month.

4. Water Quality Management Scenarios

A main benefit of the use of the SWAT model is its ability to simulate the use of agricultural best management practices (BMPs) and other "what if" scenarios in a watershed. Results of the modeling under these various scenarios provide insight on the effectiveness and overall impact that various management strategies may produce. The calibrated/validated BRW SWAT models were used to evaluate four separate BMP/management scenarios in the area, for use in informing future water quality management planning. Numerous conversations were had between HEI and local managers (including the Buffalo Red River Watershed District (BRRWD), local Soil and Water Conservation Districts (SWCDs), and the Board of Water and Soil Resources (BWSR)) to identify and design the most appropriate and realistic BMP/management scenarios to be included in the modeling. A list of the various scenarios modeled, and the approach used to simulate each in the SWAT model, is shown below. It is important to note that while SWAT is particularly strong at simulating agricultural BMPs, all representation of management scenarios in the model requires some level of generalization. As such, model results should not be used to predict the exact efficiency with which various BMPs will perform, but rather to provide a general idea of the predicted effectiveness of different strategies and for comparing different management options over the long-term.

The BMPs/management scenarios simulated in the BRW SWAT models include:

- Filter strips: 15-meter (approximately 50-foot) and 30-meter (approximately 100-foot) widths
    - Simulated using SWAT's filter strip function (in the management routines). Both 50-foot and 100-foot buffers were simulated in agricultural HRUs that border major waterways in the watershed. This resulted in approximately 57% of the agricultural lands in the BRW having filter strips (64% of agricultural lands in the South Branch model and 39% in the Upper Mainstem model).
- Reduced tillage
    - Simulated by removing fall tillage in roughly ¼ of all corn, roughly ¼ of all wheat, and roughly ¾ (an additional ¼ from the baseline condition) of all soybeans in the watershed. Reduced tillage was not simulated for corn crops in the lakeplain region of the watershed; local managers indicated this practice is not reasonable for corn in that area. Results of this scenario removed fall tillage from 26% of agricultural lands in the Upper Mainstem model and 25% of those in the South Branch model.
- Side inlet structures and water/sediment control basins
    - Simulated as temporary ponds alongside all major waterways in the watershed. The (temporary) pond design for each subbasin was determined by assuming an average depth of one-foot for all structures, a constant slope within each subbasin (taken as the average of the slope range in the SWAT input file), and a maximum hydraulic retention time of 48 hours.
    - The methods used to simulate side inlet structures and water/sediment control basins in SWAT are essentially the same (i.e., temporary ponds); as such, it was determined that the same approach would be taken to simulate these structures throughout the BRW, knowing that structures in the lakeplain of the watershed would most likely be implemented as side inlets,

  while those in the upper portions of the watershed may be implemented as water/sediment control basins. Results of this analysis are, generally, considered applicable to both practices.

- Targeted water retention projects
  - Nine floodwater retention projects were identified for inclusion in the model; these structures were identified by the BRRWD as potential future flood control projects in the area. The general locations of these structures (as simulated in the SWAT model) are shown in **Figure 19**.
  - While still in their conceptual stages (i.e., exact project locations and sizes may change), the proposed designs of the projects were interpreted for inclusion in the SWAT model as best as possible. Structures that are currently designed to be off-channel were simulated as ponds with both primary and flood pools; structures that are designed to be in-channel were simulated as reservoirs. Two exceptions to this approach are off-channel structures near South Branch subbasins 56 and 79, which were simulated as in-channel reservoirs. Both of these structures are designed to receive in-channel flows above a given flow rate. Due to limitations in the SWAT model, simulating this type of hydraulics is not possible and, as such, the structures were most appropriately simulated as reservoirs receiving all flows from upstream. It is notable that some error is associated with this simulation method, particularly under certain flow conditions, since the model simulates all flow as routing through these structures, while they are currently only designed (and sized) to receive flow during certain flow events. Also notable is the simulation of the in-channel structure downstream of South Branch subbasins 20 and 25. This structure is currently designed to have multiple outlets, which the SWAT model does not allow. As such, the structure was simulated, within the SWAT model, as having a single outlet to one downstream reach. Again, some amount of error is associated with this method of simulation. Given these required modifications to structure design for simulation within the model (and the potential errors associated with them), results for this management scenario are only reported at the outlets of the Upper Mainstem and South Branch models and not internal to the watersheds.

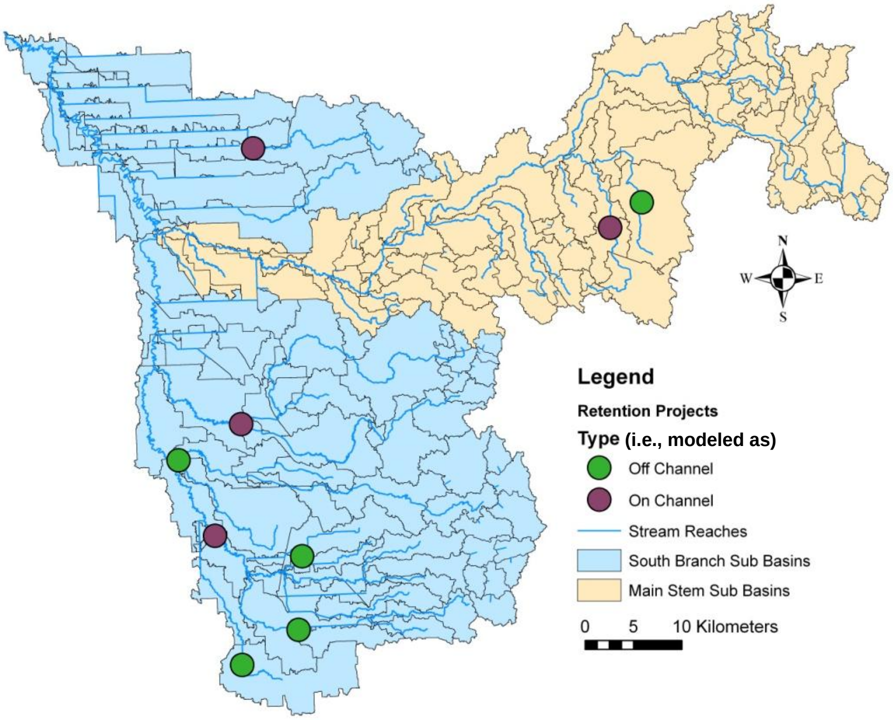


Figure 19. General location of proposed floodwater retention projects simulated in the SWAT models.

5. Model Results

5.1. Existing Conditions

The results of the BRW SWAT models can be interpreted in numerous ways. For the purposes of this report, the long-term results are presented and analyzed, since the decisions to be made from this modeling are on the watershed-scale and should represent the average condition. **Figure 20** shows the average annual predicted sediment yields from the subbasins in the BRW under existing conditions (i.e., conditions as described in **Section 2** of this report. Results from all years of modeling (1995-2009) were used to compute the yields, providing a long-term estimate of the amount of sediment that can be expected from different parts of the watershed. Results of this analysis show that higher sediment yields are predicted from steeper parts of the watershed, whereas low sediment yield values are shown in the lakeplain and the eastern, forested parts of the watershed.

