Assessment of TMDL Implementation Strategies for Nitrate Impairment of the Raccoon River, Iowa: Supplemental Material Section

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This supplemental material section contains detailed information on the input data assumptions for the SWAT modeling as well as the model calibration and validation results.

SWAT Modeling System

The data sources listed in Supplemental Table 1 were used to build the SWAT TMDL modeling system for the Raccoon River watershed, most of which are accessible in the Iowa Department of Natural Resources (IDNR) on-line digital data library (IDNR, 2008). The subwatersheds were selected to match the 12-digit HUC watershed boundaries (see USDA-NRCS, 2008b for an explanation of different standard hydrologic units) plus additional subwatersheds were created at the gage station locations (Fig. 1) to facilitate comparisons of model output with measured data. The process of watershed delineation and HRU creation was performed using the ArcView SWAT interface (AVSWATX) which is described by Di Luzio et al. (2004). Initially, a 30-meter Digital Elevation Model (DEM; USGS, 2008a) was loaded into the model and the 1:100,000 scale National Hydrography Dataset (NHD; USGS, 2008b) was used to burn the stream network into the DEM. The resulting watershed configuration consisted of 112 subwatersheds (Fig. 1).

The HRUs were then created by overlaying Soil Survey Geographic (SSURGO) data (USDA-NRCS, 2008c) and 2002 land cover data obtained from IDNR (2008). Thresholds of 1%
for land cover and 5% for soil category were chosen so that the maximum amount of information can be captured. Higher threshold value means loss of information in aggregation and vice versa. Several studies have reported that the size of subwatersheds and the number of HRUs can have significant effects on sediment yields but relatively insignificant effect on the flow generation as summarized by Gassman et al. (2007). Jha et al. (2004) further showed that variations in subwatershed delineations can impact nitrate loss estimates. The present study is focused on estimating streamflow and nitrate loads associated with the flow generation, and thus the refined delineations were important for accurately estimating the nitrate loads. To differentiate among various grass land cover uses in SWAT, Indian-grass was assumed for grasslands which were already taken out of production as part of the Conservation Reserve Program (CRP), tall fescue was assumed for pasture, and smooth brome was assumed for ungrazed grass. All together, a total of 3640 HRUs were created for modeling.

Daily weather data was obtained from the National Weather Service COOP monitoring sites available through the Iowa Environmental Mesonet (ISU, 2008). AVSWATX assigned the appropriate weather station information to each subwatershed based on the proximity of the station to the centroid of the subwatershed. Ten weather stations were used to provide the temperature and precipitation data for the entire simulation time frame. The SWAT model was run on a daily time step for the 1986 to 2004 period, with the first ten years (1986 to 1995) consisting of a model calibration period and a second nine year period (1996 to 2004) comprising a model validation period. The Hargreaves method was selected to estimate potential evapotranspiration and the Muskingum method was selected for channel flow routing simulation.
The present SWAT-Raccoon modeling framework provides a refined and improved approach relative to the previous modeling effort by Jha et al. (2007). Major refinements and/or upgrades include:

1. The latest version of SWAT (version 2005), which took advantage of several SWAT2005 enhancements including improved tile drainage components developed by Du et al. (2005) and further tested by Green et al. (2006). Accurate simulation of the tile drainage is very crucial, especially when considering that 47.4% of the Raccoon River watershed was estimated to be tile-drained. The previous study assumed a slightly higher amount of tile-drained land (based on less accurate information) and relied on SWAT version 2000. The resulting reported tile flow contribution to the overall watershed water yield was 21 mm, which was substantially less than the tile flow contribution of 56 mm estimated in this study, which was 40% of the baseflow and believed to be in the proper range (see further discussion in the Results section).

2. The watershed was delineated into 112 subwatersheds for this study, which was much more refined than the 26 subwatersheds (consistent with 10-digit watersheds) that were used previously. A total of 3,640 HRUs were also used in the current research as compared to only 213 HRUs in the earlier SWAT application, which resulted in a much more accurate representation of watershed land use, soil type, and stream system heterogeneity.

