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TETRA TECH

Memorandum

To:	Chuck Regan, Tim Larson (MPCA)	**Date:**	11/3/2015
From:	J. Butcher, P.H.	**Subject:**	**Minnesota River Basin HSPF Model Hydrology Recalibration**

1 Introduction

The MPCA has been working for many years on development and refinement of HSPF models for the Minnesota River Basin (010200). In 2015, MPCA contracted with Tetra Tech to refine the hydrologic and sediment calibrations for the Basin.

This memorandum specifically documents the hydrology recalibration and validation of the Minnesota River Basin HSPF modeling system, including the following 8-digit Hydrologic Unit Code (HUC) watersheds:

- Chippewa (07020005)
- Redwood (07020006)
- Middle Minnesota (07020007)
- Cottonwood (07020008)
- Blue Earth (07020009)
- Watonwan (07020010)
- LeSueur (07020011)
- Lower Minnesota (07020012).

The Hawk-Yellow Medicine basin (07020004) is also a HUC 8 watershed within the Minnesota River Basin. RESPEC committed to and provided an update to MPCA of the Hawk-Yellow Medicine model. Tetra Tech provided input to RESPEC as part of this effort; however, the status of the revised Hawk-Yellow Medicine HSPF model is not documented in this memorandum.

2 Approach

The Minnesota River basin HSPF models have a long history. Models for six of the HUC8 basins were originally developed by MPCA and subsequently expanded and calibrated to include the entire basin from

Lac qui Parle to Jordan, MN by Tetra Tech in 2002. Tetra Tech (2008) subsequently refined these models for sediment simulation. These models were discretized at approximately the HUC10 scale. Tetra Tech later developed finer-resolution (HUC12-scale) models of the Chippewa and Hawk-Yellow Medicine HUC8 sub-models. MPCA then contracted with RESPEC to develop HUC12-scale models of the entire basin downstream of Lac qui Parle, as well as to extend the models in time through 2012. This effort was completed in 2014.

The initial review of the RESPEC models provided to MPCA by Tetra Tech suggested that hydrology was fit reasonably well; however, sediment source attribution did not match up well with the evidence available from cosmogenic radionuclide data (e.g., Schottler et al., 2010). Subsequent analysis revealed other aspects of the hydrologic calibration that potentially affect sediment calibration. Accordingly, MPCA requested review and revisions to the hydrologic calibration as part of the sediment recalibration effort.

2.1 Objectives for Recalibration

The RESPEC models provide an excellent starting point for the current hydrology revisions. Model performance was adjusted at all calibration gages in the watershed to meet the following objectives:

- **Achieve high values of the NSE while also minimizing standard measures of volumetric error** (percent error on total volume, 10% high flows, 50% low flows, seasonal flows, and storm flows) as recommended by MPCA's modeling guidance (AQUA TERRA, 2012). The existing calibration appears to be focused more on achieving high NSE, which indicates a situation in which the model tracks the variability in observations well. It is possible to achieve a relatively high NSE while also incurring high volumetric errors, which indicates an undesirable situation where the model is relatively precise, but biased.
- **Adjust the ET simulation to better represent the seasonal pattern in MODIS data.** Comparison of modeled evapotranspiration (ET) to MODIS satellite-estimated ET showed that the model was simulating the peak of ET in June, whereas the MODIS estimates peak in July-August. (See further discussion below in Section 4.2.)
- **Control water balance components.** The consensus of MPCA staff was that the models tended to under-estimate direct surface runoff, which is important to sediment simulation. In general, the surface runoff fraction should be greater than 4 percent of total flow and higher in the lacustrine soils of the LeSueur watershed. To ensure better representation of surface runoff, tile flow, and shallow groundwater discharges, the focus was on achieving a good match between simulated and observed baseflow fraction using the sliding windows method for baseflow separation (Sloto and Crouse, 1996). Because tile flow is simulated as a mix of interflow and groundwater discharge, the baseflow fraction is judged to be the best measure of water balance components.
- **Examine and attempt to fit gage records at smaller watersheds to the extent possible.** Calibration of the existing models focused on downstream gages at the outlet of HUC8 watersheds and especially on the Nash-Sutcliffe coefficient of model fit efficiency (NSE). Average volumetric errors on total flow, high and low flows, and seasonal flows were sometimes larger than desirable for gage records on smaller watersheds. Accordingly, the hydrologic calibration was adjusted to better represent these gage records. Several caveats are necessary here. Many of the gages on smaller records are seasonal gages operated by MDNR with limited field adjustments to rating curves. Some gages have very short periods of record as well. Therefore, it is important to consider the record length and be aware of potential problems in some gage records. A cautionary example is provided by the gages on the Rush River. The Rush River mainstem is formed from four approximately equal tributaries shortly upstream of the mouth (North Branch Rush River, Middle Branch Rush River, South Branch Rush River, and

Nicollet-Sibley Judicial Ditch 1A). There is a gage at the mouth of the Rush River, and each of the tributaries has been gaged for several years. It is clear, however, that the gaged flows reported at the mouth of the Rush River are substantially greater than the sum of the four upstream gages and the intervening drainage area is not sufficiently large to explain the discrepancy. There may be some longer-range groundwater pathways that discharge into the incised channel of the lower Rush River, but the discrepancy is also present at high flows. Examination of annual hydrologist's notes suggest that the gage records themselves are at issue here. The upstream gages are generally rated as fair to poor quality, but the largest issues appear to be associated with the gage at the mouth. The hydrologist notes for 2012 (available on HYDSTRA) state "This is not a stable site. This is a constantly changing sand channel and high flows are affected by backwater from [the Minnesota River] during high flows. Rating changes most years and all rating points are coded as poor. This is due to constantly changing sand channel for lower flows and backwater effects during higher flows." Obviously, the model calibration cannot fully resolve these data issues and the calibration must attempt to provide as good a fit as possible to the four gages, while accepting that significant unresolvable discrepancies will remain.

2.2 Performance Metrics

Hydrologic calibration is performed by comparing time-series of model results to gaged flows and other water balance measures. Key considerations in the hydrology calibration are the overall water balance, the high-flow to low-flow distribution, storm flows, seasonal variation in flows, and evapotranspiration.

The level of performance and overall quality of hydrologic calibration is evaluated in a weight of evidence approach that includes both visual comparisons and quantitative statistical measures. Given the inherent errors in input and observed data and the approximate nature of model formulations, absolute criteria for watershed model acceptance or rejection are not generally considered appropriate by most modeling professionals. And yet, most decision makers want definitive answers to the questions—"How accurate is the model?" and "Is the model good enough for this evaluation?" Consequently, the current state of the art for model evaluation is to express model results in terms of ranges that correspond to "very good", "good", "fair", or "poor" quality of simulation fit to observed behavior. These characterizations inform appropriate uses of the model: for example, where a model achieves a good to very good fit, decision-makers often have greater confidence in having the model assume a strong role in evaluating management options. Conversely, where a model achieves only a fair or poor fit, decision makers may assign a less prominent role for the model results in the overall weight-of-evidence evaluation of management options.