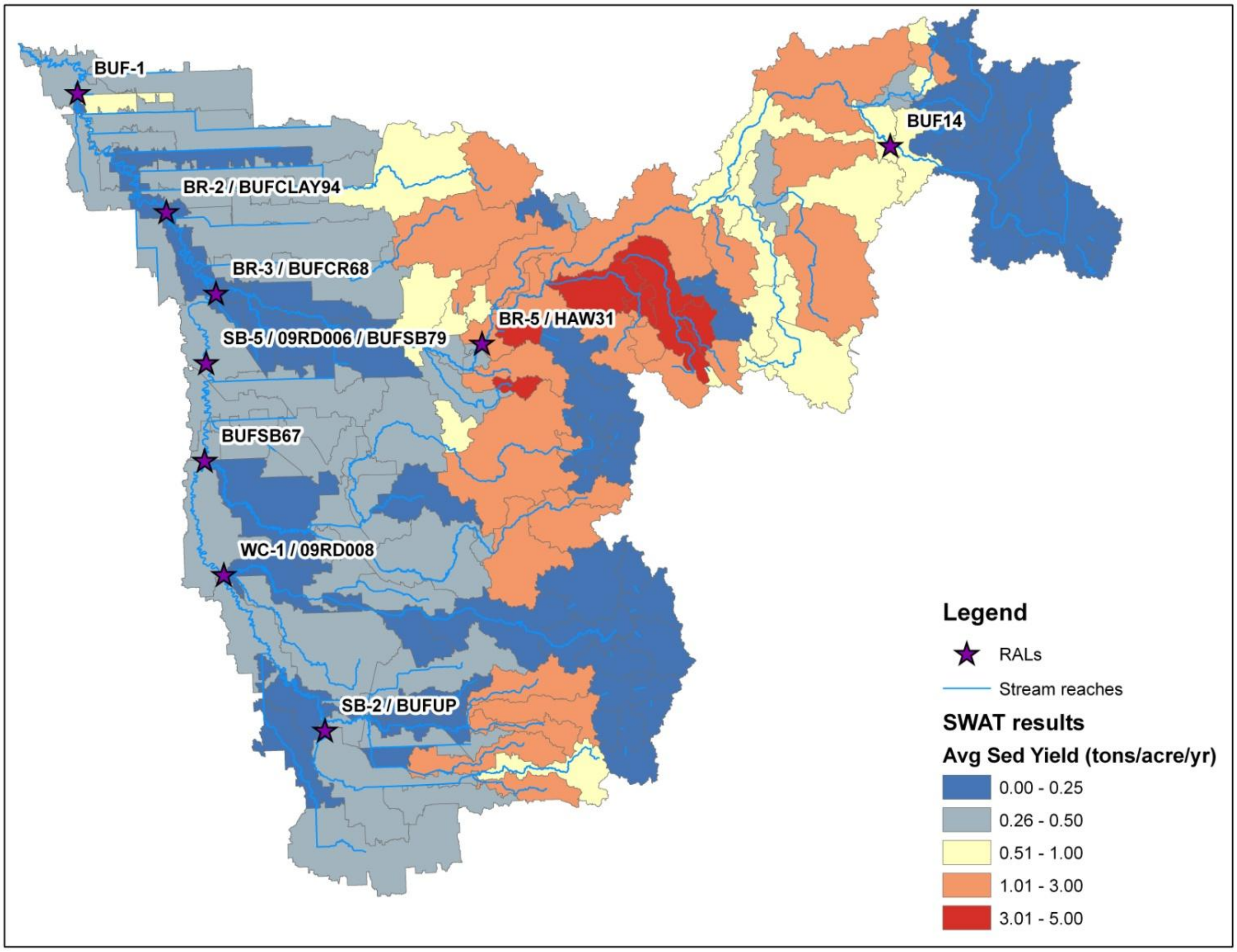


Figure 20. Average annual (1995-2009) sediment yields (tons/acre/year) under existing conditions.

Figure 21 shows the average annual (using results from 1995-2009) predicted TP yields in the area. Again, these results provide a long-term estimate of the amount of TP that is expected to be yielded from different parts of the watershed. Results are spatially similar to (though not consistently matching) those of the sediment loading.

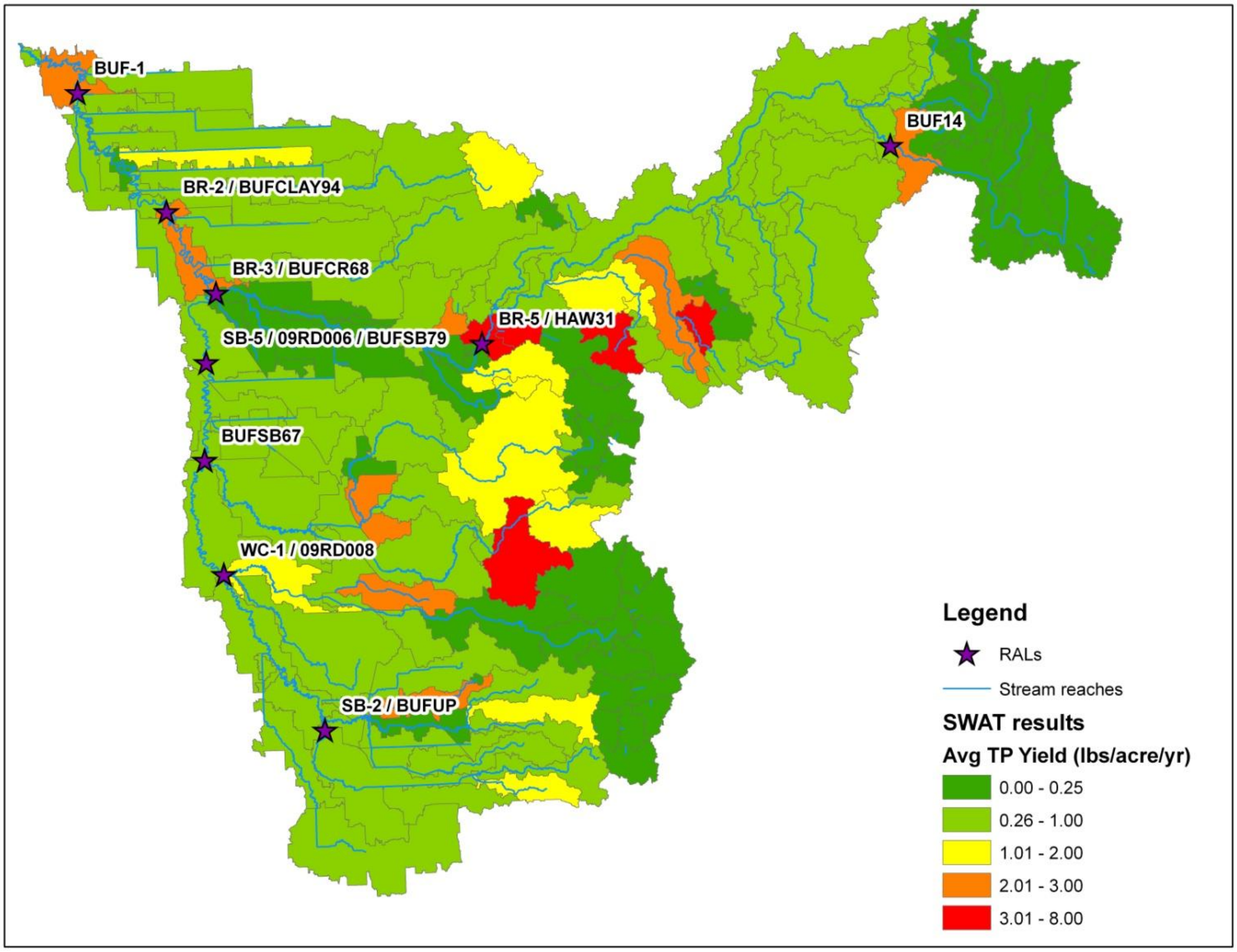


Figure 21. Average annual (1995-2009) TP yields (pounds/acre/year) under existing conditions.

For management purposes, the results of the SWAT modeling are also summarized at various BRRWD Regional Assessment Locations (RALs) throughout the watershed. These RALs have been identified by the BRRWD as locations in the watershed where project and program effectiveness should be monitored and assessed. Nine RALs were chosen for reporting the results; these RALs are identified as “primary” in the BRRWD’s Watershed Management Plan. Site BUF1 provides a location to consider hydrology, water quality, and management impacts in the BRW as a whole. Sites BUFSB67 and BR-3 / BUFCR68 provide insights on the South Branch and Upper Mainstem portions of the watershed, respectively. **Table 10** shows a summary of the average annual SWAT modeling results at the nine RALs; RAL locations are shown in **Figure 20** and **Figure 21**.

Table 10. Average annual (1995-2009) model results at BRRWD RALs under existing conditions.

	South Branch Model						Mainstem Model		
RAL	**BUF1**	**BR-2 / BUFCLAY94**	**SB-5 / 09RD006/ BUFSB79**	**BUFSB67**	**WC-1 / 09RD008**	**SB-2 / BUFUP**	**BR-3 / BUFCR68**	**BR-5 / HAW31**	**BUF14**
SWAT Reach(es)	2 (in)	17 (out)	28 (in)	30 (in)	61 (out)	92 (out)	1 (out) + 2 (out)	13 (out)	52 (out)
Avg Annual Volume (AF/yr)	226,009	218,869	94,321	85,437	13,638	8,919	128,707	104,369	13,546
Avg Annual Sediment Load (tons/yr)	18,675	6,304	7,326	1,915	326	639	1,743	7,522	44
Avg Annual TP Load (tons/yr)	129	111	41	38	6	5	69	67	4

Although simulating in-stream processes (e.g., bank failure) is not a strength of the SWAT model, model outputs can be used to get an understanding of how sediment is, generally, moving through the system. **Figure 22** shows the estimated average annual sediment balances on each of the stream reaches in the BRW SWAT model. Subtracting the average annual amount of sediment that exits each reach from the amount that enters it, provides insight to the deposition and scouring patterns within the watershed. Results of this analysis show that the majority of streams in the BRW are experiencing deposition on an average annual basis. Exceptions to this trend are shown in blue on the map.

