Mustinka/Bois de Sioux Watersheds

HSPF Modeling Final Report

Prepared for the Minnesota Pollution Control Agency

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Table of Contents

List of Figures

List of Tables

1 PROJECT OVERVIEW AND OBJECTIVES

1.1 Purpose

The U.S. Environmental Protection Agency (EPA) requires the Minnesota Pollution Control Agency (MPCA) to execute the Total Maximum Daily Load (TMDL) Program in the state of Minnesota. Minnesota has an abundance of lakes and river reaches, many of which will require a TMDL assessment. To support TMDL projects the MPCA is systematically constructing HSPF models across the state. These models have the potential to support the simultaneous development of TMDL assessments for multiple listings within 8-digit Hydrologic Unit Code (HUC) watershed or smaller. This report documents the HSPF model developed for Mustinka and Bois de Sioux HUC-8 watersheds in the southern headwaters of the Red River Basin.

The HSPF model will support restoration and protection efforts in the Mustinka River and Bois de Sioux River Watersheds. HSPF modeled flows and existing loads will be used to develop stream load duration curves and lake water quality response models for the Total Maximum Daily Load studies currently underway for all impaired lakes and streams in both watersheds. The Mustinka River draft TMDL report is currently under review by MPCA and the Bois de Sioux TMDL study is in progress. In addition, the HSPF model will be used to identify hotspots of sediment and nutrients, and to target and prioritize sediment and nutrient reduction strategies as part of the Restoration and Protection Strategy process that will begin in 2015 for both watersheds.

1.2 Impaired Waters

Multiple lakes and reaches of the Mustinka River and its tributaries (Twelvemile Creek, Eighteenmile Creek, and Fivemile Creek) were also found to be impaired for one or more designated uses during the 2010-2011 monitoring and assessment cycle. Assessments for support of aquatic life, recreation, and fish consumption indicate non-support in most cases where sufficient data has been collected. All assessed stream segments failed to support aquatic life use standards, mostly due to low oxygen levels or excess turbidity. Excessive bacteria levels resulted in aquatic recreation impairments. Only one stream segment assessed fully supported aquatic recreation use. Poor fish and macro invertebrate communities also resulted in aquatic life impairments. Most lakes had high nutrient levels and low transparency readings. Three of the 179 lakes in the watershed have sufficient data to compare with the aquatic recreation use standard and do not meet the standard. East Toqua and Lannon both have high total phosphorous concentrations and consistently low transparencies. Lightning has elevated phosphorous and chlorophyll-a concentrations. Extensive turbidity and low dissolved oxygen were the two most prevalent parameters causing aquatic life impairments. Both may be influenced by a multitude of factors, including excess nutrients that can increase algae leading to low levels of DO and increased turbidity. Soil loss from agricultural land has been identified as the main source of sediment causing excess turbidity. The highest sediment loading occurs during intense spring rain events with agricultural fields have little cover. Nutrient sources include fertilizer, wastewater treatment plants, septic systems, and nutrient recycling from stream bed sediment.

Multiple lakes and stream reaches within the Bois de Sioux and Rabbit River Watersheds were found to be impaired for one or more designated uses during the 2010-2011 monitoring and assessment cycle. Where sufficient data exists, assessments for aquatic life, recreation, and fish consumption indicate non-support of these uses. Four lakes in the watershed do not meet aquatic recreation use standards, including Upper Lightning Lake, Ash Lake, Mud Lake, and Lake Traverse. Excessive turbidity and low dissolved oxygen were the two most prevalent types of aquatic life impairments. Excessive nutrients such as nitrogen and phosphorus can increase algae in streams, resulting in low dissolved oxygen, larger fluctuations in DO and increased turbidity. In addition to high nutrient levels, high levels of bacteria found in some streams can increase biological oxygen demand further reducing dissolved oxygen. Nutrient sources within the watershed include fertilizer, wastewater treatment facilities, septic systems, and nutrient recycling from stream bed sediment. Nutrients move from fields to streams from runoff. Phosphorous levels at all stations on the Rabbit River and one station on the Bois de Sioux exceeded 350 parts per million. Levels above 150 are considered poor.

1.3 Objectives

The overall goal of this project was to construct and calibrate/validate an HSPF watershed model that can predict flow and water quality in support of conventional parameter TMDLs. The model was required to demonstrate consistency between predicted outputs and available observed monitoring data with a focus on constituents most closely tied to existing impairments in Minnesota, namely suspended sediment, phosphorus, nitrogen and dissolved oxygen. Additionally, landscape and in-stream organic matter (biological oxygen demand [BOD], phytoplankton as chlorophyll-a) were simulated because of their importance to the cycling of phosphorus, nitrogen and dissolved oxygen. The scale of predictions was at HUC-12 watershed level or finer to directly support individual impaired reaches and lakes where little or no hydrologic and water quality data currently exist.

These constituents of focus were revised based on priorities in the Mustinka/Bois de Sioux watersheds and the amount of observed data available for model calibration. Most notably, nitrogen forms were given less weight in terms of calibrated model performance because observed nitrate levels in the watersheds are low (< 1 mg/l) and organic nitrogen and ammonia measurements were lacking during the calibration/validation periods. Consequently, sediment, phosphorus and dissolved oxygen were the principal water quality model outputs.

2 WATERSHED OVERVIEW

The MPCA provides a helpful overview of the Mustinka and Bois de Sioux Watersheds in its respective Monitoring and Assessment Reports (MPCA: 2013a, 2013b). The following two sections are taken from these reports. Figure 1 shows both watersheds and general landuses.

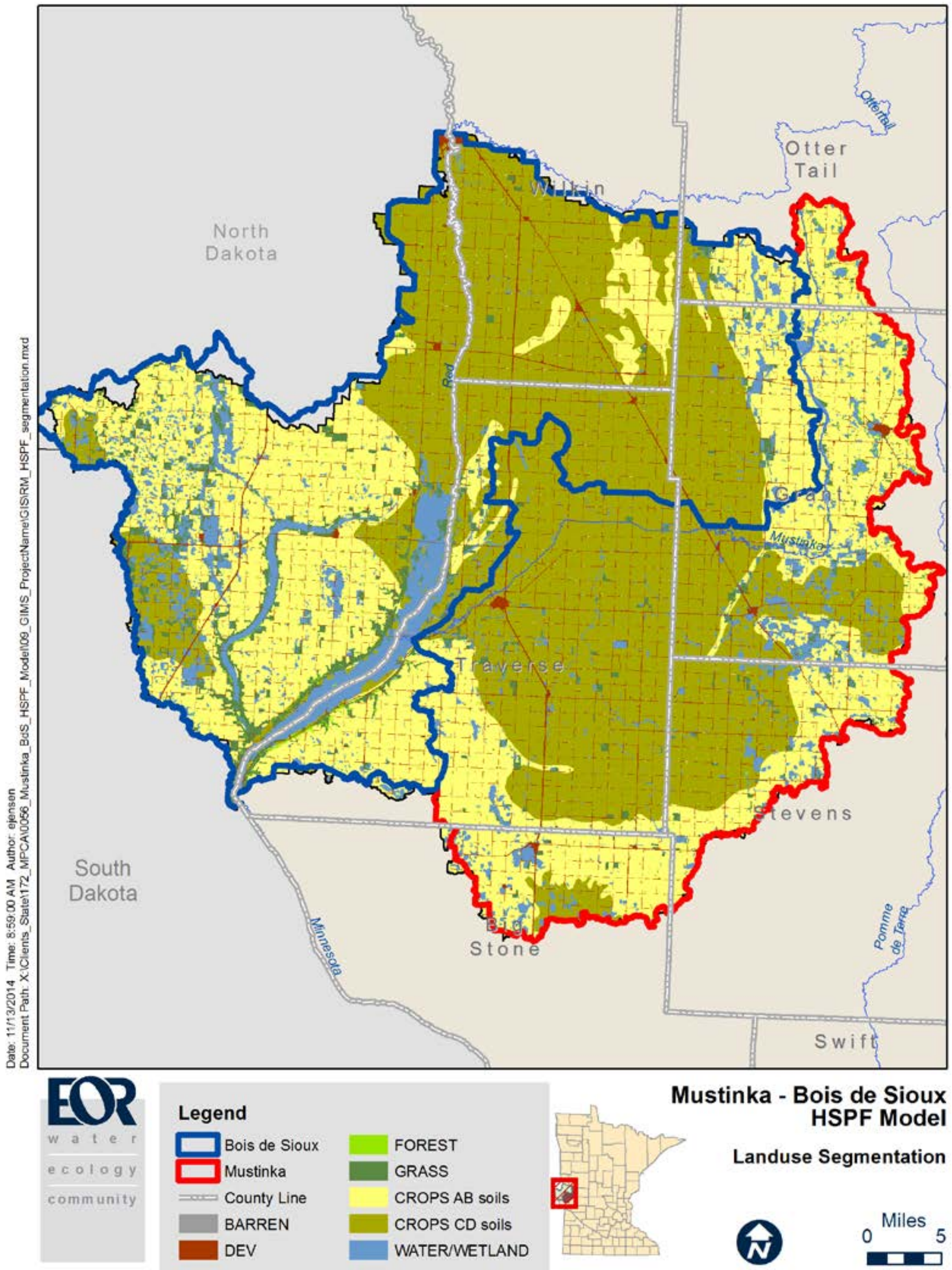


Figure 1. Watersheds overview and general landuses. Row-crops split by soil hydrologic soil groups AB and CD.

2.1 Mustinka Watershed Characteristics

The Mustinka River Watershed covers 562,112 acres (909 square miles) of west central Minnesota. Beginning its 68 mile flow length in southwestern Ottertail County, the Mustinka River flows southward into Grant County through Lightning Lake and Stony Brook Lake (Waters, 1977). The river maintains a southward course until turning west in southern Grant County. The river continues flowing west past Norcross and into Traverse County. In north-central Traverse County two main tributaries, Twelve Mile Creek and Five Mile Creek, feed into the Mustinka. Just west of the confluence of these tributaries the Mustinka River turns southwest and flows past Wheaton into Lake Traverse.

The Mustinka River Watershed lies within three of Minnesota's ecoregions. The eastern portion of the headwaters region lies within the Northern Lakes and Forests (NLF) ecoregion. The glacial soils of the NLF region are thick and nutrient poor (Omernik et al., 1988). Moraine hills, undulating till plains and lacustrine basins occur in the NLF ecoregion (Omernik et al., 1988). Both the western headwaters and west central portion of the watershed lie within the Lake Agassiz Plain (LAP) ecoregion. Glacial Lake Agassiz deposited thick layers of silt and clay to form the fertile soils of the LAP ecoregion (Krenz, 1993). Similar to most remnant lake beds, the LAP ecoregion is very flat and featureless Downstream of the headwaters the ecoregion changes to the Northern Glaciated Plains, which wraps around the entire southern half of the watershed. Soils found within this ecoregion are generally very fertile (Omernik et al., 1988). The terrain varies from flat to gently rolling hills within this ecoregion (Omernik et al., 1988).

2.2 Bois de Sioux Watershed Characteristics

The Bois de Sioux River Watershed occupies a cumulative total of 718,685 acres of land distributed within Minnesota, North Dakota, and South Dakota (MPCA, 2011). Approximately 361,222 acres of the watershed area lies within Minnesota. Early in its course the Bois de Sioux River forms the boundary between Minnesota and South Dakota. Further northward the river forms the boundary between Minnesota and North Dakota. Originating from Lake Traverse, the river flows north through Mud Lake along the western edge of Traverse County. The Bois de Sioux continues north into Wilkin County where it is joined by a primary tributary called the Rabbit River. Continuing northward the river enters the communities of Wahpeton and Breckenridge to join the Ottertail River and form the Red River of the North.

The Bois de Sioux River Watershed lies within two of Minnesota's level three ecoregions. The majority of the watershed lies within the Lake Agassiz Plain (LAP) ecoregion. Glacial Lake Agassiz deposited thick layers of silt and clay to form the soils of the LAP ecoregion (Krenz, 1993). Similar to most remnant lake beds, the LAP ecoregion is very flat and featureless, with slopes of 0 – 2 % (Krenz, 1993). The headwaters region of the watershed lies within the Northern Glaciated Plains ecoregion. Soils within this ecoregion are generally very fertile (Omernik et al., 1988). The terrain varies from flat to gently rolling hills within this ecoregion (Omernik et al., 1988).

3 MODEL CONSTRUCTION

3.1 The HSPF Model

HSPF is a continuous simulation hydrologic and water quality (WQ) watershed model. It simulates surface/sub-surface landscape and in-stream processes on an hourly timestep. HSPF supports incorporation of all landscape management processes such as agricultural and urban practices as well as in-stream point source pollutant discharges.

Like other watershed models (e.g., SWAT, AnnAGNPS), HSPF predicts hydrology and water quality by simulating the interactions between precipitation, solar radiation, soils, land covers and available nutrients. A general representation of a watershed model is presented in Figure 2.