Quantitative measures of model performance will be constructed based on relative error and the Nash-Sutcliffe coefficient of model fit efficiency (NSE; Nash and Sutcliffe, 1970). Relative error is calculated as:

$$E_{rel} = \frac{\sum |O - P|}{\sum O} \cdot 100,$$

where E_{rel}= relative error in percent. The relative error is the ratio of the absolute mean error to the mean of the observations and is expressed as a percent. A relative error of zero is ideal. NSE is calculated (at both the daily and monthly time scale) as:

$$NSE = 1 - \frac{\sum(O-P)^2}{\sum(O-\bar{O})^2},$$

in which the overbar indicates the average.

Unlike relative error, NSE is a measure of the ability of the model to explain the variance in the observed data. Values may vary from -∞ to 1.0. A value of NSE = 1.0 indicates a perfect fit between modeled and observed data, while values equal to or less than 0 indicate the model's predictions of temporal variability in observed flows are no better than using the average of observed data. The accuracy of a model increases as the value approaches 1.0.

For HSPF, LSPC, and similar watershed models, a variety of performance targets have been documented in the literature, including Donigian et al. (1984), Lumb et al. (1994), Donigian (2000), and Moriasi et al. (2007). Based on these references and past experience, HSPF performance targets are summarized in Table 1.

Model performance is generally deemed fully acceptable where a performance evaluation of "good" or "very good" is attained. It is important to clarify that the tolerance ranges are intended to be applied to mean values, and that individual events or observations may show larger differences and still be acceptable (Donigian, 2000). Moriasi et al. (2007) suggest that achieving a relative error on total volume of 10 percent or better and an NSE of 0.75 or more on *monthly* flows constitutes a good modeling fit for watershed applications.

Table 1. Performance targets for HSPF/LSPC hydrologic simulation (magnitude of annual and seasonal Relative mean error (*RE)*; daily and monthly NSE)

Model Component	Very Good	Good	Fair	Poor
1. Error in total volume	≤ 5%	5 - 10%	10 - 15%	> 15%
2. Error in 50% lowest flow volumes	≤ 10%	10 - 15%	15 - 25%	> 25%
3. Error in 10% highest flow volumes	≤ 10%	10 - 15%	15 - 25%	> 25%
4. Error in storm volume	≤ 10%	10 - 15%	15 - 25%	> 25%
5. Winter volume error (JFM)	≤ 15%	15 - 30%	30 - 50%	> 50%
6. Spring volume error (AMJ)	≤ 15%	15 - 30%	30 - 50%	> 50%
7. Summer volume error (JAS)	≤ 15%	15 - 30%	30 - 50%	> 50%
8. Fall volume error (OND)	≤ 15%	15 - 30%	30 - 50%	> 50%
9. NSE on daily values	> 0.80	> 0.70	> 0.60	≤ 0.60
10. NSE on monthly values	> 0.85	> 0.75	> 0.65	≤ 0.65

Where model fit to observations is found to be less than "good" this can be due to deficiencies in the model, deficiencies in the gage record, or a combination of the two. Calibration typically assumes that gage records are "correct" and maximizes the fit of the model to those records. It is clear in some cases, however, that uncertainty in the gage record itself is a major contributor to poor predictability. This is most likely to be true for gages that have short periods of record, locations that are impacted by backwater effects, and sites with unstable channels at which rating curve adjustments have not been frequently revised.

2.3 Calibration and Validation/Corroboration

Traditional model validation is intended to provide a test of the robustness of calibrated parameters through application to a second time period. In watershed models, this is, in practice, usually an iterative process in which evaluation of model application to a validation period leads to further adjustments in the calibration. A second, and perhaps more useful constraint, on model specification and performance is provided by the multi-objective approach described above in which the model is tested at multiple gages on the stream network in relation to multiple measures relative to both flow and other components of the water balance. In particular, obtaining model fit to numerous gages at multiple spatial scales from individual headwater streams to downstream stations that integrate across the entire Minnesota River basin helps to ensure that the model calibration is robust.

The overall model application period is 1/1/1995 – 12/31/2012. For gages with longer periods of record (primarily the HUC8 scale gages), this extended time period was segmented into calibration and validation periods, which are from 1/1/2003 – 12/31/2012 and 1/1/1995 – 1/1/2002, respectively. Separate calibration and validation period results are provided electronically. This summary memorandum focuses on model statistics over the entire available gage record coincident with the model application period.

2.4 Components not Adjusted

The adjustments to the hydrologic calibration are conditional on several aspects of the RESPEC model development (RESPEC, 2014). Most importantly, the development and assignment of meteorological variables, including the calculation of potential evapotranspiration, is left intact and not adjusted. In some cases, the assignment of single gage records to broad areas can lead to bias in simulation of adjacent areas, as in the Shakopee Creek area of the Chippewa model where NEXRAD data shows a relatively strong precipitation gradient that is not captured by the meteorological stations selected by RESPEC. Point source discharges are also accepted as specified by RESPEC.

The RESPEC models use a degree-day method for the simulation of snow melt. In general, energy-balance methods of snow simulation are preferred (AQUA TERRA, 2012); however, energy-balance simulations of snow accumulation and melt are highly dependent on the accuracy and applicability of meteorological data to local conditions. We examined the LeSueur model in detail and determined that it did not appear to be feasible to attain any significant improvements in model performance through switching to an energy-balance method.

The RESPEC (2014) models were calibrated for snow through comparison of observed and simulated snowfall and snow depth at meteorological stations. These comparisons are of necessity approximate due to wind drift and other factors that influence snow at specific gage sites. The current recalibration did not introduce any significant changes into the snow simulation. Therefore, we checked and confirmed that the snow simulation provided results similar to those reported by RESPEC, but did not redo a detailed statistical evaluation of observed versus simulated snow depth. Figure 1 shows a typical plot for snow depth, comparable to Figure 3 in RESPEC (2014).

Hydraulic functional tables (FTables) are not altered from the RESPEC models. Lake simulation is also as set up by RESPEC. Hydrologic balance for lakes is determined by the interaction of the overall water balance (total flow volume and evaporative losses) with lake FTables. As the FTables are unaltered and the total flow volumes are well simulated, detailed recalibration analyses for lakes is also not presented here.

