Thief River SWAT Modeling
Thief River Watershed, Minnesota

Numerical Modeling and Evaluation of Management Scenarios

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SECTION 1.0
INTRODUCTION

1.1 DESCRIPTION OF THE STUDY AREA AND RESOURCE PROBLEM

Water quality issues in the Red River Basin (RRB) are of great concern, and many of the watercourses of the region are impaired with respect to turbidity, nutrient, fecal coliform (FC), and dissolved oxygen levels. The erodible soils of the region, coupled with intensive agriculture, extensively modified drainage, and loss of wetlands and their natural storage capacity, have resulted in a landscape that is especially prone to sediment erosion and nutrient transport. Nutrients such as phosphorus can be especially problematic by exacerbating algal growth, sometimes to the point of widespread eutrophication such as is occurring within Lake Winnipeg and other water bodies of the region (EERC, 2009). Eutrophication can lower dissolved oxygen (DO) levels within water bodies, which adversely affects aquatic life, such as fish.

While many water quality impairments have been identified in the streams and watercourses of the RRB (MPCA, 2010), identifying the source of a particular impairment can sometimes be problematic. The most reliable means of identifying problem areas is through long-term water quality monitoring; however, the repeated collection and analysis of water samples at multiple locations throughout the RRB is time consuming and expensive. Another option is to use tools such as hydrology-based water quality models to gain a more comprehensive understanding of the various processes occurring in a watershed that can affect water quality. Modeling is not a replacement for water quality monitoring; rather it is a complimentary effort that utilizes the flow and water quality data already collected for model calibration. This helps improve the accuracy of the model in predicting the impact of land management changes and/or climate on runoff, water quality, and nutrient and sediment transport. As the availability of monitoring data increases, models can be updated for improved accuracy.

The goal of this project, which is funded by the Red Lake Watershed District (RLWD), is to assess the factors that contribute to the water quality impairments identified in the Thief River

Watershed and to estimate the effects of implementing best management practices (BMPs) using the Soil and Water Assessment Tool (SWAT). SWAT is a hydrology-based water quality model developed by the U.S. Department of Agriculture (USDA) Agricultural Research Service (ARS) to estimate the effect of land management practices on water, sediment, and agricultural chemical yields in watersheds over long periods of time. It has been used throughout the United States to evaluate sediment and nutrient water quality impairments and to aid in the development of total maximum daily loads (TMDLs) (Gassman et al., 2007, and references therein).

The Thief River Watershed (TRW; **Figure 1**) occupies approximately 1,068 square miles in Northwestern Minnesota. It joins the Red Lake River in the city of Thief River Falls, Minnesota. The Red Lake River is a major tributary to the Red River of the North which flows north into Canada. The watershed has large areas of public lands, many of which are managed to maintain quality habitat for the benefit of waterfowl and other wildlife. Much of the area has been hydrologically modified by the construction of drainage systems, roads, and similar human features. Highly managed impoundments play a significant role in the area hydrology.

Four reaches of the Thief River, one reach of the Moose River, and one reach of the Mud River are considered impaired and included on the Minnesota Pollution Control Agency's (MPCA) 303(d) (i.e., TMDL) list (MPCA, 2010), as shown in **Table 1**.

Table 1: Impaired Waterbodies in the TRW

Reach	Year Listed	Affected Designated Use	Pollutant or Stressor
Thief River: Thief Lake to Agassiz Pool	2006	Aquatic Life	Un-ionized Ammonia
Thief River: Thief Lake to Agassiz Pool	2010	Aquatic Recreation	*Escherichia coli*
Thief River: Agassiz Pool to Red Lake River	2006	Aquatic life	Dissolved Oxygen
Thief River: Agassiz Pool to Red Lake River	2006	Aquatic life	Turbidity
Moose River: Headwaters to Thief Lake	2006	Aquatic life	Dissolved Oxygen
Mud River: Headwaters to Agassiz Pool	2008	Aquatic life	Dissolved Oxygen

Considering these impairments and related water-quality concerns, HEI was tasked to apply to the SWAT model to address concerns about streamflow and loads of suspended sediment, total phosphorus, and fecal coliform bacteria. The watershed's dissolved oxygen and ammonia impairments were not addressed as part of this work, as they are not easily simulated within the SWAT model. The flow and water quality data used to calibrate and validate the SWAT model were obtained from the USGS, the MPCA or provided to HEI by RLWD staff.

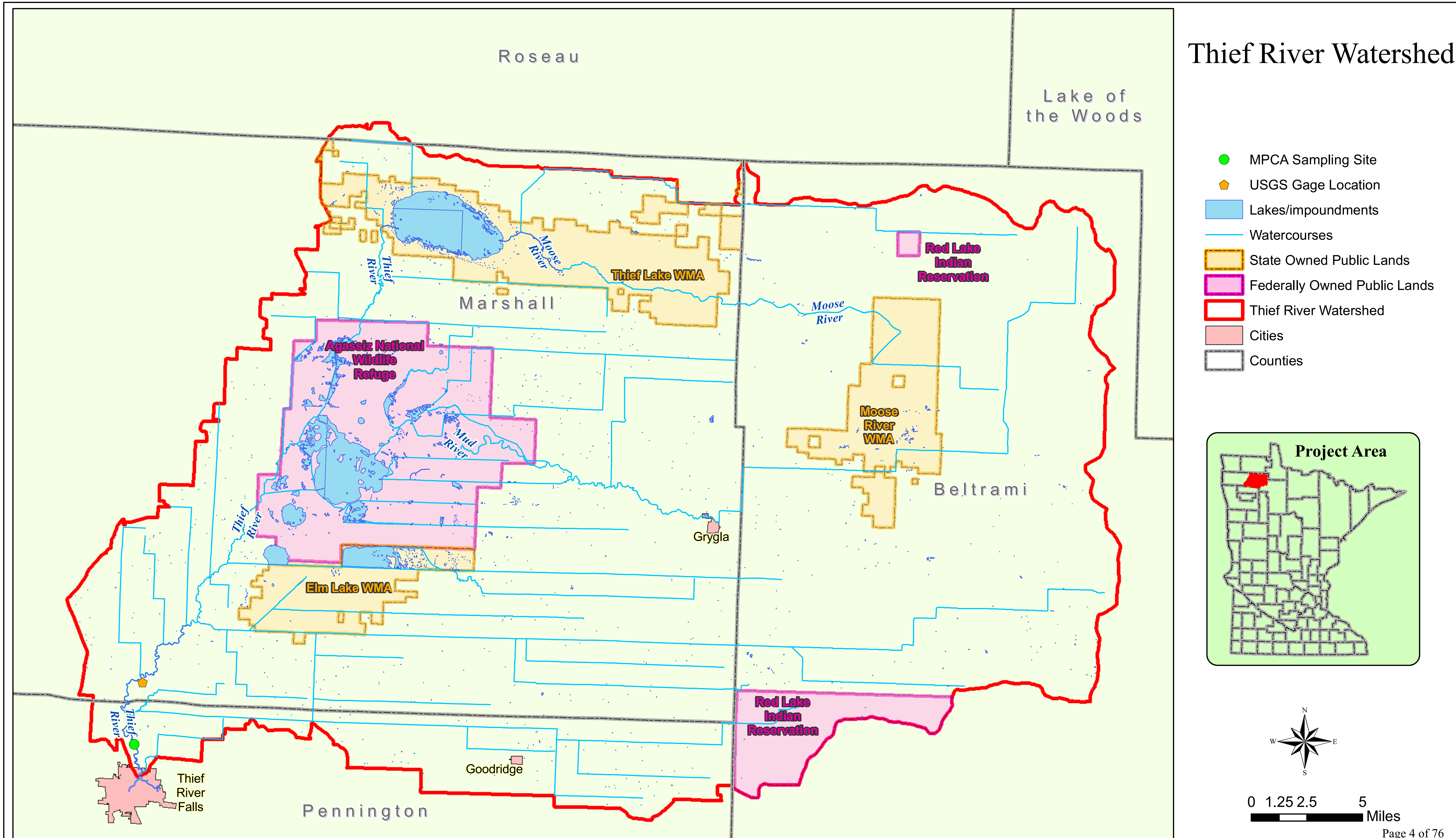

Figure 1: Thief River Watershed

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1.2 Purpose and Scope

The purpose of this document is to describe the methods used to develop and calibrate a SWAT model of the TRW and convey the results of modeling selected management scenarios (i.e., BMPs). The primary constituents modeled include streamflow, total suspended solids (TSS)[1], total phosphorus (TP), and fecal coliform (FC). The results of model runs to simulate the effects of three different management scenarios (chosen by RLWD staff) are included.

1.3 Watershed Characteristics

1.3.1 Topography

The Thief River flows primarily from east to west as it drains the flat uplands of northwestern Minnesota that are comprised mostly of the Northern Minnesota Wetlands Ecoregion (Omernik, J.M. and A.L. Gallant, 1987). The slope of the watershed increases near Thief River Falls as the Thief River joins the Red Lake River before it flows downhill into the Red River Valley.

1.3.2 Soils

The soils of the TRW were generally formed from lacustrine deposits that were formed beneath Glacial Lake Agassiz. They are classified as alfisols, which are primarily fertile soils of the forest, formed in loamy or clayey material. They are generally poorly drained. The surface layer of soil, usually light gray or brown, has less clay in it than does the subsoil. These soils are usually moist during the summer, although they may dry during occasional droughts. The primary suborders of alfisols that are present in the TRW are the aqualfs. See http://www.extension.umn.edu/distribution/cropsystems/dc2331.html for more information.

1.3.3 Climate

Long-term climate data were collected at a site on the Agassiz National Wildlife Refuge (ANWR). The 30-years of data collected from 1971-2000 are summarized by the Natural

[1] Since SWAT models suspended sediment, but total suspended solids data were the best available option for calibrating the model, the assumption that TSS = suspended sediment was made for this purpose.

Resource Conservation Service (NRCS) available at http://www.wcc.nrcs.usda.gov/cgibin/climchoice.pl?county=27089&state=mn. The average daily temperature during this time ranged from 3.8 degrees in January to 68 degrees in July, averaging 39 degrees Fahrenheit. Extreme temperatures ranged from -46 to 99 degrees Fahrenheit. Precipitation averaged nearly 22 inches per year, ranging from 0.53 inches in December to 3.6 inches in July. Precipitation during the months of May-September averaged at least 1 inch of precipitation, while the average monthly precipitation during the rest of the year was about ½ inch or less. Nearly 39 inches of the average annual precipitation occurred in the form of snow.

1.3.4 Hydrology and Sediment

The long-term average annual runoff in the TRW averages about 5 inches in the east and declines to nearly 2 inches per year to the west. This is based on data collected during 1951-1980, as reported in Gebert and others (1987). Much of the precipitation that falls on the watershed either infiltrates to the groundwater or is lost to evapotranspiration. In addition to showing snowmelt runoff and the effects of precipitation events, streams rarely respond to precipitation events later in the year and often stop flowing during the late summer and fall.

The US Geological Survey (USGS) streamgaging site 05076000, Thief River near Thief River Falls, MN has recorded streamflow from 1909 to the present. The mean of the mean daily streamflows during the period of record averaged less than 10 cubic feet per second (cfs) during the winter months, but rose rapidly in response to snowmelt runoff during the spring. Slightly increased flow was observed as early as late February, but peak streamflows typically occurred during mid-April. Flows slowly declined during the late spring and early summer, averaging about 100 cfs in August. Streamflow averaged about 100 cfs into the middle of November and then declined through the winter months. The stream stopped flowing about 10% of the time starting in August through March. About 25% of the time it stopped flowing during mid-December to mid-March.

The hydrology of the TRW is highly regulated through the use of impoundments. In lower reaches, associated with the Thief Lake and Agassiz wildlife-management areas, impoundment water levels are regulated to enhance habitat for waterfowl and reduce the occurrence of flooding in downstream areas (Knutsen, 2010).

Transport of sediment by streams in the TRW has been an issue because when the flow slows down, the sediments deposit in the impoundments, lakes and reservoirs in the watershed. This results in water depths that are shallower than is needed for optimum habitat or other intended uses, in water quality concerns, and eventually in dredging the sediment out of the pooled area. Several studies of sedimentation concerns in the TRW are documented in reports cited in the reference list, including: Houston Engineering, Inc. (2003), and U. S. Department of Agriculture - Natural Resources Conservation Service (2006).

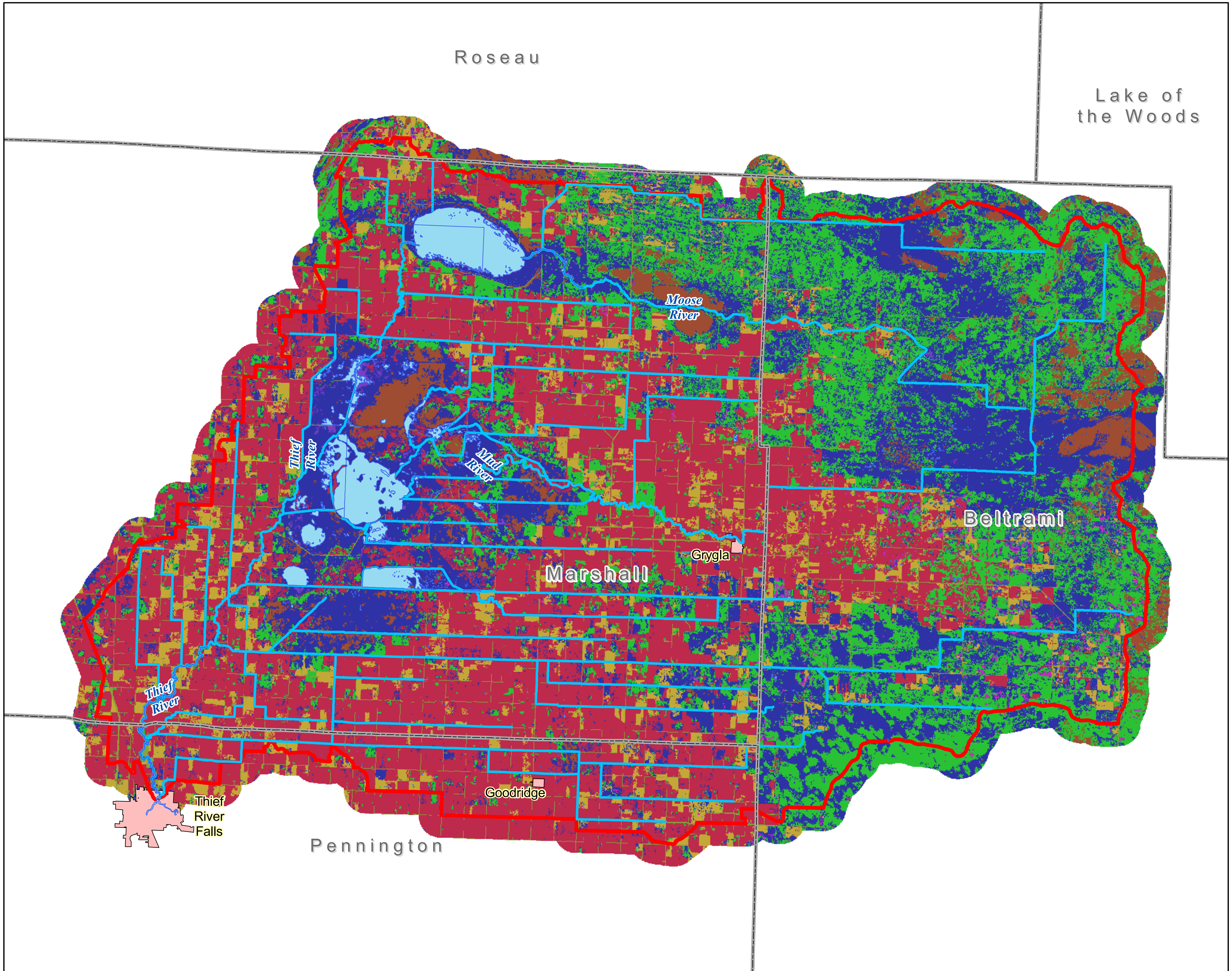
1.3.5 Land use/land cover

The TRW is situated in the Lake-Washed Till Plain physiographic area (Stoner and Lorenz, 1995). It drains mostly the Northern Minnesota Wetlands ecoregion, but western portions may be more characteristic of the Northern Great Plains ecoregion which also corresponds to the Red River Valley Lake Plain (Omernik, J.M. and A.L. Gallant, 1987).

The TRW is comprised of the Moose River, Mud River, and Thief River subwatersheds, as shown in **Figure 1**. **Figure 2** shows the generalized land use in the TRW; public lands in the eastern and western portion are dominant natural resource features. Public lands include state wildlife management areas and state-forest lands. Prominent public land-resource features that lie wholly or partially within the TRW include the Thief Lake Wildlife Management Area (WMA), Moose River Impoundment, ANWR, and Elm Lake WMA. Part of the Red Lake Indian Reservation is present in the southeast part of the watershed, with a small area in the northeast. The central portion of the subwatershed is primarily private lands used for agriculture. Much of the highly erodible agricultural land has been set aside as part of the Conservation Reserve Program (CRP) and other conservation programs. Crops grown on agricultural lands are a mixture of various cool-weather crops that generally include small grains, hay, and grassland. Confined Animal Feeding Operations (CAFOs) are scattered throughout the watershed. However, only six were considered sufficiently influential on stream-water quality (determined by RLWD staff (Hanson, 2010); defined on proximity to a waterbody) to be included in the SWAT model.

Small communities are scattered through the watershed, but generally are not considered important influences on hydrology and water quality. Goodridge and Grygla are the only cities that have permitted wastewater treatment systems that discharge directly to watercourses in the TRW. Thief River Falls discharges wastewater downstream of the TRW and does not directly affect hydrology and water quality in the TRW.

Thief River Watershed



- Lakes/impoundments
- Watercourses
- Thief River Watershed
- Cities

NLCD 2001

- 11 - Open Water
- 21 - Developed, Open Space
- 22 - Developed, Low Intensity
- 23 - Developed, Med Intensity
- 24 - Developed, High Intensity
- 31 - Barren
- 41 - Deciduous Forest
- 42 - Evergreen Forest
- 43 - Mixed Forest
- 52 - Scrub/Shrub
- 71 - Grassland
- 81 - Pasture/Hay
- 82 - Cultivated Crops
- 90 - Woody Wetlands
- 95 - Emergent Herbaceous Wetlands

N W E S

0 1.25 2.5 5 Miles

Figure 2: National Land Cover 2001

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SECTION 2.0
METHODS FOR MODEL DEVELOPMENT AND APPLICATION

2.1 DATA USED FOR SWAT MODEL DEVELOPMENT

Data used for this study were provided or obtained from the USGS, MPCA, RLWD, and other sources listed; no new data were collected. The data were quality–assured by the entities that provided it, within the criteria they have established. If anomalies were discovered while incorporating these data into the model, values were not adjusted without the concurrence of the original data provider.

The RLWD specifically requested that the SWAT model (http://www.brc.tamus.edu/swat/) be used for this study, although other models may be equally acceptable. SWAT is complex, but has several potential advantages over other modeling software, including its sophistication and compatibility with other software, including ArcMap (http://www.esri.com/). SWAT can interface with QUAL2E, a widely-accepted river and stream water quality model supported by the U.S. Environmental Protection Agency, for stream transport of nutrients. QUAL2E was not used in this application. Based on experience with the model and the needs of this study, the 2005 version of the SWAT model was used for this work. A more detailed description of the SWAT model can be found in the referenced publications by Neitsch and others [1, 2, and 3] (2005).

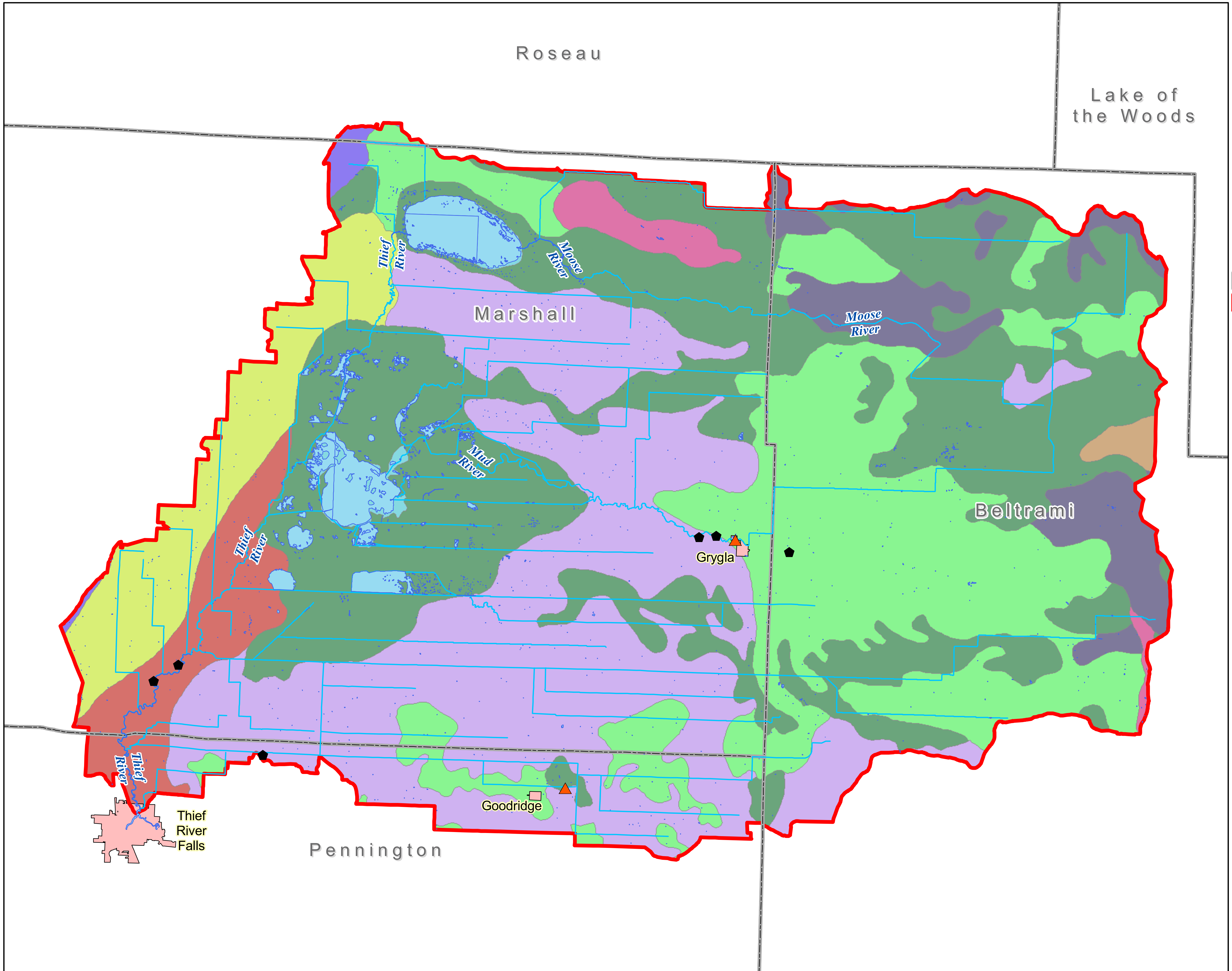
Electronic data files were obtained primarily from the following sources. More specific data are described in the model input parameters and coefficients.

- Land use data (displayed in **Figure 2**) are from the 2001 version of the National Land Cover Database (NLCD) provided by the USGS National Land Cover Institute. More information is available at: http://landcover.usgs.gov/index.php
- Soils data (displayed in **Figure 3**) were obtained from the State Soil Geographic (STATSGO) Database. This database is maintained by the U.S. Department of Agriculture, Natural Resources Conservation Service (NRCS) - National Cartography and Geospatial Center (NCGC), available at: http://soils.usda.gov/survey/geography/statsgo/

- Land-surface topography (displayed in **Figure 4**) was determined using the 30-meter Digital Elevation Model (DEM) provided by the USGS (http://edc2.usgs.gov/geodata/index.php).
- Precipitation data were compiled from 10 weather stations shown in **Figure 4** located in or near the TRW. These data are maintained by the Minnesota Climatology Working Group. The daily precipitation data from each station were processed using an extension of ArcSWAT, called PCP_SWAT. Spatial interpolation was used to fill data gaps and estimate daily rainfall values for each modeled sub-basin in the watershed. The resulting data were provided as input to the SWAT model.
- Other weather-related data, such as temperature and wind direction and speed, were defaulted to values contained within the SWAT software (station locations shown in **Figure 4**). Measured values for these parameters generally would not provide better information than estimated or default values at this temporal and spatial scale, and have less of an effect on the hydrology than variations in precipitation.
- Hydrography in the TRW, including lakes and stream information were imported from the USGS National Hydrography Dataset (NHD) available at: http://nhd.usgs.gov/
- Streamflow data were obtained for the USGS streamgaging site 05076000 on the Thief River near Thief River Falls, MN (**Figure 1**) which has recorded streamflow during 1909 to the present. This also was the point to which the model was calibrated.
- The water quality data used to calibrate and validate the model was for a nearby point sampled by, or on behalf of, the MPCA (**Figure 1**). Grab-sample concentrations of TSS (a surrogate for suspended sediment), total phosphorus, and fecal coliform were used in the model. The data were obtained from the MPCA's Environmental Data Access (EDA) data base. EDA is a subset of the U.S. Environmental Protection Agency's STORET water quality data base, and typically contains data more current than is found in STORET. All compatible data collected on behalf of the MPCA must be entered into the EDA database.