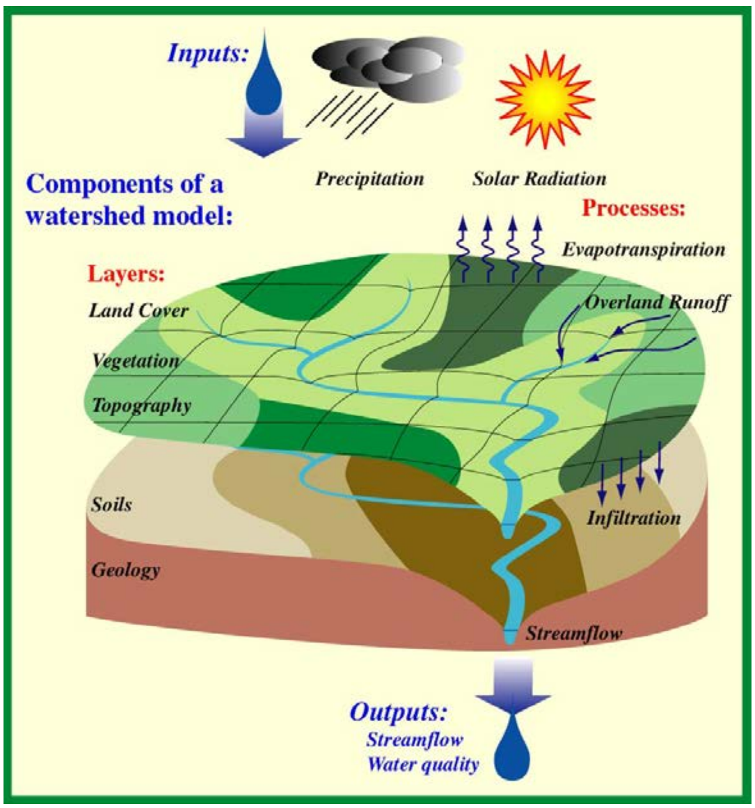


Figure 2. Major components of a watershed model (J.E. Almendinger, St. Croix Watershed Research Station, Science Museum of Minnesota. Used with permission)

HSPF is built around three major hydrology and water quality model algorithms: (1) PERLND: behavior of mainly pervious surfaces, (2) IMPLND: behavior of mainly impervious surfaces, and (3) RCHRES: behavior of streams and in-stream reservoirs. The interaction between these three algorithms comprises the core of the model's predictive framework.

3.2 Model Setup and Parameterization

Generally, watershed models are optimized to, first and foremost, predict hydrology as accurately as possible – principally, the partitioning between the amount of precipitation (rainfall/snowmelt) that infiltrates into the soil and the amount that runs off over the land surface. WQ processes are heavily dependent on this partitioning; therefore, an accurate hydrology calibration lays the foundation for an accurate WQ calibration.

In the Mustinka/Bois de Sioux (MBdS) watersheds, the HSPF model was constructed with the aim of focusing on the most influential hydrological factors – the measureable, spatially distributed properties of the MBdS landscape that are the primary drivers of spatially varying hydrologic response. The MBdS watersheds have highly varied topography and soils, ranging from very flat former glacial lake plain composed of clay-rich soils to prairie pothole glacial moraine predominated by somewhat coarser soils. It is important represent this variation for supporting TMDLs in ungauged reaches as well as providing accurate subwatershed hydrologic and WQ distributions of "hotspots" for BMP implementation planning.

HSPF is a "lumped" parameter model in that it aggregates areas of relatively homogenous hydrologic properties and assigns the same set of parameters for all areas that fall within each aggregation. The aggregations are referred to as "segments" and in the MBdS were determined primarily by the spatial intersection of meteorological zone, soils, landuse, and depressional storage. Additional segments were created to take into account row-crops receiving manure as a fertilizer source and the presence of drain tile.

3.2.1 Meteorological Zones

Meteorological zones (met-zones) are determined by the spatial distribution of climate stations in the modeled watershed area and serve to designate the segments for which a shared daily climate data record will be used. Climate data were selected and downloaded from the BASINS national climate database. In the MBdS, use of a thiessen polygon interpolation approach (available in BASINS) resulted in 13 unique met-zones.

3.2.2 Soils

Digitized county soil survey data (SSURGO) was used for soil analysis and aggregation. Soils were simplified based on their infiltration capacity expressed via the hydrologic soil group property (HSG). Possible values of HSG are primarily A, B, C, and D with A having high infiltration capacity (i.e., sandy texture) and D having low infiltration capacity (i.e., clayey texture). Dual HSG designations A/D, B/D and C/D indicate soils with A, B, C textures but high water tables making them function more like D soils *unless drained*. Based on the observed extent of high density ditch networks in the MBdS, dual HSGs were assumed A, B or C. Ultimately, soils were aggregated into AB and CD soil segments denoting high and low infiltration soils, respectively.

3.2.3 Landuse

Landuse was analyzed using the NLCD 2006 30m resolution layer (National Land Cover Dataset). 80% or more of the MBdS is agricultural and dominated by a mix of corn, soybeans and sugar beets; urban, wetland/open water, grass/hay/pasture and forest comprise the remainder. All corn, soybean and sugar beet landuse was aggregated into a single *Crop* segment. Wetland and open water was aggregated into a *Wetland* segment (however, significant and/or impaired lakes were modeled individually and not aggregated within a segment). Grass/hay/pasture was aggregated into the *Grass* segment.

3.2.4 Depressional Storage

MBdS topography and geology can be generalized into two types: (1) areas dominated by depressional wetlands, ponds and lakes (i.e., prairie pothole geology) that are found in the glacial moraine topography along the eastern (MN) and western (SD) sides of the watershed, and (2) areas dominated by glacial lake plain. Although much channelization appears to have occurred in the depressional areas of the watershed, considerable hydrologic storage was analyzed to remain. In contrast, the lake plain areas were determined to have little storage, owing to flat topography and occurrences of high-density ditch networks. Differentiating between the hydrologic and water quality responses of these two landscape types was considered an important model distinction to improve calibration and support TMDL development and implementation efforts.

Hydrologically, depressional landscapes would be expected on average to exhibit smaller flow peaks and higher inter- and base flow as well as higher ET (resulting in lower total flow volume). Reduction of all major pollutants (i.e., TSS, TP, and nitrate) would also be expected to varying degrees as a result of the hydrologic attenuation.

Wetland and open water bodies are explicitly represented in the model via standard land use segmentation but the drainage areas of these features are not. Cropland comprises the majority of these drainage areas. Therefore, to capture the hydrologic and water quality effects of cropland draining to depressions, an additional "depressional" cropland segment was created.

Thus, conceptually, depressional storage is defined here as the cumulative effect of in-field ephemeral depressions, edge-of-field ponds/wetlands and open- and closed-basin lakes that receive non-channelized surface runoff from croplands. Quantitatively, storage is a depth calculated from depressional volume divided by total depressional drainage area.

Depressional storage was determined using the ArcGIS Archydro toolset and available 5 meter LiDAR dataset. A conservative approach was taken as to not over-estimate storage. A map of potential depressions, storage volumes and drainage areas was created using the Archydro *Depression Evaluation* tool. The analysis also calculated volume for each depression. Depressions were excluded if they were obvious road bank impoundments, often a result of the DEM not having culverts "burned-in". Depressions intersected by NHD stream networks were also excluded unless they had visible open water – evidence that a significant amount of storage (with relatively high residence time) exists in the waterbody. Finally, depressions representing lakes being modeled explicitly by HSPF (as RCHRES) were excluded.

Once all spurious depressions had been eliminated, remaining depressional drainage areas were intersected with cropland type (AB, CD, Drained) to determine applicable cropland-depressional segment area for each HSPF subbasin. Depressional volumes and drainage areas were area-weighted and aggregated by cropland type and meteorological segment to calculate storage depths for each HSPF depressional crop segment.

Storage was expressed in HSPF by adjusting the UZSN (upper zone storage nominal) parameter for each depressional crop segment. In HSPF, UZSN is used to simulate the effects of surface detention storage including that of depressions. Since only a portion of total depressional storage (as defined previously) actually occurs on the cropland itself (i.e., vs. adjacent, down slope depressional features), representation by cropland UZSN is somewhat implicit. However, this parameterization was much more straight-forward to implement than alternatives (e.g., creating an aggregate depressional RCHRES feature for each subbasin, determining FTABLE parameterizations and differentially routing certain segments to each one).

Results of depressional analyses show significant storage in certain met-zones, with UZSN depths increased 0.1 to 3.6 inches over non-depressional parameter values (See Figure 3). Segments with significant storage were simulated in HSPF to have a pronounced decrease in surface runoff to channels and increases in inter- and base flow, a response hydrologically reasonable for depressional landscapes.

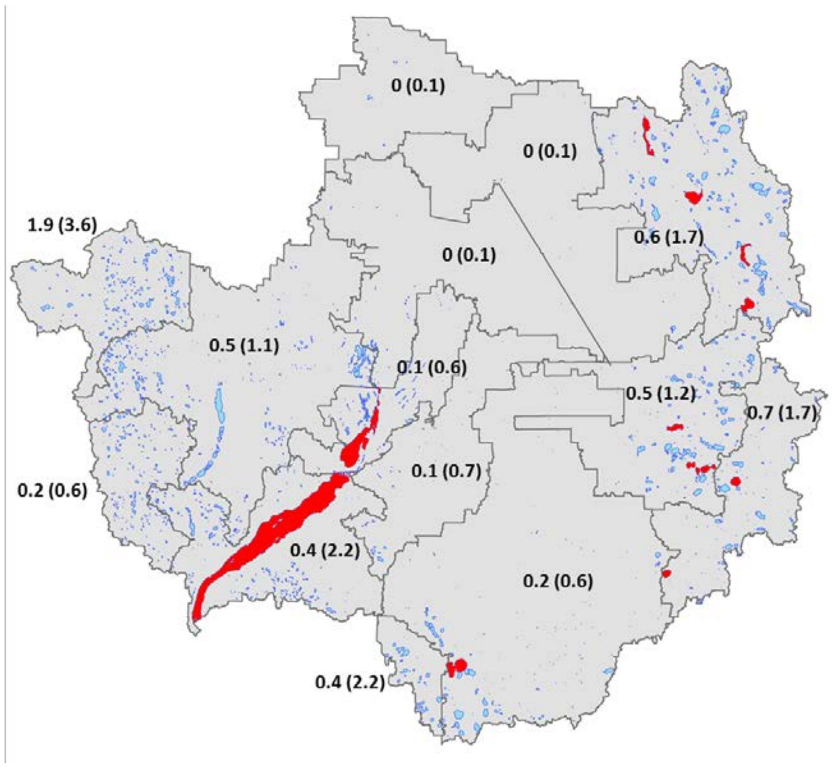


Figure 3. Depressional storage (inches) per HSPF meteorological zone (expressed in HSPF as additional UZSN). First number is total crop landuse depressional storage depth averaged over the entire meteorological segment area (a measure the total effect of depressional storage within the met-segment); number in parentheses is the max crop segment depressional storage depth for that segment. Blue polygons are surface water bodies (utilized with other GIS data to estimate depressional storage). Red polygons are lakes modeled explicitly in HSPF (and not included as depressional storage).

3.2.5 Manure

Manured crops generally export more phosphorus and nitrogen than crops receiving commercial fertilizer. This was considered an important distinction for an accurate spatial distribution of subwatershed loadings. The spatial extent of manured area was determined and the *Crop-*

manured segment added. Manured segments are discussed in more detail into the Water Quality section of this report.

3.2.6 Drain Tile

It is widely understood that sub-surface drainage is a major driver of hydrology and water quality in many parts of Minnesota. The MN Bois de Sioux Watershed District is unique in that it has a tile permitting system started in 1999 that stores GIS information on the location and length of tile installations year to year. From this data, the MBdS appears to be in a phase of widespread tile development with a significant amount added since 2006. While the tile density is relatively small during the modeling period (1995-2006), it was thought important to add it as a placeholder segment (*Crop-tile*) mainly for future model use as the model is updated with more recent flow and meteorological data.

The spatial extent of tile in the model for all periods (calibration/validation: 1995-2006) was set based on the total cumulative tile permitted from 1999-2006 (i.e., total tile present in 2006). Since North/South Dakota tile data was not available, and aerial photographs suggest significantly less surface drainage development in both states in comparison to Minnesota, it assumed that North/South Dakota had no drain tile during the modeling period.

3.2.7 Final Landuse Segmentation

Final land segmentation was conducted by intersecting the 13 met-zones with the soil, landuse and depressional storage segments. The final segments and areal breakdowns are presented in Table 1.

Table 1. Final Landuse/Soil segmentation for Mustinka and Bois de Sioux watersheds

Segment	Acres	%	Description
CropABdep	331,570	26	Row-crop, AB soils, depressional
CropCDdep	262,317	21	Row-crop, CD soils, depressional
CropCD	241,067	19	Row-crop, CD soils
CropAB	138,314	11	Row-crop, AB soils
Wetland	117,321	9	Wetlands and open water
Developed	63,034	5	Pervious and impervious urban
Grass	46,408	4	Grass/Pasture/Hay
Crop-Manured	27,279	2	Row-crop, all soils, manured
Crop-Tile	7,948	1	Row-crop, all soils, drain tiled
Crop-Tiledep	9,737	1	Row-crop, all soils, drain tiled, depressional
Forest	9,652	1	Deciduous and coniferous forest

3.2.8 Reach and Subbasin Delineation

HSPF subbasin and reach delineation involves creating the modeled drainage network composed of discrete channel stream “reaches” and the reach direct overland drainage areas called “subbasins”. This operation was conducted using the BASINS GIS interface using the 5 meter LiDAR elevation data and National Hydrography Dataset stream vector layer, and resulted in 82 reaches and subbasins. HSPF delineation simplifies the channel network, reducing the number of reaches and subbasins to limit unneeded model complexity. Additional information on reach parameterization is presented in EOR (2012a). Model subbasins, reaches and lakes are presented in Figure 4.

The last step in the spatial construction of the HSPF model was to intersect the final segmentation with the delineated subbasins. This procedure calculated the areal distribution of each segment per subbasin thereby finalizing the model framework.

3.2.9 Lakes and Reservoirs

A lake analysis was conducted in order to determine which lakes to model explicitly in HSPF. Ultimately, twelve lakes were selected to be included in the Mustinka-Bois de Sioux HPSF model: all lakes are in Minnesota. Of these twelve, Traverse and Mud Lakes are operating reservoirs that regulate flow between the Mustinka and Bois de Sioux watersheds. The lake selection criteria and reservoir operations are discussed in detail in EOR (2012a).

3.2.10 Point sources

Eight point sources were incorporated into the model – seven within the Mustinka watershed and one within the Bois de Sioux watershed (no North or South Dakota point sources were incorporated into the model). All point sources are wastewater treatment plants that discharge for relatively short periods of time during specific months of the year. Point source discharges to nearby stream reaches included (1) daily flow, (2) heat, (3) dissolved oxygen, (4) nitrate/nitrite, (5) phosphate, (6) organic N, (7) organic P, (8) ammonia, (9) BOD and (10) total organic carbon. See Table 2 for a summary of point sources used in the model. Additional information on point sources is presented in EOR (2012b).