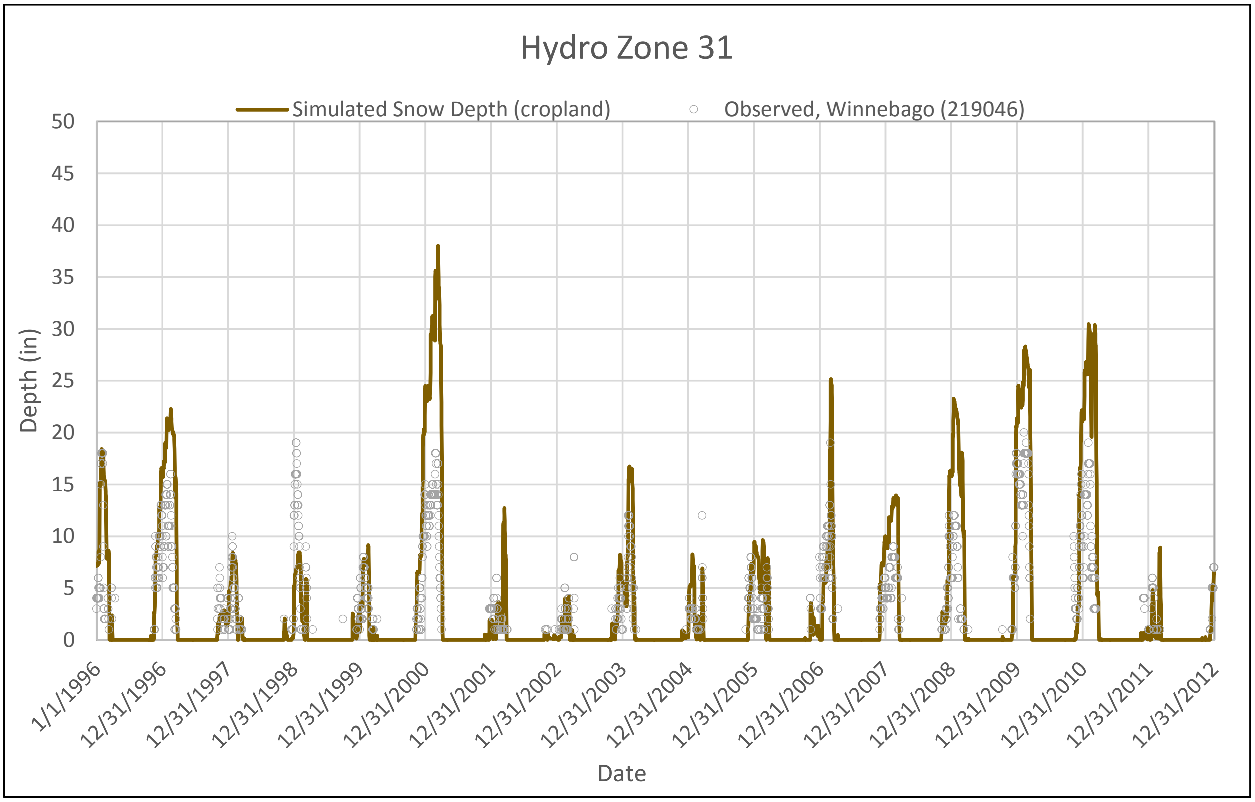

Figure 1. Observed and Simulated Snow Depth at Winnebago, MN

3 Calibration Gage Sites

A total of 57 stream gage stations were used for the Minnesota River Basin HSPF model hydrology recalibration. At least three gage sites were included for each HUC8.

The sites fall into three categories with different levels of importance for calibration. These are, in order of importance:

1. Gages with long-term, continuous flow records. These are primarily USGS gages and include the gages at the mouth of HUC8s and on the Minnesota River mainstem. Most of these gages have rating curves that are regularly updated using standard protocols; however, winter ice period records are often estimated and of poorer quality.

2. Seasonal gages with longer term records. Many of these gages are operated by MDNR and records are maintained for the non-winter period only. Spring gaging often starts in the middle of snowmelt, and small differences in timing of snowmelt between the gage and model may bias estimates of flow volume. Quality of records may vary due to the stability of the stream channel, the frequency at which adjustments to rating curves are made based on field observations, and other factors.

3. Gages with short-term, seasonal flow records are of lesser importance. Not only are these gages potentially subject to uncertainties associated with seasonal operation and potentially poor rating curves, but short periods of record are also prone to yield misleading statistics due to one or a few anomalous rainfall events that are not captured in the meteorological series.

The three categories of stream gages used in calibration are presented in Tables 2 through 4.

Table 2. Hydrology Calibration Gage Sites with Long-term, Continuous Flow Records

Site	HUC8	HYDSTRA ID	STORET ID	USGS ID	Calibration Start Date	Calibration End Date
Chippewa River near Milan, MN	07020005	26057001	S002-203	05304500	1/1/1996	12/31/2012
Redwood River near Marshall, MN	07020006	27043002	--	05315000	1/1/1996	12/31/2012
Redwood River near Redwood Falls, MN	07020006	27035001	S001-679	05316500	1/1/1996	12/31/2012
Minnesota River at Morton, MN	07020007	28012001	S000-145	05316580	10/1/2000	12/31/2012
Little Cottonwood River near Courtland, MN	07020007	28057001	S001-377	05317200	1/1/1996	6/8/2010
Minnesota River at Mankato, MN	07020007	28042001	--	05325000	1/1/1996	12/31/2012
Cottonwood River near New Ulm, MN	07020008	29001001	S001-918	05317000	1/1/1996	12/31/2012
Blue Earth River near Rapidan, MN	07020009	30092001	S001-231	05320000	1/1/1996	12/31/2012
Watonwan River near Garden City, MN	07020010	31051001	S000-163	05319500	1/1/1996	12/31/2012
Little Cobb River near Beauford, MN	07020011	32069001	S003-574	05320270	4/1/1996	10/15/2012
LeSueur River near Rapidan	07020011	32077001	S000-340	05320500	1/1/1996	12/31/2012
High Island Creek near Henderson, CSAH6	07020012	33091001	S000-676	05327000	1/1/1996	12/4/2012
Minnesota River near Jordan, MN	07020012	33145001	S000-039	05330000	1/1/1996	12/31/2012
Minnesota River at Fort Snelling State Park, MN	07020012	33143004	--	05330920	1/21/2004	12/31/2012