  Flow and water quality data from nine sites monitored by the RLWD were used as needed to verify that the model was working as intended. Typically, this involved comparing RLWD-monitored flows to those output by the model and ensuring that the general hydrology was matched. RLWD data was collected during the 2008 and 2009 field seasons.

Thief River Watershed



- Modeled Confined Animal Feeding Opperations
- Modeled Waste Water Treatment Plants
- Lakes/impoundments
- Watercourses
- Counties
- Thief River Watershed
- Cities

STATSGO Soils

- CATHRO-SEELYEVILLE-MARKEY (MN065)
- CLEARWATER-THIEFRIVER-HILAIRE (MN005)
- CORMANT-MEEHAN-EPOUFETTE (MN023)
- HAMERLY-VALLERS-ROLISS (MN041)
- KRATKA-ROCKWELL-SMILEY (MN032)
- LOHNES-SIOUX-SYRENE (MN021)
- MARQUETTE-KARLSTAD-EPOUFETTE (MN024)
- RIFLE-TACOOSH-SEELYEVILLE (MN066)
- SMILEY-REINER-HAMRE (MN042)
- WATER (MNW)

N W E S

0 1.25 2.5 5
Miles

Figure 3: STATSGO Soils

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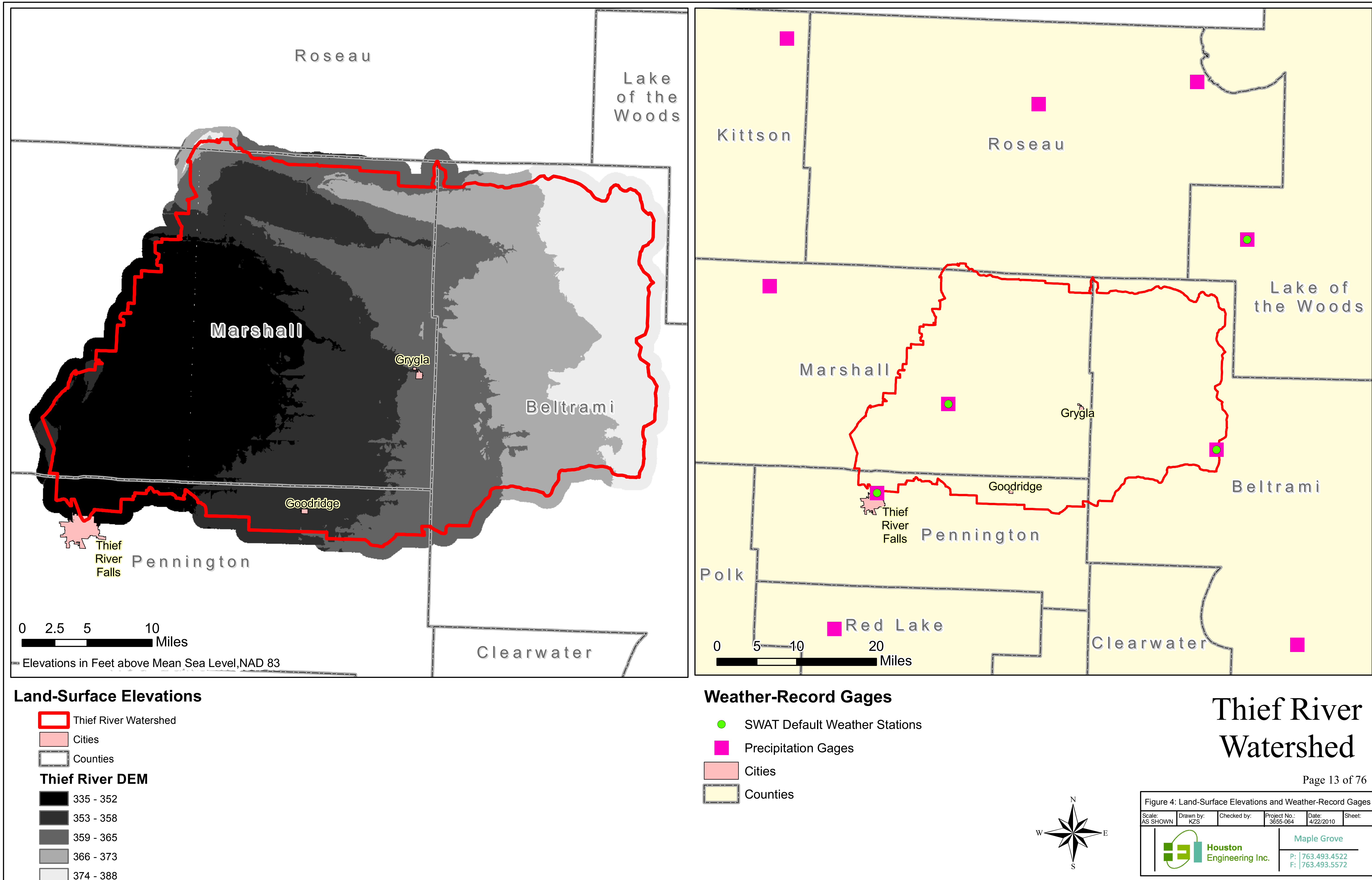

Thief River Watershed

Figure 4: Land-Surface Elevations and Weather-Record Gages

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- Information on the TRW drainage system and sub-basin boundaries was obtained from the RLWD, which provided HEI with a map of these features that was created by HDR Engineering, Inc. The density and flow patterns contained in the drainage system file were too complex for effective use in the SWAT model. Also, the sub-watershed delineations were too coarse in some cases, needing to be further defined to create the products desired from this modeling effort. HEI worked closely with the RLWD and ANWR staff to adjust the HDR-created files for use in the SWAT model. The interpretation of flow through the TRW was discussed at length with staff of the RLWD, the ANWR, and local water managers, to ensure concurrence with the selected flow directions and sub-basin delineations (Hanson, 2010; Knutsen, 2010). Their guidance was used and approval obtained before the information was used to build the SWAT model of the TRW. A copy of the memorandum addressing the results of these changes is shown in **Appendix A**.

  A summary of adjustments follows:
    - The minor waterways in the drainage file were removed so that only the major flowpaths in the watershed were explicitly used in the model (minor waterways were implicitly included in the model by "burning" the open channels into the modeled DEM prior to simplifying the file).
    - Public drainage system/waterways that have the capacity to flow in two-directions were set to flow in only one-direction. SWAT cannot accommodate the changes in flow direction that occur in many parts of the system, depending on water management techniques (i.e., pool elevations). Discussions with local water managers were used to determine the primary direction of the flow in any given drainage channel and that direction was used in the model.
    - SWAT also does not allow for flow to split when flowing downstream. Flow splits are relatively common in the TRW as flow gates and other water-control features are used to manage flow and move water to where it's needed. A similar approach to that used for two-way flows was applied here; to set a single direction of flow in channels that could be split into one downstream channel or another. The primary direction of flow of determined and set for use in the SWAT model.

- When further definition of sub-watersheds was required, NHD catchment data were used to guide the division of the HDR-derived sub-watersheds to sub-basins used in the SWAT model. When applicable, sub-basins were delineated based on the location of monitoring sites, control structures, or similar features. Otherwise, sub-basins were delineated based on the hydrography requirements of the SWAT model.
- A new outlet was recently (ca. 2007) added in the ANWR, allowing flow from Thief Lake to bypass ANWR. This feature was not included in the SWAT model because it was not operational during the majority of the modeled period (2000-2009) and using it would have resulted in a split flow situation, which SWAT is not equipped to model.
- Though tile drains have become more popular in the basin in the recent years, the occurrence and density of these drains has not been adequately recorded. Due to this lack of data, tile drains were not explicitly included in the SWAT model. Through the process of calibrating the model's hydrology, however, the impacts of any tile drains in the system were implicitly accounted for by adjusting sub-basin parameters to match the simulated and observed hydrographs.

The hydrology of the TRW is strongly affected by the numerous impoundments that dot its landscape. Six impoundments were explicitly modeled in this work; impoundments were included as permanent storage (i.e., reservoirs) in the SWAT model. Specifics of the modeling include:

- The North and South Moose River impoundments, Lost River Pool, and Thief Lake were each simulated in the model.
- The complex of pools/impoundments in the ANWR was simulated through the use of two reservoirs. Farmes Pool, which lies on the south side of the Refuge, was included as one. The remainder of the Refuge was modeled as a single, large reservoir. Extended discussions and coordination with staff of the ANWR were necessary to correctly represent the hydrology of the system through the use of a single reservoir. In the end, ANWR staff

agreed that the HEI-derived simplification provides a good general representation of impoundment-management operations (Knutsen, 2010).

- The emergency and normal spillway elevations of the modeled impoundments were based on typical summer and winter storage volumes for each reservoir, which were obtained from RLWD and ANWR staff;
- Because the hydrology of the watershed is so dependent on the management of the impoundments, details on the impoundment outflows and management techniques were needed to calibrate the model for hydrology. Additional consultation with staff of the RLWD, the ANWR, and the Thief Lake WMA was conducted to obtain the best available operational data (Hanson, 2010; Huener, 2010; Knutsen, 2010). Those data were used to develop daily or monthly outflow files with constraints that were tailored to incorporate the management characteristics for each reservoir. Operations were then included in the SWAT model as follows:
    - The North and South Moose River, and Thief Lake impoundments were modeled using pre-set monthly outflows,
    - The Agassiz and Lost River impoundments were modeled using pre-set daily outflows, and
    - Farmes Pool was modeled using monthly maximum outflows.

Point sources identified in the TRW were provided as model inputs using the following criteria and caveats:

- Discharge from the permitted wastewater treatment facilities at Goodridge (permit # MNG580022-SD-1) and Grygla (permit # MN0040771-SD-1) was established based on data from monitoring reports provided by the MPCA. Daily flow and water quality data were entered directly into the SWAT model; and
    - The RLWD requested that six CAFOs be included in the model. These operations are located directly adjacent to watercourses, creating a concern of greater potential for water contamination. Bacteria loading to the system also had to be handled in a manner consistent with the source, transport to the hydrologic system, and the ability to apply these inputs to the SWAT model. The following considerations were used for bacteria:

- The potential load of bacteria from CAFOs was computed from the reported number of cattle animal units (based on MPCA registration data) times the American Society of Agricultural and Biological Engineers (ASABE) loading value of $1x10^{11}$ colony-forming units (CFU) per animal unit per day. The load was modeled as a point source of bacteria directly into the stream, assuming that 0.5% of total potential load of CFUs actually makes it into the stream (this percentage was chosen during model calibration by adjusting the percent of loading into the stream until background concentrations at the calibration point were matched). These point sources were applied to six CAFOs distributed among three sub-basins;
- Bacteria from bird sources were modeled by applying duck manure wetland areas using the duck bacteria load estimate of $2.5x10^{9}$ CFU/duck/day. The duck manure CFU also was obtained from the ASABE;
- Duck manure was applied to all wetlands in the watershed based on bird density estimates of 0.04 birds/acre during the breeding season and 0.4 birds/acre during migratory season. These estimates were obtained from a University of Minnesota - Crookston report (Svedarsky and Huseby).
- Because of the large number of waterfowl that they host, wetlands in the ANWR and Thief Lake WMA had much higher bacterial loadings applied than other wetlands in the TRW. Staff at the ANWR provided waterfowl population estimates for the ANWR (Knutsen, 2010), which (due to lack of data specific to the WMA) were also applied to the Thief Lake WMA. To simplify CFU estimates, bacterial loadings from all waterfowl (from small to large) were simulated as “equivalent duck bacterial loadings”. The approach used was based on the assumption that the amount of bacteria deposited by the birds is a function of the bird’s size. The population of birds in the ANWR were then converted to duck equivalents (again, based on weight of bird) and multiplied by the duck bacteria load in CFU/duck/day to compute a total bacterial loading from birds. These gross estimates were acceptable to ANWR staff consulted, with the understanding that several other factors are likely to compromise any attempt to provide more accurate estimates.
- ANWR numbers were used to develop waterfowl densities per hectare of wetland which then were applied to the Thief Lake WMA. Staff at the Thief Lake WMA agreed that the

estimates provided using these methods were reasonable (Huener, 2010), so they were incorporated into the SWAT model.

2.2 Calibration and Validation

The SWAT model for the TRW was set up following the User's Manual Guidance, published by the Agricultural Research Service and the Texas Agricultural Experiment Station, Temple Texas (Neitsch[1] and others, 2005). Key procedures in this process involved:

- Delineating the watershed and sub-basins;
- Defining the hydrologic response units (HRUs) based upon land use, soils, and slope;
- Defining the weather data;
- Editing the default input files;
- Setting up (specification of the simulation period, etc.) and running SWAT – debugging the model;
- Calibrating the model;
- Validating the model; and
- Analyzing and graphing the SWAT model output

Once the base model was set up, the Theoretical Documentation (Neitsch[2] and others, 2005) and Input/Output Documentation (Neitsch[3] and others, 2005) were used as references for refining the model and interpreting the SWAT model output.

The TRW watershed was divided into the 83 sub-basins (sub-watersheds), which are a collective land area associated with a given stream reach having a defined outlet and one or more inlets. The sub-basins were further divided into a total of 550 Hydrologic Response Units (HRUs) based on land use, soils, and slope. The HRU within SWAT is essentially the computational framework; i.e., the unit to which the calculations for runoff, sediment, and TP yield are applied. A daily time step for modeled parameters was used for all model runs.

The SWAT model was run using a 2000-03 warm-up period which allowed the model compartments (soil moisture, nutrient content, etc.) to "wash" the potential influence of initial conditions from the model results. Model calibration was performed on modeling results and data from calendar years 2006-08. Model calibration is the process of "fine tuning" a model's parameters to adjust the modeled output until the results are as close to observed data as possible.

In this case, the model was calibrated to observed values of mean daily streamflow and loading of TSS, TP, and FC as measured at the MPCA monitoring site shown in **Figure 1**.

The first step in model calibration was to match up modeled and observed flows. Model parameters were adjusted to optimize the streamflow so modeled values successfully approximated what was observed. Particular attention was paid to ensure that seasonal variations in flow were modeled correctly and the magnitude, volume and duration of runoff events were similar to what was observed. The ability to successfully calibrate the hydrology of this watershed was largely dependent on the availability of impoundment management data. When good records were provided for impoundment management (i.e., outflows and elevations), the observed downstream flow was much easier to simulate. Once the flow model was satisfactory, parameters that affect estimates for the other measurements (suspended sediment [TSS], TP, and FC; most of which are related to flow) were adjusted to calibrate the model for these pollutant loads.

During calibration, a model's accuracy can be quantified through the use of statistics such as the Mean Square Error (MSE), the Nash-Sutcliffe Coefficient, or the Mann-Whitney p-value. A detailed discussion of calibration, validation, and statistical tests used to verify the quality of numerical models is presented in **Appendix B**. By adjusting the model parameters individually, and quantifying their effect on the modeled results, the modeler can identify the variables that are most influential in the calibration. These parameters can then be targeted for final "tuning". Calibration should result in a model with the least amount of error (i.e., best statistics) possible while using a set of rational and defensible parameters that fall within a "normal" or expected range.

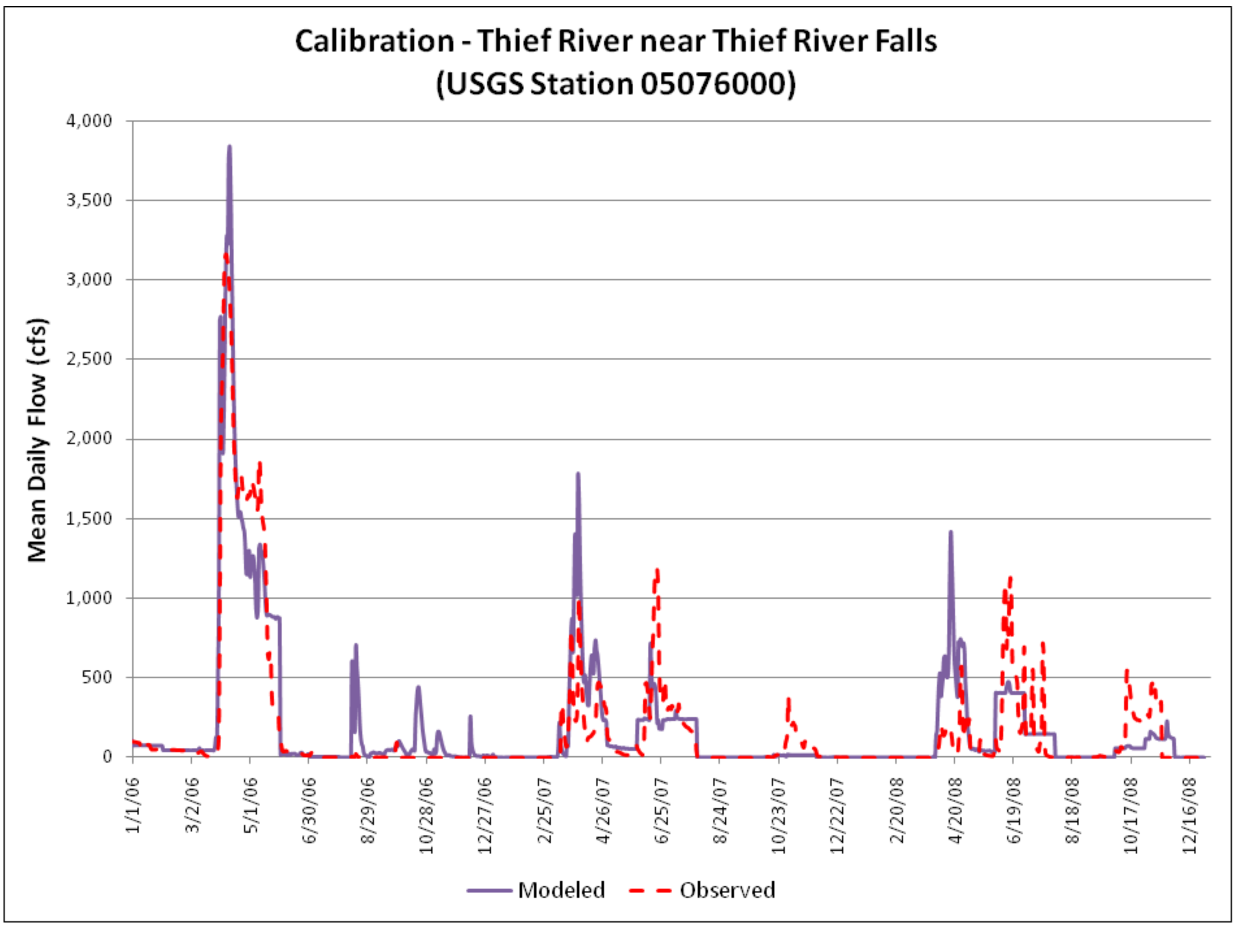
Although the SWAT model has capabilities for auto-calibration, they were not used in this work. Using a manual approach to calibrate the model gave a better appreciation for the impact of each calibrated parameter, and resulted in less overall time devoted to modeling runs. In general, the parameters that would most influence the modeled streamflow, TSS, TP, and FC, were known prior to calibration and were targeted during the calibration procedure. Parameters that were considered "known" or "well-defined," such as those associated with evaporation from open water were not adjusted. This is because the SWAT model uses well accepted equations, which default to values based on locally measured physical information, such as wind speed.

Appendix C shows the SWAT parameters that were found to be most influential during model calibration and the values that were eventually determined to be best. An explanation of each parameter is given, as well as the default range and initial values used in the SWAT model. The ranges of values explored through calibration are also shown. These parameters were adjusted during multiple model runs, the modeled outputs were compared to observed values, and model statistics were computed. The process was repeated until the modeling results and statistics no longer improved and the model at this point was considered "calibrated".

Figure 5 shows the results of the model calibration for mean daily streamflow at the calibration site. Displayed are the modeled and observed streamflow for calendar years 2006-08 and the final model statistics. As shown, the average annual percent volume difference in the modeled versus observed streamflow at this site was 9.6%, indicating a slight overestimate of annual flow. Daily discharge values were, on average, underestimated at 3.8%. The model calibration resulted in an MSE of 0.24, with a Nash-Sutcliffe Coefficient of 0.76 (see **Appendix B** for an explanation of these statistics).

Figure 5 - Results of the Model Calibration for Mean Daily Streamflow at the Thief River, near Thief River Falls, MN (2006-2008)

	Avg % Diff	MSE	Nash-Sutcliffe (E)	Mann-Whitney p-value	Mean Modeled	Mean Observed	Median Modeled	Median Observed
Daily Discharge (cfs)	-3.8	0.24	0.76	0.166	195.3	176.8	33.0	12.0
Dec-Feb Vol (AF/season)	12.1	0.06	0.94	0.827	2,863	2,547	1,369	364
Mar-May Vol (AF/season)	54.0	0.07	0.93	0.275	100,635	81,486	57,053	32,948
Jun-Aug Vol (AF/season)	23.5	0.17	0.83	0.513	25,070	27,539	32,089	38,459
Spt-Nov Vol (AF/season)	-21.2	1.53	-0.53	0.827	7,258	11,385	7,258	8,559
Annual Vol (AF/yr)	9.6	0.06	0.94	0.275	135,826	122,957	90,636	83,193

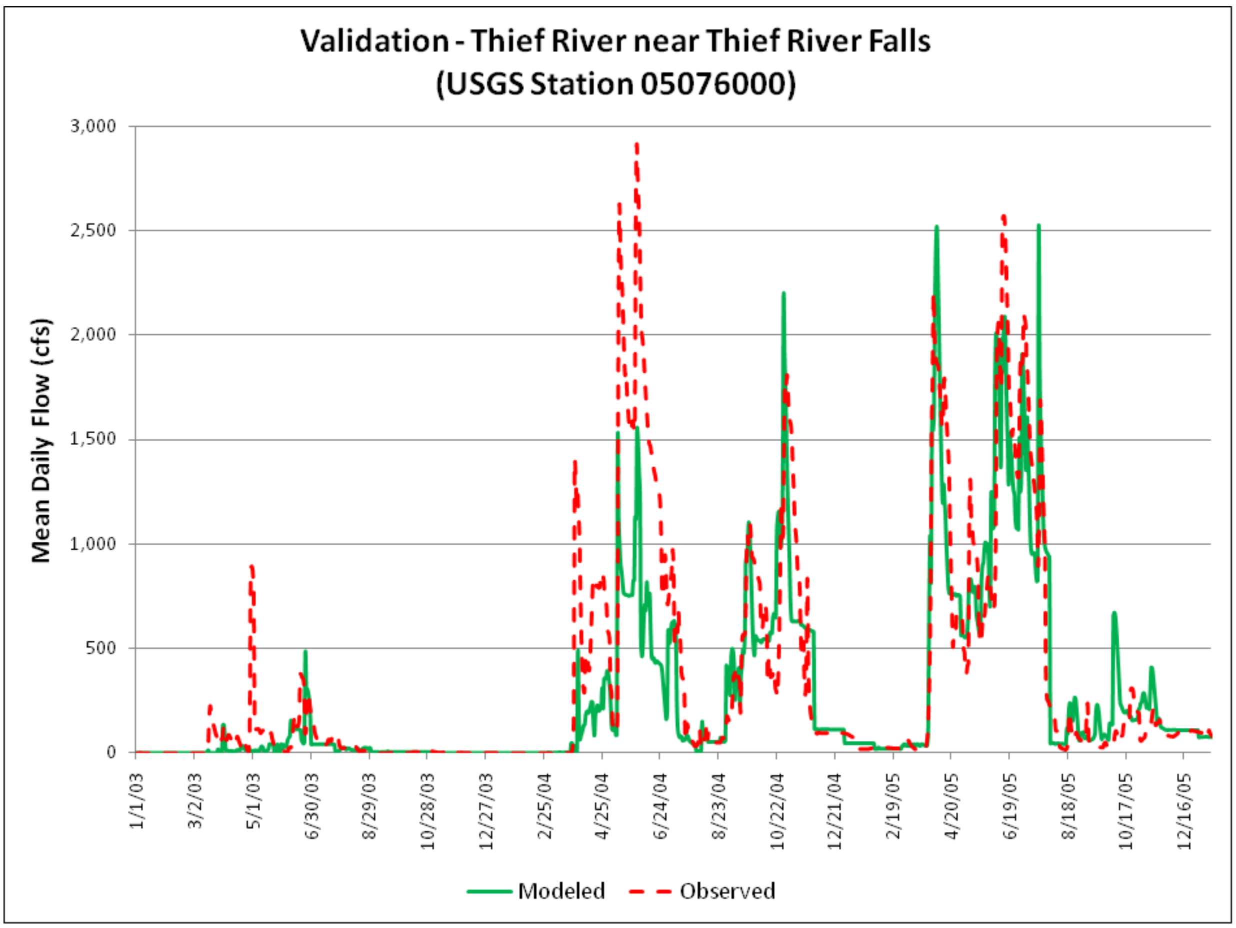


Model validation is the process of comparing the calibrated model against an additional set of field data preferably collected under conditions that differ from those used to calibrate the model (e.g., amount of streamflow, magnitude of precipitation). The parameters determined during the calibration process remain unchanged during validation, and the robustness of the calibrated model is essentially based upon comparison against a different set of field data. Assuming the behavior of the model is consistent with the validation dataset, the model "passes" and is considered acceptable for use in evaluating the results of various modeling alternatives or scenarios (such as land use or management), bounded by the parameter range used to calibrate and validate the model.