Table 2. Point sources incorporated in the HSPF model

Name	Watershed	Permit No.	Discharge HSPF Reach ID
Big Stone Co. Hutterite Colony	Mustinka	MNG580168	343
Campbell WWTF	Bois de Sioux	MN0020915	205
Dumont WWTF	Mustinka	MN0064831	338
Elbow Lake WWTF	Mustinka	MNG580082	316
Graceville WWTF	Mustinka	MNG580159	341
Herman WWTF	Mustinka	MNG580177	325
Wendell WWTF	Mustinka	MN0051501	318
Wheaton WWTF	Mustinka	MN0047287	306

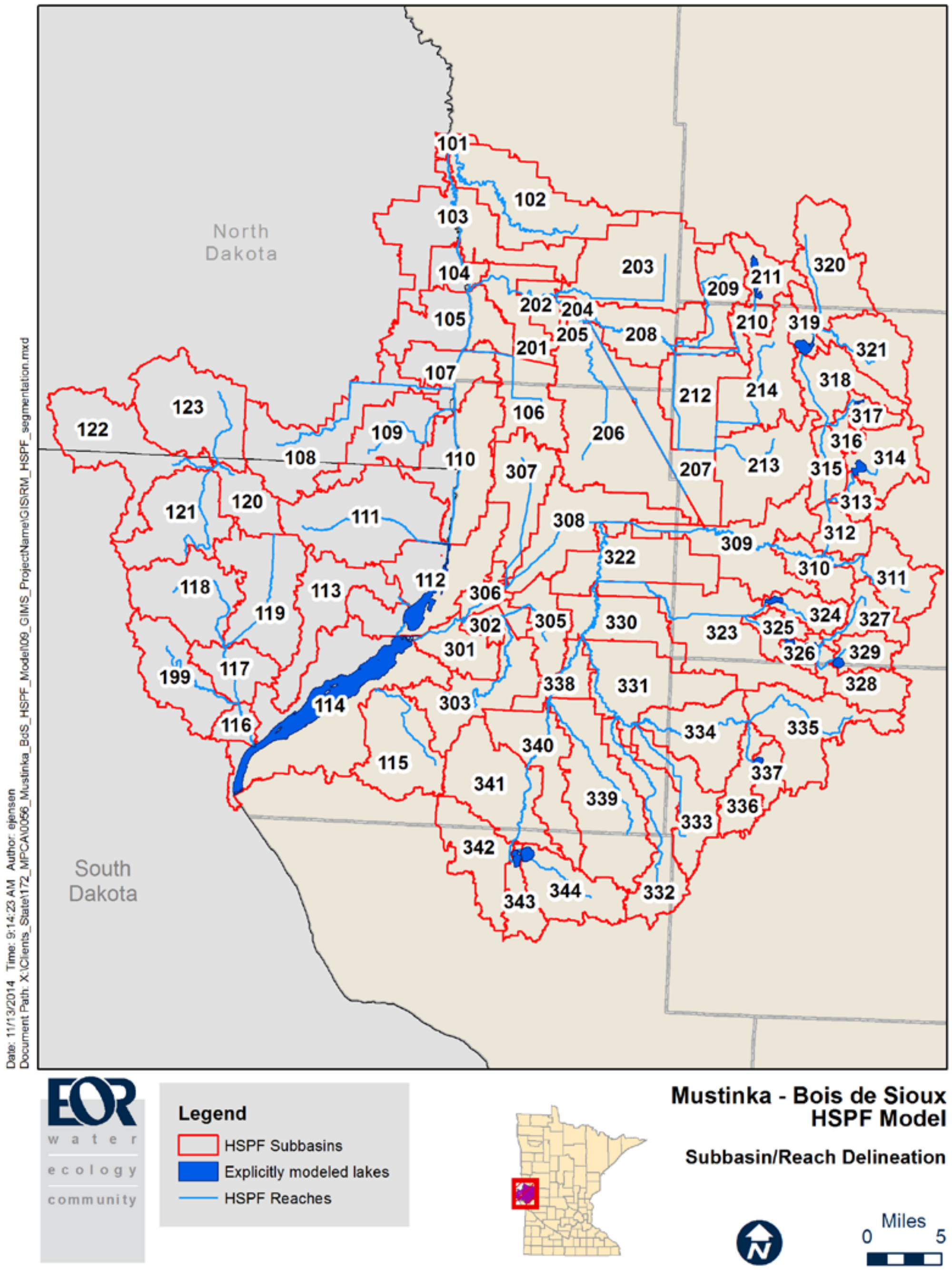


Figure 4. Model delineated subbasins, reaches and explicitly modeled lakes

4 CALIBRATION AND VALIDATION

4.1 Approach

Calibration is a process whereby model outputs are compared with observed data available at specific points in the watershed over a particular time period. Model parameters are adjusted iteratively until the model output matches the observed data in accordance with pre-determined quantitative and qualitative criteria. Validation is a second step where the calibrated output from the calibration period is compared to observed data from a different period to test the model calibration across a different set of climate conditions. The model is then adjusted if necessary until it acceptably compares with observed data from both periods.

WQ Calibration followed a step-wise procedure as outlined in the project workplan and BASINS/HSPF training materials: (1) calibrate water temperature first, (2) nitrogen and phosphorus species, and (3) dissolved oxygen, BOD and phytoplankton with the assumption that, given the inter-dependence of the nutrient cycling processes involved, (2) and (3) will be iteratively repeated until a satisfactory calibration is achieved.

4.1.1 Calibration/Validation Sites and Periods

Calibration/validation was conducted at three primary long-term monitoring sites in the MBdS watersheds and several other secondary sites (See Figure 5). Calibration/validation is largely dependent of the amount and quality of the observed data. The overarching limiting factor in the MBdS calibration/validation was the absence of climate data available in the BASINS climate database after 2006, preventing simulation in the most recent period. Additionally, flow data was limited in the Mustinka prior to 2003 therefore validation was limited to evaluating the model at three upstream impaired reaches during the calibration period. Water quality samples were available from 2001 to 2006 for the primary calibration sites but only after 2006 for the many impaired reaches distributed throughout the watersheds thereby precluding their use. From these data limits and overlaps, the calibration/validation approach was derived (See Table 3). Due to the absence of water quality data collected prior to 2001, no validation for water quality was conducted.

Table 3. Stations and periods for hydrology and water quality calibration/validation

				Calibration Period		Validation Period	
Watershed	River	Flow Gauge	WQ Gauge	Flow	WQ	Flow	WQ
Primary Sites							
Mustinka	Mustinka	5409000	S000-062	2003-06	2001-06	NA	NA
Bois de Sioux	Rabbit	54017001	S001-029	2001-06	2001-06	1998-2000	NA
Bois de Sioux	Bois de Sioux	5051300	S000-553	2001-06	2001-06	1995-2000	NA
Secondary Sites							
Mustinka	12 Mile Creek	34	S003-123	NA	NA	2001-06	2002-06[1]
Mustinka	Mustinka	1	S003-104	NA	NA	2001-06	2002-06[1]
Mustinka	18 Mile Creek	22	NA	NA	NA	2001-06	NA
Bois de Sioux	Bois de Sioux	5050000	NA	2001-06	NA	1995-2000	NA

[1] Temperature and dissolved oxygen only

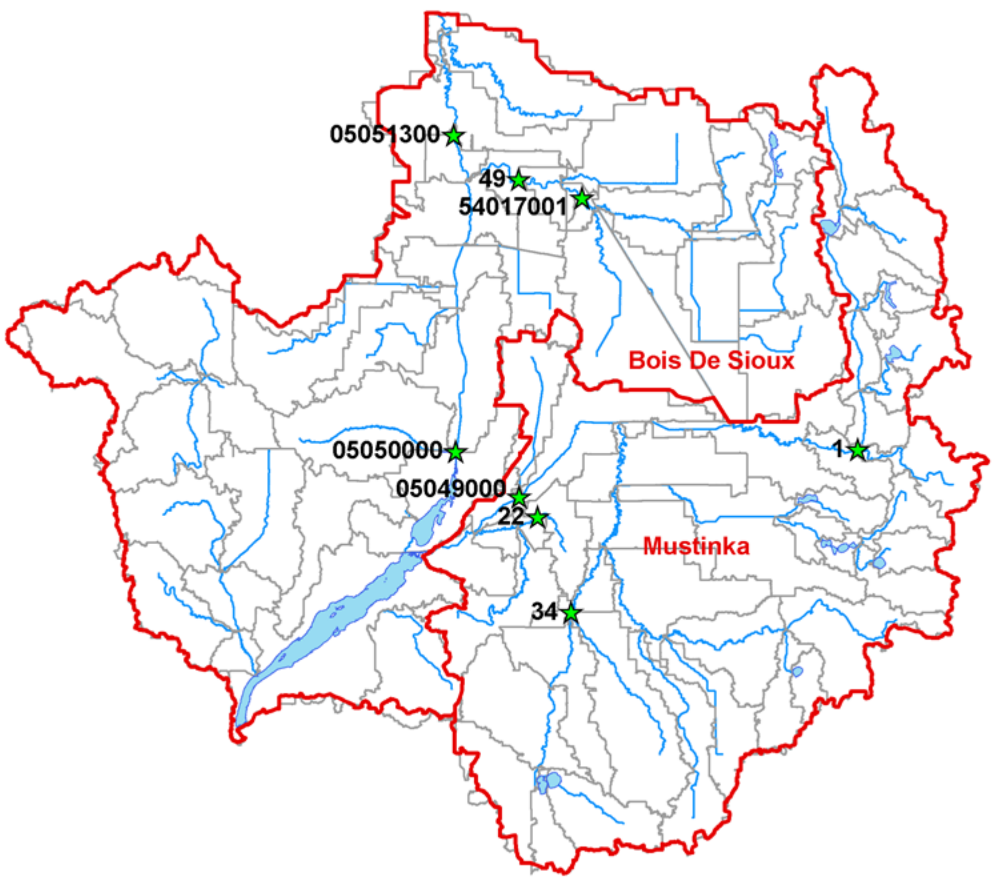


Figure 5. Monitoring stations available for hydrology and water quality calibration/validation

4.1.2 Model Performance Evaluation

Model calibration/validation was judged based on a weight-of-evidence approach as documented in Donigian (2002) and MPCA (2013c). Such an approach utilizes several statistical and visual outputs to evaluate the degree to which the model simulations match the observed data. Statistical metrics were evaluated according to numerical guidelines also in Donigian (2002) and MPCA (2013c) while graphical evaluation relied on professional judgment. The evaluation methodologies for hydrology and water quality are discussed in their respective sections below.

Hydrologic calibration benefitted from use of the HSPF Expert System statistics MS Windows application for generation of all statistical and water balance analyses as well as graphical output. For the water quality calibration, a custom HSPF toolset was developed using R statistical software (R Core Team, 2014) to create all statistical and graphical outputs.

4.2 Hydrology Results

The statistical and visual evaluation methodology for hydrology is presented in Table 4. Simulated vs observed daily and monthly flows were judged based on numerical goodness-of-fit criteria (Nash-Sutcliffe Efficiency coefficient [NSE], coefficient of determination [R^2]). Flow volumes were judged based of percent difference over the entire calibration or validation period.

Table 4. Hydrologic Calibration: Model Performance Evaluation Methodology

<table>
<tr><th>Evaluation Statistics and Numerical Criteria</th><th>Visual Evaluation</th></tr>
<tr><td>(1) NSE* and R^2 of daily/monthly flows
<table>
<tr><th>Rating</th><th>Daily</th><th>Monthly</th></tr>
<tr><td>Very Good:</td><td>> 0.80</td><td>> 0.85</td></tr>
<tr><td>Good:</td><td>0.70 - 0.80</td><td>0.75 - 0.85</td></tr>
<tr><td>Fair:</td><td>0.60 - 0.70</td><td>0.65 - 0.75</td></tr>
</table>
(2) Percent difference between simulated & observed volumes
<table>
<tr><td>Total Volume: ±10%</td></tr>
<tr><td>Storm volumes: ±15%</td></tr>
<tr><td>10% highest flows: ±15%</td></tr>
<tr><td>50% lowest flows: ±10%</td></tr>
</table>
</td><td>(1) Daily/monthly simulated vs. observed flow

(2) Simulated vs. observed flow duration curves

(3) Simulated water balance components</td></tr>
</table>

* Nash-Sutcliffe Efficiency coefficient: index of cumulative error between daily observed and simulated values. Range: -∞ to 1.0 (1.0 indicates perfect agreement between observed and simulated)

Statistical results for all primary calibration sites are presented in Table 5 and Table 6. Visual results for Mustinka and Bois de Sioux sites are shown in Figures 6 - 9. Water balance breakdowns are presented in Table 7. Additional statistical and visual results are available in EOR (2014a). Flow results were *fair* to *good* for daily and generally *good* to *very good* for monthly. Percent difference statistics and flow duration curve comparisons are generally *good* but low flow problems are evident for the Bois de Sioux; this is most likely due to the limited information available on reservoir operations from Traverse and Mud Lakes which are observed to result in complete flow stoppages during some periods. In addition, the Rabbit River – the other major source to the Bois de Sioux station – is a notably flashy stream where flows can range from the very high (>3000 cfs) to zero over relatively short time scales. Neither of these low/zero flow behaviors were simulated well by HSPF.