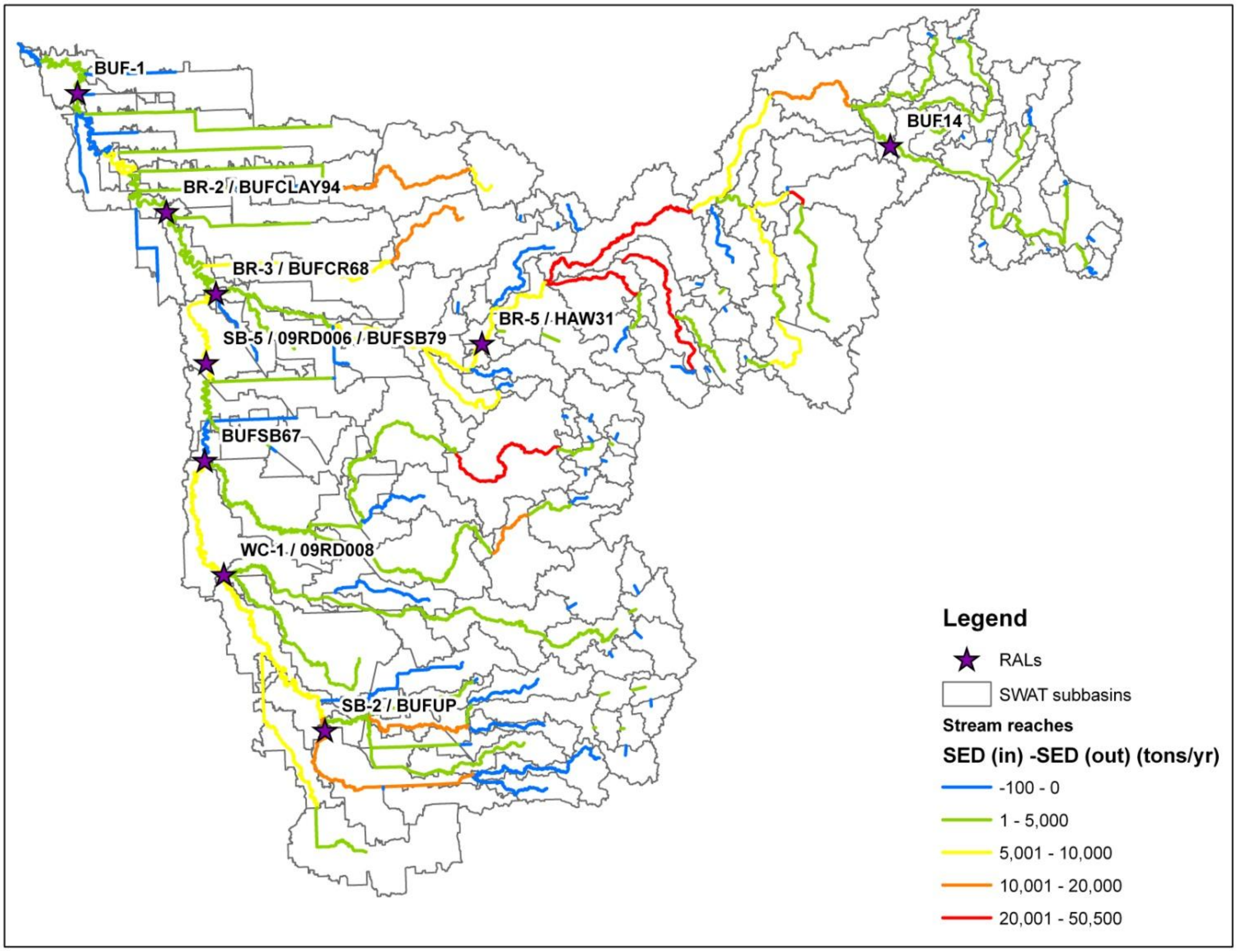


Figure 22. Average annual (1995-2009) sediment balance (in – out) on stream reaches in the BRW under existing conditions (tons/year).

5.2. Future Conditions

As mentioned, a main benefit of creating the BRW SWAT models is their use in simulating future "what if" scenarios to evaluate and compare the water quality impact of various BMPs and/or management strategies in the watershed. The following section summarizes the model results of the four BMP/management scenarios discussed in **Section 4**. Again, the modeling results are presented on an average annual basis and reported at the nine primary RALs in the watershed. Comparing the results presented in **Table 11** through **Table 15** with those in **Table 10** allows one to quantify the simulated impact of each BMP/management scenario; the percent change in average annual pollutant loading between the baseline (i.e., existing) condition scenario and each BMP/ management scenario is included in the summary tables.

Table 11 summarizes the model results for the reduced tillage scenario. Results of the SWAT model show that, on an average annual basis, the impact of reduced tillage in the BRW (when compared to baseline conditions) would have minimal impact on pollutant loadings throughout the study area.

Table 11. Average annual (1995-2009) model results at BRRWD RALs under the reduced tillage BMP scenario.

	South Branch Model						Mainstem Model		
RAL	**BUF1**	**BR-2 / BUFCLAY 94**	**SB-5 / 09RD006/ BUFSB79**	**BUFSB67**	**WC-1 / 09RD008**	**SB-2 / BUFUP**	**BR-3 / BUFCR68**	**BR-5 / HAW31**	**BUF14**
SWAT Reach(es)	2 (in)	17	28 (in)	30 (in)	61	92	1 + 2	13	52
Avg Annual Volume (AF/yr)	226,987	219,396	94,705	85,786	13,741	8,953	129,150	104,445	13,546
Avg Annual Sediment Load (tons/yr)	18,772	6,297	7,349	1,928	336	629	1,697	7,523	44
% Reduction in Avg Annual Sediment Load	**-1%**	**0%**	**0%**	**-1%**	**-3%**	**2%**	**3%**	**0%**	**0%**
Avg Annual TP Load (tons/yr)	131	111	40	38	6	5	71	67	4
% Reduction in Avg Annual TP Load	**-2%**	**-1%**	**1%**	**2%**	**0%**	**4%**	**-2%**	**-1%**	**0%**

Table 12 summarizes the model results for the 15-meter filter strip scenario, while **Table 13** summarizes results for the 30-meter scenario. In both cases, the SWAT model shows significant reduction in sediment and TP loadings when filter strips are employed. Additional benefit is provided by moving from a 15-to 30-meter buffer, but the pollutant load reductions are not directly proportional to the width increases.

Table 12. Average annual (1995-2009) model results at BRRWD RALs under the 15-meter filter strip BMP scenario.

	South Branch Model						Mainstem Model		
RAL	**BUF1**	**BR-2 / BUFCLAY94**	**SB-5 / 09RD006/ BUFSB79**	**BUFSB67**	**WC-1 / 09RD008**	**SB-2 / BUFUP**	**BR-3 / BUFCR68**	**BR-5 / HAW31**	**BUF14**
SWAT Reach(es)	2 (in)	17	28 (in)	30 (in)	61	92	1 + 2	13	52
Avg Annual Volume (AF/yr)	226,009	218,869	94,321	85,437	13,638	8,919	128,707	104,369	13,546
Avg Annual Sediment Load (tons/yr)	7,772	4,346	4,425	1,800	326	497	1,155	5,412	44
% Reduction in Avg Annual Sediment Load	**58%**	**31%**	**40%**	**6%**	**0%**	**22%**	**34%**	**28%**	**0%**
Avg Annual TP Load (tons/yr)	91	89	21	21	6	1	52	51	4
% Reduction in Avg Annual TP Load	**29%**	**19%**	**48%**	**46%**	**7%**	**75%**	**25%**	**24%**	**0%**

Table 13. Average annual (1995-2009) model results at BRRWD RALs under the 30-meter filter strip BMP scenario.