Figure 6 shows the calibrated model results for streamflow compared to the observed streamflow during calendar years 2003-05. Similar to during the calibration period (though by a larger margin), the model generally underestimated the observed daily streamflow with a -37% difference during this period. It appears that much of this underestimate can be attributed to the period during early 2004 when modeled flows considerably underestimated observed flows. Later in 2004 and through 2005, the model estimated flows improved. Unlike calibration, during the validation period the model underestimated annual flows. Validation resulted in a MSE of 0.28 and a Nash-Sutcliffe Coefficient of 0.72.

Figure 6 - Results of the Model Validation for Mean Daily Streamflow at the Thief River near Thief River Falls, MN (2003-2005)

	Avg % Diff	MSE	Nash-Sutcliffe (E)	Mann-Whitney p-value	Mean Modeled	Mean Observed	Median Modeled	Median Observed
Daily Discharge (cfs)	-37.4	0.28	0.72	0.0016	275.6	352.6	53.3	80.0
Dec-Feb Vol (AF/season)	-131	0.01	0.99	0.513	3,648	3,461	0	187
Mar-May Vol (AF/season)	-79.6	0.79	0.21	0.275	60,900	94,180	52,512	131,820
Jun-Aug Vol (AF/season)	-35.9	0.30	0.70	0.513	79,746	106,714	54,792	120,912
Spt-Nov Vol (AF/season)	10.4	0.03	0.97	0.513	53,181	48,485	34,673	19,049
Annual Vol (AF/yr)	-42.5	0.30	0.70	0.513	199,729	255,470	238,541	345,979



The TRW model was calibrated using 2006-08 data and validated using 2003-05 data for the remaining constituents: TSS, TP, and FC; those results are shown in **Figures 7 - 12**. In each of these cases, the modeled value represents a constituent load that's computed from a modeled mean daily flow and modeled mean daily constituent concentration. The observed value that it's compared to, however, is computed from an observed mean daily flow and an instantaneous constituent concentration, representative of the moment that sample was collected. The instantaneous sample may not be representative of the mean concentration (and, therefore, load) for the day and may have been a sample collected during an event that would bias the representative nature of the observed daily mean load used in the calibration/validation. Generally, the results indicate that the model performed quite well in replicating observed values.

Figure 7 - Results of the Model Calibration for Sediment Load at the Thief River near Thief River Falls, MN (2006-2008)

	Avg % Difference	MSE	Mean Modeled	Mean Observed	Median Modeled	Median Observed
Daily Load (tons/day)	**-11.2**	**2.69**	**16.9**	**13.0**	**3.9**	**0.5**

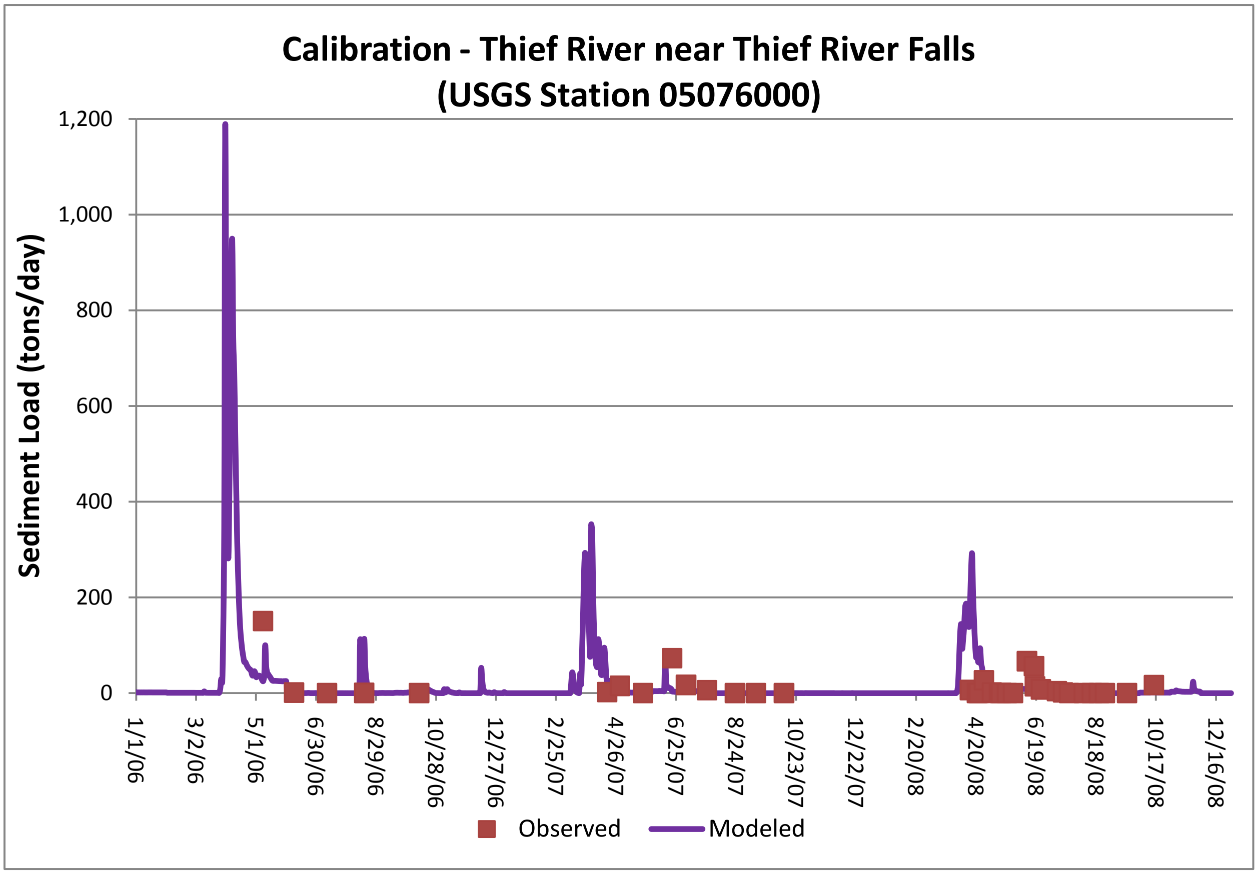


Figure 8 - Results of the Model Validation for Sediment Load at the Thief River near Thief River Falls, MN (2003-2005)

	Avg % Difference	MSE	Mean Modeled	Mean Observed	Median Modeled	Median Observed
Daily Load (tons/day)	**-14.9**	**1.06**	**10.2**	**20.4**	**1.4**	**2.2**

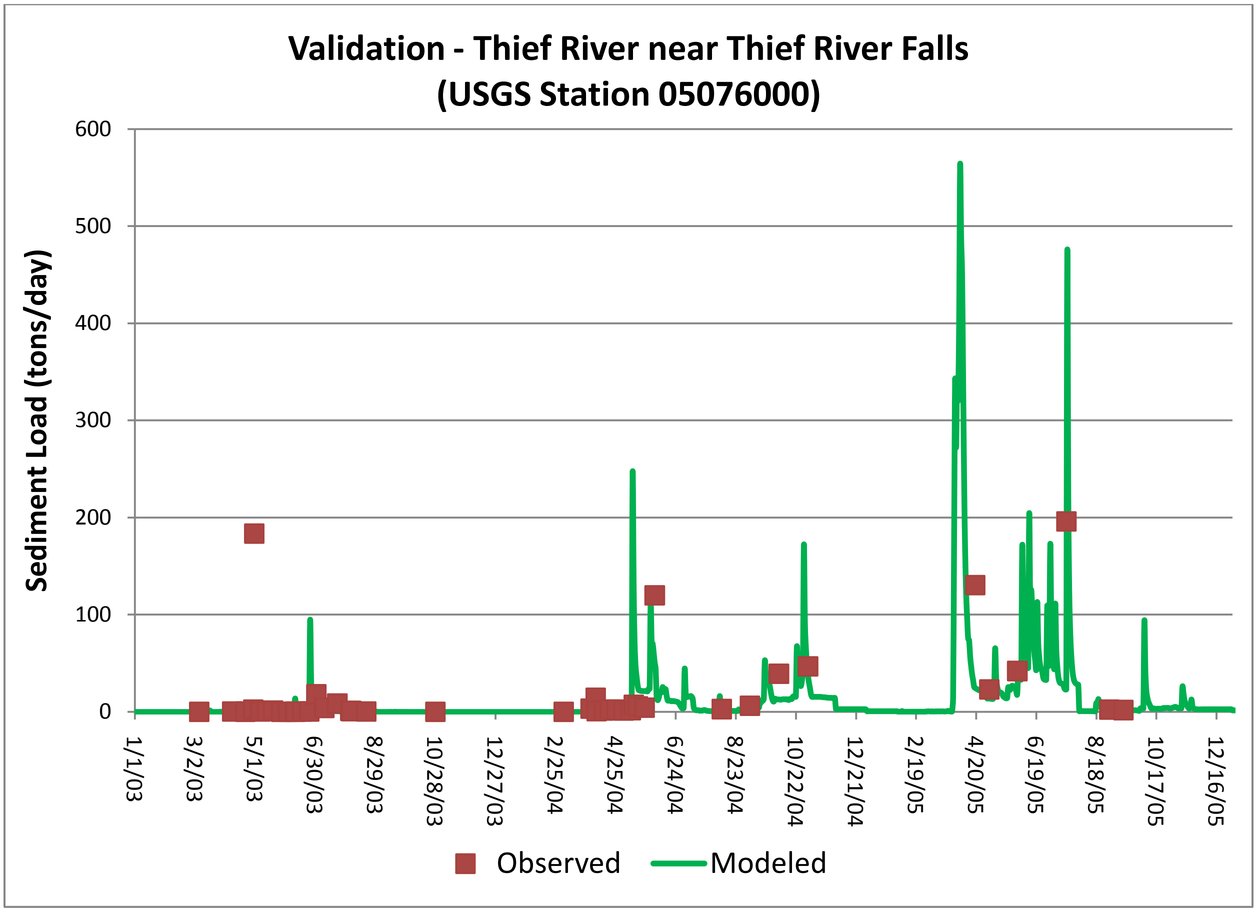


Figure 9 - Results of the Model Calibration for Total Phosphorus Load at the Thief River near Thief River Falls, MN (2006-2008)

	Avg % Difference	MSE	Mean Modeled	Mean Observed	Median Modeled	Median Observed
Daily Load (kg/day)	**-2.7**	**6.29**	**87.3**	**41.6**	**15.7**	**4.5**

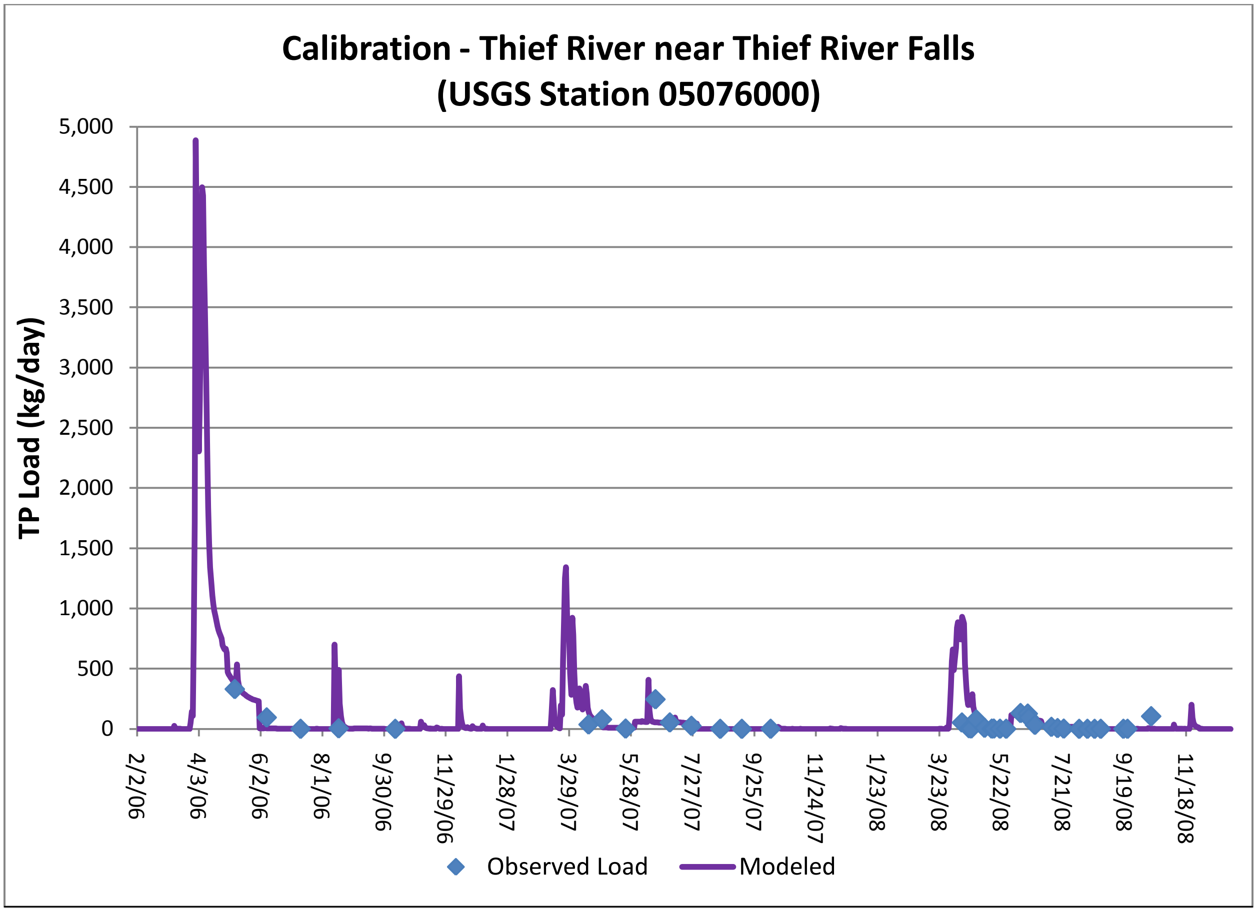


Figure 10 - Results of the Model Validation for Total Phosphorus Load at the Thief River near Thief River Falls, MN (2003-2005)

	Avg % Difference	MSE	Mean Modeled	Mean Observed	Median Modeled	Median Observed
Daily Load (kg/day)	**-108.3**	**6.64**	**83.9**	**56.7**	**0.08**	**8.1**

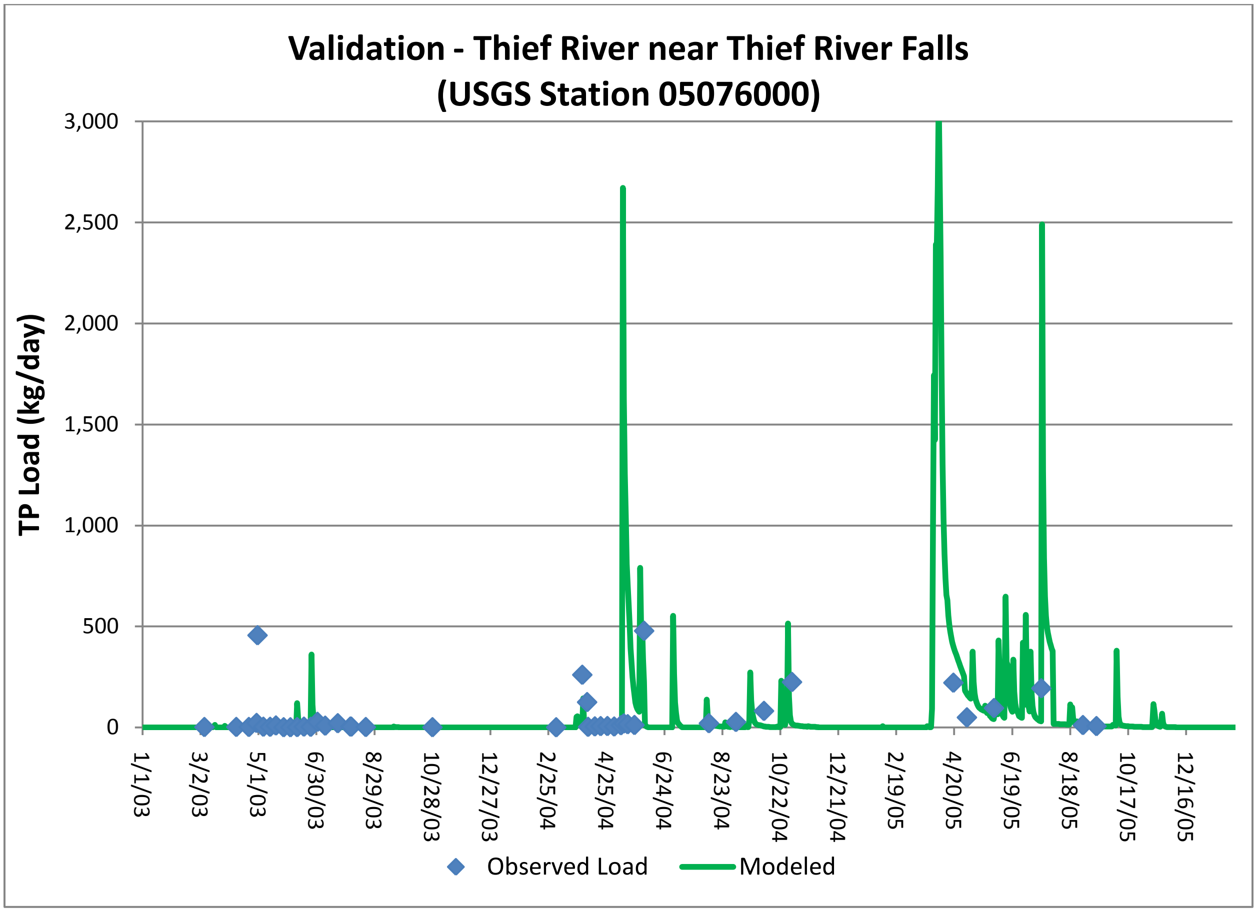


Figure 11 - Results of the Model Calibration for Fecal Coliform Load at the Thief River near Thief River Falls, MN (2006-2008)

	Avg % Difference	MSE	Mean Modeled	Mean Observed	Median Modeled	Median Observed
Daily Load (CFU/day)	**-31.4**	**1.18**	**2.96×10^{10}**	**2.10×10^{11}**	**2.67×10^{10}**	**2.89×10^{10}**

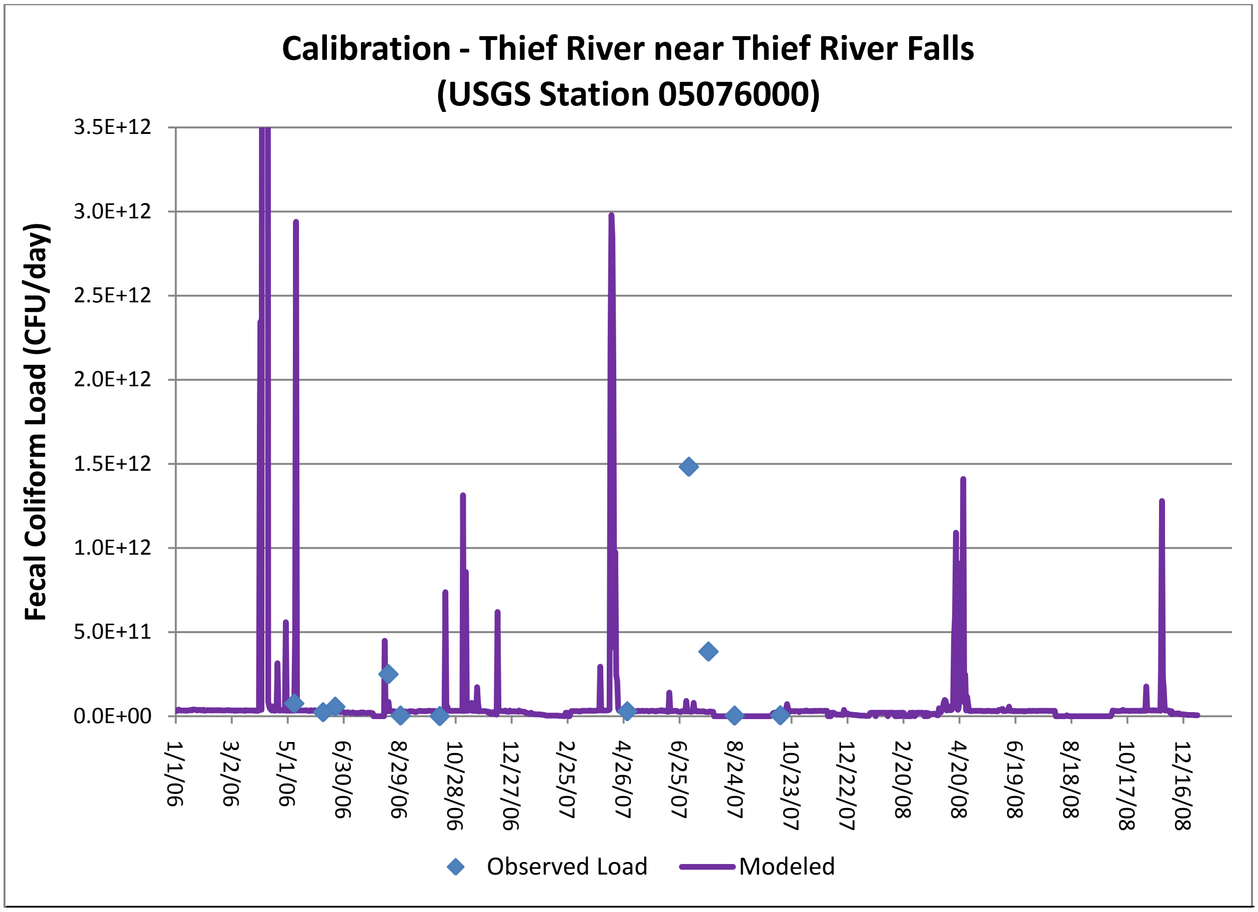
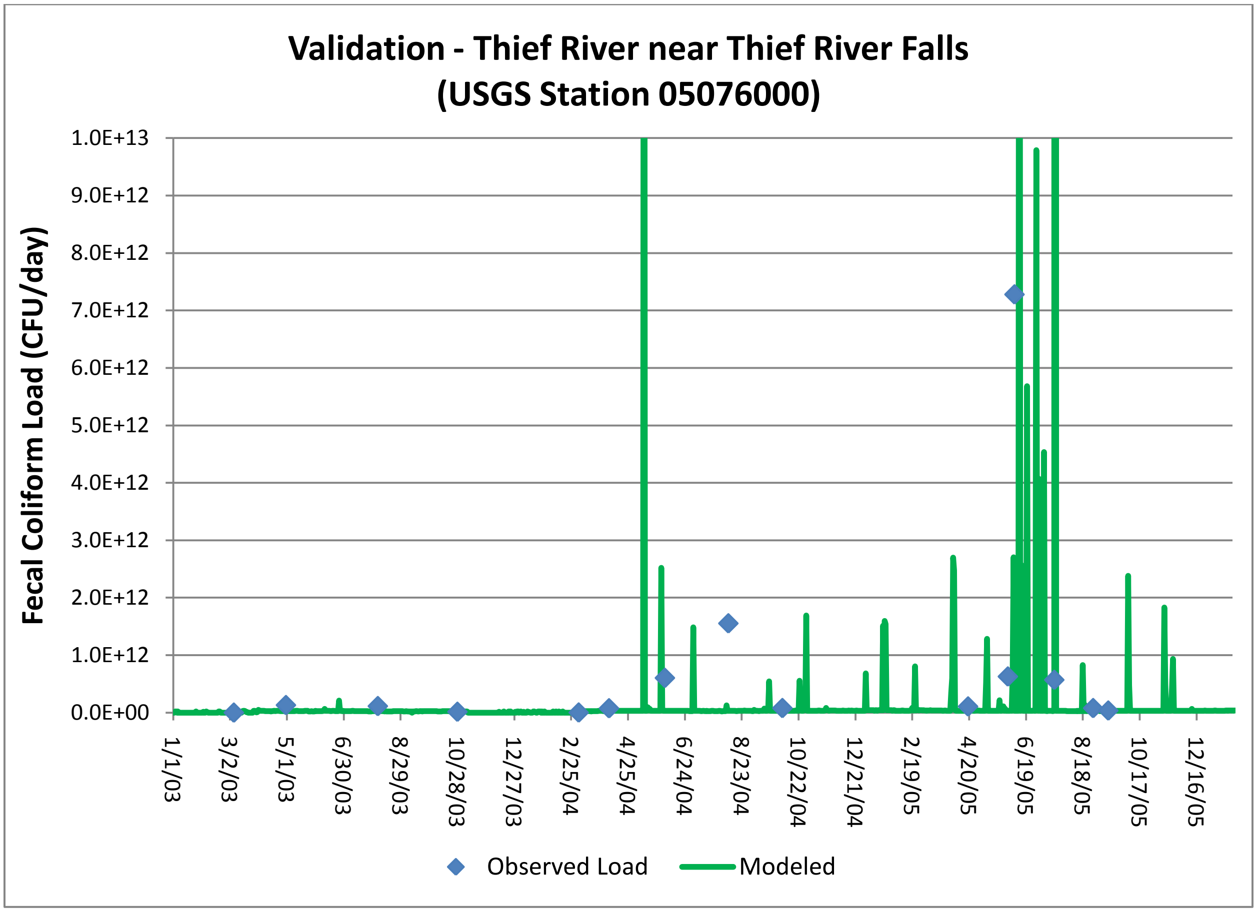