Table 5. Hydrologic Calibration: Goodness-of-Fit Statistics for Primary Sites

Goodness-of-Fit Statistic	Mustinka Wheaton 540900	Rabbit Campbell CR4 54017001		Bois de Sioux Doran 5051300	
	2003-06	2001-06	1998-00	2001-06	1995-00
Daily	**Calib.**	**Calib.**	**Valid.**	**Calib.**	**Valid.**
Coefficient of Determination (R^2)	0.79	0.56	0.19	0.70	0.48
Nash-Sutcliffe (NSE)	0.77	0.55	NA	0.70	0.41
Monthly					
Coefficient of Determination (R^2)	0.87	0.89	0.17	0.84	0.78
Nash-Sutcliffe (NSE)	0.85	0.88	NA	0.80	0.77

Table 6. Hydrology Calibration: Percent Difference Statistics for Primary Sites

		Mustinka Wheaton 5409000	Rabbit Campbell CR4 54017001		Bois de Sioux Doran 5051300	
		2003-06	2001-06	1998-00	2001-06	1995-00
Error Terms	**Criteria**	**Calib.**	**Calib.**	**Valid.**	**Calib.**	**Valid.**
	+/-	**%**	**%**	**%**	**%**	**%**
Error in total volume (%)	10	9.6	5.2	-11.5	-5.2	24
Error in storm volumes (%)	15	0.8	6.1	-19.3	-19.9	-8.2
Error in 10% highest flows (%)	15	-1.7	6.2	11.5	-16.9	4.7
Error in 50% lowest flows (%)	10	22.3	NA	NA	> 100	> 100

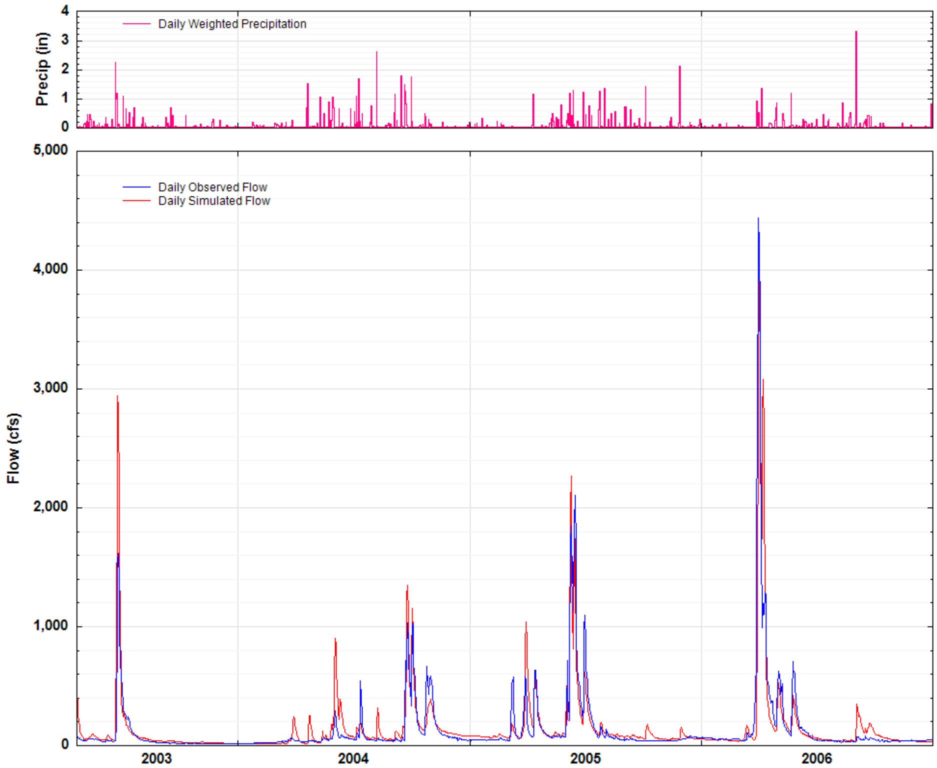


Figure 6. Calibration results for Mustinka 05049000, 2003-2006.

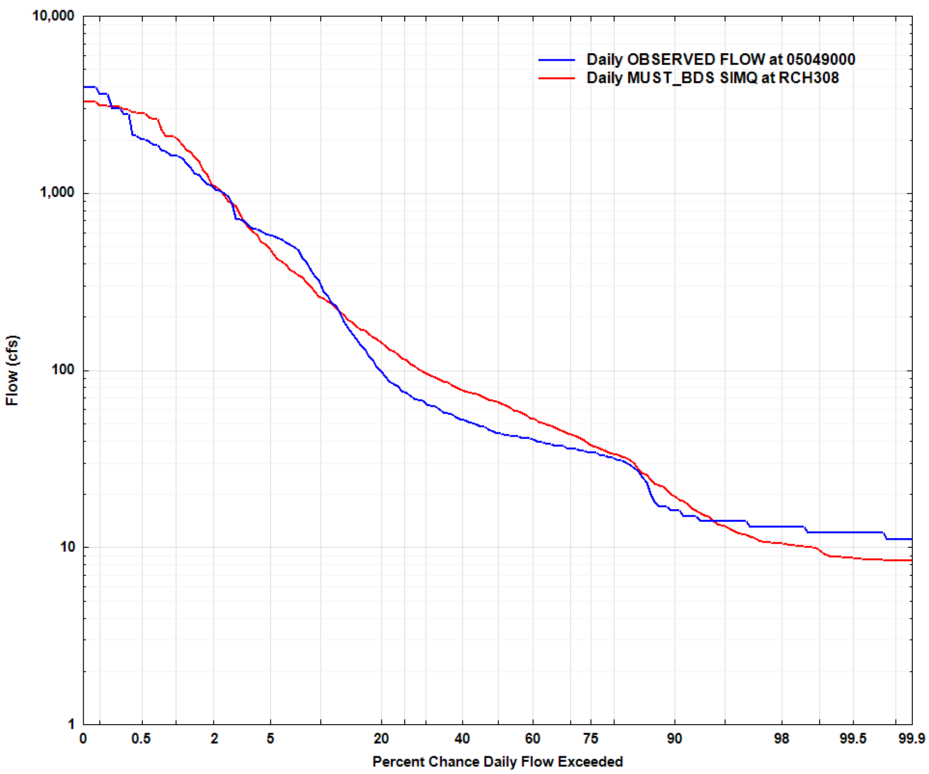


Figure 7. Calibration flow duration curves for Mustinka 05049000, 2003-2006.

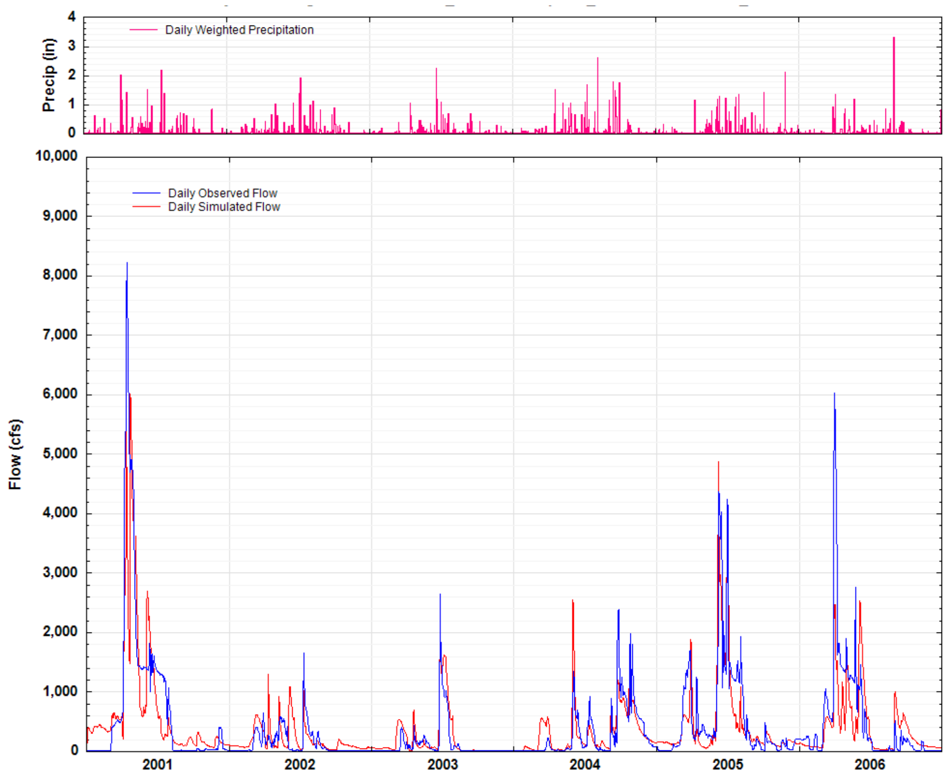


Figure 8. Calibration results for Bois de Sioux 05051300, 2001-2006

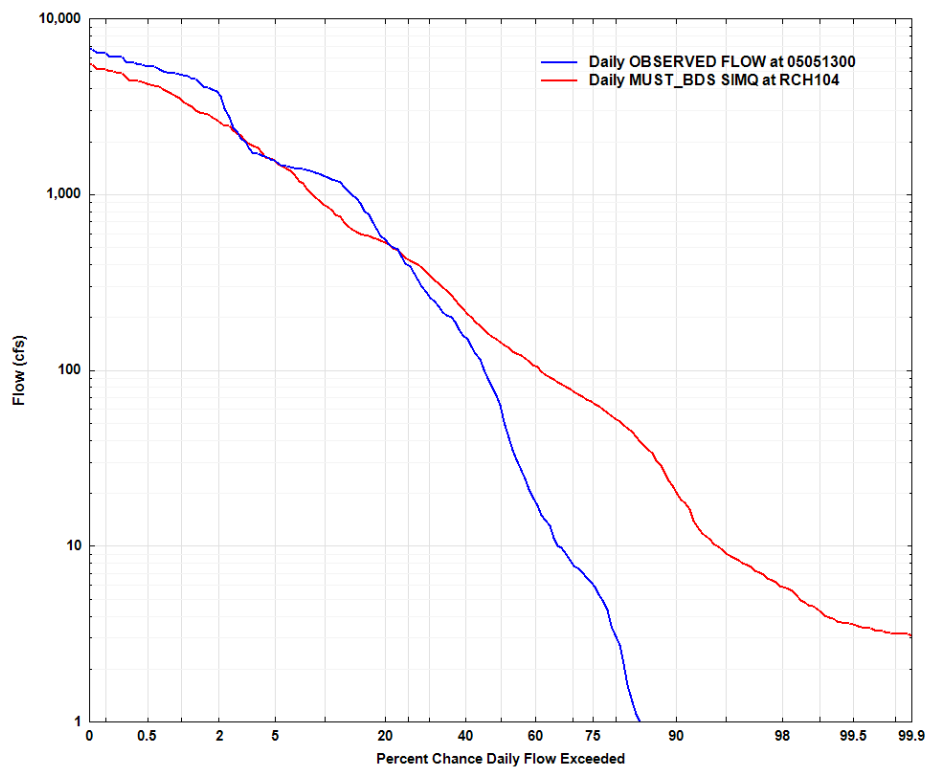


Figure 9. Calibration flow duration curves for Bois de Sioux 05051300, 2001-2006

Table 7. Simulated water balance components for calibration and validation periods. All units in inches.

Water Balance Component		Mustinka Wheaton 540900 2003-06 Calib.	Rabbit Campbell CR4 54017001 2001-06 Calib.	Rabbit Campbell CR4 54017001 1998-00 Valid.	Bois de Sioux Doran 5051300 2001-06 Calib.	Bois de Sioux Doran 5051300 1995-00 Valid.
Influx						
	Rainfall	27.2	27.4	24.6	26.9	25.7
Runoff						
	Surface-PER	1.1	1.2	0.4	1.1	1.0
	Surface-IMP	0.0	0.1	0.0	0.0	0.0
	Interflow	0.8	0.8	0.3	0.8	1.1
	Baseflow	1.2	1.2	0.9	1.2	1.5
	Total	3.2	3.2	1.7	3.1	3.7
GW	Inflow					
	Deep	0.7	0.7	0.4	0.5	0.6
	Active	1.3	1.4	0.8	1.5	1.7
Evaporation						
	Potential	40.1	39.0	43.9	39.0	36.0
	Intercep	6.2	6.1	6.1	5.9	5.7
	Upper Zone	6.1	6.4	5.4	6.2	5.1
	Lower Zone	11.2	11.1	11.7	11.1	10.7
	Grnd Water	0.29	0.29	0.20	0.36	0.31
	Baseflow	0.04	0.04	0.05	0.04	0.04
	Impervious	0.02	0.02	0.02	0.01	0.01
	Total	23.9	23.9	23.5	23.7	21.9

4.3 Water Quality Results

Sediment, water temperature, nitrogen (NO_3, NH_3, TKN: total kjeldahl nitrogen), phosphorus (total and orthophosphate), dissolved oxygen, phytoplankton, and biological oxygen demand were calibrated at some or all of the three primary sites in the MBdS (depending on available observed data). Of these constituents, suspended sediment, total phosphorus (TP), orthophosphate (Ortho-P), and nitrate (NO_3) time-series *loads* were more rigorously calibrated and evaluated using numerical criteria. Calibrated constituent *concentrations* were evaluated based on visual examination only. In addition, nitrogen, given its low observed concentrations, is less important in existing MBdS impairments than phosphorus (and the latter's link to dissolved oxygen). Therefore, phosphorus was given greater weight for attaining accurate calibrations. Because of the lack of nitrate data at the Rabbit calibration site, nitrogen forms were not calibrated there.

The statistical and visual evaluation methodology for water quality is presented in Table 8. Because of the spatial and temporal complexity of landscape and stream water quality processes as well as uncertainties in observed data, simulated water quality is generally judged by lower numerical standards and at longer temporal scales than flow (monthly and annually vs. daily). Water quality numerical model performance criteria were estimated from thresholds suggested in the MPCA Guidance doc (MPCA, 2013c).