3. The previous study relied on relatively coarse land use, soil type, and management practices data derived from the 1997 U.S. Department of Agriculture’s National Resources Inventory (NRI) database (USDA-NRCS,
2008a), which is statistically justifiable only at the 8-digit level. The NRI land use, soil and management data were initially aggregated for the two 8-digit level watersheds that comprise the Raccoon River watershed, and then were manually allocated to the 26 delineated subwatersheds. These resolution and methodology limitations were addressed in the present study by using more refined input data including GIS layers of 2002 land use data and detailed SSURGO soil database.

(4) The previous study relied on manure nutrient application rates and associated application areas based on a previous national-level assessment of Comprehensive Nutrient Management Plans (USDA-NRCS, 2003), which were then imposed on selected crop and pasture land in the two 8-digit watersheds using criteria from the national assessment. In the present study, this cumbersome process was replaced with manure application rates and associated application areas that were calculated as a function of CAFOs and feedlots located in the watershed (Figure 2) as described by Schilling et al. (2008).

(5) The present study used point source inputs from 77 wastewater treatment plants (Figure 1) and contributions from septic systems, which were not considered in the previous study. This facilitates TMDL analysis of point source contribution impacts from human wastes on nitrate loads, adding some key information to a politically-charged debate of point versus nonpoint sources.

(6) A more refined calibration and validation effort is introduced into the present study including daily streamflow calibration and additional validation of streamflow prediction at several upstream points within the watershed.
Input Data and Modeling Assumptions

*Tile drainage* is known to be an important component to the hydrology and nutrient loss from poorly drained lands typical of the Des Moines Lobe landscape region. Two methods were used to estimate the amount of land with subsurface tile drainage in the watershed. Both methods were based on identifying soil types that would require tile drainage in order for farming to occur. The first method, developed by the USDA National Soil Tilth Lab (D. Jaynes, personal communication), identifies soils that have a slope less than 2%, a drainage class of poor to very poor and a hydrologic group code with the “D” determination. The second method, developed at Iowa State University (J. Miller, personal communication), considers a slope less than 5%, a drainage class code greater than 40 and a subsoil group of 1 or 2. The variables for both methods are found in the ISPAID (Iowa Soil Properties and Interpretations Database) soil database (Miller et al., 2006). Soils that met either of these criteria were combined with the 2002 land cover information to identify row crop ground with probable tile drainage. Differences in tile density on row crop lands were evident in the Raccoon River watershed (Fig. 3). At the subwatershed level, the amount of row crop land with drainage tiles ranged from 4 to nearly 100% and averaged 64%. Approximately 78% of the crop land in the North Raccoon was assumed to be tile-drained compared with 42% in the South Raccoon. Overall, 47.4 % of the total Raccoon River watershed area was simulated as tiled area.

*Nitrogen and phosphorus fertilizer* were applied to row-crop lands at rates and times based on the information available from Agriculture’s Clean Water Alliance (ACWA), a group comprised of 11 fertilizer dealers in the Raccoon River Watershed. ACWA indicated that on average 170 kg ha\(^{-1}\) of N was applied to 95% of the corn ground and an average of 36 kg ha\(^{-1}\) of N was applied to 15% of the soybean acreage in the watershed. In this study, N fertilizer was
applied to 100% of the corn ground: anhydrous ammonia was applied in the fall after soybeans are harvested and di-ammonium phosphate fertilizer was applied to soybean ground before planting.

*Manure applications* in the Raccoon River Watershed are derived from three main sources: manure from grazing operations (cattle on pasture), manure from feedlots (cattle manure), and manure from confined animal feeding operations (CAFOs) (Fig. 2). The number of cattle for each county from 2002 Ag Census data was divided by the amount of land in pasture from the 2002 land cover coverage for that county to obtain a cattle loading rate per hectare of pasture. Cattle were assumed to graze from May through October. The locations of cattle feedlots and CAFOs were used to estimate the amount of crop land where nitrogen from manure was applied. A manure distribution program from the USDA National Soil Tilth Lab was run to determine how many hectares of row crop ground were needed to distribute the manure in each subwatershed at a rate of 200 kg ha$^{-1}$ of N for a two-year crop rotation. The area needed in each subwatershed was then matched up with area of row crop HRUs in that subwatershed. Manure was distributed on ground to be planted with corn (half applied in the spring and half applied in the fall).