	South Branch Model						Mainstem Model		
RAL	**BUF1**	**BR-2 / BUFCLAY94**	**SB-5 / 09RD006/ BUFSB79**	**BUFSB67**	**WC-1 / 09RD008**	**SB-2 / BUFUP**	**BR-3 / BUFCR68**	**BR-5 / HAW31**	**BUF14**
SWAT Reach(es)	2 (in)	17	28 (in)	30 (in)	61	92	1 + 2	13	52
Avg Annual Volume (AF/yr)	226,009	218,869	94,321	85,437	13,638	8,919	128,707	104,369	13,546
Avg Annual Sediment Load (tons/yr)	5,096	3,207	3,351	1,775	326	466	1,026	4,948	44
% Reduction in Avg Annual Sediment Load	**73%**	**49%**	**54%**	**7%**	**0%**	**27%**	**41%**	**34%**	**0%**
Avg Annual TP Load (tons/yr)	82	84	17	17	6	0	48	47	4
% Reduction in Avg Annual TP Load	**36%**	**24%**	**59%**	**57%**	**9%**	**93%**	**31%**	**30%**	**0%**

Results of the side inlet/sediment control basin BMP scenario are summarized in **Table 14**. Similar to the filter strip scenario, SWAT is predicting significant reductions in sediment and TP loadings from this practice. Reductions vary across the watershed, but at most locations are comparable to those seen under the 15-meter filter strip scenario.

Table 14. Average annual (1995-2009) model results at BRRWD RALs under the side inlet/sediment control basin BMP Scenario.

	South Branch Model						Mainstem Model		
RAL	**BUF1**	**BR-2 / BUFCLAY94**	**SB-5 / 09RD006/ BUFSB79**	**BUFSB67**	**WC-1 / 09RD008**	**SB-2 / BUFUP**	**BR-3 / BUFCR68**	**BR-5 / HAW31**	**BUF14**
SWAT Reach(es)	2 (in)	17	28 (in)	30 (in)	61	92	1 + 2	13	52
Avg Annual Volume (AF/yr)	198,358	197,725	74,772	67,117	11,156	7,854	118,151	99,413	13,507
Avg Annual Sediment Load (tons/yr)	11,489	4,455	4,323	1,182	254	503	1,093	6,144	43
% Reduction in Avg Annual Sediment Load	**38%**	**29%**	**41%**	**38%**	**22%**	**21%**	**37%**	**18%**	**4%**
Avg Annual TP Load (tons/yr)	103	95	28	27	4	4	62	61	4
% Reduction in Avg Annual TP Load	**20%**	**14%**	**31%**	**31%**	**37%**	**22%**	**10%**	**9%**	**8%**

Table 15 presents a summary of the targeted water retention projects scenario at three RALs in the watershed. Given the number of assumptions and generalizations required to simulate the water retention projects in SWAT, and also the conceptual nature of their design (i.e., uncertainty in exact sizes or location), the results of this scenario are reported only at the outlets of the major drainage areas (i.e., Upper Mainstem, South Branch, and BRW overall) in the BRW. Results of the SWAT modeling show that, as simulated, these projects have some water quality benefit; this benefit is less than that seen from implementing filter strips and/or side inlets/sediment control basins.

Table 15. Average annual (1995-2009) model results at BRRWD RALs under the targeted water retention projects scenario.

	South Branch Model		Mainstem Model
RAL	**BUF1**	**BUFSB67**	**BR-3 / BUFCR68**
SWAT Reach(es)	2 (in)	30 (in)	1 + 2
Avg Annual Volume (AF/yr)	199,343	73,866	124,980
Avg Annual Sediment Load (tons/yr)	17,229	1,677	1,691
% Reduction in Avg Annual Sediment Load	**8%**	**12%**	**3%**
Avg Annual TP Load (tons/yr)	107	26	65
% Reduction in Avg Annual TP Load	**17%**	**32%**	**6%**

6. Conclusion

Two SWAT models, one covering the Upper Mainstem of the Buffalo River and the other covering the South Branch, were created to simulate the long-term hydrology and water quality of the BRW. The models were developed to simulate conditions from 1995 through 2009. The models were calibrated using data from 2001 through 2006 and validated using data from 1996 through 2000. Overall, the models proved to perform well, with simulated mean daily flow values within -3.7 and -31.5% of the observed mean values (for the Upper Mainstem and South Branch models, respectively) for the calibration period and within -6.0 and 3.4% of the observed mean values for the validation period. Model performance at the outlet of the watershed showed simulated and observed mean daily flows were within -12.9% of each other during the entire calibration/validation period (1996-2006).

The SWAT model did a good to excellent job predicting sediment and TP loads at most monitoring points. A notable exception is model under-prediction of sediment at a monitoring point located near the watershed outlet. In contrast to generally good agreement at upland monitoring locations, under-prediction of sediment near the watershed outlet suggests that other sources of suspended solids such as re-worked channel sediments or in-stream primary productivity may be important in downstream reaches of the Buffalo River. Although the model performed poorly at simulating sediment loading at this site, TP values showed less error. It is notable that a lack of observed flow data at water quality monitoring stations required simulated flows to be used when estimating “observed loads” for calibration/validation purposes; this may have impacted the outcomes of the water quality calibration/validation process.

While the BRW SWAT models were developed to simulate bacterial loadings in the watershed based on inputs from local managers and the best available data in the area, model results do not represent bacterial water quality in the area. Based on these results, it is not recommended that the SWAT models be employed to evaluate fecal coliform water quality problems in the BRW at this time, but rather that empirical methods be used to evaluate the issue. It is recommended that additional work be done to refine the identification of bacterial sources and pathways in the BRW, potentially including the performance of a microbial tracking study.

A main benefit of developing SWAT models for the BRW is their use in evaluating future BMP/management scenarios in the watershed. In this case, the BRW SWAT models were used to evaluate four different management scenarios, based on input from local management agencies including the identification of which strategies are most likely to be used to protect and restoration water quality in the BRW in the future. Of the four management scenarios evaluated, filter strips and side inlets/sediment control basins were shown to be most effective at reducing sediment and TP loads throughout the watershed. Reduced tillage was shown to have minimal, if any, water quality impact, while the targeted retention project scenario showed some water quality benefit.

The fact that reduced tillage is not simulated to have greater water quality benefits in this watershed is not necessarily surprising. The flat landscape that dominates the BRW means surface runoff is likely not a dominant erosion pathway during minor to moderate rainfall events at most sites. During larger events that do generate surface runoff, filter strips and side inlet structures are more effective than reduced fall tillage at reducing edge-of-field losses. (In SWAT simulations of other watersheds with steeper landscapes, conservation tillage has been shown to be effective in reducing sediment and phosphorus runoff). While there can be other benefits to increasing crop residue in surface soils such as soil organic matter maintenance and soil moisture retention, reduced fall tillage (as simulated in this model) is not expected to achieve substantial sediment and phosphorus water quality improvements in the BRW.

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Appendix A - Summary of crop and manure management scenarios for BRW SWAT models (under Existing Conditions).

General Information:

Total cropland area: (manure-applied land is divided proportionately between SWAT models)

BR_South	159,484 ha	71%
BR_Main	63,132 ha	29%

Assume that manure is applied to 10% of cropland (distributed proportionately between SWAT models)

Commercial Nitrogen fertilizer application rates = 141 and 67 kg ha^{-1} (as N) for corn and wheat, respectively.

Dairy Manure

Watershed-Wide Waste Creation = 112,783,421 kg/yr (source: HEI summary data for Buffalo River)

Nutrient Content Based on Dairy manure in SWAT fertilizer database:

- Mineral P = 0.005 kg P/kg manure
- Organic P = 0.003 kg P/kg manure
- Mineral N = 0.007 kg/kg manure
- Organic N = 0.031 kg/kg manure

Swine Manure

Watershed-Wide Waste Creation = 47,355,450 kg/yr (source: HEI summary data for Buffalo River)

Nutrient Content Based on Dairy manure in SWAT fertilizer database:

- Mineral P = 0.011 kg P/kg manure
- Organic P = 0.005 kg P/kg manure
- Mineral N = 0.026 kg/kg manure
- Organic N = 0.021 kg/kg manure

Beef Manure

Watershed-Wide Waste Creation = 178,995,816 kg/yr (source: HEI summary data for Buffalo River)

Assume 50% is applied to cropland.

Nutrient Content Based on Dairy manure in SWAT fertilizer database:

- Mineral P = 0.004 kg P/kg manure
- Organic P = 0.007 kg P/kg manure
- Mineral N = 0.01 kg/kg manure
- Organic N = 0.03 kg/kg manure

Manure application rates were varied by manure type in order to result achieve manure application on 10% of the cropland in the watershed. When converted to the mineral N content of the manure, this resulted in a 3-year average N application rate of 131 kg ha^{-1}, this is 1.89 times greater than the 3-year average rate for fields receiving commercial fertilizer (69 kg ha^{-1}).