Table 8. Water Quality Calibration: Model Performance Evaluation Methodology

<table>
<tr><th>Evaluation Statistics and Numerical Criteria</th><th>Visual Evaluation</th></tr>
<tr><td>
(1) NSE* and R^2 of monthly loads
<table>
<tr><td>Rating</td><td>Sediment</td><td>TP, NO_3</td></tr>
<tr><td>Very Good:</td><td>> 0.65</td><td>> 0.75</td></tr>
<tr><td>Good:</td><td>0.55 - 0.65</td><td>0.65 - 0.75</td></tr>
<tr><td>Fair:</td><td>0.45 - 0.55</td><td>0.55 - 0.65</td></tr>
</table>
(2) Percent difference between simulated & observed total loads
<table>
<tr><td>Rating</td><td>Sediment</td><td>TP, NO_3</td></tr>
<tr><td>Very Good:</td><td>< 20%</td><td>< 15%</td></tr>
<tr><td>Good:</td><td>20-30%</td><td>15-25%</td></tr>
<tr><td>Fair:</td><td>30-45%</td><td>25-35%</td></tr>
</table>
</td><td>
(1) Monthly/annual simulated vs. observed loads

(2) Simulated vs. observed load duration curves

(3) Daily simulated time-series vs. observed grab samples concentrations[1]
</td></tr>
</table>

* Nash-Sutcliffe Efficiency coefficient: index of cumulative error between daily observed and simulated values. Range: -∞ to 1.0 (1.0 indicates perfect agreement between observed and simulated)

4.3.1 Sediment

Statistical results for all primary calibration sites are presented in Table 9. Graphical results for Mustinka and Bois de Sioux sites are shown in Figures 10 - 15. Additional statistical and visual results are available in EOR (2014b).

An important component of the calibration at all stations was parameterization of a groundwater contribution of clay to the stream channel. Minimum observed MBdS suspended sediment concentrations (SSC) are ~ 20-30 mg/l (recall this concentration excludes organics) and it was not possible to simulate this concentration without an additional input. Following the work of TetraTech in the MN River HSPF models, 25 mg/l of groundwater clay concentration was added via the MASS-LINK block. It is not known what source or process -- groundwater entrainment vs. low flow channel/bank erosion vs. lake release of suspended sediment -- is actually responsible for the high low flow SSC. Therefore, this representation is somewhat implicit but was necessary for calibrating the models with a reasonable level of certainty for both sediment and phosphorus.

Weighting each calibration statistic in Table 9 evenly, sediment results at each site were generally *good* to *very good*. *Poor* monthly NSE statistics in the Mustinka are heavily influenced by June 2003 under-predictions; however, load duration curves (LDCs) and concentrations can be judged as *good*. Somewhat opposite calibration trends are observed at the Bois de Sioux where LDCs are not exemplary but calibration statistics are *good*. These contrasting outputs reinforce the need for a weight-of-evidence approach whereby multiple calibration outputs are analyzed to judge model performance.

Table 9. Sediment load calibration statistics and ratings

Site	Monthly NSE	Monthly R^2	Percent Difference
Mustinka	0.19 (Poor)	0.47 (Fair)	+3% (Very Good)
Bois de Sioux	0.62 (Good)	0.69 (Very Good)	-28% (Good)
Rabbit	0.36 (Poor)	0.73 (Very Good)	+29% (Good)

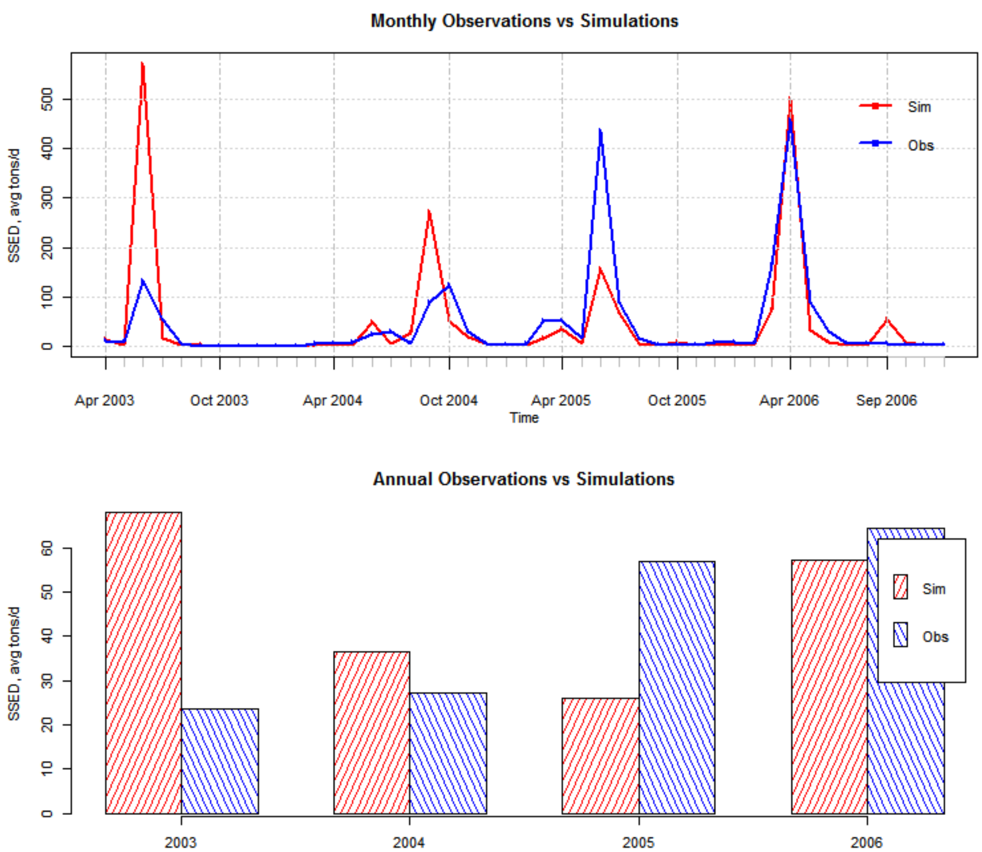


Figure 10. Mustinka monthly and yearly simulated vs observed sediment loading

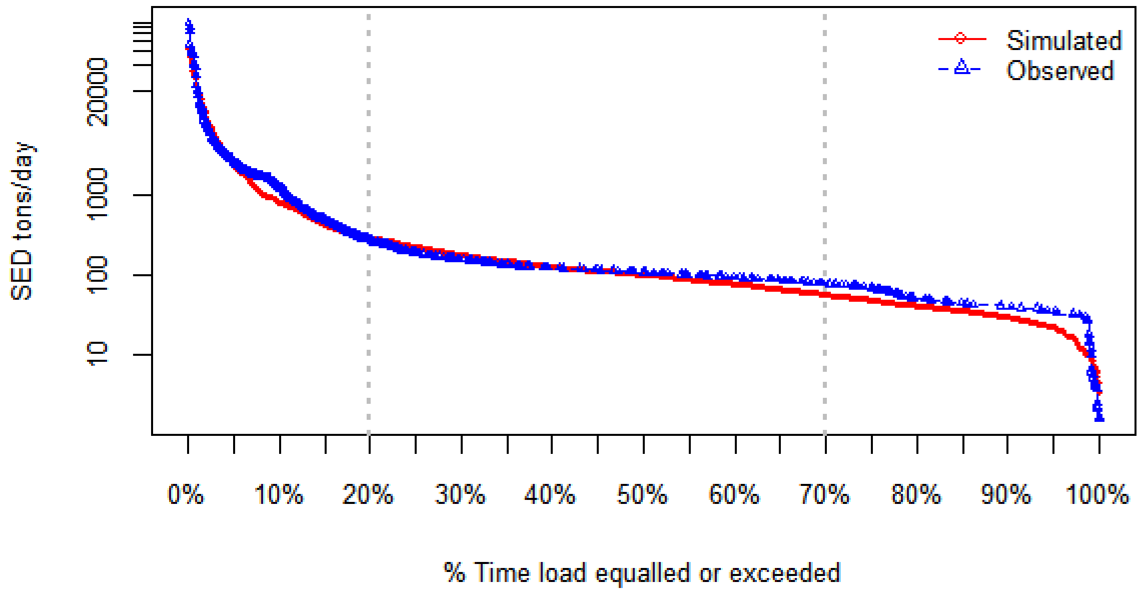


Figure 11. Mustinka simulated vs observed daily suspended sediment load duration curves

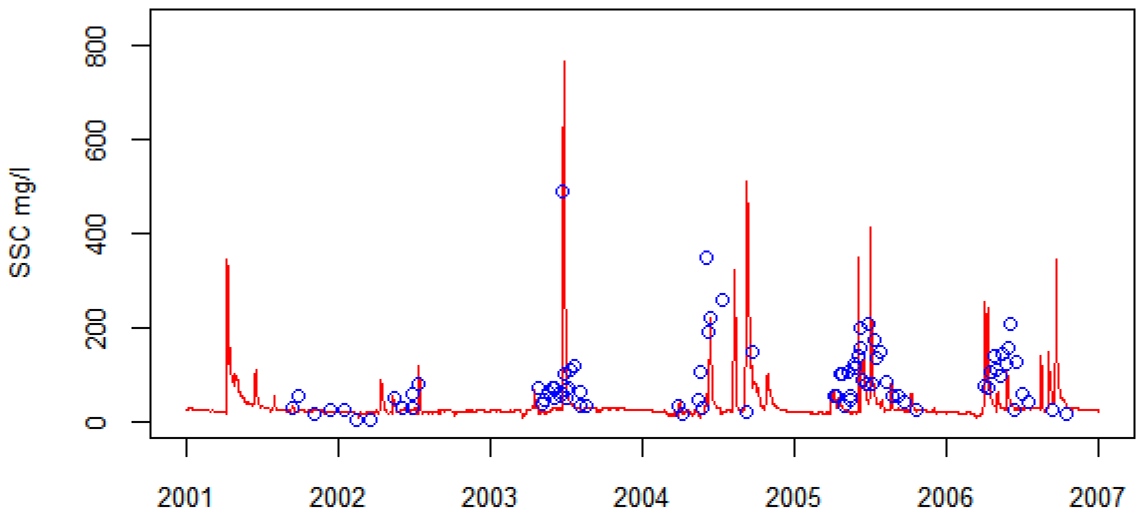


Figure 12. Mustinka simulated vs. observed daily suspended sediment concentrations

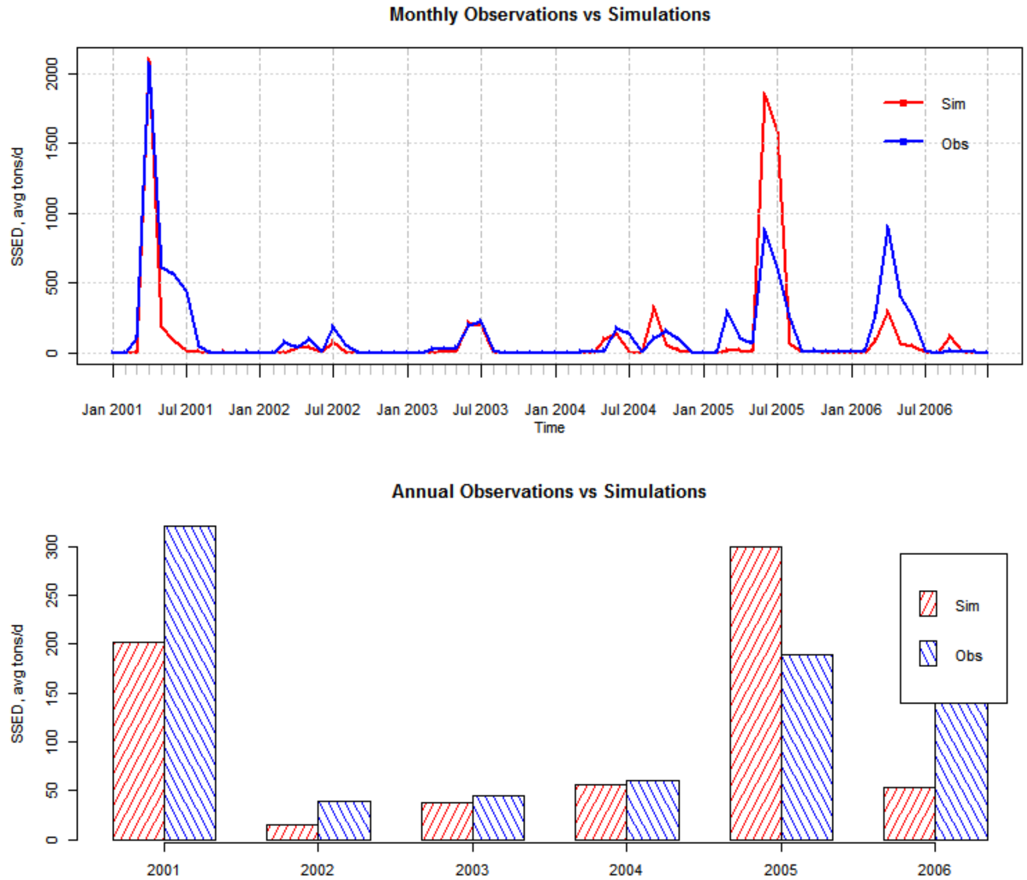


Figure 13. Bois de Sioux monthly and yearly simulated vs observed suspended sediment loading

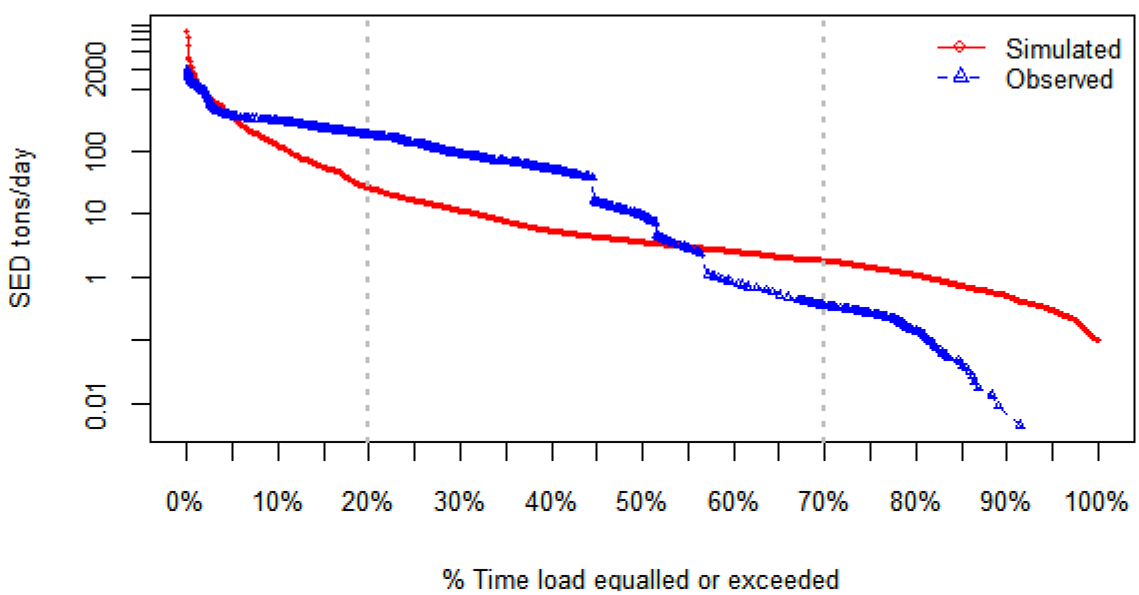


Figure 14. Bois de Sioux simulated vs observed daily suspended sediment load duration curves