Table 3. Hydrology Calibration Gage Sites with Long-term, Seasonal Flow Records

Site	HUC 8	HYDSTRA ID	STORET ID	USGS ID	Calibration Start Date	Calibration End Date
Chippewa River at Cyrus	07020005	26003001	S002-190	05301930	3/25/2003	12/31/2012
Chippewa River at Benson, MN	07020005	26037001	--	05303500	6/26/1998	11/11/2012
Shakopee Creek near Benson	07020005	26038001	S002-201	--	3/19/2004	10/7/2012
Dry Weather Creek near Watson	07020005	26078001	S002-204	05304800	3/30/2004	10/7/2012
East Branch Chippewa River near Benson	07020005	26088001	S002-196	05303470	3/28/2003	10/7/2012
Redwood River at Russell CR15	07020006	27043001	S000-696	05314973	10/1/1998	12/31/2012
Threemile Creek near Green Valley, CR 67	07020006	27039001	S002-313	--	4/9/2004	10/2/2012
Clear Creek near Seaforth, CR56	07020006	27030001	S002-311	--	4/8/2004	10/2/2012
Nicollet CD46A near North Star, CSAH13	07020007	28066001	S002-936	--	4/3/2002	7/14/2012
Seven Mile Creek near North Star	07020007	28063001	S002-937	--	4/3/2002	12/17/2012
Nicollet CD13A near North Star, MN99	07020007	28062001	S002-934	--	4/2/2002	7/11/2012
Cottonwood River near Lamberton, US14	07020008	29062002	S002-247	--	6/15/1998	11/23/2012
Cottonwood River near Springfield, CR2	07020008	29015001	--	05316950	10/1/1999	11/12/2012
Cottonwood River near Leavenworth CR8	07020008	29022001	S001-920	05316970	4/15/2004	10/8/2012
Sleepy Eye Creek near Cobden, CR8	07020008	29011001	S001-919	05316992	3/19/2004	10/8/2012
Center Creek near Huntley, CR1	07020009	30028001	S003-024	--	4/1/2004	10/1/2008
Elm Creek near Huntley, CR159	07020009	30051001	S003-025	--	4/1/2004	10/1/2008
Maple River near Rapidan, CR35	07020011	32072001	S002-427	05320408	4/24/2003	10/16/2012
Little Beauford Ditch near Beauford, MN22	07020011	32073001	S001-210	--	3/21/1996	11/30/2007
High Island Creek near Arlington, CR9	07020012	33075001	S001-891	05326700	4/9/2001	9/27/2012
Buffalo Creek near Jessenland, 270th St.	07020012	33092001	S001-807	05326900	4/9/2001	9/30/2012
Rush River near Henderson, MN93	07020012	33096001	S000-822	05326400	3/15/2003	9/30/2012

Table 4. Hydrology Calibration Gage Sites with Short-term, Seasonal Flow Records

Site	HUC 8	HYDSTRA ID	STORET ID	USGS ID	Calibration Start Date	Calibration End Date
Minnesota River at Judson, CSAH42	07020007	28054001	S001-759	05317500	1/1/2008	12/31/2012
Crow Creek near Morton, Noble Ave	07020007	28098001	S005-628	--	4/2/2009	10/25/2010
Wabasha Creek near Franklin, CSAH11	07020007	28102001	S005-627	--	4/2/2009	10/25/2010
North Eden Creek near Franklin, CSAH10	07020007	28095001	S005-626	--	4/2/2009	10/25/2010
Nicollet CD24 near North Star, Timber Ln	07020007	28063002	S002-464	--	3/31/2006	11/1/2009
Plum Creek near Walnut Grove, CSAH10	07020008	29048001	S001-913	--	4/2/2005	10/27/2009
North Fork Watonwan River near Sveadahl, MN	07020010	31030001	--	--	4/1/2000	11/6/2002
Watonwan River near La Salle, CSAH16	07020010	31040001	S002-253	--	4/1/2000	9/30/2002
Watonwan River near La Salle, CSAH3	07020010	31028001	S002-254	--	4/1/2000	11/7/2002
South Fork Watonwan River near Madelia, CSAH13	07020010	31021001	S002-251	--	4/1/2000	11/7/2002
Maple River near Sterling Center, CR18	07020011	32062001	S004-101	05320450	3/30/2006	10/16/2012
Big Cobb River near Beauford, CR16	07020011	32071001	S003-446	05320330	3/29/2006	10/2/2012
LeSueur River at St. Clair, CSAH28	07020011	32079001	S003-448	--	3/26/2007	10/2/2012
LeSueur River near Rapidan, CR8	07020011	32076001	S003-860	--	3/29/2006	10/2/2012
High Island Creek near Fernando, CSAH7	07020012	33010001	S001-629	--	4/9/2001	7/15/2002
High Island Creek near New Auburn, CSAH13	07020012	33003001	S001-626	--	4/9/2001	7/15/2002
Buffalo Creek (County Ditch 59) near New Rome, CSAH17	07020012	33092002	S002-306	--	4/9/2001	7/15/2002
North Branch Rush River near New Rome, CSAH9	07020012	33071001	S002-930	--	3/15/2003	10/26/2005
Middle Branch Rush River near New Sweden, CR63	07020012	33069001	S002-931	--	3/20/2003	10/26/2005
South Branch Rush River near Norseland, CR63	07020012	33065001	S002-932	05326189	4/30/2003	10/7/2008
Nicollet Sibley JD1A near Norseland, CSAH3	07020012	33068001	S002-933	05326205	3/15/2003	10/26/2005

4 Model Updates

4.1 Modifications to Land Use Representation

Several adjustments were made to the representation of land use developed by RESPEC (2014) at the request of MPCA. Most significantly, the categories for conventional and conservation tillage cropland were split according to hydrologic soil group using SSURGO soil coverages (using the drained designation for dual classification soils). This is important to identify marginal crop areas that may contribute disproportionately large amounts of runoff and solids. Two groups were used: A+B and C+D soils. Conservation and conventional tillage area totals by subbasin were preserved in this splitting process.

MPCA also requested separate representation of lands receiving manure applications. The RESPEC models contain a placeholder for this category, but no area is assigned. This modification has not been accomplished as MPCA is still debating the best means of calculation of this area. Effects on hydrology are expected to be small.

The RESPEC models specify bluffs and major ravines as separate pervious land areas, but did not do this for the Chippewa and Hawk-Yellow Medicine models where the land cover was originally developed by Tetra Tech. Bluff areas were added to these models based on the bluff coverage provided by MPCA. Full coverage of ravine areas is not yet available.

4.2 Evapotranspiration

Evapotranspiration is the sum of evaporation from soil, water, and leaf surfaces and transpiration of soil water by plants. Actual evapotranspiration predicted by the RESPEC models tended to peak in June with a fall-off over the remainder of the summer.

Data gathered by remote sensing technology can be used to check and improve the representation of evapotranspiration in watershed models. Evapotranspiration data is calculated from remote sensing data collected by the Moderate Resolution Imaging Spectroradiometer (MODIS) aboard NASA’s Terra and Aqua satellites. Monthly evapotranspiration data was extracted from the global MOD16 dataset at a resolution of 1 km^2 for the Minnesota River Basin to identify seasonal evapotranspiration patterns.

It is important to recognize that MODIS does not directly measure evapotranspiration. Rather, an algorithm that considers MODIS land cover, albedo, leaf area index, and enhanced vegetation index is combined with daily meteorological data from NASA’s Global Modeling and Assimilation Office reanalysis datasets using a Penman-Monteith type of approach (Mu et al., 2011). A validation study (Velpuri et al., 2013) showed that MODIS was able to estimate monthly ET within about 25 percent based on comparison to FLUXNET studies. For Köppen climatic zone Dfb (which includes the Minnesota Corn Belt) MODIS was shown to have a positive bias during warmer months with an overall root mean squared error of 31 mm/mo. Nonetheless, it is anticipated that MODIS should correctly identify the annual peak ET pattern.