*Point source* contributions to streams include inputs from cattle in streams, septic discharge, and waste water treatment plant (WWTP) discharge. The total point source input from these three sources were individually assessed and then summed for each subwatershed for input into the model. The number of cattle with access to streams was estimated by intersecting the pasture polygons with the NHD stream network coverage and summing the number of cattle in those selected polygons for each subwatershed. The amount of time cattle spend in streams was assumed to be 6% during the months of May through October, which is consistent with the
a percentage of 5.7% observed during a cattle grazing experiment in central Iowa (Haan et al., 2005). This percentage was multiplied by the amount of nitrate generated daily by the cattle to estimate daily N load to the stream by cattle on pasture.

The amount of human nitrogen discharged into streams from septic systems was estimated for each subwatershed by summing the rural population from the 2000 census block coverage and multiplying the population by the average amount of nitrogen generated by an individual. For nitrogen it was assumed that 9.9 pounds of nitrogen was generated per person per year. For WWTPs, three methods were used to determine the amount of nitrogen discharged to streams. If a facility had a design limit for nitrogen, this limit was used at all times. If a facility had no design limits, a constant nitrogen value was assumed that was derived from the population estimate (or population equivalent). If the WWTP was a controlled discharge, a worksheet was used to determine how much nitrogen was stored until discharge using the rate constant.

**Calibration and Validation**

SWAT was initially calibrated for the watershed hydrologic balance. The model was executed with baseline land use, soil, management information, and observed climate data for 21 years; the first two years served as a warm-up period, 1986-1995 as the calibration period, and 1996-2004 as the validation period. Results were excluded for the first two years and the hydrologic balance was assessed over the 19-year period. Daily streamflow data collected from a sampling site located at Van Meter (Fig. 1) (station # 05484500; USGS, 2008c) were used for flow calibration and validation; approximately 95% of the entire watershed drains to this location. The model was first calibrated for annual flow volumes, then for monthly flow volumes and seasonal trends, and then finally for daily flow volumes. Several model parameters, which
affect the seasonal trends, recession, daily peaks and others, were adjusted within the recommended ranges to final calibrated values.

Additional validation of annual and monthly streamflows was then performed at three upstream gage sites (Fig. 1): the North Raccoon river at Sac City (drainage area = 1813 km²), North Raccoon river at Jefferson (drainage area = 4193 km²), and South Raccoon river at Redfield (drainage area = 2574 km²). No further calibration of the model parameters were performed for this validation phase.

Accurate simulation of various watershed hydrologic components such as snowmelt, evapotranspiration, streamflow, baseflow to surface runoff ratio, and tile flow contribution lead to accurate prediction of nitrate load. The nitrate calibration was performed in a manner to match the SWAT simulated nitrate loads to the measured values at the Van Meter monitoring site. The monitoring site at Van Meter was chosen as the calibration point because it is the upstream point of compliance for the impaired river segment for nitrate (Fig. 1). It should be noted that “measured” in this case does not refer to the actual measured nitrate loads, but rather loads estimated using the USGS Load Estimator (LOADEST) regression model (Runkel et al., 2004). Thus, in this calibration procedure, one modeled result (SWAT) was essentially being calibrated to another modeled result (LOADEST). Weekly or bi-weekly samples of nitrate concentrations were converted into continuous load data using regression models developed by LOADEST. Nitrate sampling data were obtained from the Des Moines River Water Quality Network (Lutz and Francois, 2006). So, this study compared SWAT model simulated nitrate with LOADEST simulated nitrate (and not the directly measured data).