Determining which subbasins receive manure:

For each manure type, subbasins were selected sufficient to receive manure at the N application rate described above. Three subbasins (with similar crop area) were selected for each manure type in order to ensure that similar amounts of manure are applied throughout the 3-year rotation). Subbasins for each manure type are summarized below:

Subbasins - South Branch Model			Subbasins - Upper Mainstem Model		
Dairy	Sub	Area	Dairy	Sub	Area
	2	1560		10	561
	42	1490		13	550
	82	1467		17	569
Swine	Sub	Area	Swine	Sub	Area
	12	2018		18	1076
	55	2437		24	910
	61	2244		34	815
Beef	Sub	Area	Beef	Sub	Area
	17	1655		26	644
	58	1646		33	596
	63	1664		52	686

Subbasins were selected based on their row-crop area in order to simulate the three-year crop rotation on the appropriate amount of land. It is important to note that these subbasins may not necessarily be representative of where manure is applied in the watershed and it is likely that manure application areas vary from year to year. This approach, however, is necessary to simplify model management and results from these subbasins provide a meaningful contrast against subbasins that do not receive manure.

Prior to implementing manure management files to the subbasins indicated above, all subbasins received basic management files (commercial fertilizer) as follows:

Subbasin	Crop Rotation
1	S-C-W
2	C-W-S
3	W-S-C
4	S-C-W
5	C-W-S
6	W-S-C
…	…
…	…
…	…
91	S-C-W
92	C-W-S
93	W-S-C

Following implementation of crop management files with commercial fertilizer, appropriate manure management files were over-written to the indicated subbasins.

Beef Manure applied to pasture:

Watershed-Wide Waste Creation = 178,995,816 kg/yr (source: HEI summary data for Buffalo River) assume half is applied to pasture.
Total Hay area in both models = 22,456 ha (assume that half receives beef manure)
Assume that beef manure is only applied to hay land from March 15 to November 15 (245 days).
Total annual beef manure application to hay areas = 7,971 kg ha^{-1} yr^{-1}. (adjust to daily rate = 32.5 kg ha^{-1} day^{-1})
Subbasins with hay land receiving beef manure are summarized below.

Subbasins Receiving Beef Manure from March 15 to November 15

Upper Mainstem Model		South Branch Model	
Sub#	Hay area (ha)	Sub#	Hay area (ha)
15	404	46	1214
40	1086	56	834
47	667	58	1139
48	1312	59	749
49	794	65	1191
52	356	67	503
68	359		

Duck Manure:

Duck manure is based on two scenarios:
The generic condition (all wetlands outside of the wildlife refuge) assumes duck manure is applied at a rate of 1.7 kg/ha/day from March 15th through October 31st.
In the national wildlife refuge the manure rates are as follows:

- 0.38 kg/ha/day from March 15th to May 30th
- 1.7 kg/ha/day from May 30th to September 15th
- 3.6 kg/ha/day from September 15th to October 31st.

Appendix B – Technical Memorandum on Bacterial Sources in the BRW.

MEMO

(External Correspondence)

Houston Engineering Inc.

To: Bruce Albright, BRRWD
Jack Frederick, MPCA

Date: January 21, 2013

File: 1915-185

From: Jennifer Swanson

Through: Stephanie Johnson, PhD, PE

Subject: BRW Bacteria Source Assessment & Quantification

INTRODUCTION

The following memorandum is intended to summarize rural bacteria sources in the Buffalo River Watershed (BRW) (HUC 09020106) for purposes of source identification and quantification. The findings will be used to inform the on-going watershed restoration and protection efforts in the area, including the creation of watershed loading models (SWAT). Findings of this work were informed by numerous state and local datasets, in addition to discussions amongst stakeholders and resource managers within the BRW.

The BRW currently has 22 stream assessment units listed as impaired for bacteria (MPCA, 2012). Land use within the BRW is primarily agriculture, accounting for 73 percent of the landscape. The remaining land uses include forest (9%), urban (5%), grasslands (2%), and open water/wetlands (11%) (NLCD 2006). Nine municipalities lie within the watershed ranging in population from 125 to 2,173, with three of them having populations over 1,000. Seven of these municipalities operate wastewater treatment facilities (WWTFs). This bacteria source assessment focuses on rural sources of bacteria, since large urban areas are non-existent in the watershed (a large portion of the 5% urban area in the watershed accounts for roads). Bacteria loadings from the non-road urban areas are primarily accounted for through inclusion of the WWTFs. **Figure 1** provides a visual of the physical setting of the BRW, indicating those streams that are considered impaired for bacteria.

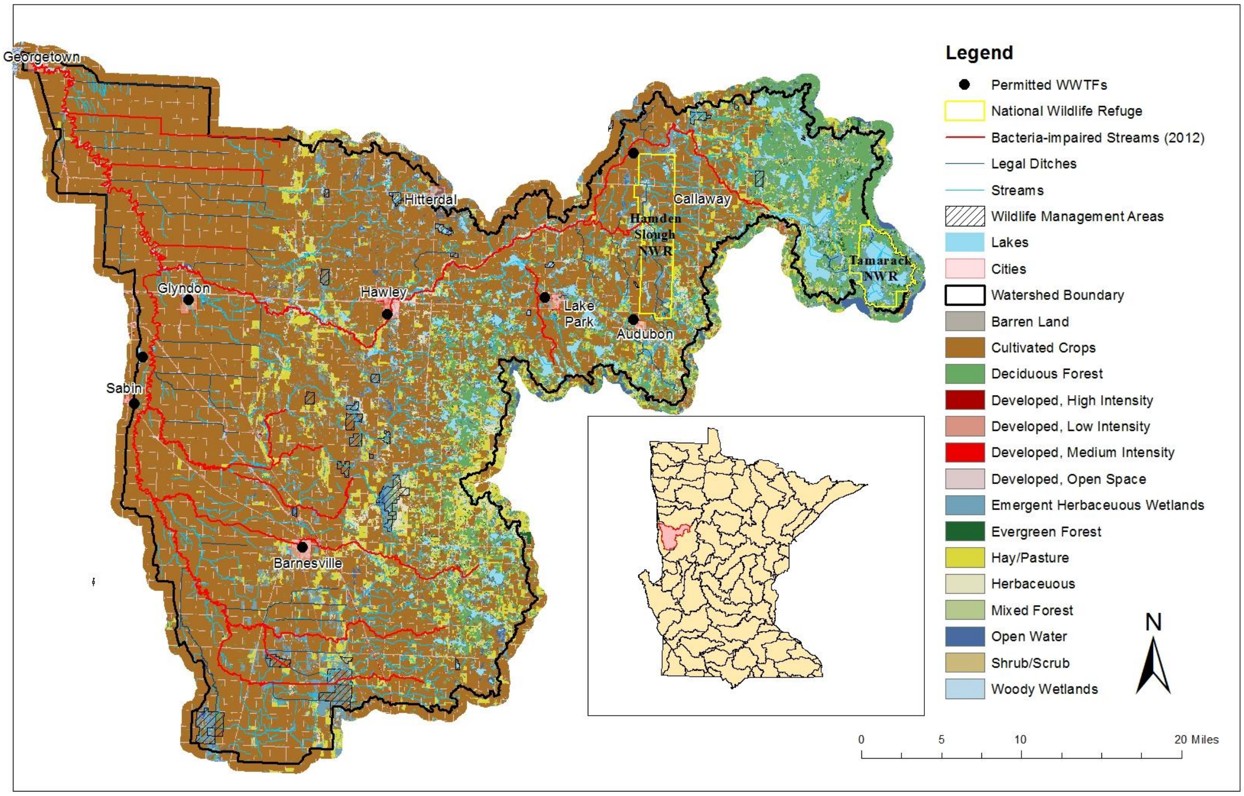

Figure 1. BRW physical setting and bacteria-impaired streams

Fecal contamination of waterways is a widespread public health problem. Fecal coliform bacteria are a group of organisms common to the intestinal tracts of warm blooded organisms (EPA, 2012) and typically enter the environment through a variety of sources, including urban and agriculture runoff, livestock feedlots, inadequately treated domestic sewage, and wildlife. Per federal guidance, *Escherichia coli* (i.e., *E. coli*) are the bacteria most commonly-used to indicate fecal contamination of freshwater systems (*E. coli* are a subset of fecal coliform bacteria). The presence of *E. coli* in water is thought to indicate recent fecal contamination and in turn signals the possible presence of pathogens. Limitations in monitoring tools can make it difficult to determine the source of bacterial contamination. Monitoring the presence and levels of fecal indicator bacteria, such as *E. coli*, alone can only determine the degree of contamination and not the host species responsible for it.