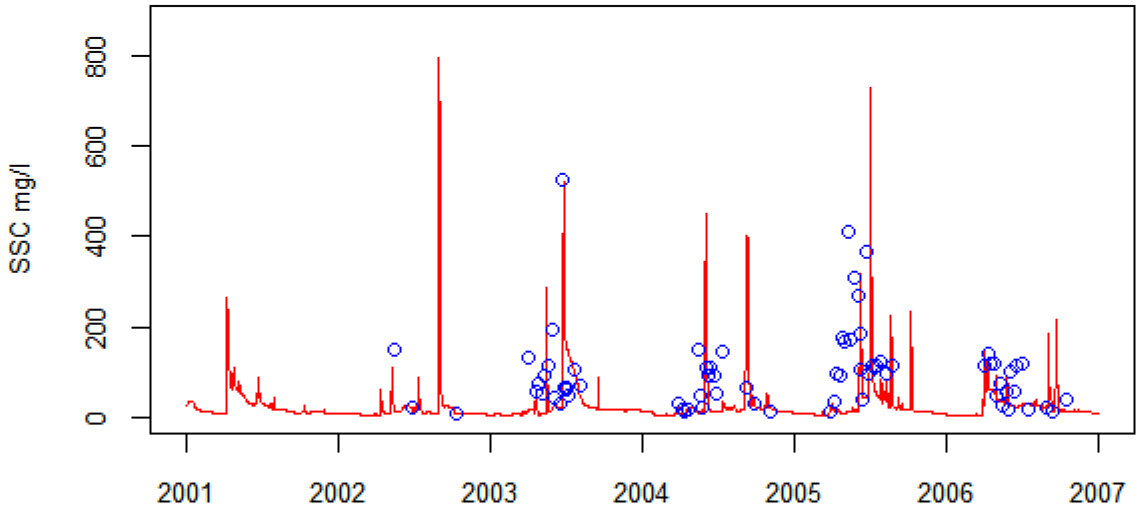


Figure 15. Bois de Sioux simulated vs. observed daily suspended sediment concentrations

4.3.2 Nutrients and Physical Properties

Calibration results and discussion for in-stream temperature, nitrogen, phosphorus, dissolved oxygen, biological oxygen demand (BOD) and phytoplankton are present below. Additional detail as well as graphical output for temperature, BOD and phytoplankton were omitted for conciseness but are available in EOR (2014c).

4.3.2.1 Temperature

Temperature was calibrated at the three sites using a robust set of observed data. HSPF's temperature algorithms appear to be very accurate – despite setup using default parameters -- as no additional calibration at any site was necessary. However, it is not clear to what extent temperature may be over-predicted in smaller, shallower streams of the MBdS. HSPF produced warnings in several lower order reaches during summer, low flow periods indicating simulated temperature exceeded reasonable values (a common warning in the HSPF model simulations). Adjusting the ADCALC activity flag to "2" remedied some but not all of these warnings.

4.3.2.2 Nitrogen

Nitrate calibration results are presented in Table 10 and Figures 16 - 20. As discussed above, the MBdS watersheds (along with the Red River basin on the whole) are somewhat unique in that, unlike most central/southern MN agricultural watersheds, they exhibit relatively low river NO_3 loads; in most cases, concentrations are roughly an order of magnitude lower than similarly managed (i.e., fertilizer, tillage, etc.) agricultural watersheds in the Minnesota River basin.

<u>Nitrate (NO_3)</u>
Low observed NO_3 concentrations at the two primary calibration sites necessitated a pronounced decrease in the surface runoff component of NO_3 transport to prevent over-prediction of simulated concentrations during high flow periods. Daily accumulation and storage limits (ACCUM, SQOLIM) were decreased to reduce the storm event concentration peaks. Low flow

NO_3 was calibrated by adjustment of interflow and groundwater concentrations. Calibrated subsurface concentrations were calibrated to be notably higher during the months of April, May and June where observed concentrations are generally higher.

Mustinka NO_3 numerical calibration results were *good* to *very good*. Percent difference in cumulative loads over the entire period was *good* with an under-prediction bias of ~20%. Review of the load duration curve shows the NO_3 calibration is representative at all flow ranges. Simulation of concentrations appears adequate but with some simulated peaks during non-spring periods that are likely not representative of actual conditions.

Bois de Sioux NO_3 numerical calibration results were *fair* to *good* with the load duration curve indicating a good calibration on the highest loading days (which is driving the strength of numerical GOF statistics) but correspondence with the observed data in most other flow ranges was . Percent difference in cumulative loads over the entire period was *fair* with an under-prediction bias of 27%. Daily simulated concentrations appear *very good* but, similar to Mustinka, most likely over-predicting some peak flow concentrations.

Total Ammonia (NH_3)

Mustinka NH_3 concentrations were simulated and compared with periodic grab samples. HPSF most likely over-predicted high flow peak concentrations (ranging from ~0.5 mg/l to ~1.0 mg/l) but overall, the median of the simulated time series compared well to the median grab sample concentration (0.034 vs. 0.038 mg/l, respectively). While Rabbit NH_3 was not rigorously calibrated for any nitrogen forms, simulated vs. observed median concentrations compared well there also (0.109 vs. 0.095, respectively).

Total Kjeldahl Nitrogen (TKN)

TKN is the sum of NH_3 and organic nitrogen and served as the proxy for evaluating total nitrogen. Overall, the simulations substantially under-predicted observed grab sample TKN concentrations. Comparison of simulated vs. observed medians exhibited a poor correlation as well (0.72 vs. 1.72 mg/l respectively). Because of the lesser weight given to calibrating nitrogen species in general, this under-prediction was not investigated beyond adjustment of BOD surface potency and subsurface concentrations.

4.3.2.3 Phosphorus

Calibration of phosphorus was the principal focus of the model calibration given its importance in TMDL impairments in the MBdS and was calibrated at all three sites. Calibration results are presented in Table 10. Evaluation statistics were rated *fair* to *very good* at all three calibration sites. Percent difference in cumulative loads exhibited a consistent trend across all three sites with Ortho-P over-predicted and TP under-predicted although all differences are rated *fair* to *very good*. Graphical results for TP are shown below in Figures 21 - 26. LDC and concentrations show *good* to *very good* agreement. Ortho-P graphical results were very similar to that of TP and were omitted for conciseness, as were Ortho-P and TP Rabbit results. Detailed results may be found in EOR (2014c).

HSPF simulates Ortho-P as the sum of particulate and dissolved phosphate forms. TP is simulated as the sum of Ortho-P and organic P present in stream plankton. Ortho-P was calibrated by adjusting the POTFW (surface runoff sediment Ortho-P potency factor) and monthly interflow and groundwater Ortho-P concentrations, while maintaining the ratios between manured and non-manured row-crop segments and non-row-crop segments (as discussed in the *Parameterization* section). After Ortho-P was calibrated, the resulting TP calibration was reviewed but did not require adjustment of parameters governing the organic P fractions.

Mustinka calibration goodness-of-fit (GOF) and percent difference statistics were *fair* to *good* for Ortho-P and *good* to *very good* for TP indicating generally good monthly/yearly agreement between simulated and observed phosphorus. Comparison of load duration curves indicate good agreement in the upper 15% of flows where most TP loading occurs during the model period, but an over-prediction at medium flows. Simulated TP concentrations vs. observed grab samples appear to represent periodic grab samples well.

Bois de Sioux calibration results yielded GOF and percent difference statistics that were *good* to *very good* for Ortho-P and *fair* for TP indicating generally good monthly/yearly agreement between simulated and observed phosphorus. Comparison of load duration curves indicate good agreement in the upper 50% of flows but an over-prediction in the lower 50% of flows, where loads are off roughly one order of magnitude. Simulated TP concentrations vs. observed grab samples appear to represent periodic grab samples adequately but exhibit significant over-prediction error during 2004 and likely excessive peak flow concentrations throughout.

Phosphorus calibration GOF results were *fair* to *good* for Ortho-P and TP but the overall percent differences were *very good* and *good*, respectively. Comparison of load duration curves show very good agreement in the majority of flow ranges (upper 70-90%). Simulated TP concentrations vs. observed grab samples appear to represent periodic grab samples adequately but indicate probable high flow/peak flow over-predictions.

Table 10. NO_3, TP and Ortho-P load calibration statistics and ratings

Site	Constit.	Monthly NSE	Monthly R^2	Percent Diff.
Mustinka	NO_3	0.79 (Very Good)	0.89 (Very Good)	-19% (Good)
	TP	0.72 (Good)	0.73 (Good)	-7% (Very Good)
	Ortho-P	0.60 (Fair)	0.69 (Good)	+17% (Good)
Bois de Sioux	NO_3	0.69 (Good)	0.71 (Good)	-26% (Fair)
	TP	0.62 (Fair)	0.60 (Fair)	-27% (Fair)
	Ortho-P	0.75 (Very Good)	0.79 (Very Good)	+16% (Good)
Rabbit	NO_3	NA	NA	NA
	TP	0.64 (Fair)	0.65 (Good)	-17% (Good)
	Ortho-P	0.61 (Fair)	0.65 (Good)	+7% (Very Good)