Seasonal patterns of actual ET simulated by HSPF depend on both the calculated PET and the assignment of monthly lower zone evapotranspiration parameters (MON-LZETPARM). We conducted experiments with the LeSueur model and found that modification to the seasonal pattern of this parameter can successfully move the simulated ET peak to July and maintain a good match to MODIS estimates of ET through the fall, as shown for example from the Middle Minnesota basin in Figure 2. It was not possible, however, to maintain a complete match over the early summer without throwing off the summer low flow simulation. Essentially, MODIS predicts a slower ramp up of summer ET than is necessary to predict summer flows. This may be because the MODIS algorithm relies on leaf area whereas a significant portion of the total evaporation during early periods of crop growth may come directly from the soil surface. Simulated evaporation in winter is less than predicted by MODIS, in part because the degree-day approach to snow simulation does not allow for direct sublimation of snow. However, it also appears likely that MODIS over-estimates winter evaporation in this climate zone.

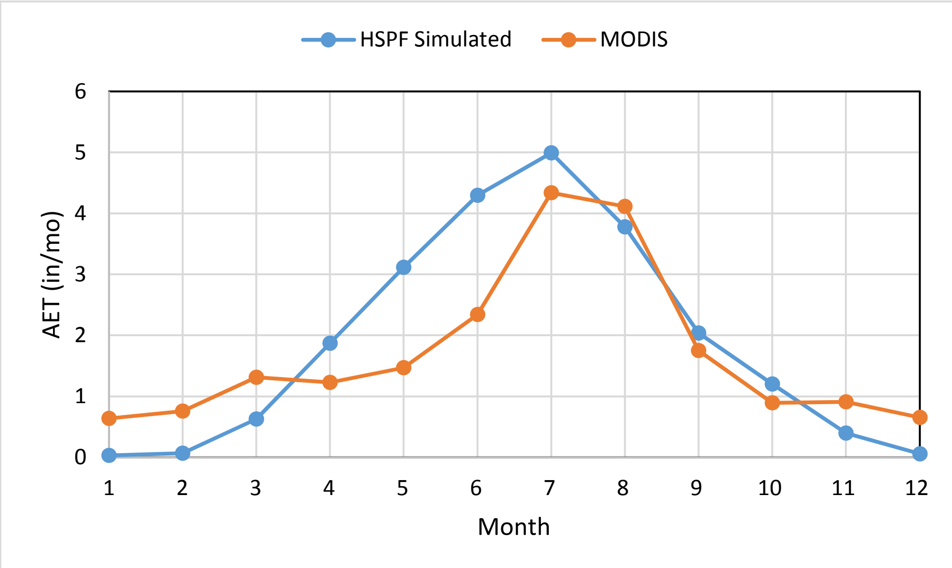

Figure 2. Comparison of MODIS ET and Revised HSPF Actual ET for the Middle Minnesota River Basin Model

MODIS was also used as a guide to shape the monthly ET pattern of individual land cover types. The evapotranspiration patterns were applied to update the monthly variable lower zone evapotranspiration parameter for all of the HUC 8 watersheds discussed in this memorandum. The remote sensing-based lower zone evapotranspiration parameter values for the Cottonwood watershed are provided as an example in Table 5.

Table 5. Monthly Values of the Lower Zone Evapotranspiration Parameter (MON-LZETPARM) for the Cottonwood Watershed

Land Use/ Land Cover	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
Urban	0.1	0.1	0.1	0.2	0.6	0.57	0.64	0.7	0.64	0.51	0.33	0.1
Forest	0.1	0.1	0.1	0.2	0.6	0.69	0.74	0.74	0.71	0.57	0.33	0.1
Cropland	0.1	0.1	0.1	0.1	0.05	0.15	0.45	1.05	0.85	0.4	0.15	0.1
Grassland	0.1	0.1	0.1	0.2	0.6	0.57	0.75	0.7	0.64	0.51	0.33	0.1
Pasture	0.1	0.1	0.1	0.2	0.6	0.57	0.75	0.7	0.64	0.51	0.33	0.1
Wetland	0.1	0.1	0.1	0.2	0.4	0.44	0.64	0.7	0.64	0.51	0.33	0.1
Feedlot	0.1	0.1	0.1	0.2	0.6	0.57	0.75	0.7	0.64	0.51	0.33	0.1
Bluff	0.1	0.1	0.1	0.2	0.6	0.69	0.74	0.74	0.71	0.57	0.33	0.1
Ravine	0.1	0.1	0.1	0.2	0.6	0.69	0.74	0.74	0.71	0.57	0.33	0.1

4.3 Interception

Interception of moisture by vegetation is another important contributor to total evapotranspiration and is generally determined by leaf area index. Vegetative cover patterns are also important to the estimation of surface erosion. As noted above, remote sensing data can be used to identify the seasonal pattern of vegetative cover in the watershed. MODIS surveys global vegetative cover at 16-day intervals and the data can be aggregated and downloaded at varied spatial scales. MODIS vegetative cover data was retrieved for the entire Minnesota River Basin. Seasonal vegetative cover patterns, which vary spatially across the Minnesota River Basin, were analyzed. The results from this analysis directed the selection of monthly variable interception parameters for all of the HUC 8s. The interception parameters assigned to the Cottonwood watershed are shown for example in Table 6.

Table 6. Monthly Values of the Vegetative Interception Parameter (MON-INTERCEP) for the Cottonwood Watershed

Land Use/ Land Cover	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sep.	Oct.	Nov.	Dec.
Urban	0.09	0.09	0.09	0.09	0.1	0.1	0.1	0.1	0.1	0.09	0.09	0.09
Forest	0.06	0.06	0.06	0.1	0.16	0.18	0.19	0.19	0.17	0.1	0.06	0.06
Cropland (Conservation Till)	0.03	0.03	0.03	0.06	0.07	0.12	0.15	0.13	0.14	0.08	0.05	0.04
Cropland (Conventional Till)	0.01	0.01	0.01	0.03	0.06	0.12	0.15	0.13	0.14	0.06	0.03	0.02
Grassland	0.06	0.06	0.07	0.08	0.12	0.13	0.15	0.13	0.13	0.08	0.07	0.07
Pasture	0.06	0.06	0.07	0.08	0.12	0.13	0.15	0.13	0.13	0.08	0.07	0.07
Wetland	0.04	0.04	0.04	0.04	0.05	0.08	0.12	0.14	0.15	0.11	0.07	0.05
Feedlot	0.02	0.02	0.03	0.04	0.05	0.1	0.07	0.09	0.09	0.06	0.04	0.03
Bluff	0.06	0.06	0.06	0.1	0.16	0.18	0.19	0.19	0.17	0.1	0.06	0.06
Ravine	0.06	0.06	0.06	0.1	0.16	0.18	0.19	0.19	0.17	0.1	0.06	0.06