Figure 12 - Results of the Model Validation for Fecal Coliform Load at the Thief River near Thief River Falls, MN (2003-2005)

	Avg % Difference	MSE	Mean Modeled	Mean Observed	Median Modeled	Median Observed
Daily Load (CFU/day)	-101.4	1.16	2.88×10^{10}	7.52×10^{11}	3.10×10^{10}	1.08×10^{11}



It is important to recognize that errors between modeled and observed values are the product of numerous considerations. All environmental data, including the observed discharge and water quality data used in this work, inherently has some error associated with it. This error results from natural variability, as well as sampling techniques, sample handling, and lab analysis of the samples. As indicated, models are simply a tool for simulating natural processes and also inherently have errors associated with their output. This error includes errors derived from the use of equations to simulate natural processes, as well as errors in the 'driver' data that's put into the model. The overall goal of this type of project is to represent general trends in watershed processes and use these trends to predict what may occur under future modeling scenarios. Errors that are present in the calibrated base modeling results (such as under predicting flows during certain months) will also occur during the modeled scenarios. Using the relative difference between the modeled and base scenarios to make management decisions is, therefore, justifiable. The model was then used to evaluate various management scenarios for potentially improving flow characteristics and water quality.

2.3 Management Scenarios Modeled

Three different management scenarios were chosen by RLWD staff to represent different BMPs that may be implemented in the watershed to improve water quality and are summarized in **Table 2**. Scenario 1 was selected to simulate the use of filter strips in agricultural lands that border the main drainage channels in the watershed. Filter strips are generally understood to be an effective agricultural management option and are widely accepted and employed. SWAT models filter strip trapping efficiency for sediment and nutrients as:

$$\text{Trap efficiency} = 0.367 \text{ X } (\text{width of strip})^{0.2967}$$

where trap efficiency is the fraction of the constituent loading trapped by the filter strip, and width of strip is the width of the filter strip in meters. For this project, we modeled both 50- and 100-foot wide filter strip scenarios. Through consultation with RLWD staff, it was determined that filter strips would be applied to agricultural HRUs that were bisected or adjacent to the major waterways in each sub-basin. **Figure 13** shows the HRUs that met these criteria and were modeled by applying a filter strip to the edge of the HRU. (Given the size of the HRUs in this model – a function of the input datasets that were chosen during model development – the land area that was modeled with filter strips may be larger than is reasonable for implementation. Results of these simulations, however, provide a general sense of the effectiveness of this BMP and the relative load reductions that could be accomplished if this management option is used.)

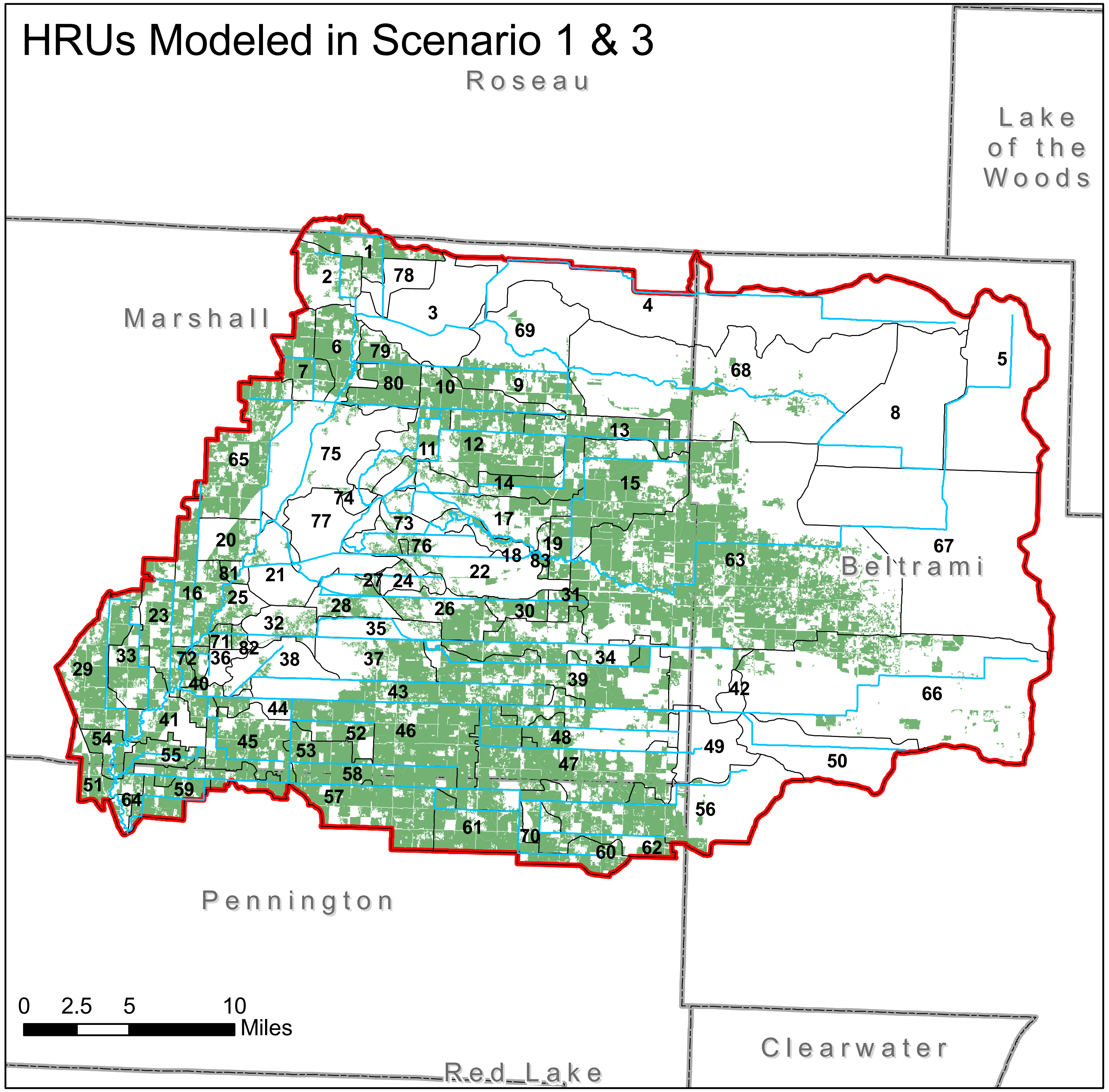
Table 2 – Management Scenarios Modeled in the Thief River Watershed

Scenario Number	Scenario Name	General Approach	Comment
1a	Filter Strips - 50 feet	Apply a 15.2 m filter strip to the edge of all HRUs that have agricultural land use and border a channel/stream.	
1b	Filter Strips - 100 feet	Apply a 30.5 m filter strip to the edge of all HRUs that have agricultural land use and border a channel/stream.	
2 min	Convert to Permanent Cover - Minimum Area	Change tilled crop to Alamo switchgrass, remove management operations, and change CN to reflect permanent cover.	Converted the smallest agricultural HRUs (maximum of 25% of sub-basin area) in each sub-basin.
2 max	Convert to Permanent Cover - Maximum Area	Change tilled crop to Alamo switchgrass, remove management operations, and change CN to reflect permanent cover.	Converted the largest agricultural HRUs in each sub-basin.
3a	Distributed Temporary Storage (Limited implementation)	Changed 30 feet of cultivated land along watercourses to wetlands.	Side-inlet controls along half of adjacent watercourses.
3b	Distributed Temporary Storage (Full implementation)	Changed 30 feet of cultivated land along watercourses to wetlands.	Side-inlet controls along all adjacent watercourses.

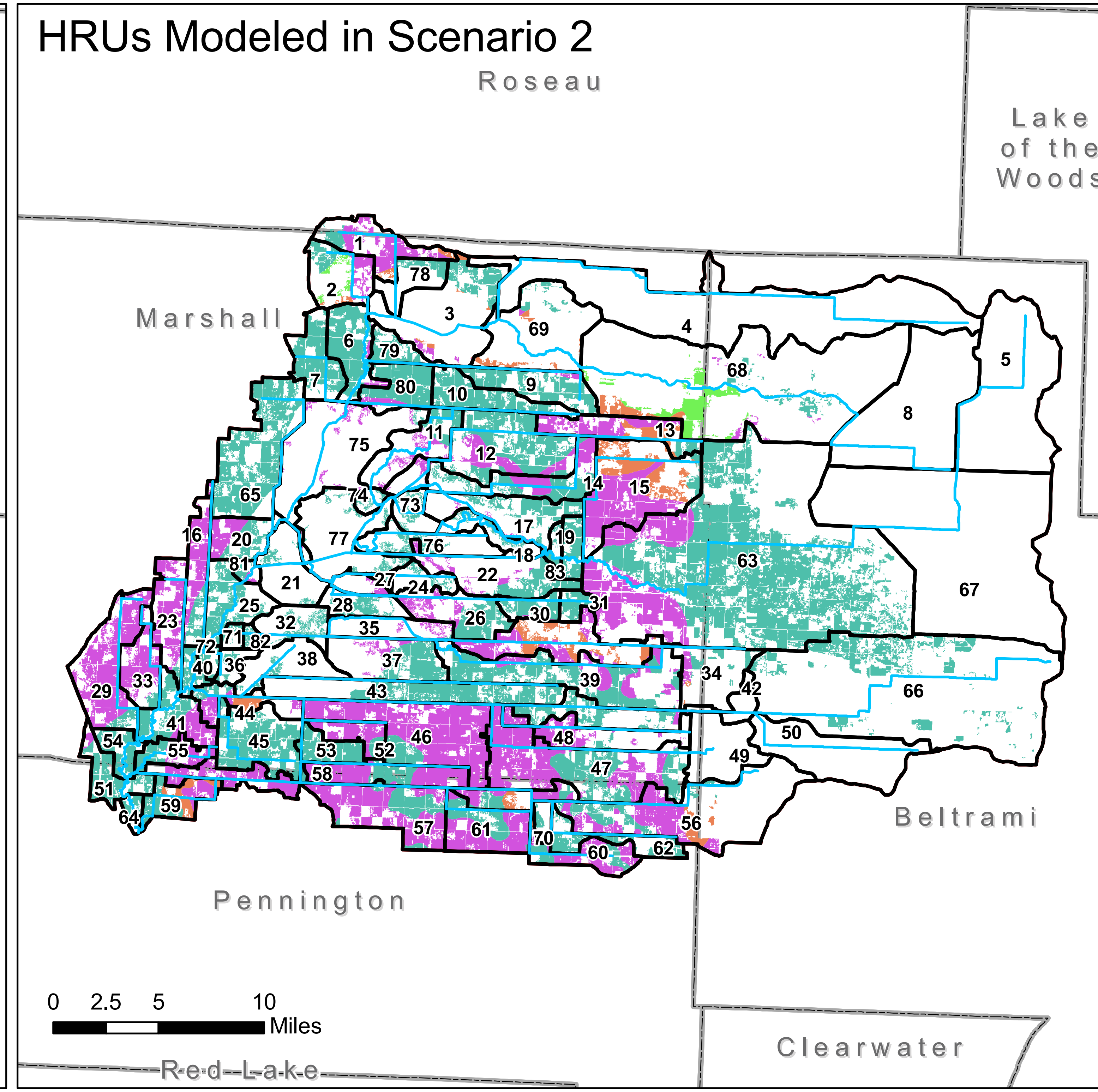
Scenario 2 was designed to simulate the conversion of agricultural land to permanent cover as may be done under a program like WHIP (Wildlife Habitats Improvement Program). Such a scenario simulates the elimination of tillage as an agricultural practice. This conversion was applied to all agricultural HRUs in the watershed, as shown in **Figure 13**. Given the size of the HRUs in this model, simply converting all or one of the agricultural HRUs in the sub-basins to permanent cover may not reflect a realistic management goal (for example, the main agricultural HRU in sub-basin 23 comprises 53% of the sub-basin area; it's unlikely that this large percentage of the sub-basin would be converted from agriculture). Though a smaller area may be desirable to model as converted, the area (and/or percent of each sub-basin) that can be modeled as converted to permanent cover is constrained by the size of the HRUs in the SWAT model. To use the setup of the SWAT model to simulate a realistic conversion of agricultural land, a suite of model runs was performed, converting each agricultural HRU in the sub-basins to permanent cover individually while documenting the impact on constituent loading and the % of sub-basin that HRU comprised. The result is a range of converted agricultural area per sub-basin. In the case of sub-basin 23, for example, two HRU conversions were modeled: 4% and 53%, giving insight to the range of load reductions that can be expected from this management approach. To quantify the range of impacts at the outlet of the watershed, the smallest agricultural HRU in each sub-basin was converted to permanent cover (using only HRUs that comprise less than 25% of their respective sub-basin; if all HRUs in a sub-basin were greater than 25% of the area, no conversion was modeled in that sub-basin) and the model was run; this scenario is known as Scenario 2 min. The upper extent of impacts was then simulated by converting the largest agricultural HRU in each sub-basin to permanent cover and running the model. This scenario is known as Scenario 2 max. The right-hand panel in **Figure 13** shows the individual agricultural HRUs in each sub-basin in the watershed; the sub-basin with the most has four, a number of sub-basins don't have any.

Switchgrass was selected as the permanent cover for the agriculture to permanent cover conversion scenarios because it allows the harvesting of a biomass-rich cash crop that requires minimal maintenance. The only variety of switchgrass programmed into the SWAT model is Alamo switchgrass, so it was used for these simulations. While Alamo switchgrass is unlikely to be used in the TRW, it is expected to have more in common with the type of switchgrass that might be cultivated in northwestern Minnesota than routinely-planted crops would have.

Scenario 3 was designed to simulate the use of side-inlet controls on agricultural fields that border the main drainage channels in the watershed. Side inlet controls were simulated in the model as ponds because SWAT does not have the capability to explicitly incorporate side inlet controls. Since SWAT models ponds as simple temporary storage, the general hydrologic modeling technique is similar to what would be used to simulate side inlets if the option were available. A generic design of a "typical" waterbody created from these side-inlet controls was modeled as having an average depth of 1 foot and an average width (measured back from each side of the channel) of 30 feet. The length of the waterbody was simulated in two ways. The first approach was to measure the length of contact between each targeted HRU (**Figure 13**) and the adjacent watercourse. Full implementation was assumed (i.e., side inlet controls would be placed along the whole length of the waterway) and is presented as Scenario 3b. The second approach was to assume that partial implementation would occur in the targeted HRU, and the length was modeled as one-half of the potential length (simulated as Scenario 3a).



- Watercourses
- Modeled Sub-basins
- Counties
- Agricultural HRUs Bisected by Stream



- Watercourses
- Modeled Sub-basins
- Counties

Agricultural HRUs

Number in Sub-Basin

- #1
- #2
- #3
- #4

Thief River Watershed

Figure 13: Characteristics of Hydrologic Response Units (HRUs) for Scenarios Modeled

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SECTION 3.0
MODELING RESULTS

3.1 EVALUATION OF LOAD REDUCTION SCENARIOS

Table 3 shows the results of the SWAT modeling at the watershed outlet, designated as Reach 64 in the model. The calibrated model was run over the period 2000-08, using 2000-02 as a "warm-up" period during which no model outputs are created. **Table 3** summarizes the results of each model run, including the base model and different scenarios, allowing for comparison of average annual streamflow and TSS, TP, and FC loads. Similar tables are included in **Appendix D** to show model results at five other target locations in the watershed (as requested by RLWD staff). Because loads are the product of streamflow and concentration, some of the differences in loads should be considered in relation to changes in the average annual streamflow.

Table 3 – SWAT Modeling Results at the Watershed Outlet (i.e., Reach 64)

Scenario	Average Annual Streamflow (acre-feet)	Average Annual Sediment Load (Tons)	Average Annual Total Phosphorus Load (Pounds)	Average Annual Fecal Coliform Load (CFUs)
Baseline: Existing Conditions (2003-2008)	175,000	7,640	71,200	2.89×10^{15}
1a: 50 Foot Filter Strips	175,000	5,510	41,600	2.89×10^{15}
1b: 100 Foot Filter Strips	175,000	4,820	35,300	2.89×10^{15}
2 min: Minimum Ag land to permanent cover	175,400	7,350	67,500	2.72×10^{15}
2 max: Maximum Ag land to permanent cover	180,000	4,280	59,700	1.98×10^{15}
3a: Partially Implemented Side-Inlet Controls	180,000	5,530	58,500	1.51×10^{15}
3b: Fully Implemented Side-Inlet Controls	180,000	5,400	57,200	1.43×10^{15}

Results of modeling the two filter-strip scenarios resulted in no change in the streamflow or the fecal coliform load at the watershed outlet. This was expected because the impact of adding filter strips to the SWAT model is to remove contaminants through the trapping efficiency approach described above, not to impact the hydrology. The main sources of fecal coliform in this model were included as direct inputs to waterbodies (as point sources or manure applied to wetland areas) and not as contaminants running off of agricultural land via overland flow; so the filter strips would have no opportunity to interact with and attenuate those inputs.

Sediment and phosphorus loading were considerably reduced by the use of filter strips in the model. Sediment loads were reduced 28% and 37%, respectively, by the 50- and 100-foot filter strips. Phosphorus loads were reduced 42% and 50%. Although increasing the width of the filter strips improves the reduction of sediment and phosphorus, the effectiveness is proportionately less. This is conveyed in the trap efficiency calculation shown in the methods section of this report. Although runoff from CAFOs was directed past filter-strip BMPs in the model, if filter strips were used in areas adjacent to CAFOs, that runoff presumably would also be filtered and would be subject to a similar numerical attenuation rate as was evident for other constituents. Added to that might be other factors that affect the survivability of the bacteria as they traverse filter strips.

Modeling the conversion of tilled cropland to permanent cover resulted in a slight increase in the streamflow; less than 1% in the minimum level of conversion and nearly 3% for the maximum conversion modeled. This likely resulted from an increase in the runoff curve number when some of the agricultural management operations were removed from the HRUs, resulting in slightly more runoff. The loads of sediment, TP, and FC were reduced by 4%, 5%, and 6%, respectively under the minimal crop-conversion scenario. Under the maximum crop-conversion scenario they were reduced by 44%, 16%, and 31%, respectively. The model results suggest that increasing the amount of land converted to permanent cover is most effective at reducing sediment load, and least effective at reducing TP load. However, the reductions in TP load are not as dramatic as seen with the application of filter strips.

Results of the numerous model runs that were created to simulate the conversion of a range of agricultural areas in each sub-basin to permanent cover are given in **Appendix E**. Results provide insight to the range of load reductions that can be expected from implementing this management scenario, since the scenarios simulate under minimum and maximum conversion to permanent cover (Scenarios 2 min and 2 max) are neither, probably, realistic to implement on a watershed-scale.

Modeling of side inlet controls also resulted in slight increase in streamflow due to the way that SWAT models temporary storage and affects other aspects of the hydrology (primarily the groundwater) in a sub-basin. Although loads of all modeled constituents were reduced substantially by the use of side inlets, there was little improvement or gain by fully implementing side-inlet controls compared to only a partial implementation.

The reductions in fecal coliform loading seen in Scenarios 2 and 3 are likely a consequence of the impacted sub-basin hydrology during these simulations. Bacterial inputs to the model were not changed and the primary inputs to the model (CAFOs modeled as point sources, bird manure applied to wetland HRUs, and point source inputs from the WWTPs) should not be directly impacted by the BMPs. The model transparency associated with modeling bacterial loading is, unfortunately, less than provided for other variables, so tracking the bacterial movement (and reductions) through the watershed is difficult. Hydrologic impacts of the Scenario 2 and 3 BMPs, however, could impact bacterial concentrations by shifting groundwater/surface water balances (which impacts the amount of bacteria that wash-off via overland flow), adjusting time travels in the watershed, and adjusting residence times in the waterways.