The simulated and measured streamflows were compared graphically on an annual, monthly and daily basis; the nitrate graphical comparisons were performed for annual and
monthly time scales. Statistical evaluation was assessed using two performance criteria: coefficient of determination (R²) and Nash-Sutcliffe’s coefficient (E) (Nash and Sutcliffe, 1970). The R² value is an indicator of the strength of relationship between measured and simulated values, whereas E value measures how well the simulated values agree with the measured value. Both values typically range from zero to one, with a value of one considered a perfect match. Explicit criteria for judging the statistical performance of water quality models have not been established. Several studies report suggested criteria for specific modeling studies. For example, Van Liew and Garbrecht (2003) and Van Liew et al. (2005) considered values of E greater than 0.75, between 0.75 and 0.36, and less than 0.36 to indicate good, satisfactory, and poor model performance, respectively, for SWAT applications in Oklahoma and Georgia. Chung et al. (1999) relied on criteria of R² greater than 0.5 and E greater than 0.3 to define satisfactory performance of the EPIC field-scale model for two small watersheds in southeast Iowa. Moriasi et al. (2007) developed statistical evaluation criteria for water quality models based on analysis of statistics reported in nearly 20 studies, which is likely the most in-depth assessment reported to date in the literature. They suggest that an E value greater than 0.5 should generally be considered acceptable for SWAT (and other model) monthly predictions, and that higher and lower thresholds would be appropriate for annual and daily comparisons. These criteria developed by Moriasi et al. (2007) were used to judge the accuracy of the model results in this study, and were assumed to be applicable to both the R² as well as the E values.

**Watershed Hydrologic Balance**

Calibration of the watershed hydrology predicted by the SWAT model required adjustment of several parameters such as *curve number* (CN2), *soil available water capacity* (SOL_AWC),
and soil evaporation compensation factor (ESCO) within their recommended ranges. The calibration process included adjusting baseflow ratio to the surface runoff, amount of evapotranspiration, and total water yield. The CN2 values were changed within ± 10 % of the standard CN values for a given land cover, soil type and antecedent moisture condition. The soil layer SOL_AWC values were changed within ± 0.04 of the original values given in the soil layer properties. The ESCO parameter was set to 0.85 for the entire watershed. Supplemental Table 2 lists all model parameters, which are used in the calibration process, with their recommended ranges and final calibrated values. The annual water balance for the Raccoon River watershed computed with SWAT found that, on average, streamflow comprises 28% of precipitation (237 mm) and annual evapotranspiration comprises 71% of precipitation (595 mm). Baseflow in the model output was summed for three components (lateral flow + tile flow + groundwater flow) and found to be 143 mm, or 60% of total streamflow. The baseflow fraction provided by the model was similar to the value of 54% determined by Schilling and Zhang (2004) for the period of 1972-2000.

Tile flow was estimated to contribute an average annual flow of 56 mm, which was 24% of the total streamflow and 40% of the overall baseflow. Results suggest that flow from drainage tiles contributes substantially to streamflow and baseflow in the Raccoon River. The spatial distribution of average annual tile flow in the Raccoon River watershed was estimated with SWAT (Fig. 3). More than 26 mm of tile flow was associated with much of the North Raccoon River watershed, with flow exceeding 50 mm in HUC12 basins located in the northern half of the watershed.

**Streamflow Calibration and Validation**
Calibration of the SWAT model for the inter-annual, monthly, and daily streamflow predicted at the watershed outlet, required adjustment of additional model parameters including *snowmelt temperature* (SMTMP), *groundwater delay* (GW_DELAY), *groundwater recession coefficient* (GW_ALPHA), *re-evaporation coefficient* (REVAP), and *surface runoff lag coefficient* (SURLAG). Table 3 lists the final values of the calibrated parameters. Supplemental Figure 1 shows the graphical comparison of the measured and SWAT simulated annual streamflow at Van Meter for both calibration and validation periods. R² and E values are 0.94 and 0.93 for calibration period (1986-1995) and 0.80 and 0.76 for validation period (1996-2004). Over the entire simulation period, the modeled average annual streamflow at Van Meter (220 mm) was very close to the measured value (215 mm). Similarly, the comparison of monthly values resulted in R² and E values of 0.86 and 0.86 for calibration and 0.88 and 0.87 for validation (Supplemental Figure 2). Again, the modeled average monthly streamflow (18.4 mm) closely matched the measured monthly average (17.9 mm) over the 228 month (19 years) simulation period. Calibration was also performed for daily streamflow values even though SWAT is not an event-based model and is not sensitive to rainfall intensity (Arnold et al., 1998). Visual inspection indicates a very good prediction by SWAT even at a daily time step (Supplemental Figure 3). The R² and E values were 0.50 and 0.46 during the calibration period and 0.53 and 0.45 during the validation period.