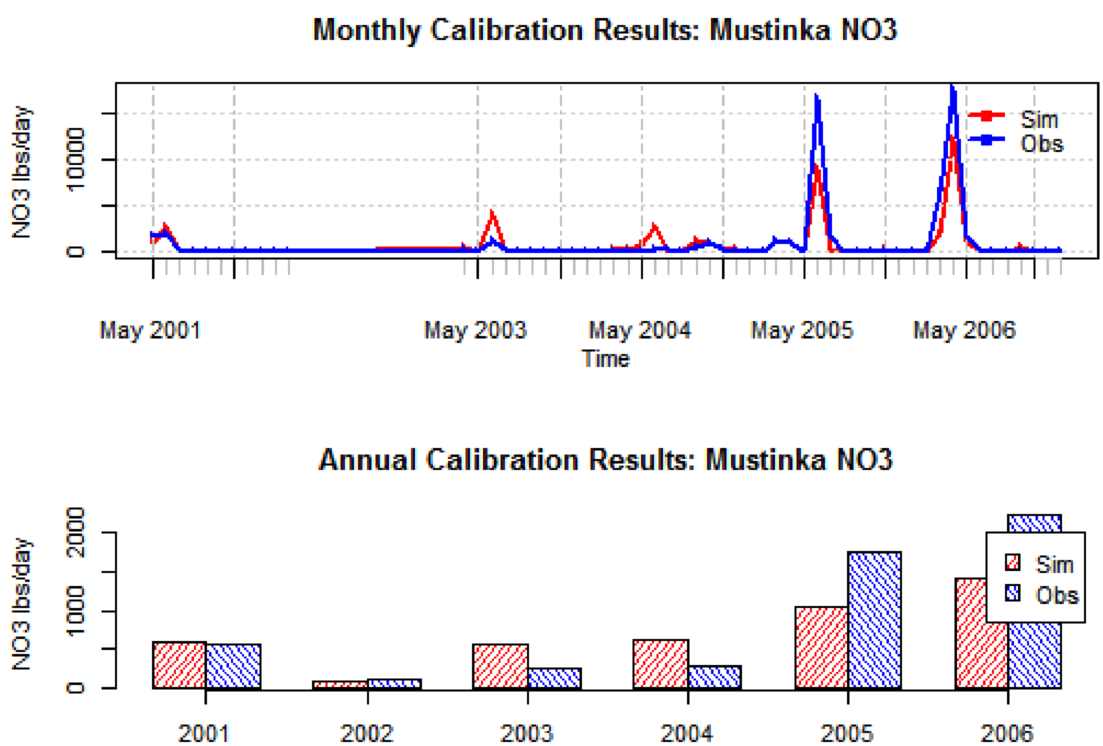


Figure 16. Simulated vs. observed monthly and yearly NO3 loads for Mustinka

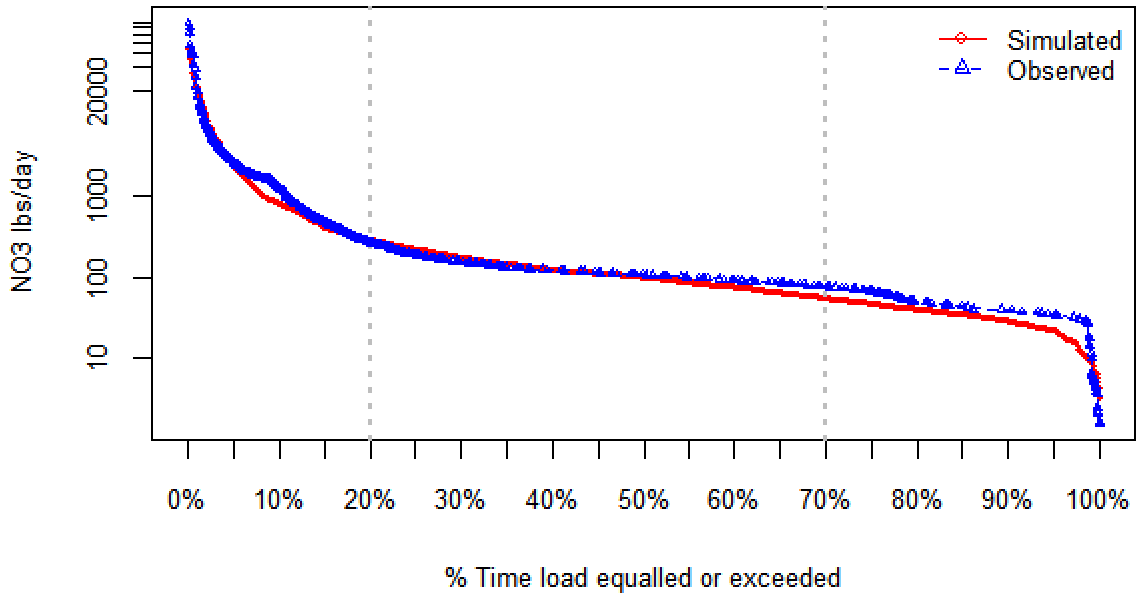


Figure 17. Simulated vs. observed daily NO3 load duration curves for Mustinka

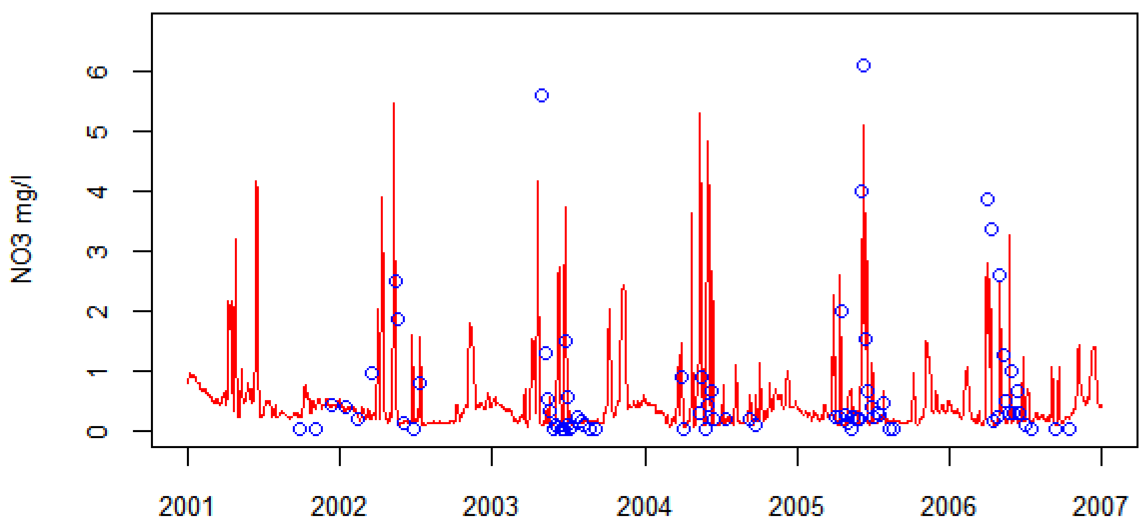


Figure 18. Simulated vs. observed daily NO3 concentrations for Mustinka

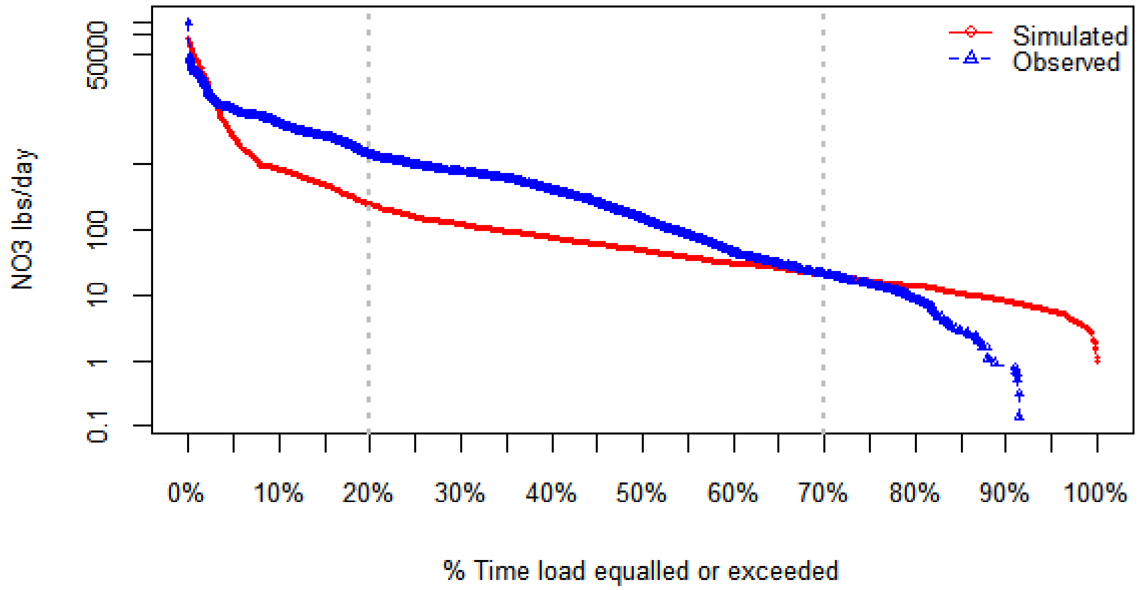


Figure 19. Simulated vs. observed daily NO3 load duration curves for Bois de Sioux

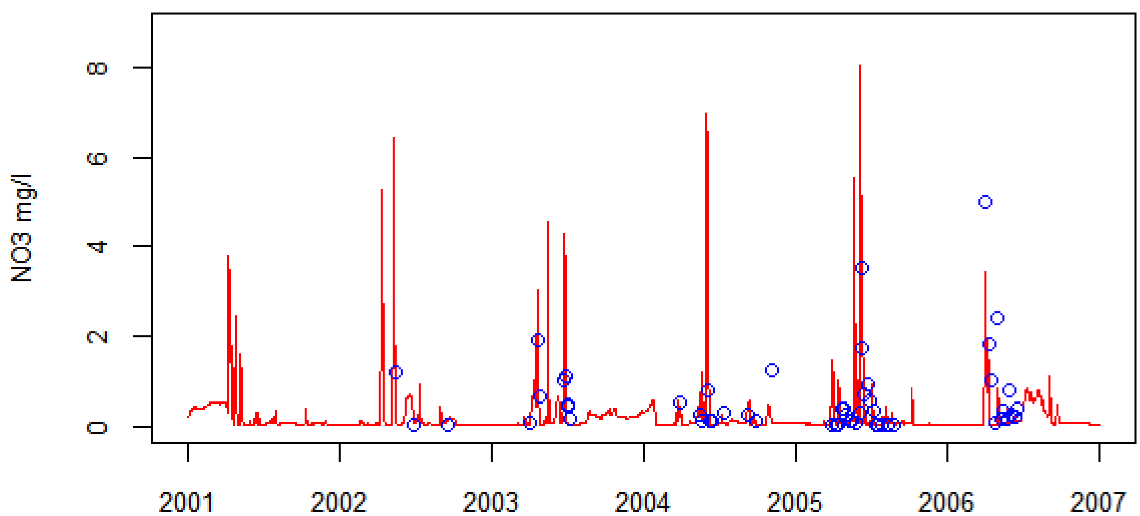
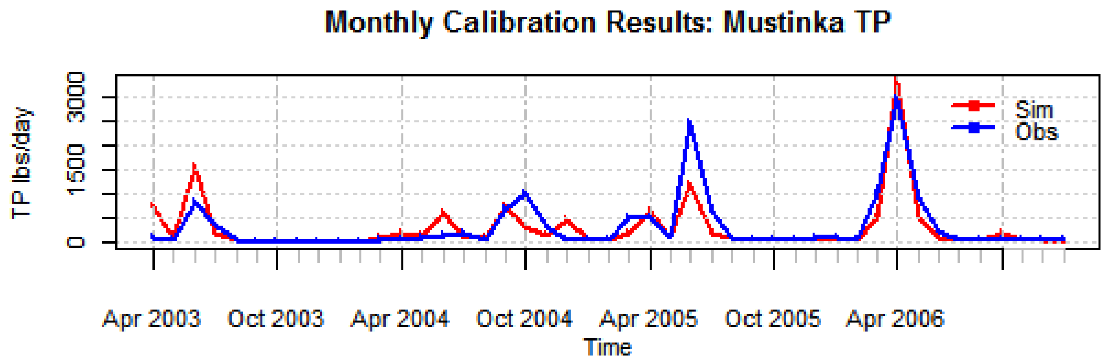