3.2 SUB-BASIN YIELDS FOR SCENARIOS RELATIVE TO BASELINE

Figure 14 shows the average daily yield of TSS for each of the 83 sub-basins in the TRW using the calibrated model and input data from 2003-08. In the baseline (‘Base’) condition, yields generally were smallest in the wetter, eastern parts of the watershed and increased substantially in watersheds draining the western portions of the TRW. The subsequent maps, **Figure 15 and 16**, show the yields for two versions of the TSS Scenario 1 using the same breakpoints in the yield levels. As the maps progress from baseline to adding 50-foot filter strips, then 100-foot filter strips, the yields are reduced and more of the sub-basins drop into lower yield categories. Many of the central sub-basins fall into the lowest-yield category with

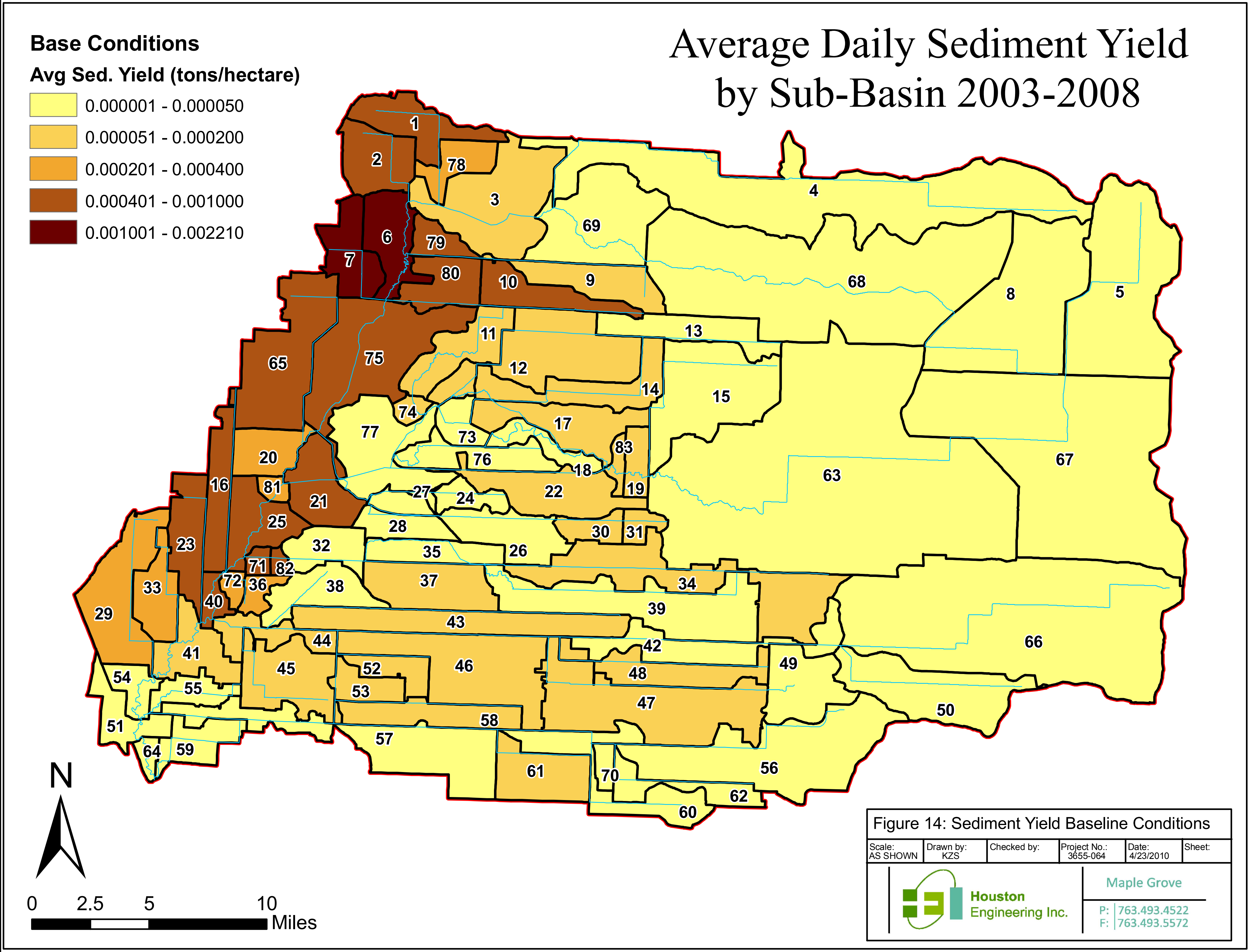
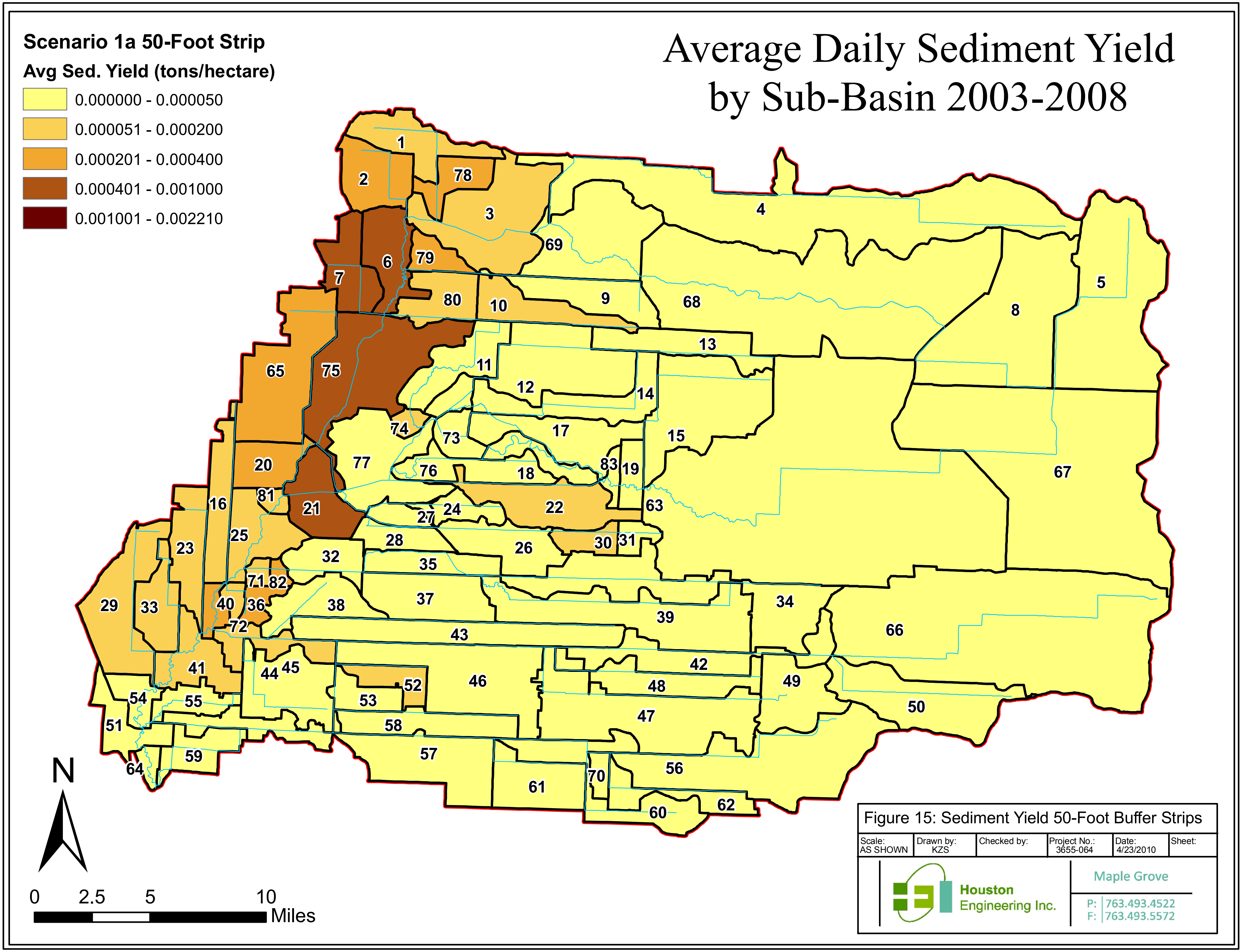


Figure 14: Sediment Yield Baseline Conditions


Average Daily Sediment Yield
by Sub-Basin 2003-2008
Scenario 1a 50-Foot Strip
Avg Sed. Yield (tons/hectare)
0.000000 - 0.000050
0.000051 - 0.000200
0.000201 - 0.000400
0.000401 - 0.001000
0.001001 - 0.002210
N
0 2.5 5 10
Miles
Figure 15: Sediment Yield 50-Foot Buffer Strips
Scale: AS SHOWN
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Checked by:
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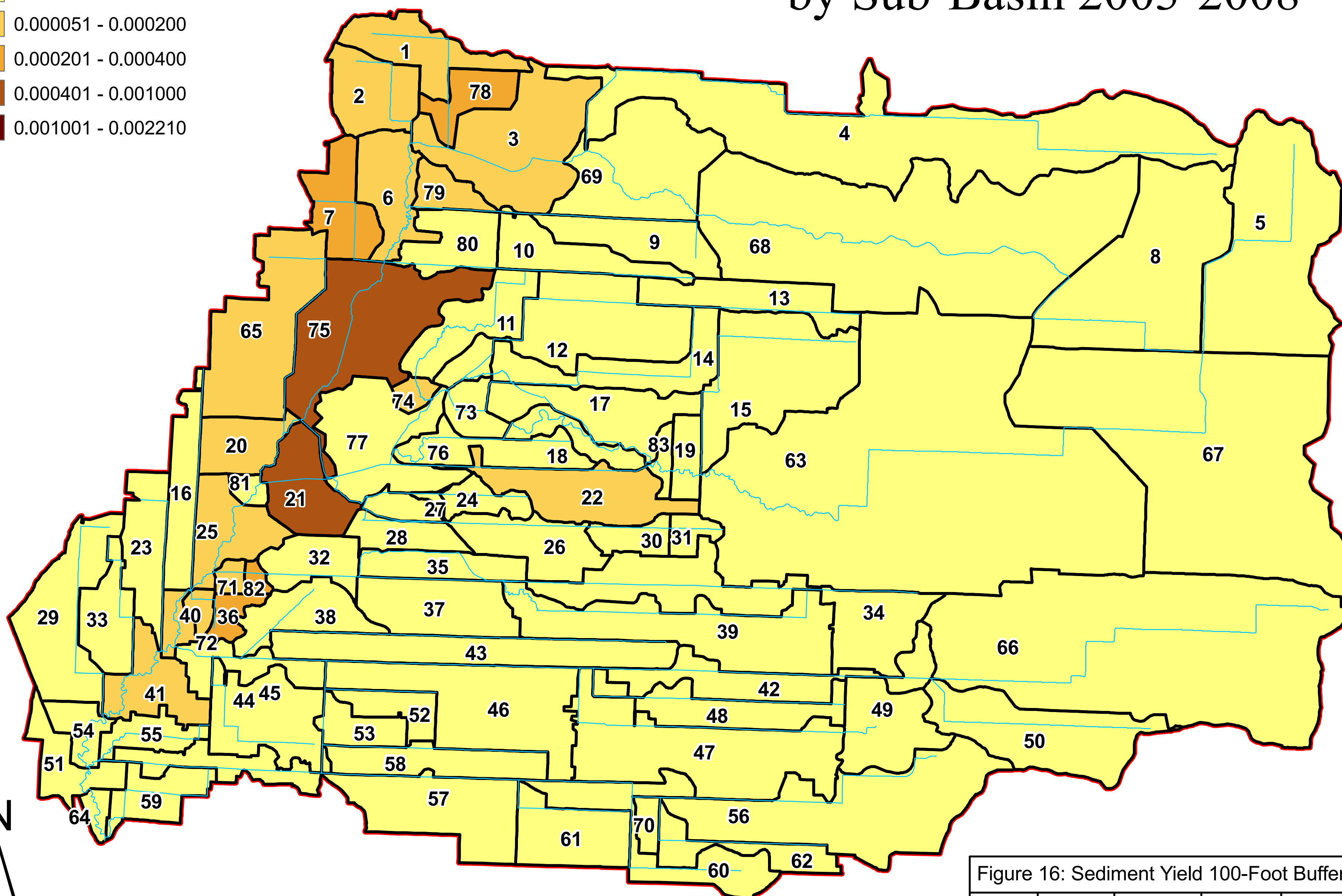
Average Daily Sediment Yield by Sub-Basin 2003-2008

Scenario 1b 100-Foot Strip

Avg Sed. Yield (tons/hectare)

- 0.000000 - 0.000050
- 0.000051 - 0.000200
- 0.000201 - 0.000400
- 0.000401 - 0.001000
- 0.001001 - 0.002210



N

0 2.5 5 10 Miles

Figure 16: Sediment Yield 100-Foot Buffer Strips

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the addition of the 50-foot filter strips, although Sub-basin 22 persistently remains in its original category even when the filter strip is increased to 100-feet. Many of the western sub-basins respond progressively as filter-strip width is increased during the modeling of each scenario.

The results of modeling Scenario 2, changing tilled agriculture to permanent cover, as compared to the baseline simulation are shown in **Figures 17 and 18**. The minimal change to permanent cover appears to have almost no effect of the grouping of the sub-basins compared to baseline. However, the maximum modeled change to permanent cover caused many of the sub-basins to drop to the lowest yield category and none of the sub-basins were in the highest yield category.

The modeled use of temporary storage as side inlet controls as compared to baseline conditions is shown in **Figures 19 and 20**. Adding partial side-inlet controls has a substantial effect in reducing sediment yields from many sub-basins. Fully-implementing side-inlet controls does little to reduce yields compared to partial implementation, so that relatively few sub-basins drop from one yield category to another.

Figure 21 shows the average daily yield of TP for each of the 83 sub-basins in the TRW using the calibrated model and input data from 2003-08. In the baseline ('Base') condition, yields generally were smallest in the wetter, eastern parts of the watershed and increased substantially in watersheds draining the western portions of the TRW. This is much the same as was observed for the sediment yields. **Figures 22 and 23** show the yields for the two versions of Scenario 1 using the same breakpoints in the yield levels. As the maps progress from baseline to adding 50-foot filter strips, then 100-foot filter strips, the yields are reduced and more of the watersheds drop into lower yield categories. Many of the central sub-basins fall into the lowest-yield category with the addition of the 50-foot filter strips. Many of the most western and northwestern sub-basins respond progressively as filter-strip width is increased during the modeling of each scenario. **Figure 3** shows that many of the soils in this part of the watershed are unique compared to other parts of the TRW.

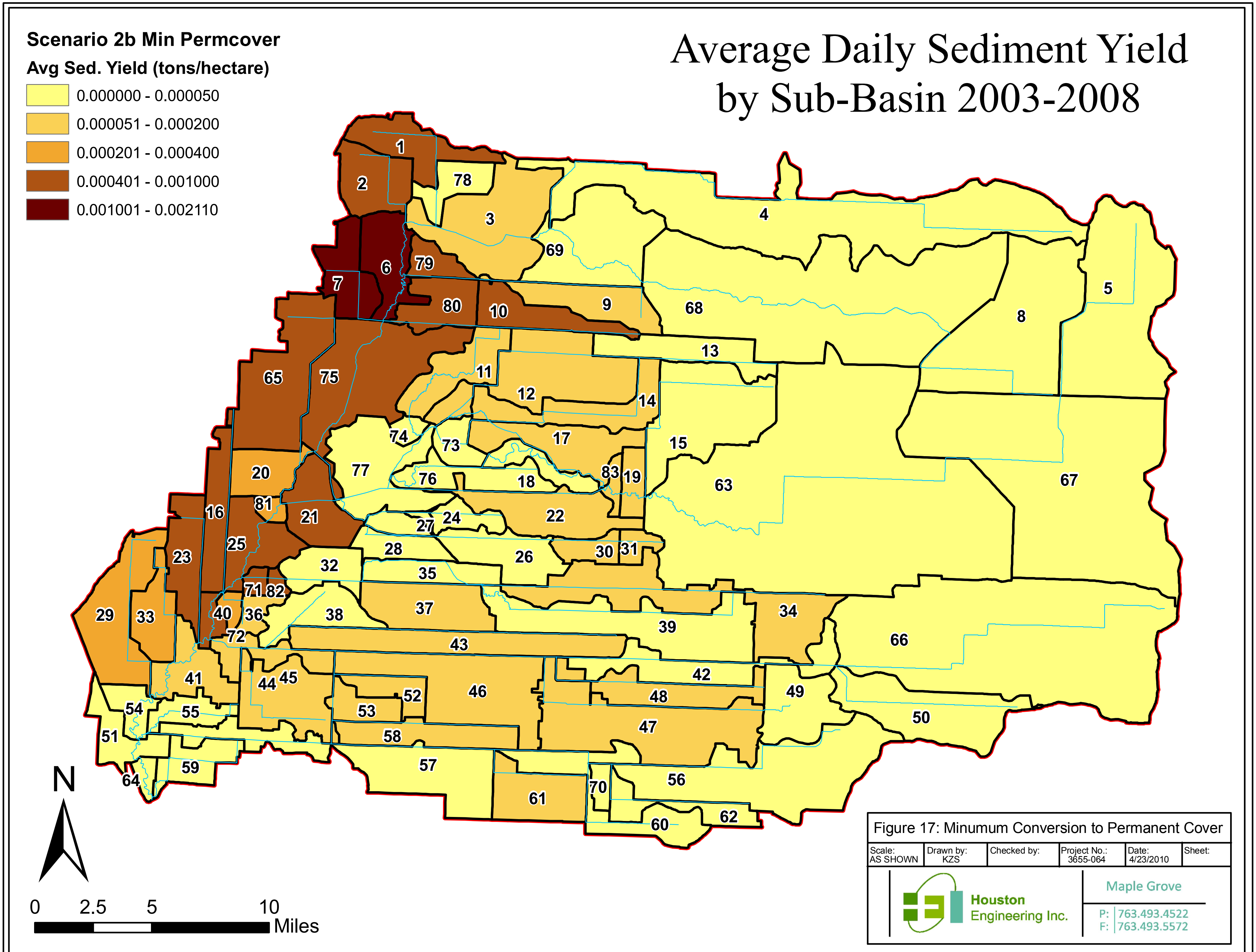
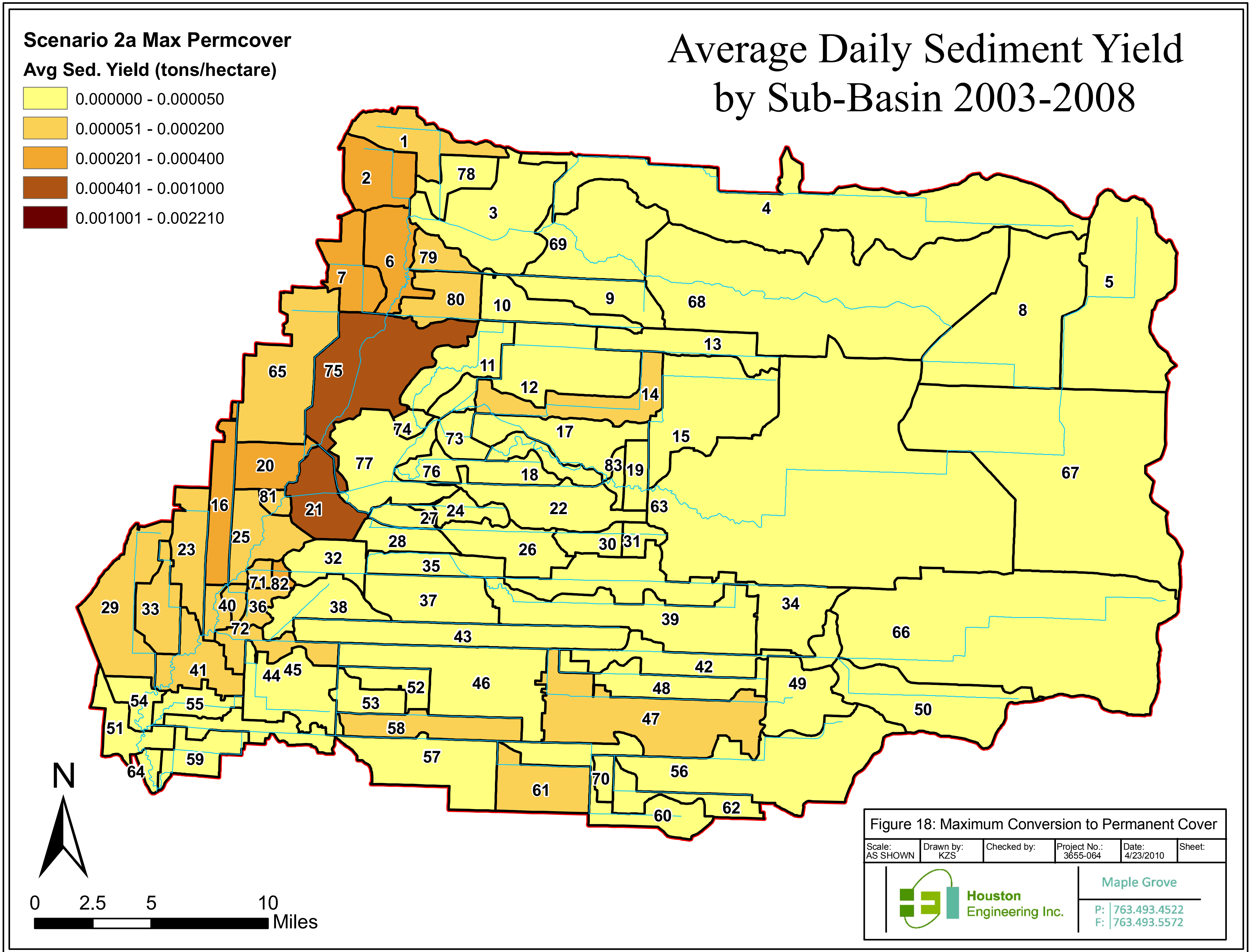


Figure 17: Minumum Conversion to Permanent Cover


Average Daily Sediment Yield
by Sub-Basin 2003-2008
Scenario 2a Max Permcover
Avg Sed. Yield (tons/hectare)
0.000000 - 0.000050
0.000051 - 0.000200
0.000201 - 0.000400
0.000401 - 0.001000
0.001001 - 0.002210
N
0 2.5 5 10
Miles
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40 41 42 43 44 45 46 47 48 49 50 51 52 53 54 55 56 57 58 59 60 61 62 63 64 65 66 67 68 69 70 71 72 73 74 75 76 77 78 79 80 81 82 83
Figure 18: Maximum Conversion to Permanent Cover
Scale: AS SHOWN
Drawn by: KZS
Checked by:
Project No.: 3655-064
Date: 4/23/2010
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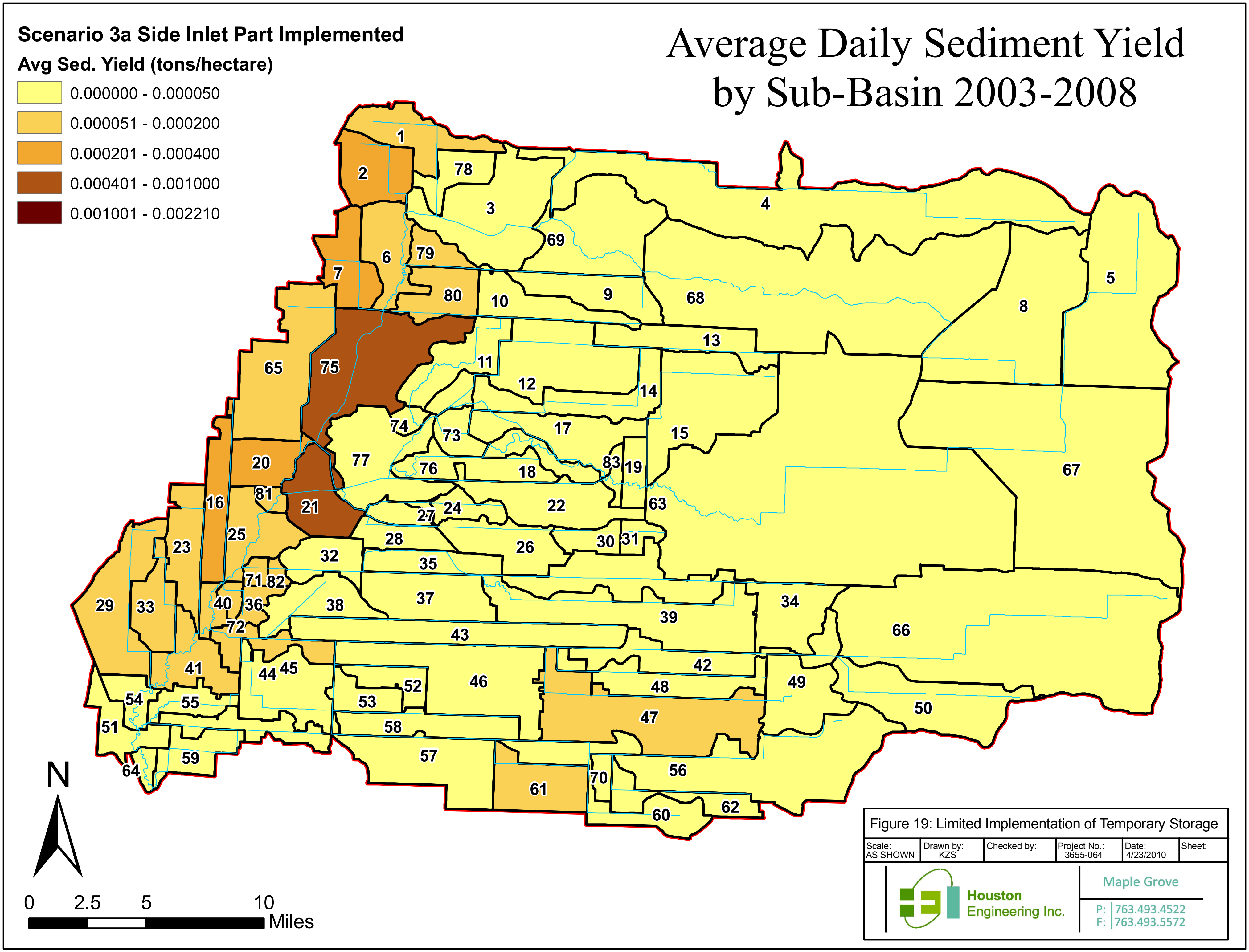
Houston Engineering Inc.
Maple Grove
P: 763.493.4522
F: 763.493.5572