4.4 Interflow Inflow

Under-prediction of surface runoff in the existing models occurred primarily because the vast majority of potential direct runoff was being diverted to interflow as a representation of tile drainage. Tile drainage is certainly a key aspect of the water balance in these basins, but was likely over-represented in some basins. The monthly interflow inflow parameter for agricultural lands ranged up to 8 in Watonwan and up to 7.5 in Cottonwood and Redwood, both much higher than the maximum value of 5.5 used for LeSueur, which is generally characterized as the basin with the greatest tiling density. Therefore, this parameter was scaled back in accordance with the analysis of tiling density done for the 2002 models, which was found to be generally consistent with specifications for field drainage rates, and set so that the values generally decline from LeSueur and Middle Minnesota basins to the Chippewa. For example, the revised maximum monthly interflow inflow parameter for Cottonwood is revised to be 4.0.

4.5 Additional Updates

Model goodness of fit was evaluated at each calibration gage following the implementation of the updated evapotranspiration, vegetative interception, and tile drainage parameters. Additional parameters were adjusted as necessary to improve the hydrologic simulation. The main processes that were modified during the hydrology recalibration include interflow and groundwater recession, infiltration rates, and nominal soil storage capacities in the upper and lower soil zones.

5 Results

5.1 Water Balance Components

As described above, the RESPEC models are believed to generally under-estimate the surface runoff component of flow. The updated models predict a slightly higher surface fraction of total flow, ranging from a high of about 12 percent in the lacustrine soils of the LeSueur watershed to a low of about 4 percent in the Chippewa when expressed as a weighted average across whole watersheds. Figure 3 compares the current results to those from RESPEC (2014) and earlier Tetra Tech (2008) models. The flow components for the revised simulation are summarized in Table 7 and shown graphically in Figure 4.

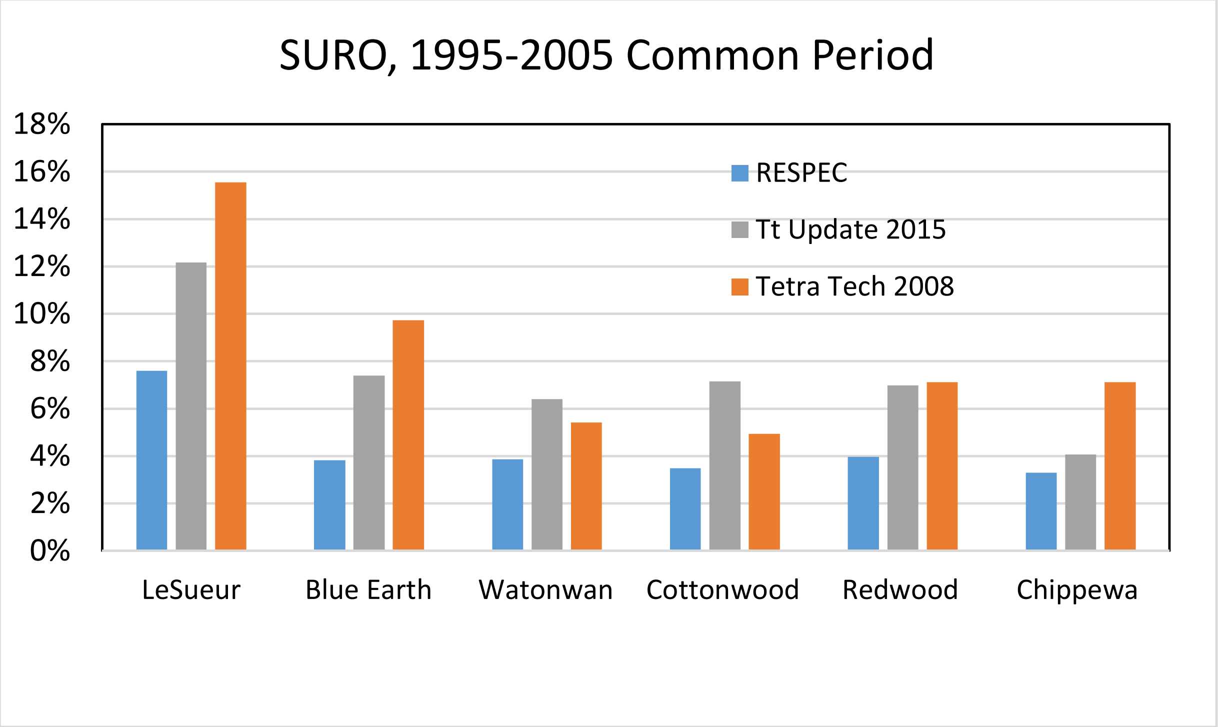

Figure 3. Surface Runoff (SURO) as an Area-Weighted Fraction of Total Flow; Current Recalibration Compared to RESPEC (2014) and Tetra Tech (2008) Results
Note: Results are shown for the period of 1995-2005 common to all three modeling efforts.

Table 7. Flow Components for Revised Models, 1995-2012

	LeSueur	Blue Earth	Watonwan	Cottonwood	Redwood	Chippewa
Surface	12.59%	7.45%	7.06%	7.76%	6.94%	4.31%
Interflow	40.61%	28.41%	26.08%	21.92%	16.61%	9.37%
Groundwater	46.81%	64.13%	66.86%	70.32%	76.45%	86.33%