The relationship between bacterial sources and bacterial concentrations found in streams is complex, involving precipitation and flow, temperature, livestock management practices, wildlife activities, survival rates, land use practices, and other environmental factors. Despite the complexity of the relationship between sources and in-stream bacterial concentrations, the following can be considered major sources in rural areas: livestock facilities, livestock manure, wildlife, malfunctioning subsurface sewage treatment systems (SSTSs), and WWTFs. Recent research has shown that some bacteria persist in soil and sediments throughout the year without the continuous presence of sewage or mammalian sources (Sadowsky et al., 2010). In addition, growth and the eventual resuspension of bacteria from sediments can be a bacterial source (Marino and Gannon, 1991). Quantifying the amount of bacteria that may enter a system through persistence, regrowth, and resuspension is extremely difficult, due to a lack of data. As such, the role of these potential sources in the BRW was not estimated; the potential for their influence, however, is an important consideration in the future development of restoration and protection strategies.

COUNTY AND WATERSHED AREAS

Many of the datasets available for computing the population of bacteria sources (e.g., wildlife) in the BRW report values on a county-wide basis. The first step in using these datasets for our work was to compute the proportion of each project area county that actually lies within the BRW. Four counties (Becker, Clay, Otter Tail, and Wilkin) lie within the BRW boundary. Geographic Information System (GIS) data layers, downloaded from the Minnesota Department of Natural Resources (MN DNR) DataDeli website, were used within ArcGIS to determine the total area of each county. Next, the area of each county that falls within the BRW was determined using the *intersect* and the *calculate geometry* tools within ArcGIS. Finally, the area of each county within the watershed was divided by the total area of the county and converted to a percentage. The resultant numbers are shown in **Table 1** and were used in estimating the number of deer and waterfowl in the BRW.

Table 1. Square miles in BRW, by county

	Becker	Clay	Otter Tail	Wilkin
Area (miles^2)	1,445	1,054	2,225	752
Area in BRW (miles^2)	288	801	45	231
% of area in BRW	20%	76%	2%	31%

LIVESTOCK FACILITIES

The Minnesota Pollution Control Agency (MPCA) regulates the collection, transportation, storage, processing and disposal of animal manure and other livestock operation wastes (MPCA, 2011). The MPCA currently uses the federal definition of a Concentrated Animal Feeding Operation (CAFO) in its regulation of animal facilities. In Minnesota, the following types of livestock facilities are issued, and must operate under, a National Pollutant Discharge Elimination System (NPDES) permit: a) all federally defined (CAFOs); and b) all CAFOs and non-CAFOs which have 1,000 or more animal units (MPCA, 2010). Facilities with less than 1,000, but more than 50, animal units (and are outside of shoreland areas) are regulated by MPCA under a registration program. Facilities with more than 10 animal units and inside shoreland areas are also regulated under this program. Shoreland is defined in MN Statute § 103F.205 to include: land within 1,000 feet of the normal high-watermark of lakes, ponds, or flowages; land within 300 feet of a river or stream; and designated floodplains (MPCA, 2009).These smaller facilities are subject to state feedlot rules which include provisions for registration, inspection, permitting, and upgrading.

MPCA provided four livestock datasets, one for each county, which report the following information: the registered livestock facility number, owner name and associated contact information, and number of livestock at the facility by livestock group. MPCA also provided a shapefile of registered facility locations within the BRW. Per guidance from MPCA staff, the reported number of livestock at each facility was taken from the county-based datasets, while the shapefile was used to note facility location (Michael Sharp, 2012). To compute the number of livestock facilities (and associated livestock) in the BRW, the registration number in the county-based datasets was paired with the registration number in the GIS shapefile to identify the livestock facilities within the BRW. The number of animals at these facilities was then summed and reported by livestock group and by county.

According to the MPCA's data, there are a total of 2,141,831 agricultural animals (in registered and permitted facilities) in the BRW. The majority of these animals are birds (2,092,190), followed by bovine (26,847) and all other animals (22,794). **Table 2** contains a summary of this data, by county. **Figure 2** shows the location of the facilities. Currently, seven livestock facilities in the BRW operate under NPDES permits. These facilities contain 1,478,336 - or 69 percent - of the agricultural birds in the watershed. Per their permit requirements, these facilities must be designed to totally contain all surface water runoff and also have manure management plans.

Table 2. Livestock population estimates for BRW, by county

	Becker	Clay	Otter Tail	Wilkin	Watershed Total
MPCA-Registered Facilities[1]					
Bovine					
Beef	3,413	11,810	643	2,140	**18,006**
Dairy	2,934	3,060	1,744	373	**8,111**
Birds					
Broilers	60	100	25	75	**260**
Layers	20	305,552	0	20	**305,592**
Turkey	48,000	0	140,002	120,000	**308,002**
Goats/Sheep	80	415	0	0	**495**
Horses	51	155	13	7	**226**
Pigs	25	15,856	12	0	**15,893**
NPDES-Permitted Facilities[2]					
Bovine					
Dairy		730			**730**
Birds					
Broilers		2,000			**2,000**
Layers		1,339,000			**1,339,000**
Turkey		137,336			**137,336**
Pigs		6,180			**6,180**

[1] Facilities outside shoreland with >50 and <1,000 animal units or within shoreland and having >10 animal units; [2] Facilities with >1,000 animal units

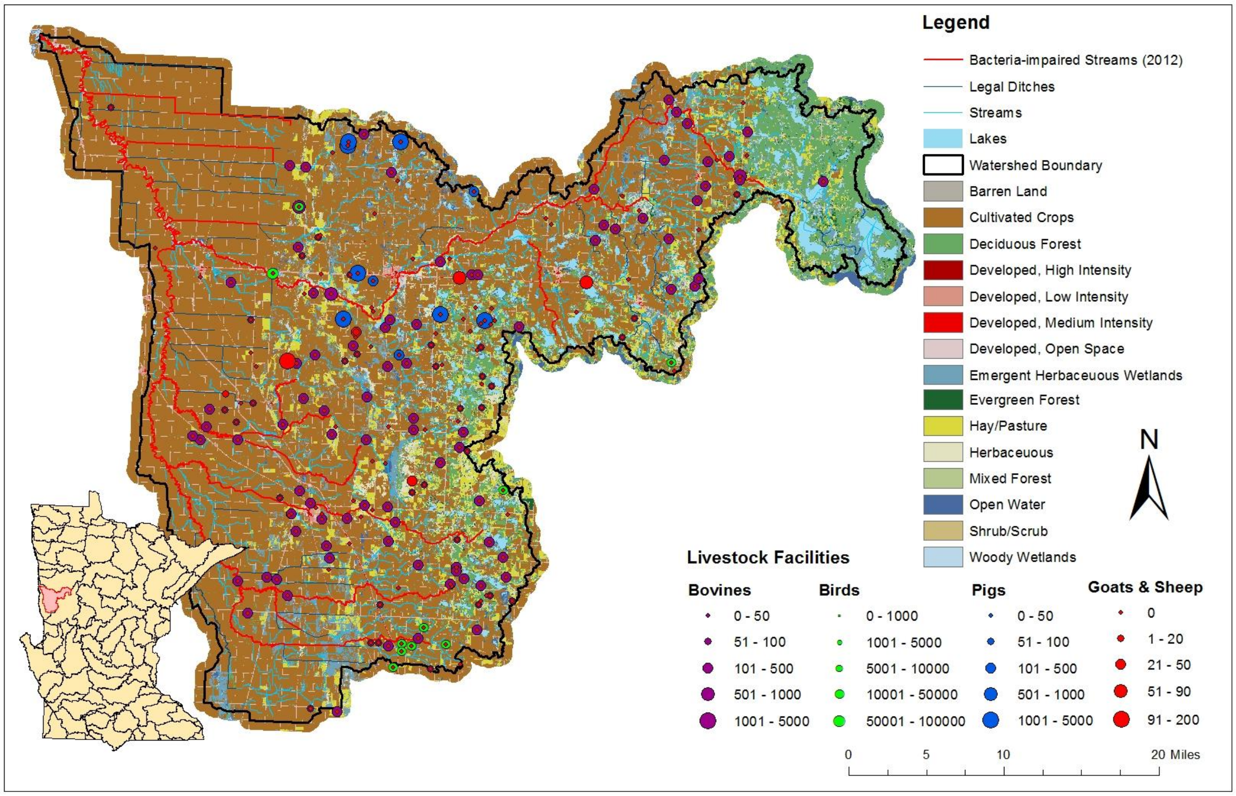

Figure 2. BRW NPDES-permitted and MPCA-registered livestock facilities

LIVESTOCK MANURE

Runoff from livestock facilities, pastures, and (manure) land application areas has the potential to be a significant source of fecal bacteria and other pollutants to surface water systems. Spatial variation in the type and density of livestock across the BRW varies considerably. In order to identify the major sources of surface water bacterial contamination in the BRW, livestock contained in NPDES-permitted facilities were separated from livestock in MPCA-registered facilities.