Average Daily Sediment Yield
by Sub-Basin 2003-2008
Scenario 3a Side Inlet Part Implemented
Avg Sed. Yield (tons/hectare)
0.000000 - 0.000050
0.000051 - 0.000200
0.000201 - 0.000400
0.000401 - 0.001000
0.001001 - 0.002210
1
78
2
3
4
69
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75
11
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57
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64
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70
60
62
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2.5
5
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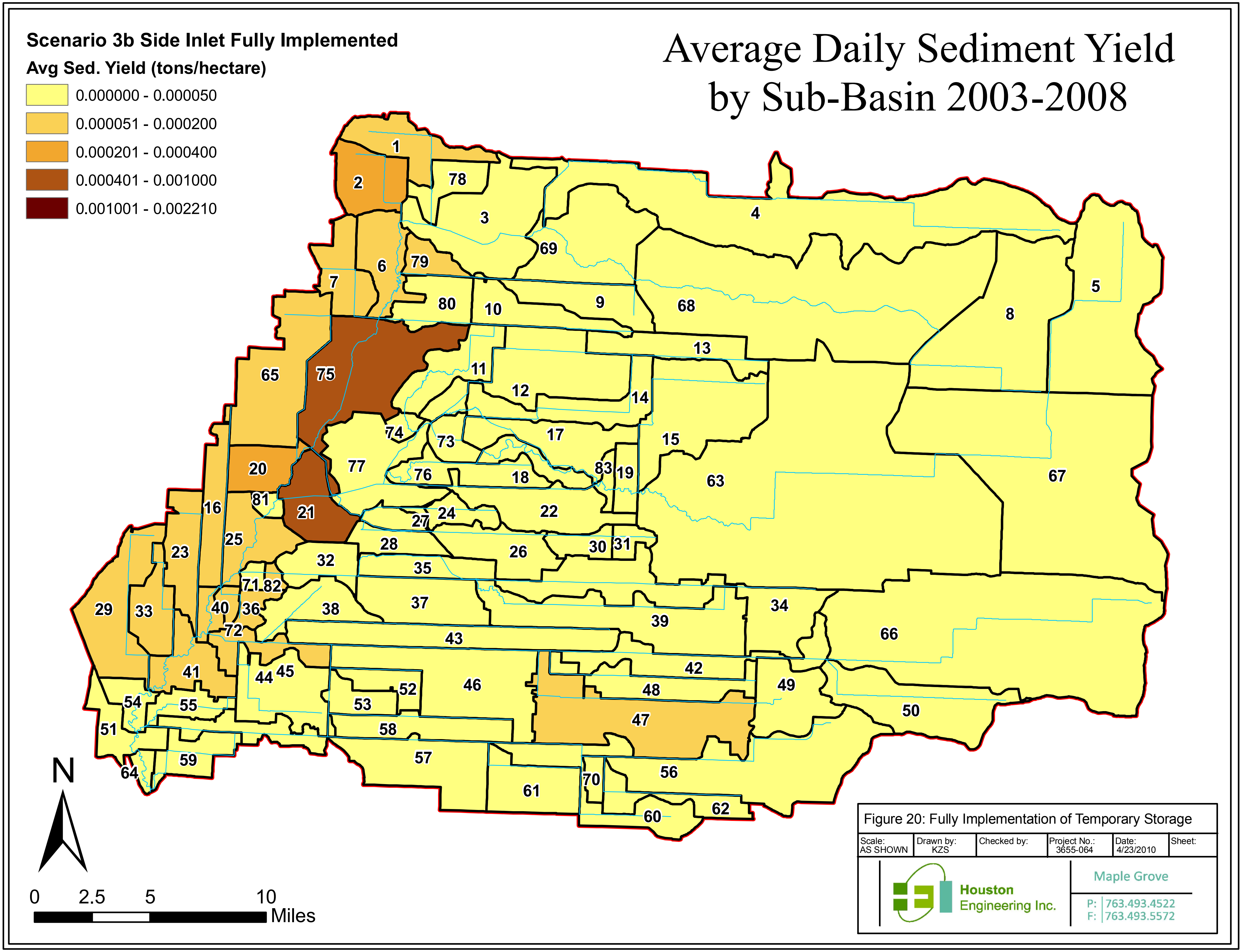
Miles
Figure 19: Limited Implementation of Temporary Storage
Scale: AS SHOWN
Drawn by: KZS
Checked by:
Project No.: 3655-064
Date: 4/23/2010
Sheet:
Houston Engineering Inc.
Maple Grove
P: 763.493.4522
F: 763.493.5572


Average Daily Sediment Yield
by Sub-Basin 2003-2008
Scenario 3b Side Inlet Fully Implemented
Avg Sed. Yield (tons/hectare)
0.000000 - 0.000050
0.000051 - 0.000200
0.000201 - 0.000400
0.000401 - 0.001000
0.001001 - 0.002210
N
0 2.5 5 10
Miles
Figure 20: Fully Implementation of Temporary Storage
Scale: AS SHOWN
Drawn by: KZS
Checked by:
Project No.: 3655-064
Date: 4/23/2010
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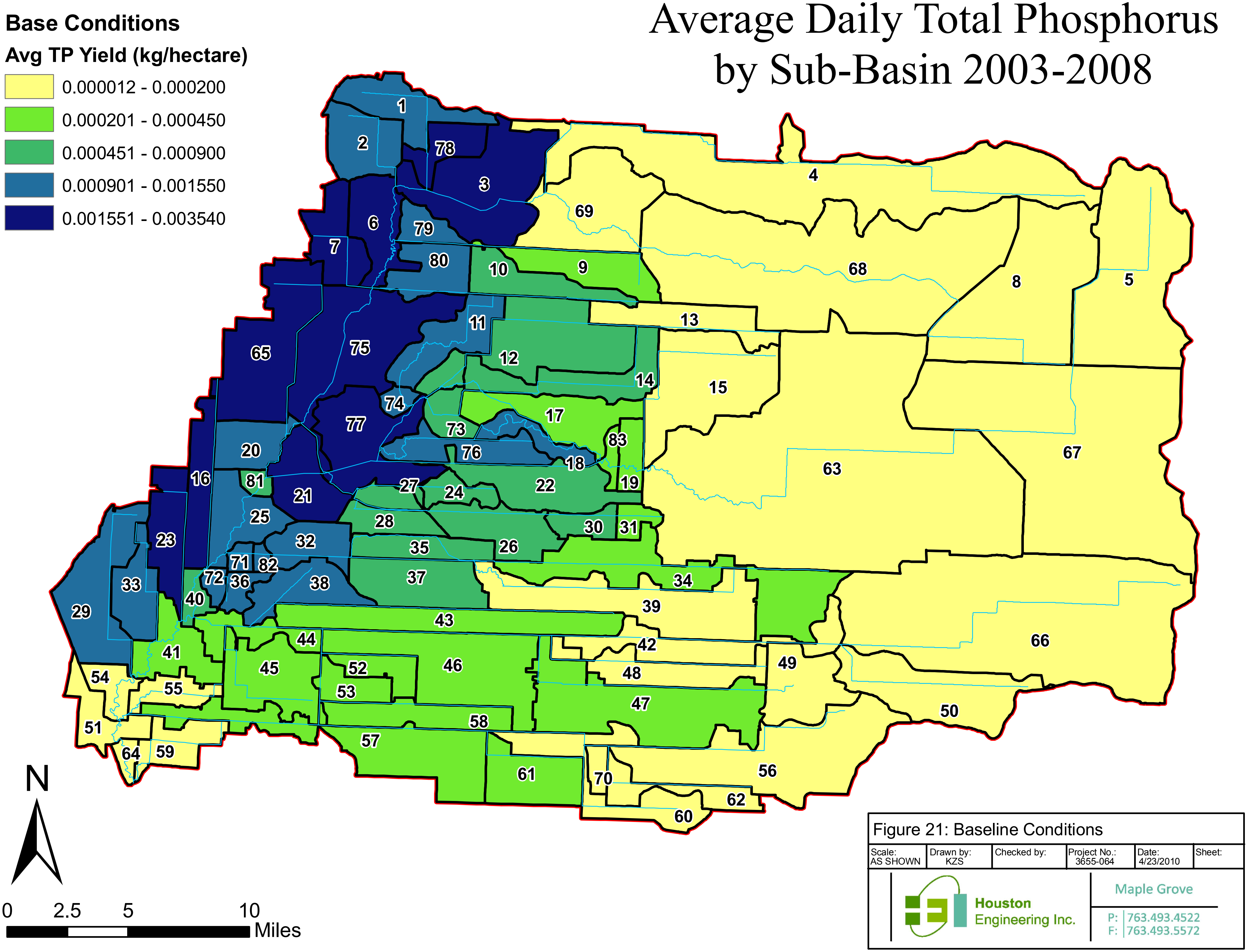
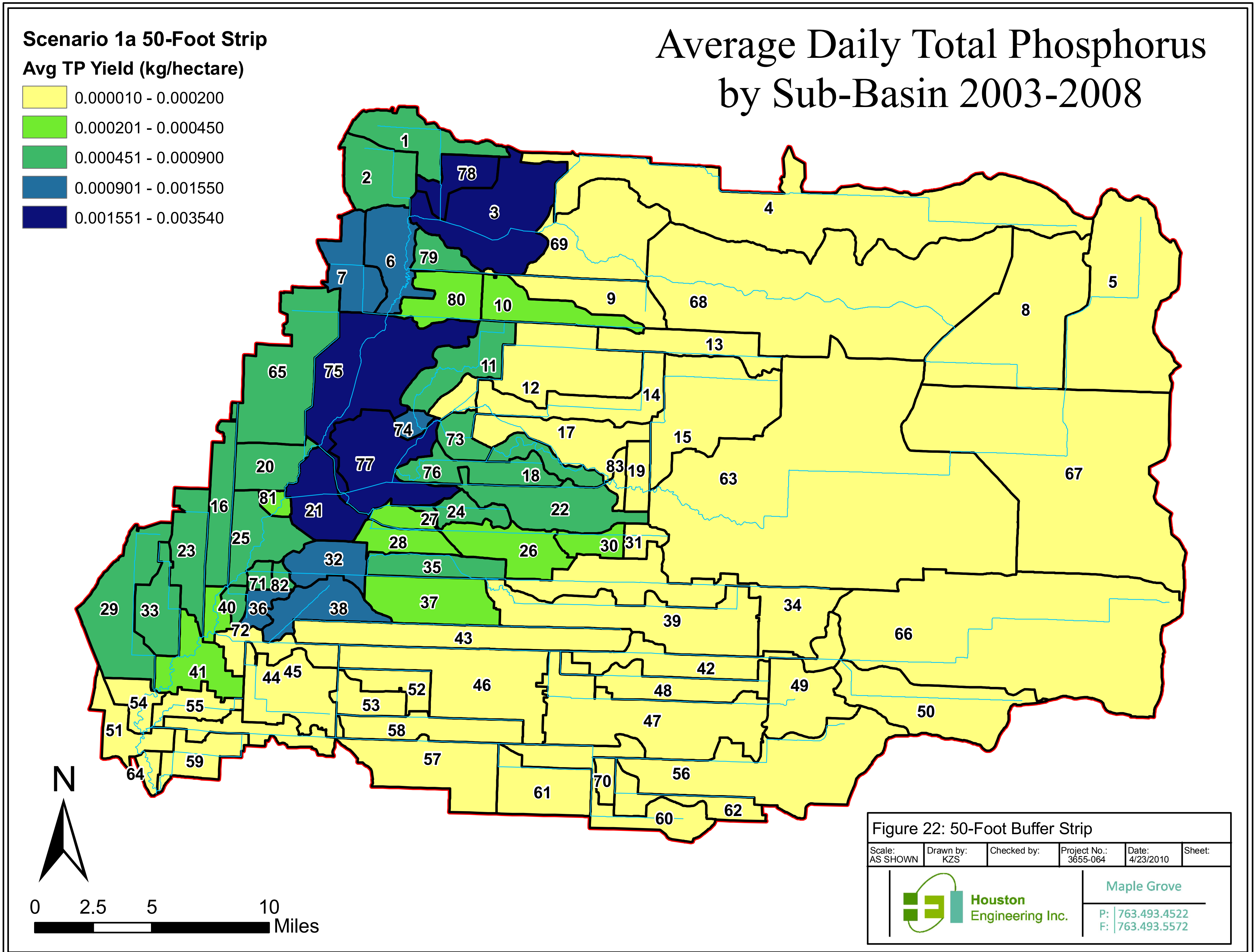
Average Daily Total Phosphorus by Sub-Basin 2003-2008





Average Daily Total Phosphorus
by Sub-Basin 2003-2008
Scenario 1a 50-Foot Strip
Avg TP Yield (kg/hectare)
0.000010 - 0.000200
0.000201 - 0.000450
0.000451 - 0.000900
0.000901 - 0.001550
0.001551 - 0.003540
N
0 2.5 5 10
Miles
Figure 22: 50-Foot Buffer Strip
Scale: AS SHOWN
Drawn by: KZS
Checked by:
Project No.: 3655-064
Date: 4/23/2010
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Average Daily Total Phosphorus by Sub-Basin 2003-2008

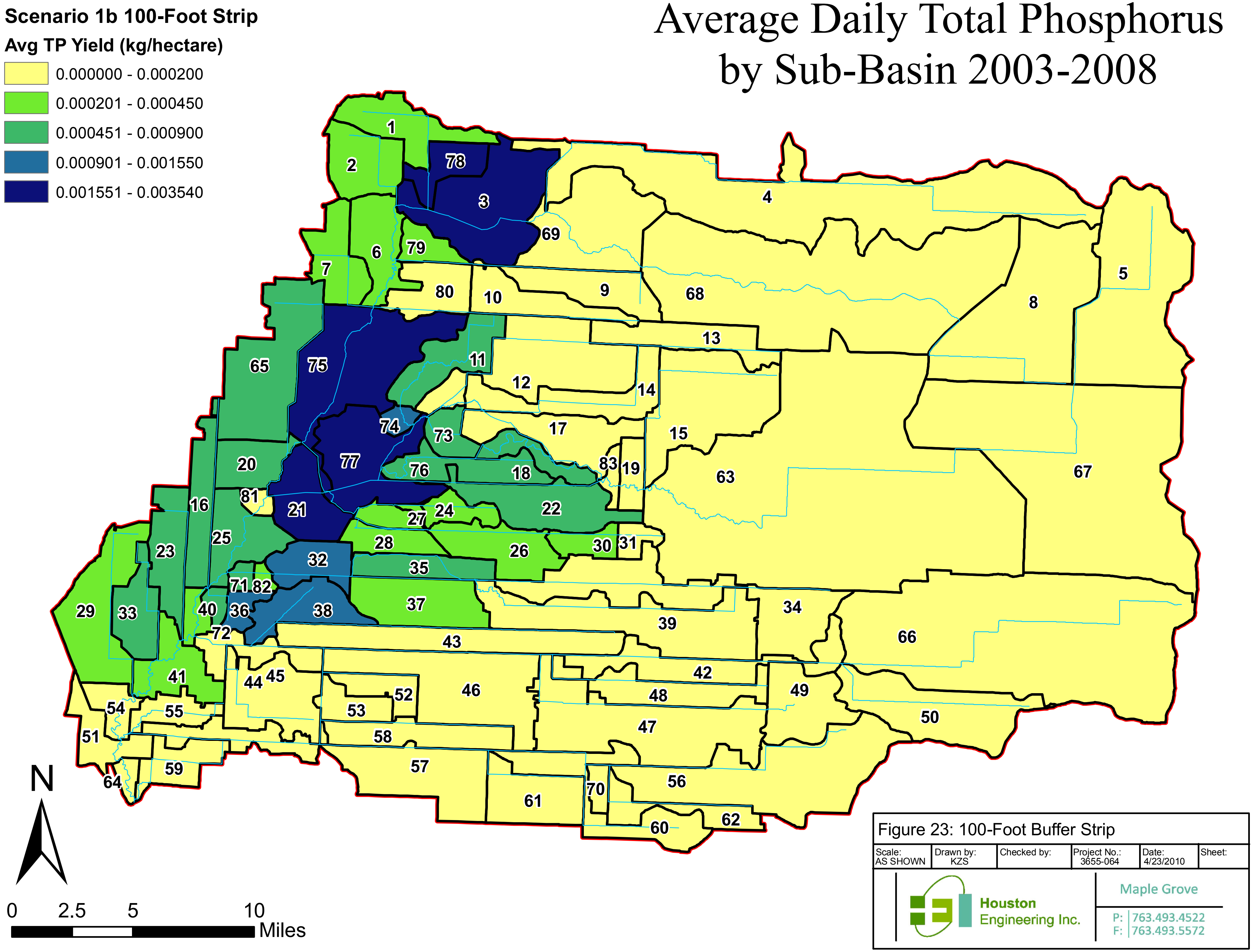

Figure 23: 100-Foot Buffer Strip

The results of modeling Scenario 2, changing tilled agriculture to permanent cover, compared to baseline is shown in **Figures 24 and 25**. The minimal change to permanent cover appears to have minimal effect on the grouping in yield categories of the sub-basins compared to baseline, with the effects apparent mostly in sub-basins located near the set-central part of the TRW. The maximum modeled change to permanent cover produced mixed results with some watersheds dropping to a lower yield category while others had increased yields that shifted them into a higher yield category. Declines were observed mostly in the west while increases occurred primarily in the west-central.

The modeled use of temporary storage as side inlet controls is compared to baseline conditions is shown in **Figures 26 and 27**. Adding partial side-inlet controls has a substantial effect in reducing TP yields from many sub-basins; especially in the western sub-basins. Fully-implementing side-inlet controls does little to reduce TP yields compared to partial implementation, so that relatively few sub-basins drop from one yield category to another.

3.3 Loading to Impoundments Relative to Baseline

A particular concern in the TRW is the movement of sediment from field, streambank, and other sources to downstream areas such as impoundments where it will deposit, filling those waterbodies. This deposition requires periodic maintenance to intercept or remove the sediment, so the useful depth of the reservoirs is maintained. Phosphorus loading to the impoundments is also a concern because it could lead to eutrophication if phosphorus is the nutrient limiting productivity. Some of this phosphorus may be associated with the sediment transported to the reservoirs.

Although the SWAT model was calibrated to approximate hydrology at a point nearest the downstream end of the TRW, the parameters used to build the model, including soils, land use, climate, etc., likely provide a reasonable approximation of the hydrology of most of the TRW. Therefore, the user is justified in using the SWAT output to infer whether changes in management practices can affect the movement of water and materials in various parts of the watershed.

Average Daily Total Phosphorus by Sub-Basin 2003-2008

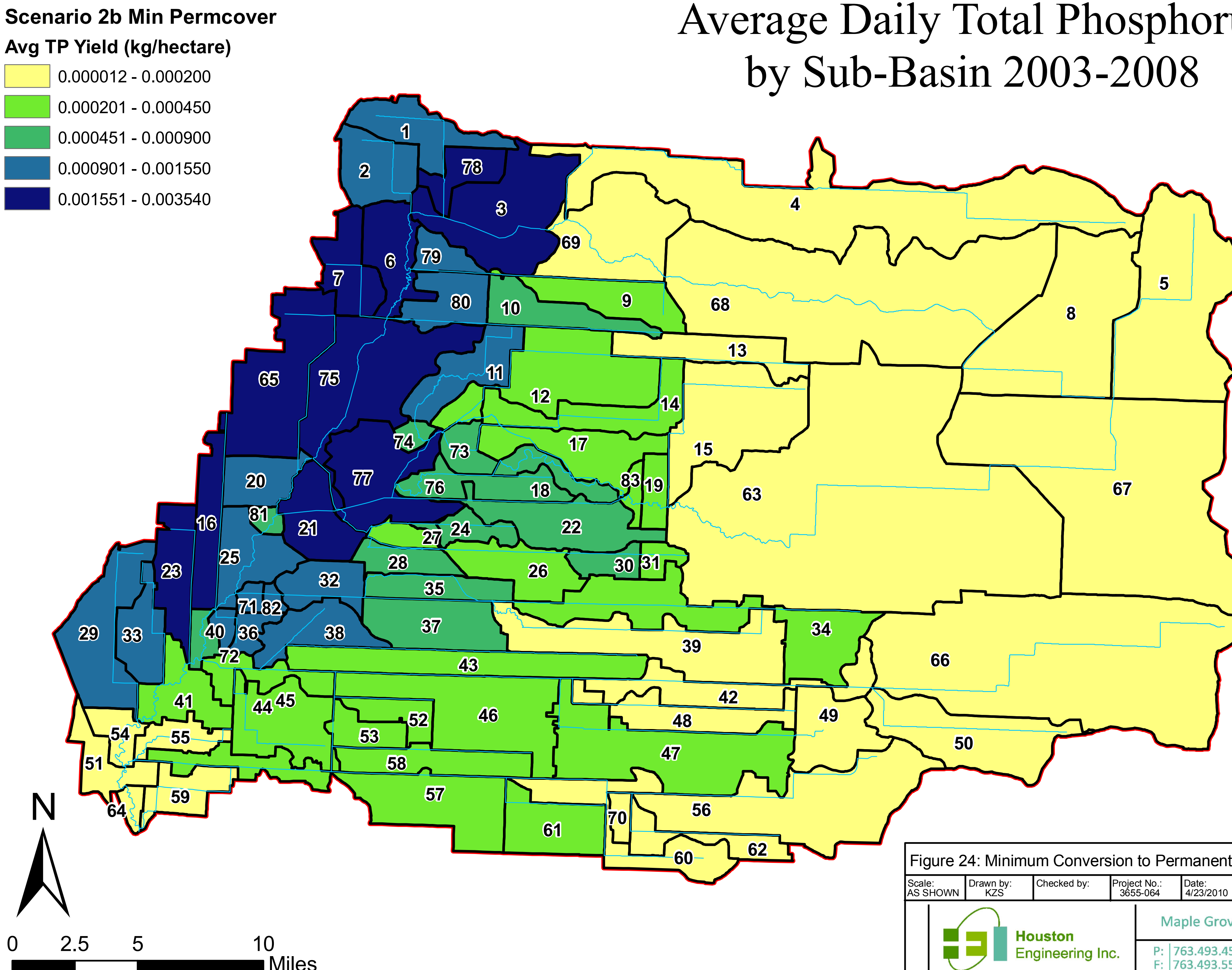

Figure 24: Minimum Conversion to Permanent Cover

Scale:	Drawn by:	Checked by:	Project No.:	Date:	Sheet:
AS SHOWN	KZS		3655-064	4/23/2010	

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Average Daily Total Phosphorus by Sub-Basin 2003-2008

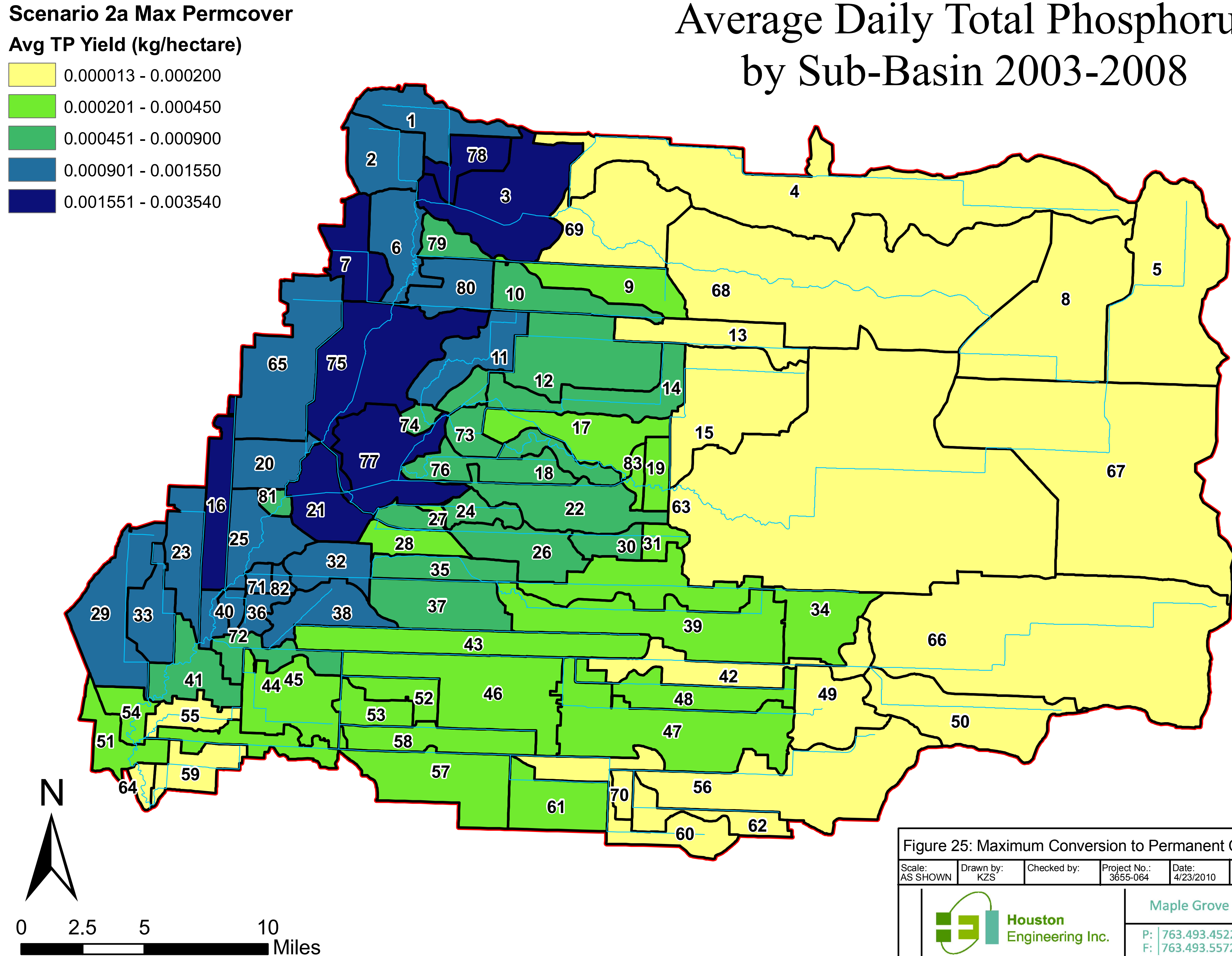

Figure 25: Maximum Conversion to Permanent Cover

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Average Daily Total Phosphorus by Sub-Basin 2003-2008