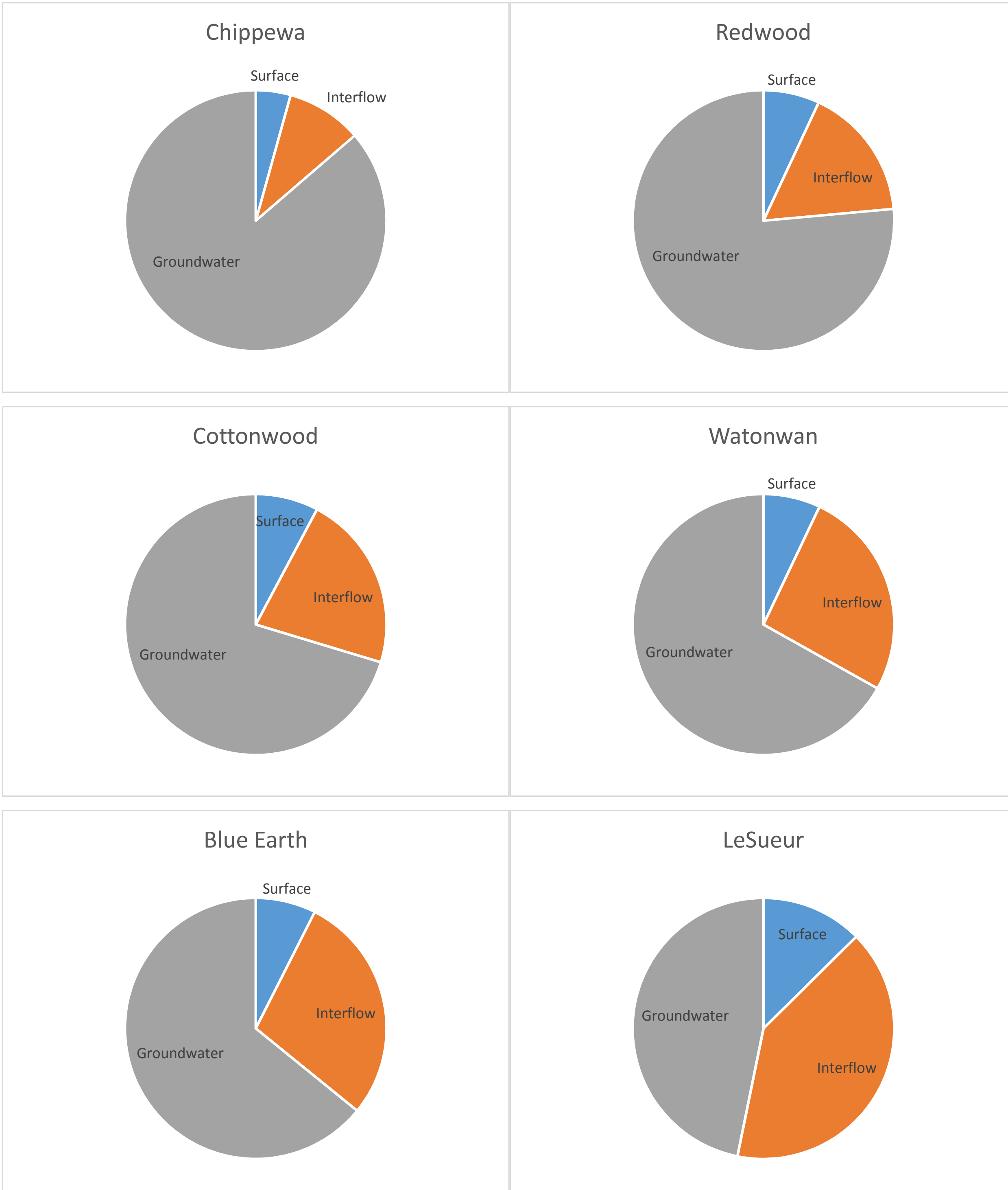

Figure 4. Water Balance Components, 1995-2012

5.2 Hydrologic Calibration

Separate calibration and validation tests were conducted for a number of stations with longer periods of record. These are summarized in electronic spreadsheets provided as a supplement to this memorandum. Final results are summarized in this section for the full period in which the gage data coincides with the model for each calibration site. Period-of-record calibration spreadsheets are also provided electronically.

Results are reported according to the three groups of gages (continuous gages with long periods of records, seasonal gages with long periods of record, and seasonal gages with short periods of record) in the next three sub-sections. A representative calibration site was selected for each group and graphical results are provided for those stations for example. Comprehensive graphics for each gage are provided in the electronic files.

The summary statistics include the annual, seasonal, and flow regime-based volumetric errors. Three versions of the NSE are reported: daily and monthly standard NSE (based on squared error) and Garrick's adjusted NSE, which is based on absolute errors and thus is more robust against the influence of outliers. Simulated and observed baseflow fractions are also compared as an indicator of the model's ability to reproduce flow components.

5.2.1 Gage Sites with Long-term, Continuous Flow Records

Table 8 (in two parts) shows the results for the highest priority gages. The quality of fit is generally in the good to very good range. Flows below the median appear to be under-estimated for Little Cottonwood River and over-estimated for High Island Creek – possibly due to estimated flow records in winter. For Minnesota River at Fort Snelling State Park the USGS summary states "discharges less than 2,000 cfs are poor", due to backwater from the Mississippi River. The baseflow fraction is matched within a few percent with the exception of the mainstem stations. For these, which integrate large upstream areas, the baseflow fraction is not a very direct indicator of the water balance, but instead is dominated by the specification of upstream boundary flows and the hydraulic response within the channel.

Graphical examples of the calibration for Minnesota River at Morton are provided in Figure 5 through Figure 11. Results for all other gages are contained in the electronic files.

Table 8. Summary Statistics for Gage Sites with Long-term, Continuous Flow Records

	Chippewa River near Milan, MN	Redwood River near Marshall, MN	Redwood River near Redwood Falls, MN	Minnesota River at Morton, MN	Little Cottonwood River near Courtland, MN	Minnesota River at Mankato, MN	Cottonwood River near New Ulm, MN
HYDSTRA ID	26057001	27043002	27035001	28012001	28057001	28042001	29001001
USGS ID	05304500	05315000	05316500	05316580	05317200	05325000	05317000
Error in total volume (%):	0.40	-4.19	1.75	0.86	-8.55	-2.10	-4.15
Error in 50% lowest flows (%):	-9.86	-8.45	9.63	1.43	-25.29	-0.71	7.77
Error in 10% highest flows (%):	6.01	-5.96	-0.89	4.94	-4.15	-2.00	-7.76
Seasonal error – Summer (%):	4.80	-4.24	-3.35	-6.80	10.35	-2.15	0.30
Seasonal error – Fall (%):	-7.20	-11.97	-3.06	1.98	-20.23	-7.86	-9.47
Seasonal error – Winter (%):	-17.92	-9.42	6.83	11.19	-19.02	2.29	-10.91
Seasonal error – Spring (%):	5.83	-1.07	2.30	-0.03	-6.54	-2.12	-2.08
Error in storm volumes (%):	12.98	-2.61	2.97	24.66	-7.31	11.58	-7.64
Error in summer storm volumes (%):	12.75	-8.20	-7.39	19.59	11.68	3.22	-26.31
Nash-Sutcliffe Coefficient of Efficiency, E:	0.805	0.772	0.789	0.907	0.694	0.920	0.815
Baseline adjusted coefficient (Garrick), E':	0.627	0.627	0.622	0.785	0.636	0.772	0.659
Monthly NSE	0.901	0.876	0.860	0.960	0.895	0.953	0.888
Observed Baseflow Fraction	77.57%	71.6%	72.4%	77.4%	79.3%	74.4%	64.0%
Simulated Baseflow Fraction	80.07%	71.1%	72.1%	72.0%	79.1%	70.8%	65.3%

Note: Summer = Jun, Jul, Aug; Fall = Oct, Nov, Dec, Winter = Jan, Feb, Mar; Spring = Apr, May Jun

(Table 8 continued)