Per information from the MPCA, five of the NPDES-permitted facilities in the BRW compost their manure and sell it commercially, one facility transfers its waste, and one facility land applies its waste. It is unknown how much of the waste from these facilities stays in the watershed versus what is transported outside the watershed boundary. Given the regulations under which these facilities operate, however, (including the zero discharge effluent limitation) they should not be a major contributor to fecal contamination in the BRW. Therefore, for purposes of source identification, it is assumed that none of the bacterial contamination in the surface waters of the BRW originates from the NPDES-permitted facilities.

Livestock facilities registered by the MPCA are also required to perform various measures to reduce their impact on the environment. The majority of MPCA-registered cattle operations are relatively small (<500 animals), with open feedlots, presenting the potential for polluted runoff much of the year. In addition, MPCA estimates nearly 100% of both the registered and non-registered facilities in the BRW land apply their manure. Manure application typically occurs in the fall months, September through November, with the highest volume of manure application in October (Brands, 2012). As such, manure from these facilities has a high likelihood of transport into the surface waters of the BRW.

WILDLIFE

Wildlife populations can be difficult to effectively estimate. In order to determine if wildlife are major contributors to fecal production in the BRW the efforts of this project focused on estimating deer and waterfowl populations. These species are known contributors of fecal contamination to surface waters, have considerable populations within the BRW, and have data readily-available on their densities in the area. Waterfowl are often a major contributor of bacteria to surface waters since they defecate directly into the water. Although deer do not defecate directly into surface water they are also common contributors, given their commonality and abundance.

Data for deer and waterfowl estimates in the BRW were obtained from the MN DNR and U.S. Fish and Wildlife Service (USFWS), respectively. This data was paired with the watershed area data calculated above to estimate the number of deer and waterfowl in the BRW. Base waterfowl numbers were estimated for the entire watershed and additional waterfowl numbers were estimated for spring breeding and fall migration in the Tamarac National Wildlife Refuge (Tamarac NWR).

Deer estimates for the majority of the BRW were calculated utilizing the MN DNR 2011 Pre-Fawn Deer Density from Deer Population model results. In areas not covered by the DNR data, the Tamarac NWR and Wetland Management District Comprehensive Conservation Plan (CCP) was used to supplement. Both data sources estimate the number of deer/mile^2 in the area. To compute deer populations in the BRW, ArcGIS was used to overlay the watershed boundary map on the 2011 Pre-Fawn Deer Density from Deer Population Map (MN DNR, 2011), which reports deer densities by hunting unit. It was assumed that the reported density within each hunting unit is uniform and the area of each hunting unit in the BRW was estimated. The area of each hunting unit in the BRW was combined with the deer density in each unit and summed to compute both the number of deer in each county of the BRW, as well the total number of deer in the watershed overall. **Table 3** contains a summary of the results.

Waterfowl estimates were calculated utilizing the USFWS Waterfowl Breeding Populations and Production Estimates Annual Report for 2011 and are based off estimates of pairs/mile^2 for thirteen species (USFWS, 2011). The Glacial Lakes Prairie Area of the Fergus Falls Wetland Management District (WMD) covers Wilkin and Otter Tail County and the Agassiz Ridge Prairie Area of the Detroit Lakes WMD covers Clay and Becker County. Since Clay and Becker County account for the majority (80%) of the BRW, the waterfowl density estimate of 14.5 pairs/mile^2 for the Agassiz Ridge Prairie Area was applied to the entire BRW for purposes of estimating base waterfowl populations (i.e., the population of birds that is present throughout the BRW from April through October). The area of the watershed (1,364 miles) was multiplied by the waterfowl density to compute the number of waterfowl pairs in the BRW. This number was then multiplied by two to estimate the base number of individual birds in the watershed (39,564 birds) from April through October.

In addition to the waterfowl that are typically within the watershed throughout the spring to fall months, certain areas of the watershed experience considerable population increases during spring and fall migrations. Given its size and the availability of data to estimate migratory populations, the Tamarac NWR was the one area in the BRW that these population increases were taken into account. The Tamarac NWR CCP indicates that 50,000 waterfowl typically migrate through the Refuge between mid-September and the end of October. For this work, we assumed the waterfowl were evenly distributed across the refuge and estimated the fall migration populations in the BRW portion of the Tamarac NWR by multiplying the percent of the Refuge in the BRW(19%) by the overall fall migration number. **Table 3** shows the result of this calculation.

The Tamarac NWR CCP also identifies the spring breeding pair density in the Refuge to be 40 pairs/mile^2. To account for this increase in waterfowl populations in the watershed, a calculation similar to what was done for the fall population estimates was made. The computed number of spring breeding pairs in the BRW portion of the Refuge was then multiplied by two to compute the population of waterfowl in this area during spring breeding (mid-March through the end of May). Again, **Table 3** summarizes the results.

Table 3. Wildlife population estimates in the BRW, by county

	Becker	Clay	Otter Tail	Wilkin	Watershed Total
Deer	4,969	2,402	494	692	8,557
Waterfowl base numbers (April-October)	8,354	23,215	1,303	6,692	39,564
Tamarac NWR (Spring breeding)	1,019				
Tamarac NWR (Fall Migration)	9,544				

SUBSURFACE SEWAGE TREATMENT SYSTEMS (SSTSs)

Malfunctioning SSTSs can be an important source of fecal contamination to surface waters, especially during dry periods when these sources continue to discharge and surface water runoff is minimal. Of the rural population in the BRW, an estimated 1,252 households - or 38 percent - have inadequate treatment of their household wastewater. This includes individual residences and un-sewered communities.

Data obtained from the U.S. Department of Commerce United States Census Bureau's 2000 Census was used to identify the potential number of SSTSs in the BRW, by county. This identification was performed by assuming that all households outside of the city limits use a SSTS. Data contained in a report from the MPCA to the State Legislature in 2011 (MPCA, 2011) were used to estimate the percent of these systems that are failing and those that are an Imminent Public Health Threat (IPHT).

Following is an excerpt from that report on the current status of SSTS compliance and strategies counties are pursuing to improve compliance.

> *"Once a SSTS is inspected, the owner receives a Certificate of Compliance (CoC) or Notice of Noncompliance (NoN). A CoC for a new SSTS is valid for five years; a CoC for an existing system is valid for three years. Noncompliance falls into two categories: IPHT or Failing to protect groundwater. IPHT indicates the SSTS discharges sewage to surface water; sewage discharge to ground surface; sewage backup; or any other situation with the potential to immediately and adversely affect or threaten public health or safety. Failing to protect groundwater indicates the bottom of the system does not have the required separation to groundwater or bedrock." (MPCA, 2011)*

The MPCA document reports numbers from 2000-2009 on the total number of SSTSs by county, along with the average estimated percent of SSTSs that are failing versus the percent that are considered IPHTs. Although estimates of the number of SSTSs per county were provided in this report, Becker County had no data reported for this parameter, so the U.S. Census-based estimates of SSTS numbers were used for this work. The total numbers of SSTSs per county were then multiplied by the estimated percent IPHT and percent failing within each area (MPCA, 2011) to compute the number of potential IPHTs and potentially failing SSTSs per county and in the BRW overall. **Table** 4 summarizes the results.