The calibrated SWAT model was further tested by comparing simulated streamflow with measured streamflow at the three upstream locations within the watershed (Supplemental Figure 4) as previously described. The predicted streamflow values at all three locations using the watershed-outlet calibrated SWAT model were found to be in close agreement with the measured streamflow values both on average annual and average monthly basis; all deviation
varied from 5 to 8 % from the measured values. The $R^2$ and E values exceeded 0.6 for all of the annual and monthly comparisons.

These statistical results can be viewed as quite strong for the annual and monthly results, and definitely adequate for the daily results, when viewed in the context of the suggested criteria by Moriasi et al. (2007). The SWAT streamflow calibration and validation statistics found here were also similar to values obtained by Hu et al. (2007) and Green et al. (2006) for large tile-drained watersheds in east-central Illinois and north central Iowa, respectively, and compared favorably to statistics compiled by Gassman et al. (2007) for 115 SWAT studies reported in the literature, including limited subsets of studies that reported daily streamflow and/or additional validation statistics. The successful daily and additional validation comparisons provide increased confidence in the overall SWAT model representation of the Raccoon River watershed hydrology.

**Nitrate Calibration and Validation**

Calibration of nitrate transport in the watershed required adjustments of SWAT model parameters (within the recommended ranges) related to nitrogen cycle dynamics and in-stream nitrogen routing including the *organic nitrogen enrichment ratio*, *hydrolysis of organic N to NH$_4$*, *biological oxidation of NH$_4$ to NO$_2$*, and *biological oxidation of NO$_2$ to NO$_3$*. See Table 3 for the final calibrated values of the model parameters for the Raccoon River watershed.

Generally nitrate loads simulated with SWAT agreed well with measured values except for deviations in 1990, 1993 and 1997 (Supplemental Figure 5). The $R^2$ and E values are 0.56 and 0.52 for the calibration period (1986-1995), and 0.85 and 0.85 for the validation period (1996-2004). The better agreement during the later years in the model probably reflects using recent
information (i.e., 2005 data) for input into the model. The 2005 conditions input into the model may not accurately represent conditions in the 1980s and early 1990s, particularly with respect to animal manure management. Monthly time-series comparison (Supplemental Figure 6) follows similar calibration/validation trajectories, with $R^2$ and $E$ values of 0.62 and 0.47 for the calibration period and 0.74 and 0.71 for the validation period. Overall, the nitrate loading predictions were considered reasonable on an average annual and monthly basis, considering that the measured nitrate loads were estimates developed from weekly samples. The results again are strong relative to statistics reported by Gassman et al. (2007) for several SWAT studies that included testing of the model for nitrate movement and generally stronger than corresponding statistics reported by Hu et al. (2007).

References


Figure Captions

Supplemental Figure 1. Annual streamflow comparison for the Raccoon River at Van Meter.

Supplemental Figure 2. Monthly streamflow comparison for the Raccoon River at Van Meter.

Supplemental Figure 3. Daily streamflow comparison for the Raccoon River at Van Meter.

Supplemental Figure 4. SWAT model validation at several locations upstream within the watershed.

Supplemental Figure 5. Annual nitrate+nitrite load comparison for the Raccoon River at Van Meter.

Supplemental Figure 6. Monthly nitrate+nitrite load comparison for the Raccoon River at Van Meter.
### Supplemental Table 1. Digital data layers used for the Raccoon River watershed SWAT TMDL modeling system

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<th>Data Type</th>
<th>Data layer description (source)</th>
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<tr>
<td>Soil</td>
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<tr>
<td>Topographic</td>
<td>National Elevation Data (NED) 30 m GRID of Iowa (USGS, 2008a)</td>
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<tr>
<td>Hydrologic units</td>
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<td>Surface water</td>
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<td>Climate data</td>
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*Metadata documentation is provided for each data layer included in the IDNR on-line library (IDNR, 2008); additional sources are provided here if available.*
**Supplemental Table 2.** List of SWAT parameters used in the model calibration and their final calibrated values for the Raccoon River watershed.

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<th>SWAT Calibration Parameter</th>
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