Scenario 3a Side Inlet Part Implemented

Avg TP Yield (kg/hectare)

- 0.000013 - 0.000200
- 0.000201 - 0.000450
- 0.000451 - 0.000900
- 0.000901 - 0.001550
- 0.001551 - 0.003540

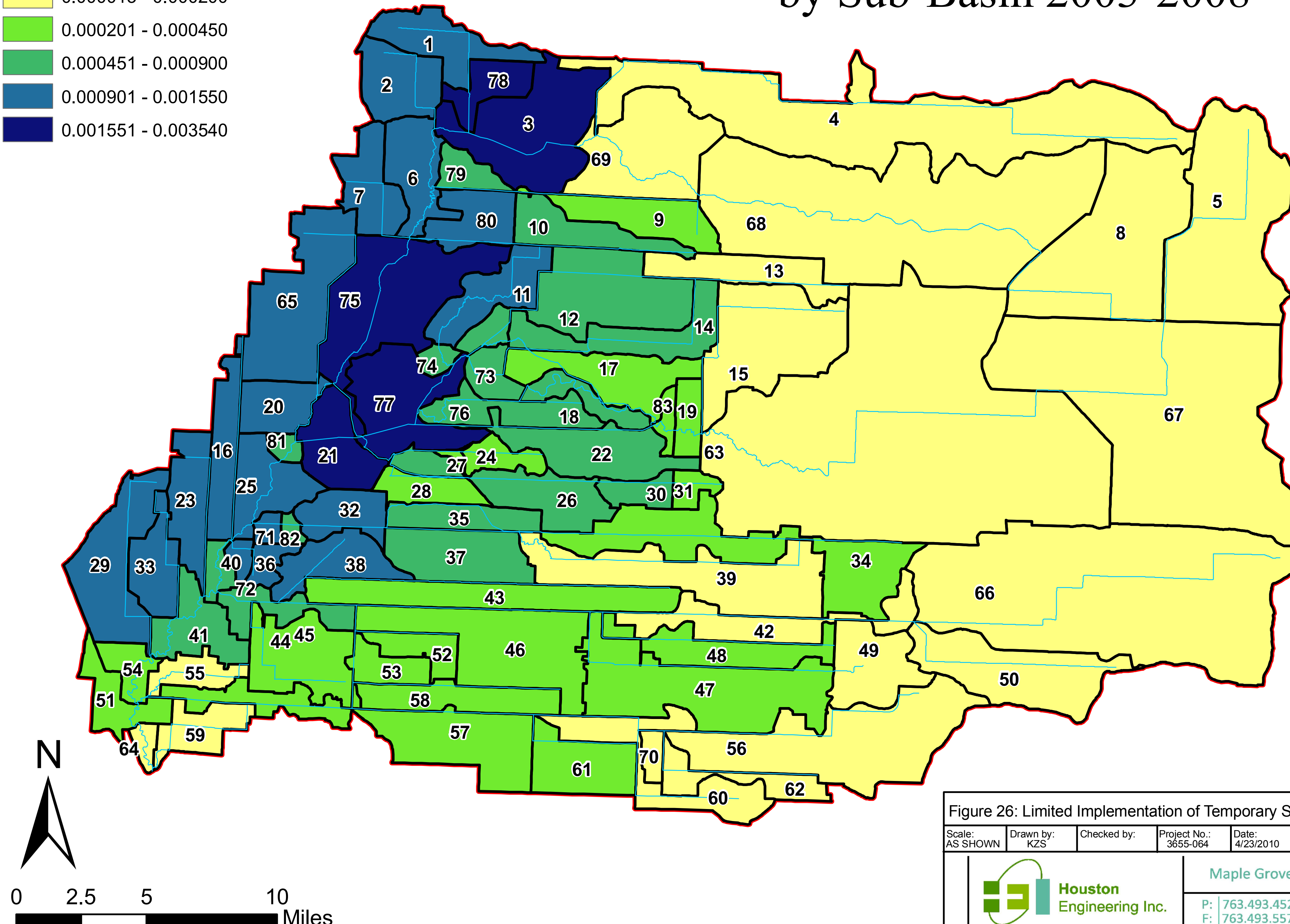

Figure 26: Limited Implementation of Temporary Storage					
Scale: AS SHOWN	Drawn by: KZS	Checked by:	Project No.: 3655-064	Date: 4/23/2010	Sheet:

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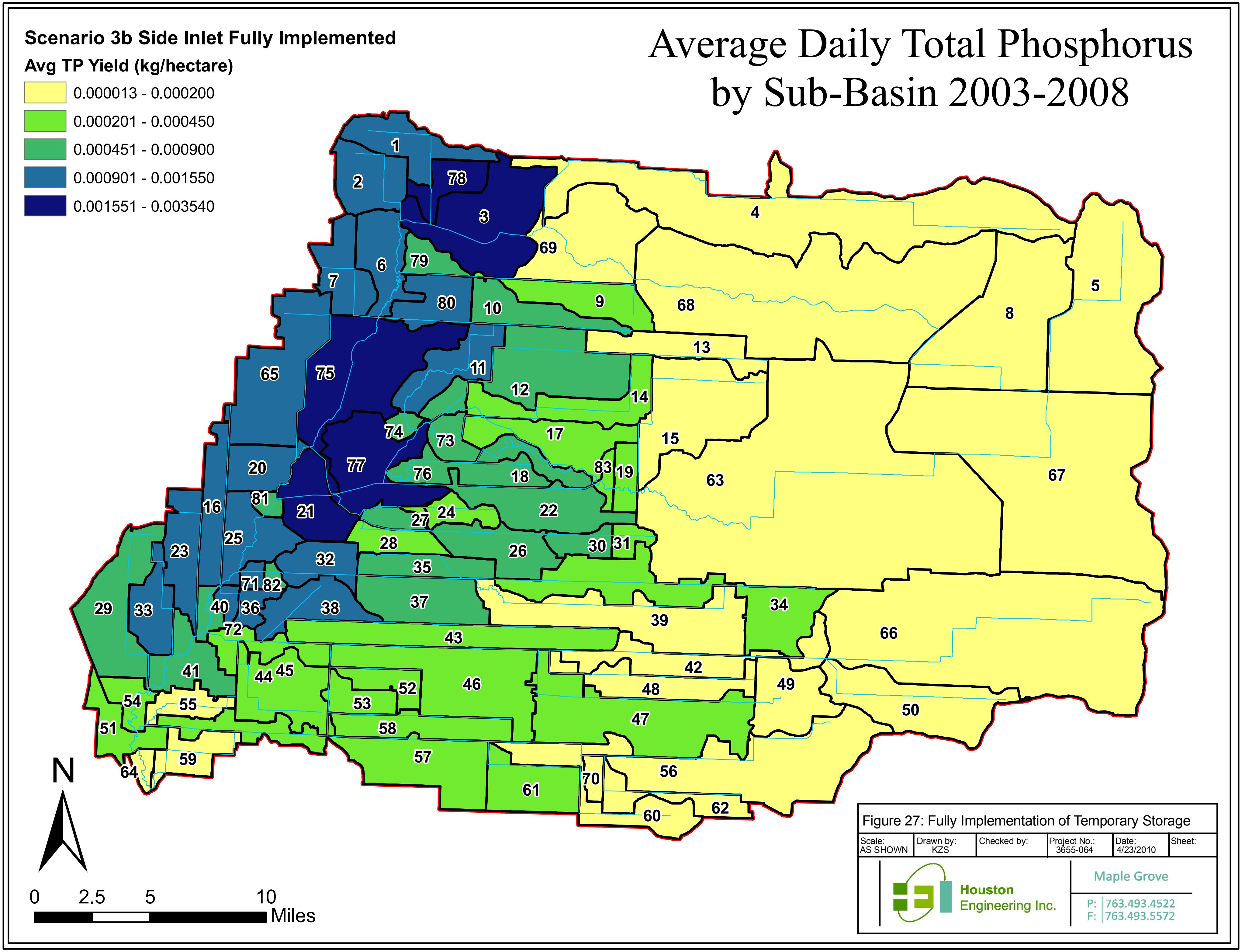

Average Daily Total Phosphorus by Sub-Basin 2003-2008
Scenario 3b Side Inlet Fully Implemented
Avg TP Yield (kg/hectare)
0.000013 - 0.000200
0.000201 - 0.000450
0.000451 - 0.000900
0.000901 - 0.001550
0.001551 - 0.003540
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5
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Miles
Figure 27: Fully Implementation of Temporary Storage
Scale: AS SHOWN
Drawn by: KZS
Checked by:
Project No.: 3655-064
Date: 4/23/2010
Sheet:
Houston Engineering Inc.
Maple Grove
P: 763.493.4522
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SWAT models all permanent storage (including impoundments, as included in this work) as reservoirs. To assess the impact of the management scenarios on the impoundments included in the SWAT model, reservoir inflows from each management scenario model run were compared to those from the baseline conditions. Results were averaged on an annual basis over the entire modeling period (2003-2008). The SWAT-assigned reservoir number and associated sub-basin for each of the modeled impoundments are shown in **Table 4**.

Table 4 – Reservoir Numbers and Associated Sub-basins for Modeled Impoundments

Impoundment	Reservoir Number	Sub-basin
South Moose River	1	67
North Moose River	2	8
Thief Lake	3	3
Agassiz NWR	4	21
Lost River	5	35
Farmes	6	32

Model output showed that altering management scenarios resulted in no measurable changes compared to baseline in the most upstream reservoirs; South and North Moose River. **Table 5** provides a summary of the percent change in annual loading to the remaining reservoirs. A negative value indicates a reduction in loading while a positive value shows that loading was increased rather than reduced by the management option that was modeled.

The table indicates that filter strips generally provide the most consistent reduction in the amount of loading to the reservoirs, removing at least 14% to nearly 40% of the TSS and TP that would have been delivered to the reservoirs in the baseline scenario. Permanent cover produced mixed results, with minimum permanent cover increasing sediment and phosphorus delivery to the Lost River reservoir while substantially reducing loads to the Farmes reservoir (due to the modeled increase in surface flow). The effects were increased with maximum permanent cover except in the load to Farmes reservoir which had a reduction in TSS loading and a large increase in TP loading, the result of a very small TP (particularly mineral phosphorus) loading in 2008.

Table 5 -- Percent Change in Annual Inflow Loads Compared to Baseline for Reservoirs in the TRW (Averaged over 2003-2008)

Reservoir	50-foot Filter Strip		100-foot Filter Strip		Minimum Permanent Cover		Maximum Permanent Cover		Partial Side Inlet		Full Side Inlet	
	TSS	TP	TSS	TP	TSS	TP	TSS	TP	TSS	TP	TSS	TP
Thief Lake	-16%	-14%	-23%	-17%	-3%	-3%	-37%	-11%	-38%	-11%	-39%	-12%
ANWR	-18%	-32%	-29%	-38%	-2%	-6%	-18%	-15%	-20%	-16%	-22%	-17%
Lost River	-21%	-38%	-31%	-46%	2%	4%	5%	10%	2%	8%	-1%	4%
Farmes	-29%	-31%	-38%	-37%	-20%	-23%	-14%	27%	-18%	21%	-17%	11%

Model results suggest that side inlet controls were very effective in reducing TSS and TP loading to Thief Lake and ANWR impoundments. Increasing the side inlets from partial to full did not result in much improvement to load reductions. Model results suggested that changes in TSS and TP loading to Lost River reservoir were unchanged, and possibly increased. TSS loads to Farmes reservoir were reduced while TP loads were increased by the modeled side-inlet controls.

SECTION 4.0
INTERPRETATION AND IMPLICATIONS OF THE MODELING RESULTS

Computerized watershed and water quality models consist of a set of equations intended to simulate the processes occurring in a natural environment. These models are representations of the natural environment that can be used for a variety of purposes, including evaluating watershed management options. Models are often used to understand and predict what may happen when certain characteristics of the watershed are modified. In the case of computer models, including SWAT, the watershed processes are represented by a set of equations and formulas that are derived from measurements and observations made in one or more environmental settings. As such, the applicability of a particular equation within the model to the watershed or water body that is being modeled needs to be reviewed and the appropriateness evaluated. SWAT is a complex model that incorporates many interrelated watershed processes that include a broad array of environmental variables ranging from the field- to watershed-scale. In any given application, a model may generate results which either attain or differ from those expected. Calibrating the model reasonably ensures that the model-predicted results mimic measured results, and presumably therefore, the processes within a specific watershed.

As with any complex system, trying to control all the inputs and variables that affect the model outcome can reach a point of diminishing return compared to the level of effort expended to match the observed or measured data. When definitive data to assign values to model parameters and coefficients are lacking, it is incumbent upon the modeler to provide a best estimate for those coefficients. Generally, that best estimate is the default coefficient provided with the SWAT model or a value adjusted to reflect local information.

The SWAT modeling results resulting from this study are reasonable and defensible. In addition to calibrating and verifying the results, various "practical" criteria were evaluated to ensure reasonable and defensible results. These criteria included: comparing the average annual runoff volumes to those within the Minnesota Hydrology Guide; comparing the average annual yields to those provided in the related studies (Tornes, 1986); and evaluating whether the runoff volumes and sediment, phosphorus, and fecal coliform loads and yields and are consistent with experience and measured values.

The SWAT model completed for this study can continue to serve as a useful tool for making resource management decisions as the RLWD proceeds with the implementation of practices comprising the watershed management plan. Regardless of the model limitations, the model can be used to compare the relative change in the volume of runoff and loads of sediment and phosphorus. A valuable use of the model is to establish water quality expectations; i.e., goals for the sediment, phosphorus, and fecal coliform loads. Water quality expectations can be established by identifying the probable future landscape-scale characteristics (e.g., proportions of filter strip, permanent cover, and wetland) and the corresponding water quality.

When interpreting and using the model results, some understanding of how the equations within the model treat various conditions or scenarios seems warranted. There are differing crops and cropping patterns within the watershed. The watershed also has a variety of slopes that affect the stability of soils and control the flow of water. Because of these complexities, applying land treatment in select areas of the watershed may produce different load or runoff volume results than in other parts of the watershed. Models such as SWAT are used as tools to determine how different land management practices behave in various parts of the watershed.

The model can also be used to assess the result of landscape-scale changes in the land cover type or management practices occurring within the watershed. For example, the model was used to evaluate the effects on the amount of runoff and TSS, TP, and FC loads associated with changing various portions of the landscape from tilled crops to "permanent cover". In this scenario, the crops were changed from plants that could provide good canopy cover during much of the summer growing season, tend to remove moisture from the soils, and may deplete ground water during the summer growing season compared to grasses that have much less canopy during the growing season. This could have a variety of effects, but would suggest that increased baseflow could effectively increase the transport (loads) of modeled constituents because is a product of the flow and the concentration.

The effect of temporarily storing runoff through side inlet controls was also evaluated using the model. The modeling parameters for the temporary storage within SWAT are designed to take into account the surface area (which varies with change in the volume), direct precipitation, evaporation, inflow from the sub-basin (but not from other sub-basins) seepage to the subsurface, and outflow. In the SWAT model, the temporary waterbody releases outflow water as soon as it reaches its maximum volume. Because of this, the waterbody functions of attenuating water, sediment, and other materials becomes insignificant as the retention time declines to near zero allowing no time for water to move into other compartments, such as sub-surface flow, and for sediment particles to settle. As with other surface-storage systems in the SWAT model, the portion of water that seeps into the ground water becomes part of the subsurface flow and is transported to the stream reach in that sub-basin, and a portion of that subsurface flow will be conveyed to the deeper groundwater where it is lost from the model.

Within the scope of this study, the default settings generally were used during runs of the SWAT model. Using the default settings provides a useful range of outputs relative to the modeling limitations. Additional work could be focused on controlling those model parameters to provide a better projection of what the effects might be. At just about any level of the SWAT model, there are parameter coefficients that could be modified that control sediment mobilization, transport, and deposition. The flow of water through various components of the hydrologic system can be controlled including how water behaves in the sub-surface environment and flow through reservoirs. Many parameters including precipitation, evaporation, and transpiration probably are well handled with the calibrated default settings. However, the model may not correctly handle snow accumulation, redistribution, sublimation, melting, and other factors that are important in this northern environment.

Changing parameters in models can have unexpected effects because of subtle nuances and the way model state equations interact. The primary consideration from any model is that it is a tool designed to help infer the relative magnitude of effects that might result from implementing management strategies. What actually happens when decisions are implemented in the real world could differ from what the model suggests will happen. This provides justification for follow-up monitoring to determine whether intended changes actually resulted in beneficial effects and help decide whether the model was appropriately applied to the watershed being studied.

SECTION 5.0
SUMMARY AND CONCLUSIONS

This report provides the results of developing, calibrating, and validating a SWAT model of the Thief River Watershed in northwestern Minnesota. Selected management scenarios were run on the calibrated model to estimate the effects of various land-use and management practices on the quality of streamwater near the outlet of the watershed. The management scenarios were selected in an effort to simulate realistic management scenarios that could be used in the area and to optimize the reduction of sediment and total phosphorus loads leaving the watershed. The modeled scenarios included the addition of filter strips, landscape permanent cover, and distributed temporary storage (side –inlet controls). While most scenarios were effective in reducing loads, a few resulted in minimal reductions while others suggested that flows and loads increased. The increased loads were determined to result from a number of factors, most of which related to increased runoff. Also considered was the impact of modeled scenarios on average annual sediment and TP loadings to the watershed's impoundments. In most cases, the loads were reduced; those situations where loads increased were, again, a consequence of increased runoff.

SECTION 6.0
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MEMO

(External Correspondence)

HoustonEngineering Inc.

To: Corey Hanson

Date: October 8, 2009

Cc: File 3655-064

From: Stephanie Johnson, Ph.D., P.E. Stephanie Johnson

Through: Mark Deutschman, Ph.D., P.E. Mark

Subject: Sub-watershed and flowline development for ArcSWAT modeling

Under the Red Lake Watershed District (RLWD) Work Order #1: Thief River Watershed Soil and Water Assessment Tool (SWAT) Model, Houston Engineering ("Houston") is preparing a water quality model for the Thief River Watershed. Up to this time, Houston has been in the data collection and development stage of the modeling. The purpose of this memo is to present the sub-watersheds and flowlines that Houston has developed for the study area and to get approval from RLWD before moving forward with model development.

As requested by the RLWD, Houston used the sub-watershed and ditch GIS layers developed by HDR Engineering as the basis of our sub-watershed development. These layers contained 70 sub-watersheds and 2,749 ditch segments. Preparing these layers for use in the ArcSWAT model required an increase in the number of sub-watersheds and a reduction in the number of ditches. The original HDR sub-watersheds were divided to allow for the modeling of water quality at key locations, as requested by the RLWD. These locations include USGS Sites 05076000 and 05075700 and STORET sites S004-966, S004-494, S004-493, S004-499, S002-089, S004-055, S002-088, and S002-084. Sub-watersheds were also split to allow for a single flowline in each sub-watershed, as required by the ArcSWAT model. Sub-watersheds were split using the NHD Plus catchments (Horizon Systems, 2006) as a guide, while taking into account the placement of ditches as shown in the ditch layer. The flowline layer was created from the ditch layer, simplifying the layer to show only the main ditch routes through each modified sub-watershed. Minor ditches will still be accounted for in the modeling procedure, but are not explicitly included in the flowline layer.

The attached figure shows the resultant sub-watershed and flowline layers to be used in the ArcSWAT model. A total of 91 sub-watersheds, with an average area of 11.7 sq. miles will be modeled. Also included on this figure are the water quality stations (listed above) where model output was explicitly requested by the RLWD. The locations of two wastewater treatment plants (Grygla and Goodridge) that will be modeled as point sources are indicated with stars. Lastly, six animal feedlots that are located close to waterways in the watershed are shown as crosses. Discussions are on-going as to whether these feedlots will be considered as point sources in the model.

Please review the attached figure and ensure that the modified sub-watershed and flowline layers are to your satisfaction. Once approval is given, we will move forward with the ArcSWAT modeling.

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References

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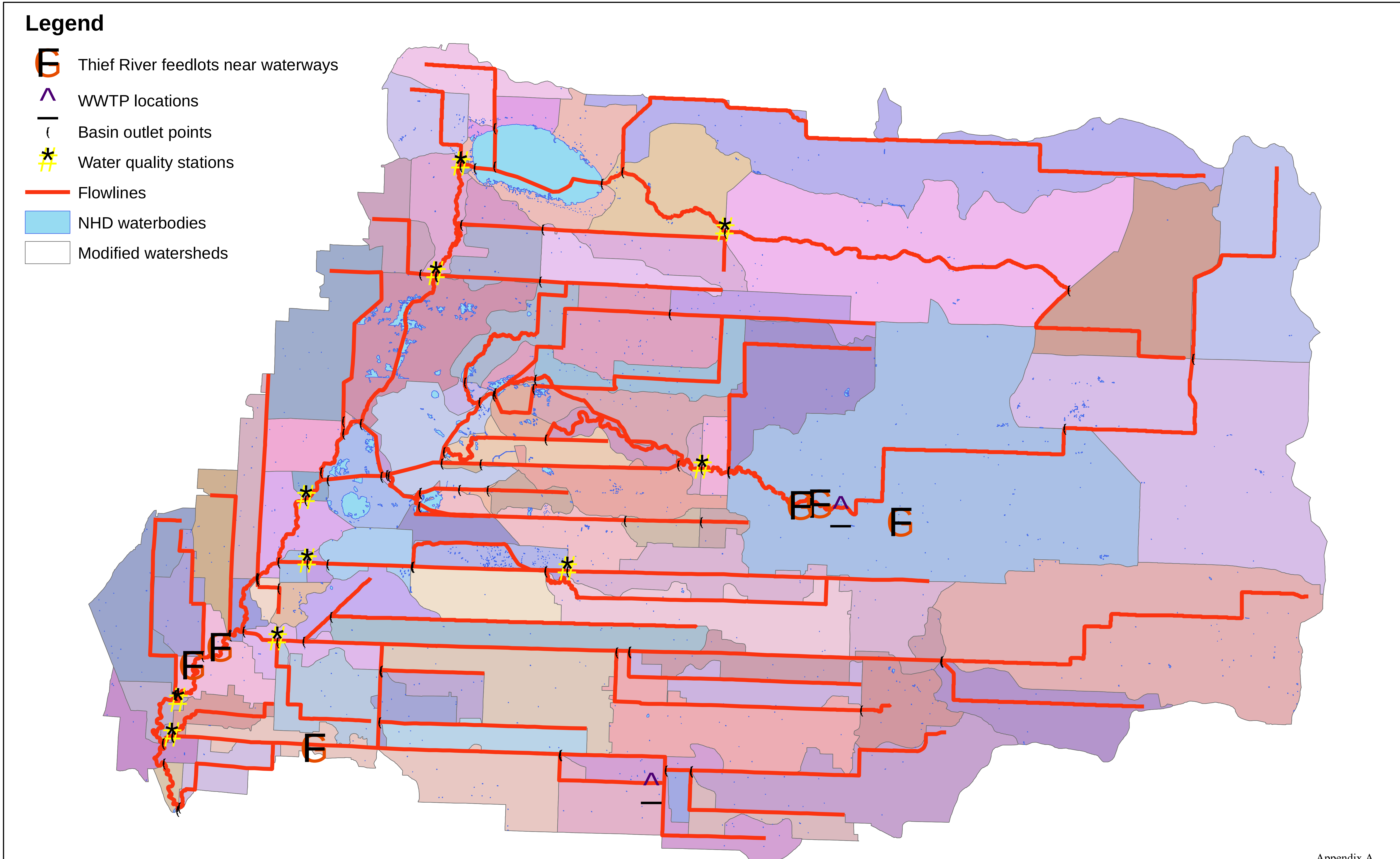
Legend
Thief River feedlots near waterways
WWTP locations
Basin outlet points
Water quality stations
Flowlines
NHD waterbodies
Modified watersheds

MEMO

External Correspondence

Houston Engineering, Inc.