Table 4. SSTS compliance status in the BRW, by county

	Becker	**Clay**	**Otter Tail**	**Wilkin**	**Watershed Total**
Identified # of SSTSs	842	2,141	114	190	3,287
Estimated % IPHT	0%	12%	13%	16%	---
Estimated % Failing	28%	27%	40%	48%	---
# of potential IPHTs	0	257	15	30	302
# of potentially failing SSTSs	236	578	46	91	951

WASTEWATER TREATMENT FACILITIES (WWTFs)

There are seven WWTFs in the BRW. Information on the location, permitted flow and concentrations, and monitored flow and concentrations for each of these facilities were provided by MPCA. All permitted WWTFs in the State of Minnesota are required to monitor their effluent to ensure that concentrations of specific pollutants remain within levels specified in their discharge permit. Effluent limits require that fecal coliform concentrations remain below 200 organisms per 100 milliliters from April 1 through October 31 (MPCA, 2002).

The WWTFs in the BRW are all pond-type treatment plants with primary and secondary treatment lagoons. The general operation of these facilities is to discharge their treated waste into the surface water system in the spring/early summer and again in the late fall of each year. The most typical windows for releases are in April-June and then again in September-November. The exact timing of these releases depends on a number of factors, including the amount of water in the receiving waters (Johnson, 2012).

Table 5 identifies the WWTFs in the BRW, by county and the permitted volume of inflow. All of these facilities lay within Clay and Becker counties; neither Wilkin nor Otter Tail counties have

WWTFs in the BRW. (Note that the Barnesville WWTF is unique in having three separate treatment lagoons.)

Table 5. WWTFs in the BRW, by county

County	WWTF	Permitted Inflow[1]
Clay	Barnesville: 8 acres pond 10.9 acres pond 24 acre pond	 1.59 mgd 2.00 mgd 2.69 mgd
	Glyndon	1.57 mgd
	Hawley	2.73 mgd
	Hitterdahl	0.28 mgd
Becker	Audubon	0.61 mgd
	Callaway	0.47 mgd
	Lake Park	1.30 mgd

[1] mgd = million gallons per day.

WATERSHED-WIDE WASTE CREATION AND FECAL COLIFORM PRODUCTION

To convert the populations of the various bacterial sources in the BRW into estimates of fecal bacteria produced, the amount of waste created by each source was computed and published literature values of fecal coliform densities per waste type were used. Fecal bacteria production was computed in terms of fecal coliform, since data on *E. coli* production is not widely available in the literature at this time. When these data are used for modeling and computing total maximum daily loads (TMDLs), fecal coliform results will be converted to estimates of *E. coli* based on accepted conversion values.

The majority of published data on estimates of waste produced by animals (particularly agricultural animals) are based on animal units (AU). As such, the estimated livestock and poultry populations in the BRW were converted to AUs based on Minnesota Feedlot Rules that 1 AU equals 1,000 pounds of liveweight. For wildlife, an animal unit was assumed equal to one animal. Published estimates of waste created per AU were then used to compute the average annual amount of waste created by each animal source in the BRW. Literature values on the bacterial concentration in each of the animal's waste (reported as colony forming units – or CFUs – per gram) were then used to compute the average annual amount of bacteria created by each source type.

Table 6 summarizes the results of this analysis. The estimated "Watershed-Wide Fecal Coliform Production" values shown in the table represent the estimated average annual amount of fecal coliform that is created by agricultural animals and wildlife in the watershed, not necessarily the amount that is entering the surface water system.

Table 6. Average annual waste and fecal coliform production rates for agricultural animals and wildlife in the BRW

	Watershed Total Population (# animals)	Watershed Total Population (AU)[a]	Daily Waste Production (gm/AU)	FC Density (10^6 CFU/gm)	Watershed-Wide Waste Creation (lbs/yr)	Watershed-Wide FC Production (10^{16} CFU/yr)
Agricultural Animals						
Bovine						
Beef	18,006	18,006	27,240[e]	1.14[f]	394,685,774	20.5
Dairy	8,111	8,111	27,216[b]	1.14[f]	248,687,443	12. 9
Birds						
Broilers	260	9	24[c]	3.63[i]	166	0.00
Layers	305,592	10,085	42[c]	3.22[i]	340,826	0.05
Turkey	308,002	5,544	128[c]	0.73[i]	571,036	0.02
Goat/Sheep	495	50	18,144[j]	16.00[k]	7,227,122	0.52
Horse	226	226	18,598[b]	0.01[d]	3,382,220	0.00
Pigs	15,893	6,357	20,412[b]	3.30[d]	104,418,766	15.6
Wildlife						
Deer	8,557	8,557	772[f]	0.45[f]	5,315,997	0.11
Waterfowl base numbers (April-Oct)	39,564	39,564	231[f]	16.23[b]	7,354,200	5.4
Tamarac NWR (Spring waterfowl breeding)	1,019	1,019	231[f]	16.23[b]	189,461	0.14
Tamarac NWR (Fall waterfowl migration)	9,544	9,544	231[f]	16.23[b]	1,773,979	1.3

[a] For livestock and poultry, 1 animal unit (AU)=1,000 lbs of live weight; for wildlife, 1 AU=an individual animal

b = ASAE, 1998
c = Mostaghimi et al., 2000a, b, c, d
d = Geldreich, 1977
e = MWPS, 1993
f = Yagow, 2001a
g = Cox, 2005
h = Mukhtar, 2007
i = Yagow, 2001b

The amount of fecal contamination entering the surface water system from SSTSs is dependent on the number of failing or IPHT systems in the area. Data and methods used in the *MN Septic System*

Improvement Estimator Users Guide (U of MN 2012) were used to inform the estimation of loading from malfunctioning SSTSs in this work. Based on methods in the Users Guide and discussions with SSTS experts at the University of MN Extension Service (Heger 2012), it was assumed that 100 percent of raw sewage exits SSTSs that are IPHTs and enters the surface water system. This is mainly due to the definition of IPHT, which states that these systems discharge directly to surface water or groundwater. For failing SSTSs, it was assumed that 50 percent of the raw sewage would reach the surface water system. This lower rate is due to the fact that some of the fecal contamination will be filtered out of the sewage as it moves through the soil or via overland flow toward surface waters.

Addition assumptions made from information in the *MN Septic System Improvement Estimator Users Guide* include: the fecal coliform concentration in raw sewage (1.58×10^6 MPN/100mL); and the average discharge from a SSTS (70 gallons/person/day). All calculations of bacterial loadings from malfunctioning SSTSs were made under the conservative assumption that these systems are malfunctioning constantly (i.e., every day of the year). **Table 7** summarizes the results of this analysis, showing the estimated bacterial loading from malfunctioning SSTSs in the BRW.

Table 7. Average annual fecal coliform production rates for IPHT and failing SSTSs

	Watershed Total	Watershed-Wide FC Production (10^{16} CFU/yr)
IPHT SSTSs	324	0.12
Failing SSTSs	951	0.19

Information from Discharge Monitoring Reports (DMRs) from each WWTF in the BRW were used to compute average annual loadings of fecal coliform from each of these facilities. DMR records from 1995-2009 were used to compute fecal coliform loadings during each reported discharge event. These values were then summed for each year and averaged. The results are summarized in **Table 8**. Loads from the Barnesville WWTF were summed for all treatment lagoons and are presented as one number in the table.

Table 8. Average annual fecal coliform production rates for WWTFs

WWTF	Discharge (mgd)	Watershed-Wide FC Production (10^{16} CFU/yr)
Audobon	0.61	0.00000088
Callaway	0.47	0.00000043
Lake Park	1.30	0.0000014
Barnesville	6.28	0.0000080
Glyndon	1.57	0.0000039
Hawley	2.73	0.0000041
Hitterdahl	0.28	0.00000028

CONCLUSIONS

The BRW is rural area with significant bacterial contamination in its surface waters. The purpose of this memorandum was to identify the rural sources of bacteria in this watershed and estimate fecal bacteria creation from each of the sources. The findings will be used to inform the on-going watershed restoration and protection efforts in the area, including the creation of watershed loading. Results of this work show that (of the sources investigated) the main creators of fecal coliform in the BRW are beef and dairy cattle, pigs, and waterfowl. All other sources, including WWTFs and malfunctioning SSTSs are estimated to create less than $1x10^{16}$ CFU/year of fecal; dairy cattle, on the other hand, are estimated to create over twenty-times this amount. The results presented in this memorandum represent the amount of fecal bacteria created by each bacterial source, not necessarily the amount that will reach the surface waters of the BRW. Subsequent steps in the watershed restoration and protection efforts in the watershed will use these results to estimate the amount of bacteria received by the area's streams.

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Appendix C – BRW TSS-Turbidity Relationship.