Figure 20. Simulated vs. observed daily NO3 concentrations for Bois de Sioux



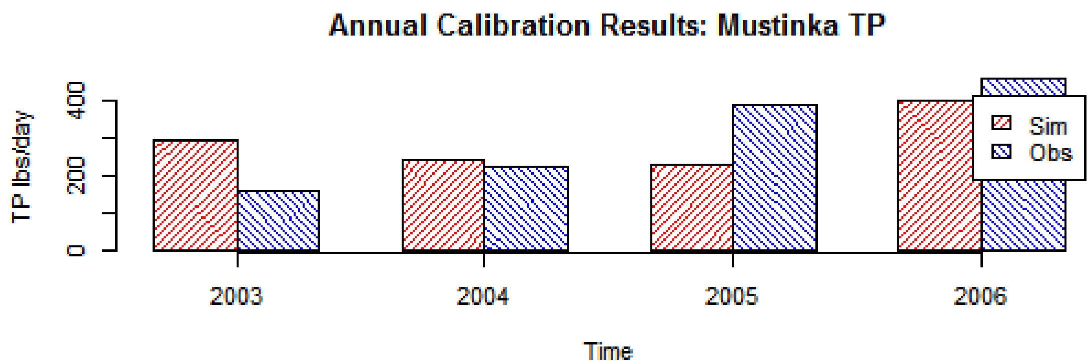


Figure 21. Simulated vs. observed monthly and yearly TP loads for Mustinka

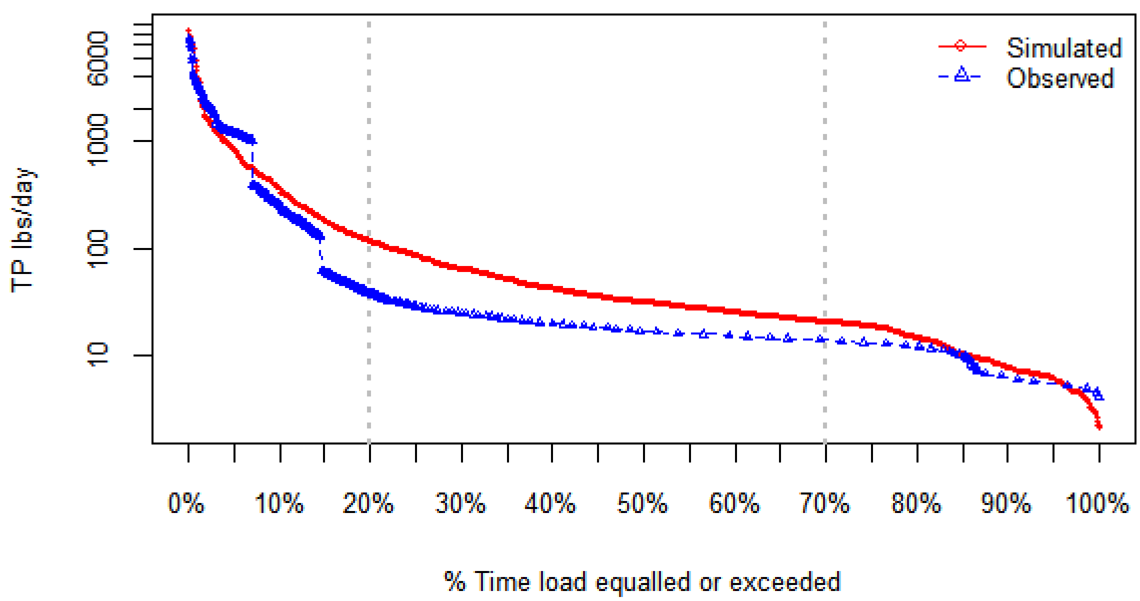


Figure 22. Simulated vs. observed daily TP load duration curves for Mustinka

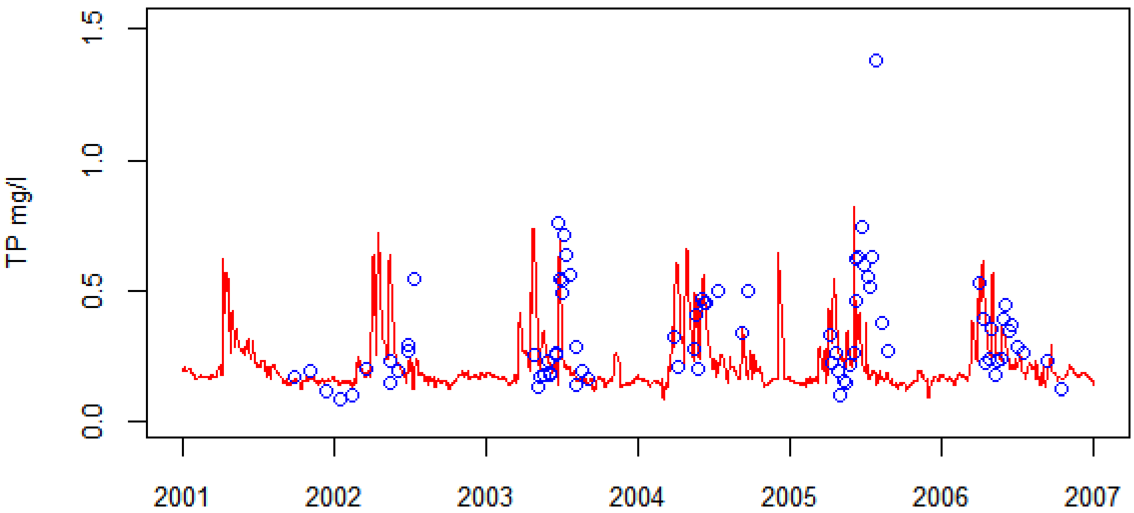


Figure 23. Simulated vs. observed daily TP concentrations for Mustinka

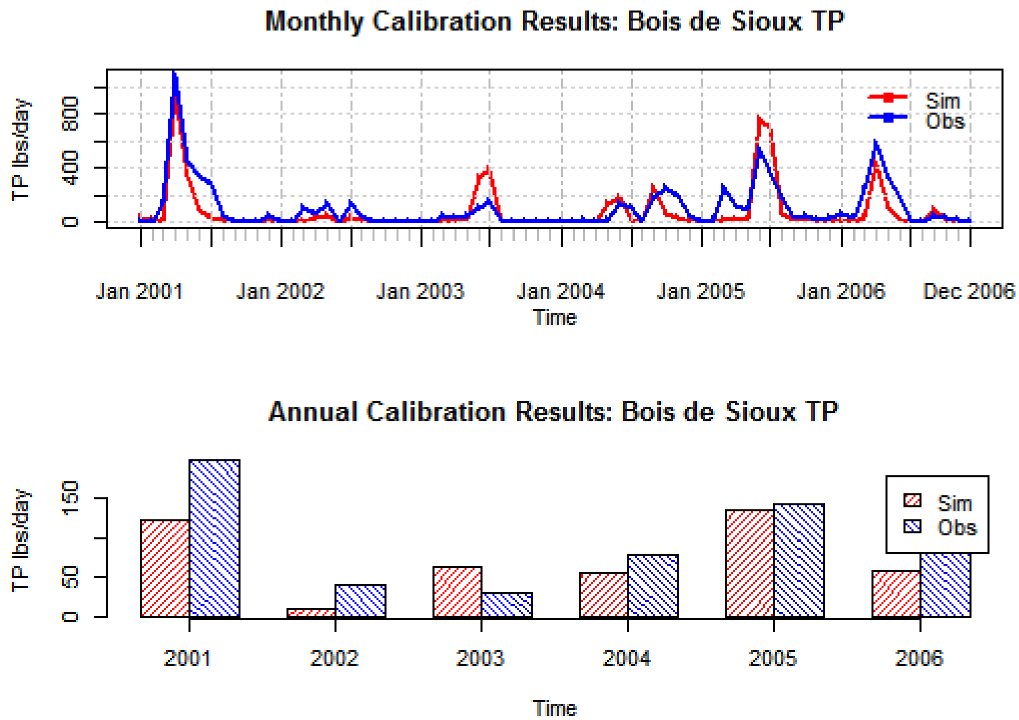


Figure 24. Simulated vs. observed monthly and yearly TP loads for Bois de Sioux

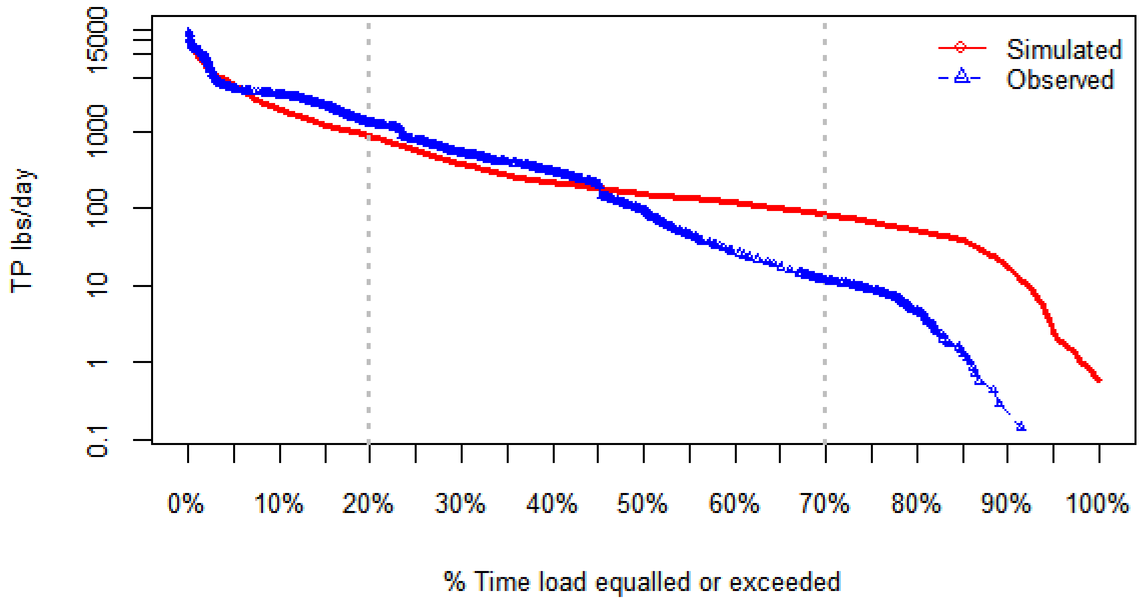


Figure 25. Simulated vs. observed daily TP load duration curves for Bois de Sioux

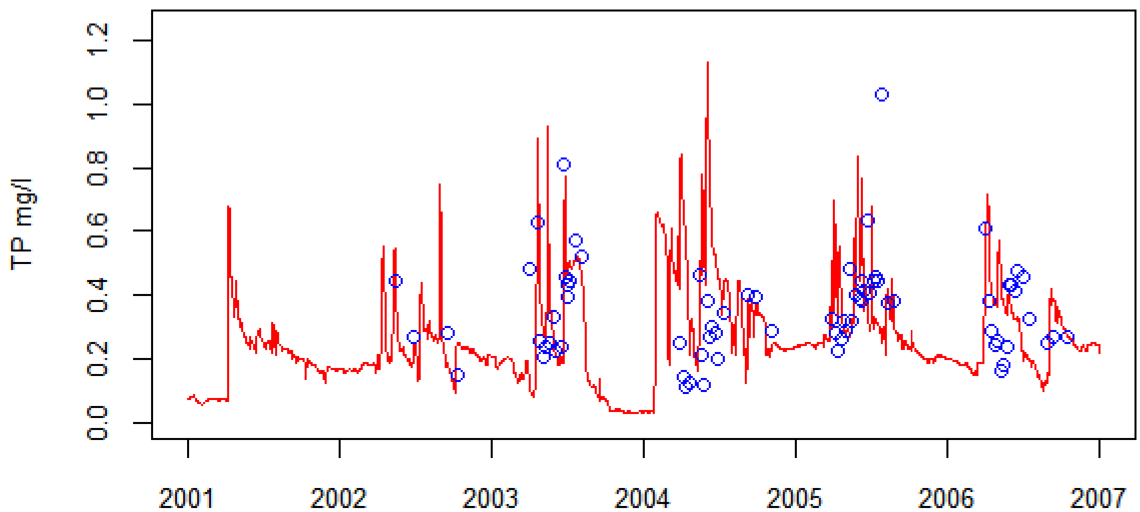


Figure 26. Simulated vs. observed daily TP concentrations for Bois de Sioux

4.3.2.4 Dissolved Oxygen

Dissolved oxygen was only evaluated graphically due to the lack of grab sample data. However, graphical agreement can be judged to be *good* to *very good* at both Mustinka and Bois de Sioux sites. See Figure 27 and Figure 28. Updates to the model incorporating more recent periods (after 2006) would enable the model to be calibrated/validated at multiple upstream impairment locations.

Despite similar observed DO ranges at the three calibration stations and identical initial HSPF parameterization, initial simulated results varied widely with the BdS needing little or no calibration, Mustinka somewhat over-predicting and Rabbit significantly over-predicting DO during the low DO summer months. DO was calibrated via adjustments to KBOD20 and REAK parameters (BOD decay O2 consumption rate and reaeration rate, respectively). Visual inspection indicates a reasonable DO calibration at all sites.

4.3.2.5 Biological Oxygen Demand

Calibrating BOD was problematic because of the dearth of observed data available at all three calibration sites. Initial parameter values for sediment potency and interflow/groundwater concentrations were set based on Tetra Tech, 2009. It was then assumed given the tight interdependence between BOD and most other biological and chemical processes that the reasonableness of the BOD calibration could be judged by the performance of the interdependent nutrient calibrations. Minor tweaks to the POTFW and interflow/groundwater concentration parameters were made to increase simulated organic N and P concentrations.

4.3.2.6 Phytoplankton

Phytoplankton densities were calibrated based on graphical comparison with Chl-A grab samples at Mustinka and Rabbit sites. A reasonable calibration was achieved through manipulation of the MALGR parameter in HSPF although performance evaluation was limited to 2001-2003. The Mustinka observed concentrations vary widely over the growing season; HSPF could not simulate this variability but efforts were made to achieve a representative mean concentration. Observed Rabbit concentrations varied less than those of the Mustinka and consequently calibration results were better.

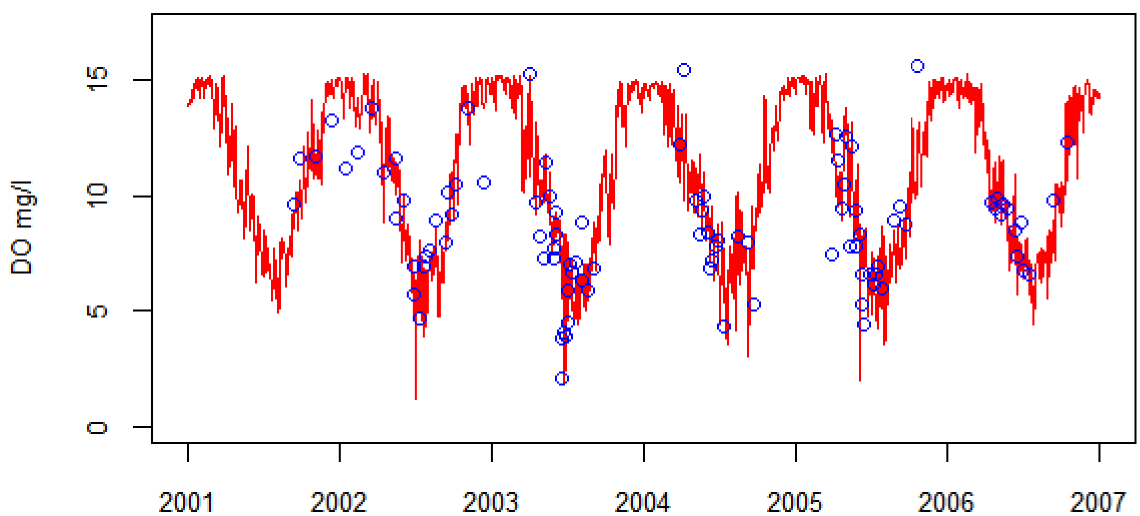


Figure 27. Simulated vs. observed daily DO concentrations for Mustinka

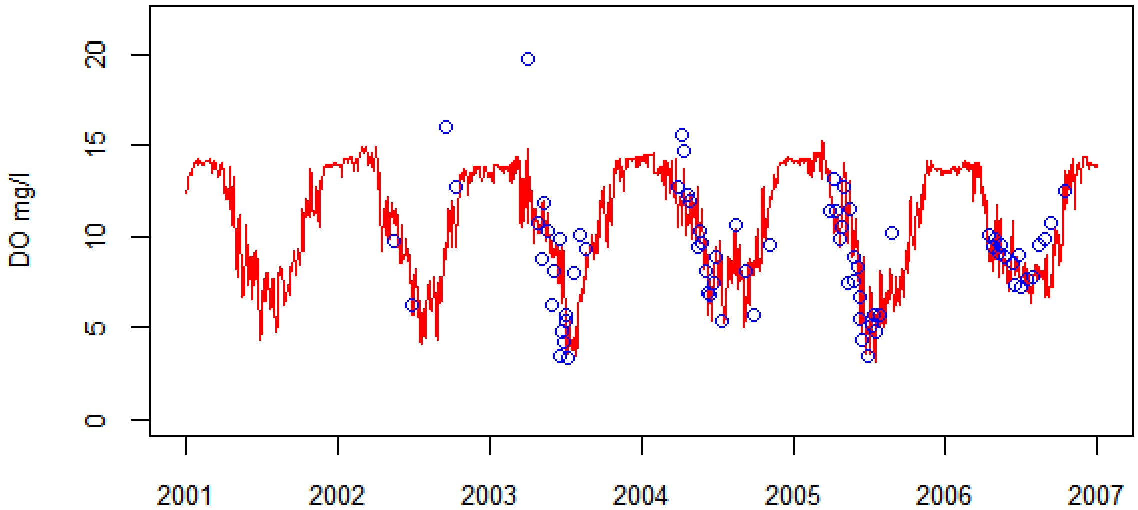


Figure 28. Simulated vs. observed daily DO concentrations for Bois de Sioux

5 MODEL UNCERTAINITIES AND TMDL SUPPORT SUITABILITY

The calibrated MBdS HSPF model, judged by the weight-of-evidence approach taken and discussed previously, can be considered a good representation of hydrologic and water quality processes and is able to support TMDL activities in the watersheds. However, sources of uncertainty -- if assessed objectively -- are significant in all watershed modeling projects of this scope, and these individual sources usually compound. Compounding begins with errors in observed flow measurements (usually relatively small) plus the error in hydrologic calibration. This combined error is passed on to the sediment calibration phase where it is compounded by large errors (measurement error and variability per flow regime) in sediment measurements plus the resulting calibration error. Finally, sediment-dependent constituents – most importantly, phosphorus – receive this cumulative error where observed measurement and calibration errors add yet again another layer of uncertainty.

Overall, the uncertainty in the MBdS model is driven primarily by the relatively short calibration period. The short period limits the number of WQ samples that can be used to generate representative flow and loading relationships with concentration. It also limits the number of discrete observed flow events available for calibration and thus limits the sample size and variability of boundary conditions that heavily influence flow and WQ response such as short- and long-term antecedent moisture condition, coincident agricultural management events and seasonal vegetative characteristics. Updates to the model that add more climate data as well as utilize the increase in sampling frequency and spatial distribution of WQ sampling that has occurred since the end of the modeling period (2006) would greatly enhance the certainty and utility of the model.

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