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Ph. (763) 493-4522
Fax (763) 493-5572

Date: February 13, 2009

To: Paul Nelson,
Scott Co. WMO

Cc: File 6268-001

From: Mark R. Deutschman, PhD., PE
Brennon Schaefer
Lan Tornes

Subject: Calibration/Validation Criteria
West Raven Creek modeling project

1. Calibration/Validation Criteria Overview

Calibration and validation have very specific meanings in the development and application of environmental models. Calibration is generally defined as the first stage in "tuning" model output by making adjustments to model parameters, based upon comparisons against a set of measured field data. A sensitivity analysis helps guide and focus the "tuning" process by determining the unique parameters the watershed appears to be sensitive to. Some models include internal algorithms and routines that automate the calibration process, through the use of an analytical method that minimizes the error between the model results and the measured data. Model calibration is expected to result in a set of rational and defensible parameters that fall within a "normal" or expected range. Validation is the process of comparing the calibrated model against an additional set of field data preferably collected under conditions that differ from those used to calibrate the model; e.g., amount of flow, magnitude of precipitation. The parameters determined during the calibration process remain unchanged during validation, and the robustness of the calibrated model is essentially based upon comparison against a different set of field data. Assuming the behavior of the model is consistent with the validation dataset, the model "passes" and is considered acceptable for use in evaluating the results of various modeling alternatives or scenarios (such as land use or management), bounded by the parameter range used to calibrate and validate the model.

Criteria are needed to assess and determine when a model is considered calibrated, as well as to characterize the quality of the validated model. These criteria are typically based upon some measure of the accuracy and precision of the model results. Accuracy relates to how closely the model output matches an observed or known metric, such as a monitored discharge for a certain rainfall event. Precision relates to the degree of refinement with which an operation is performed; for instance, modeling consistently to achieve confidence in understanding relative changes (such as runoff loads) due to an external variable such as land use modifications. Model criteria with better accuracy and precision than the measurement error are unrealistic - no model should be expected to perform better than field data can be measured. The measurement accuracy and precision of field data should be considered the lower bound (i.e., best accuracy and precision) for calibration criteria[1]. The upper bound for calibration criteria, although difficult to determine, should be based upon consideration of field measurements, sampling results, and the inherent variability in environmental systems.

Averaging across a longer temporal and a larger spatial scale makes calibration easier and validation results appear better. For example, calibrating to annual runoff volume is generally easier than to the instantaneous peak runoff rate. Calibration at a single location near the outlet of a large watershed is also generally easier than near the outlet of several smaller subwatersheds. As such, calibration criteria should be consistent with the temporal and spatial scale of the implementation activities comprising the scenario evaluation.

[1] It is recognized that is certainly possible to adjust parameters and coefficients during calibration to achieve accuracy and precision better than possible by measurement.

2. Evaluation Criteria Relative to the West Raven Creek Modeling Project

Present expectations are to utilize the sensitivity analysis and auto-calibration features in the Soil and Water Assessment Tool (SWAT) computer model for the calibration process. Hydrometeorologic data provided by Scott County will be analyzed and evaluated for the hydrologic years that will be used in the SWAT modeling of the West Raven Creek watershed. The SWAT model will be executed on a daily time step, and model output (flow, total suspended solids, and total phosphorus) from the model for the years selected for calibration and validation will be evaluated. Calibration and validation criteria are needed for the West Raven Creek modeling project to evaluate the SWAT model output.

The following criteria are proposed for use in evaluating the reliability of the modeling output in the SWAT model calibration and validation process. These recommendations are based upon Houston Engineering's experience with modeling projects and acknowledgement of limitations in the temporal and spatial scale of field measurements and the SWAT model's capabilities. First, the definition of certain statistical measures that will be utilized in this project is required.

The normalized Mean Square Error (MSE^*) is one of several statistics used to quantify accuracy. The MSE^* is defined as:

$$MSE^* = \frac{\sum_{i=1}^{n}(O_i - P_i)^2}{\sum_{i=1}^{n}\left(O_i - \bar{O}\right)^2}$$

where O_i is an observed value, P_i is the paired predicted or modeled value, and $\bar{O}$ is the mean of the observed values. The MSE^* is the mean square error divided, or normalized, by the standard deviation of the observed values. An MSE^* value of zero corresponds to a perfect fit; a large value indicates a poor fit. An assumption of the MSE^* is that a large range in observed data is more difficult to simulate than a small range.

The normalized Root Mean Square Error ($RMSE^*$) is another statistic used to quantify accuracy. The $RMSE^*$ is defined as:

$$RMSE^* = \frac{\sqrt{\dfrac{\sum_{i=1}^{n}(O_i - P_i)^2}{n}}}{\bar{O}}$$

where O_i, P_i, and $\bar{O}$ are defined as previous; n is defined as the total number of paired observed and predicted values. The $RMSE^*$ is the root mean square error normalized by the mean of the observed values. An $RMSE^*$ close to zero is ideal, and it should be used when the means are a superior indicator of degree of difficulty in modeling the system.

The MSE^* and $RMSE^*$ will be used to assess the accuracy of the calibration and validation. These statistics are preferred because they are measures of non-linear regression; normalization of these statistics provides for an equal basis of comparison.

We also plan to qualitatively assess the calibration and validation results using:

- Time series plots;
- Bivariate normal distribution (notched box) plots; and
- Cumulative frequency plots.

The instances when these statistical measures and methods will be used are defined in the following Table.

Modeled Variable	Accuracy	Precision	Comment
Discharge			
Daily Value (cubic feet per second)	Computed MSE* for modeled and measured daily discharges equal to or less than 20%.	Mann-Whitney test (or other comparable non-parametric method) for comparison of modeled and measured daily discharges.	The accuracy of measured discharges can be evaluated as follows, which is similar to quality rating descriptions used by the USGS: -"excellent" means 95% of the daily measured values are within 5% of the true value; -"good" means 90% of the daily measured values are within 10% of the true value; and -"fair" means 85% of the daily measured values are within 15% of the true value.
Runoff Volume			
Monthly Total (acre-feet)	Monthly modeled and measured volume comparison less than 25%.	Relative comparison of monthly runoff volumes using notched box plots.	None.
Seasonal Total (acre-feet)	Seasonal modeled and measured volume comparison less than 20%.	Relative comparison of seasonal runoff volumes using notched box plots.	None.
Annual Total (acre-feet)	Annual modeled and measured volume comparison less than 15%.	Relative comparison of annual runoff volumes using notched box plots.	None.
Total Suspended Solids (TSS) and Total Phosphorus (TP) Concentrations			
Daily Flow Weighted Mean (milligrams/liter)	RMSE* computed based upon measured instantaneous grab samples and modeled daily average concentrations equal to or less than 20% of the laboratory determined analytical accuracy.	Mann-Whitney test (or other comparable non-parametric method) for comparison of modeled and measured daily flow weighted mean concentrations.	The analytical accuracy is based only on the spike recovery from laboratory analysis and excludes other errors. The actual (field) accuracy is greater than the analytical accuracy.
Total Suspended Solids (TSS) and Total Phosphorus (TP) Loads			
Annual Total: TSS – (tons) TP – (pounds)	Annual modeled and measured load comparison less than 20%.	Relative comparison of annual loads using notched box plots.	None.

These criteria should be considered preliminary, for project planning purposes. Expectations are that these criteria may be adjusted and/or further refined based upon the availability and statistical analysis of field data.

Appendix C -- Thief River Watershed SWAT Model Parameters Adjusted During Calibration

Parameter	Description	SWAT Range		SWAT Default	Range Evaluated		Modeled Value
		Low	High		Low	High	
Water Balance							
SMFMX	Melt factor for snow on June 21 (mm $H_2O/^oC$-day)	0	500	4.5	1.5	4.5	1.5
SMFMN	Melt factor for snow on Dec 21 (mm $H_2O/^oC$-day)	0	10	4.5	3.5	4.5	3.5
SFTMP	Snowfall temperature (^oC)	-5	5	1	1	1.5	1.5
SMTMP	Soil melt base temperature (^oC)	-5	5	0.5	0.5	0.8	0.8
SNOCOVMX	Min water content at 100% snow cover (mm H_2O)	0	500	1	1	30	30
SNO50COV	Fraction of SNOCOVMX snow vol at 50% snow cover	0	1	0.5	0.2	0.5	0.2
TIMP	Snow pack temperature lag factor	0	1	1	0.25	1	0.25
ESCO	Soil evaporation	0.01	1	0.95	0.7	0.95	0.7
SOL_AWC()	Available water capacity in soil layer	0	1	Computed in model	Computed in model	Increase computed values by 4%	Increase computed values by 4%
Surface Runoff							
CN2	Initial SCS runoff Curve Number for AMC II	35	98	Computed in model	Decrease computed values by 10%	Original	Decrease computed values by 10%
FFCB	Initial soil water storage as a fraction of field capacity	0	1	Computed in model	Computed in model	1	0.8

Parameter	Description	SWAT Range		SWAT Default	Range Evaluated		Modeled Value
		Low	High		Low	High	
Groundwater							
GW_DELAY	Delay for aquifer recharge (days)	0	500	31	0	31	2
GWQMN	Threshold level for return flow from shallow aquifer (mm H_2O)	0	50,000	0	0	5000	5
ALFA_BF	Baseflow recession constant (days)	0.1	1	0.048	0.048	0.6	0.6
RCHRG_DP	Deep aquifer percolation factor.	0	1	0.05	0.05	0.25	0.05
GW_REVAP	Revap coefficient	0.02	0.2	0.02	0.02	0.2	0.15
Reservoirs							
NDTARGR	# of days to reach target storage from current storage	1	200	1	1	7	5 (sub-basins 21 & 32)
RES_K	Hydraulic conductivity of reservoir bottom (mm/hr)	0	50	0	0	0.3	0.1 – 0.25 (depending on reservoir)
Sediment							
CH_EROD	Channel erodibility factor	0	1	0	0.1	0.3	0.2
ADJ_PKR	Peak rate adjustment factor for sediment routing	0.5	2	1	1	1.5	1.3
PRF	Peak rate adjustment factor for sediment routing in the main channel	0	2	1	1	1.5	1
CH_COV	Channel cover factor	0	1	0	0	1	0.1
USLE_P	USLE equation support practice factor	0.6	1	1	0.8	1	0.9

Parameter	Description	SWAT Range		SWAT Default	Range Evaluated		Modeled Value
		Low	High		Low	High	
Bacteria							
BACT_SWF	Fraction of manure with active colony forming units	0	1	0.15	0.15	1	1
BACTKDQ	Bacteria soil partitioning coefficient (m^3/Mg)	0	500	175	175	500	175
WDPRCH	Die-off factor for bacteria in streams (day^{-1})	0	2	0	0	2	2
WDRES	Die-off factor for bacteria in reservoirs (day^{-1})	0	2	0	0	2	1
WDPQ	Die-off factor for bacteria in soil solution (day^{-1})	0	2	0	0	1	0.5
WDPS	Die-off factor for bacteria absorbed to soil (day^{-1})	0	2	0	0	1	0.5
WDPF	Die-off factor for bacteria in foliage (day^{-1})	0	2	0	0	1	0.5
WOF_P	Bacteria wash off fraction	0	1	0	0	1	0.8
Water Quality							
PHOSKD	P soil partitioning coefficient (m^3/Mg)	0	500	175	0	200	20
RS5	Organic P settling rate in the reach at 20^{o}C (day^{-1})	0.001	0.1	0.05	0.01	0.05	0.02
ERORGP	P enrichment ratio for loading with sediment	0	5	0	0	5	0
PSETLR1	P settling rate in a reservoir during settling months (m/yr)	<0	>16	10	0	10	2
IRES1	Beginning month of mid-year sediment settling period	1	12	1	2	6	4 (SubBasin 21)
IRES2	Ending month of mid-year sediment settling period	1	12	1	8	10	9 (SubBasin 21)

Table D.1 – SWAT Modeling Results at the Mud River Watershed Outlet (STORET site S002-089; Outflow from Reach 68)

Scenario	Average Annual Streamflow (acre-feet)	Average Annual Sediment Load (Tons)	Average Annual Total Phosphorus Load (Pounds)	Average Annual Fecal Coliform Load (CFUs)
Baseline: Existing Conditions (2003-2008)	15,440	136	982	$5.05x10^{11}$
1a: 50 Foot Filter Strips	15,440	113	581	$5.05x10^{11}$
1b: 100 Foot Filter Strips	15,440	106	495	$5.05x10^{11}$
2 min: Minimum Ag land to permanent cover	15,444	135	978	$4.96x10^{11}$
2 max: Maximum Ag land to permanent cover	15,364	91	591	$5.30x10^{11}$
3a: Partially Implemented Side-Inlet Controls	15,364	118	591	$5.30x10^{11}$
3b: Fully Implemented Side-Inlet Controls	15,364	118	591	$5.30x10^{11}$

Table D.2 – SWAT Modeling Results at the Moose River Watershed Outlet (STORET site S002-078; Outflow from Reach 19)

Scenario	Average Annual Streamflow (acre-feet)	Average Annual Sediment Load (Tons)	Average Annual Total Phosphorus Load (Pounds)	Average Annual Fecal Coliform Load (CFUs)
Baseline: Existing Conditions (2003-2008)	29,495	588	3,382	$1.28x10^{15}$
1a: 50 Foot Filter Strips	29,495	370	1,467	$1.28x10^{15}$
1b: 100 Foot Filter Strips	29,495	278	1,059	$1.28x10^{15}$
2 min: Minimum Ag land to permanent cover	29,587	585	3,328	$1.31x10^{15}$
2 max: Maximum Ag land to permanent cover	30,103	229	3,238	$1.30x10^{15}$
3a: Partially Implemented Side-Inlet Controls	30,117	379	3,173	$4.85x10^{14}$
3b: Fully Implemented Side-Inlet Controls	30,131	371	3,103	$4.25x10^{14}$

Table D.3 – SWAT Modeling Results at Thief River coming into ANWR from North (STORET site S004-055; Outflow from Reach 6)

Scenario	Average Annual Streamflow (acre-feet)	Average Annual Sediment Load (Tons)	Average Annual Total Phosphorus Load (Pounds)	Average Annual Fecal Coliform Load (CFUs)
Baseline: Existing Conditions (2003-2008)	69,055	2,133	20,545	$2.63x10^{12}$
1a: 50 Foot Filter Strips	69,055	1,353	7,637	$2.63x10^{12}$
1b: 100 Foot Filter Strips	69,055	678	4,872	$2.63x10^{12}$
2 min: Minimum Ag land to permanent cover	69,123	2,116	19,813	$2.58x10^{12}$
2 max: Maximum Ag land to permanent cover	70,688	1,018	11,555	$1.84x10^{12}$
3a: Partially Implemented Side-Inlet Controls	70,848	858	11,251	$1.84x10^{12}$
3b: Fully Implemented Side-Inlet Controls	71,006	759	10,948	$1.84x10^{12}$

Table D.4 – SWAT Modeling Results at the Thief River leaving the ANWR area at Cnty Rd 7 (STORET site S002-088; Outflow from Reach 81)

Scenario	Average Annual Streamflow (acre-feet)	Average Annual Sediment Load (Tons)	Average Annual Total Phosphorus Load (Pounds)	Average Annual Fecal Coliform Load (CFUs)
Baseline: Existing Conditions (2003-2008)	116,406	1,408	43,675	$3.33x10^{13}$
1a: 50 Foot Filter Strips	116,406	1,044	27,125	$3.33x10^{13}$
1b: 100 Foot Filter Strips	116,406	859	23,584	$3.33x10^{13}$
2 min: Minimum Ag land to permanent cover	116,432	1,407	40,895	$3.37x10^{13}$
2 max: Maximum Ag land to permanent cover	118,282	2,973	33,867	$3.01x10^{13}$
3a: Partially Implemented Side-Inlet Controls	118,300	937	33,435	$1.90x10^{13}$
3b: Fully Implemented Side-Inlet Controls	118,329	926	32,993	$1.88x10^{13}$

Table D.5 – SWAT Modeling Results at the Thief River leaving Thief Lake (STORET site S002-084; Outflow from Reservoir 3)

Scenario	Average Annual Streamflow (acre-feet)	Average Annual Sediment Load (Tons)	Average Annual Total Phosphorus Load (Pounds)
Baseline: Existing Conditions (2003-2008)	39,189	51	2,680
1a: 50 Foot Filter Strips	39,189	51	2,268
1b: 100 Foot Filter Strips	39,189	51	2,180
2 min: Minimum Ag land to permanent cover	39,198	51	2,567
2 max: Maximum Ag land to permanent cover	39,222	45	2,314
3a: Partially Implemented Side-Inlet Controls	39,228	45	2,307
3b: Fully Implemented Side-Inlet Controls	39,226	45	2,300

Appendix E - Results of model runs to simulate conversion of agricultural areas in each sub-basin to permanent cover

Subbasin	% of Subbasin Area Converted from Agriculture to Permanant Cover		% Change in SYLD		% Change in ORGP		% Change in SOILP		% Change in SEDP	
	Minimum	Maximum	Minimum	Maximum	Minimum	Maximum	Minimum	Maximum	Minimum	Maximum
1	4.8%	38.9%	-77	-4	-70	-7	-5	15	-79	-4
2	2.8%	14.1%	-34	-8	-31	-14	-10	7	-33	-11
3	1.7%	12.5%	-74	-6	-56	-15	-1	2	-57	-5
6	6.6%	63.4%	-90	-5	-92	-3	3	58	-90	-5
7	65.5%	65.5%	-88	-88	-89	-89	55	55	-89	-89
9	2.9%	54.3%	-96	-4	-82	-16	-6	44	-100	0
10	70.6%	70.6%	-99	-99	-99	-99	36	36	-100	-100
11	11.1%	18.9%	-75	-19	-56	-38	-6	4	-53	-19
12	16.9%	42.8%	-74	-18	-53	-41	-31	31	-74	-34
13	7.2%	43.0%	-61	-23	-57	-9	-32	27	-50	-13
14	23.2%	37.5%	-65	-23	-61	-34	-40	29	-63	-26
15	3.5%	39.9%	-62	-6	-67	-6	-59	31	-60	0
16	15.5%	47.1%	-61	-37	-72	-25	8	29	-65	-37
17	4.2%	29.2%	-75	-7	-61	-24	-10	24	-77	-15
18	24.0%	24.0%	-97	-97	-95	-95	-15	-15	-75	-75
19	69.8%	69.8%	-98	-98	-100	-100	56	56	-100	-100
20	0.4%	32.5%	-53	0	-46	0	0	29	-57	0
21	6.6%	6.6%	-1	-1	-2	-2	-6	-6	-4	-4
22	9.4%	25.5%	-88	-13	-59	-40	-7	9	-74	-13
23	3.7%	53.0%	-85	-7	-88	-5	2	28	-87	-7
24	16.4%	16.4%	-96	-96	-95	-95	-14	-14	-69	-69
25	50.4%	50.4%	-79	-79	-80	-80	33	33	-81	-81
26	17.1%	28.8%	-77	-23	-61	-39	-18	12	-76	-41
27	37.4%	37.4%	-97	-97	-97	-97	-28	-28	-80	-80
28	32.8%	32.8%	-99	-99	-97	-97	-29	-29	-79	-79
29	4.8%	61.0%	-66	-17	-72	-11	3	31	-76	-16
30	6.0%	61.6%	-87	-5	-78	-17	-8	37	-92	-9
31	67.2%	67.2%	-100	-100	-100	-100	51	51	-100	-100
32	21.7%	21.7%	-60	-60	-84	-84	-10	-10	-20	-20
33	5.8%	51.1%	-75	-14	-80	-9	3	24	-82	-15
34	4.2%	19.5%	-42	-11	-51	-6	-25	25	-32	-18
35	1.3%	8.8%	-75	-38	-84	-9	-6	0	-33	0
36	24.9%	24.9%	-47	-47	-50	-50	14	14	-51	-51
37	7.5%	32.9%	-81	-20	-52	-45	-8	11	-67	-19
38	6.5%	6.5%	-43	-43	-74	-74	-3	-3	-18	-18
39	14.0%	43.8%	-56	-31	-65	-28	-32	43	-60	-40
40	66.4%	66.4%	-55	-55	-59	-59	65	65	-54	-54
41	27.4%	41.3%	-44	-23	-46	-24	13	57	-44	-30
42	2.0%	28.1%	-34	0	-41	-25	-10	27	-60	-20
43	49.4%	49.4%	-86	-86	-84	-84	56	56	-96	-96
44	11.6%	26.7%	-42	-8	-32	-27	-22	20	-49	-13

Appendix E - Results of model runs to simulate conversion of agricultural areas in each sub-basin to permanent cover - continued

Subbasin	% of Subbasin Area Converted from Agriculture to Permanant Cover		% Change in SYLD		% Change in ORGP		% Change in SOILP		% Change in SEDP	
	Minimum	Maximum	Minimum	Maximum	Minimum	Maximum	Minimum	Maximum	Minimum	Maximum
45	67.4%	67.4%	-100	-100	-100	-100	46	46	-100	-100
46	9.0%	75.4%	-75	-24	-78	-24	7	62	-95	-25
47	25.1%	44.0%	-57	-31	-58	-31	28	48	-57	-29
48	3.6%	36.1%	-67	-3	-71	-3	3	42	-71	0
51	3.5%	59.5%	-32	-8	-32	-18	7	123	-67	0
52	17.9%	61.2%	-77	-23	-78	-21	15	46	-81	-29
53	86.6%	86.6%	-100	-100	-100	-100	77	77	-100	-100
54	65.1%	65.1%	-32	-32	-43	-43	126	126	-40	-40
55	32.4%	39.0%	-56	-38	-56	-47	65	155	-50	-38
56	3.6%	22.4%	-42	-5	-47	-29	-14	20	-100	0
57	14.5%	60.5%	-43	-37	-48	-36	9	33	-78	-44
58	20.2%	66.7%	-74	-24	-75	-26	17	51	-80	-33
59	18.8%	31.3%	-57	-8	-61	-6	77	246	-33	-33
60	5.6%	42.4%	-52	-7	-46	-25	-16	43	-50	0
61	24.7%	56.8%	-71	-29	-71	-29	21	44	-80	-25
62	53.0%	53.0%	-80	-80	-90	-90	43	43	-100	-100
63	11.2%	41.4%	-72	-16	-74	-17	5	33	-78	-11
64	35.8%	35.8%	0	0	-7	-7	21	21	0	0
65	61.6%	61.6%	-84	-84	-85	-85	42	42	-87	-87
66	11.7%	11.7%	-74	-74	-70	-70	18	18	-100	-100
68	0.8%	5.2%	-19	-5	-57	-2	-33	0	-60	0
69	0.5%	4.5%	-42	-3	-74	-2	-10	0	0	0
70	19.3%	19.3%	-21	-21	-61	-61	-57	-57	-80	-80
71	43.1%	43.1%	-81	-81	-82	-82	23	23	-85	-85
72	57.6%	57.6%	-79	-79	-81	-81	36	36	-79	-79
73	18.8%	18.8%	-92	-92	-90	-90	-14	-14	-44	-44
74	24.9%	24.9%	-96	-96	-95	-95	-13	-13	-64	-64
75	0.8%	4.8%	-3	-1	-4	0	-2	0	-5	-1
76	19.1%	19.1%	-100	-100	-98	-98	-10	-10	-100	-100
77	8.1%	8.1%	-100	-100	-95	-95	-1	-1	-63	-63
78	23.5%	23.5%	-96	-96	-84	-84	3	3	-71	-71
79	60.4%	60.4%	-92	-92	-92	-92	28	28	-93	-93
80	10.0%	73.9%	-94	-5	-78	-21	-13	39	-95	-7
81	11.7%	37.3%	-82	-4	-72	-16	-17	42	-89	-5
82	50.4%	50.4%	-61	-61	-63	-63	48	48	-66	-66
83	52.1%	52.1%	-93	-93	-94	-94	47	47	-97	-97