	Blue Earth River near Rapidan, MN	Watonwan River near Garden City, MN	Little Cobb River near Beauford, MN	LeSueur River near Rapidan	High Island Creek near Henderson, CSAH6	Minnesota River near Jordan, MN	Minnesota River at Fort Snelling State Park, MN
HYDSTRA ID	30092001	31051001	32069001	32077001	33091001	33145001	33143004
USGS ID	05320000	05319500	05320270	05320500	05327000	05330000	05330920
Error in total volume (%):	-5.20	-9.38	-10.39	-5.95	-8.65	-4.32	-5.43
Error in 50% lowest flows (%):	6.82	9.88	11.98	-3.97	30.42	-8.67	-11.24
Error in 10% highest flows (%):	-3.47	-7.70	-8.48	-5.19	-9.73	-3.43	-3.80
Seasonal error – Summer (%):	4.49	-4.16	-10.24	-6.94	-21.85	-4.40	0.01
Seasonal error – Fall (%):	-20.74	-29.05	-34.09	-17.45	-19.38	-13.44	-16.39
Seasonal error – Winter (%):	-7.39	0.91	-9.40	0.05	-1.64	-2.40	-9.56
Seasonal error – Spring (%):	-3.96	-10.27	-4.23	-5.06	-5.03	-2.80	-2.31
Error in storm volumes (%):	-3.31	0.39	3.77	0.96	-6.54	9.21	9.18
Error in summer storm volumes (%):	-7.31	-6.38	-10.17	-9.96	-32.84	2.97	22.48
Nash-Sutcliffe Coefficient of Efficiency, E:	0.862	0.764	0.483	0.802	0.712	0.894	0.846
Baseline adjusted coefficient (Garrick), E':	0.701	0.619	0.530	0.667	0.652	0.743	0.700
Monthly NSE	0.924	0.882	0.808	0.895	0.879	0.941	0.908
Observed Baseflow Fraction	66.9%	69.4%	73.2%	58.8%	76.5%	75.6%	76.6%
Simulated Baseflow Fraction	66.2%	66.1%	69.0%	55.7%	75.9%	72.2%	73.0%

Note: Summer = Jun, Jul, Aug; Fall = Oct, Nov, Dec, Winter = Jan, Feb, Mar; Spring = Apr, May Jun

USGS 05316580 Minnesota River at Morton, MN

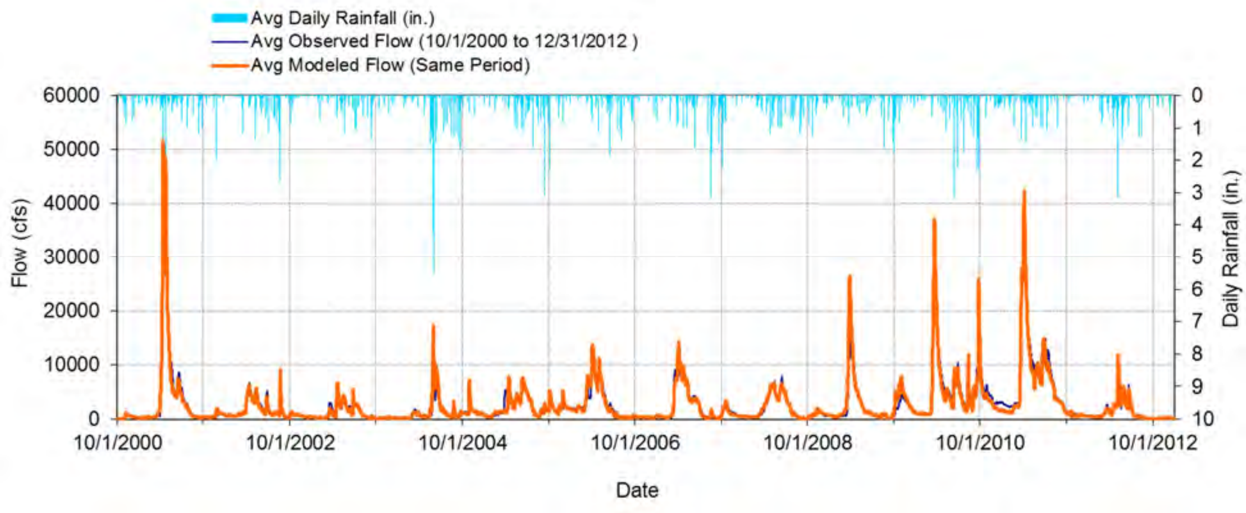

Figure 5. Mean daily flow at USGS 05316580 Minnesota River at Morton, MN

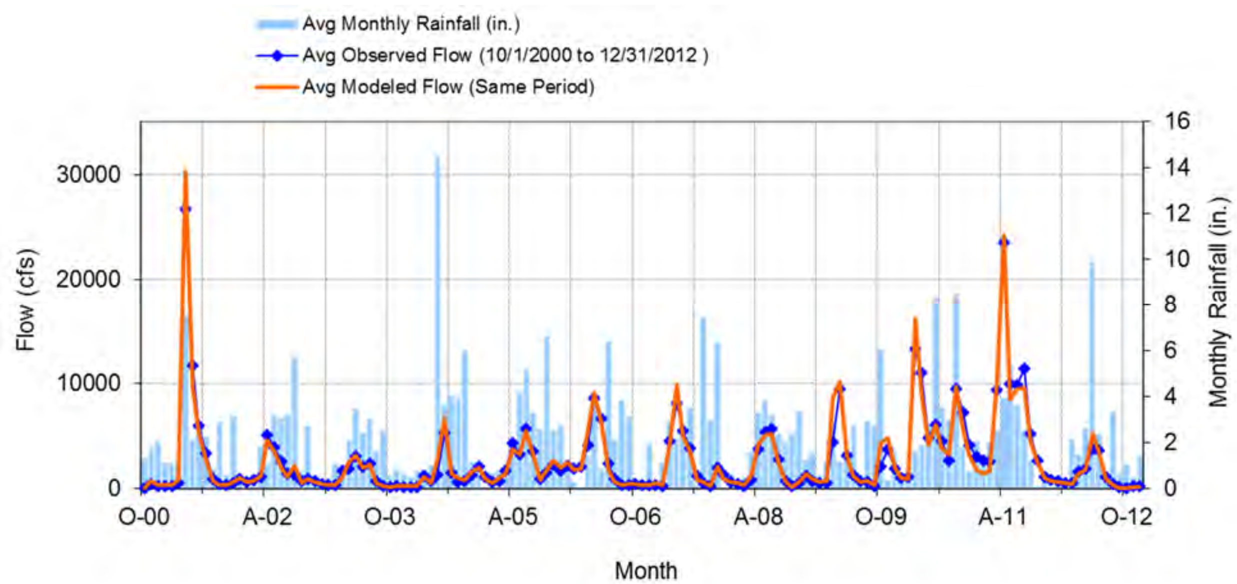

Figure 6. Mean monthly flow at USGS 05316580 Minnesota River at Morton, MN

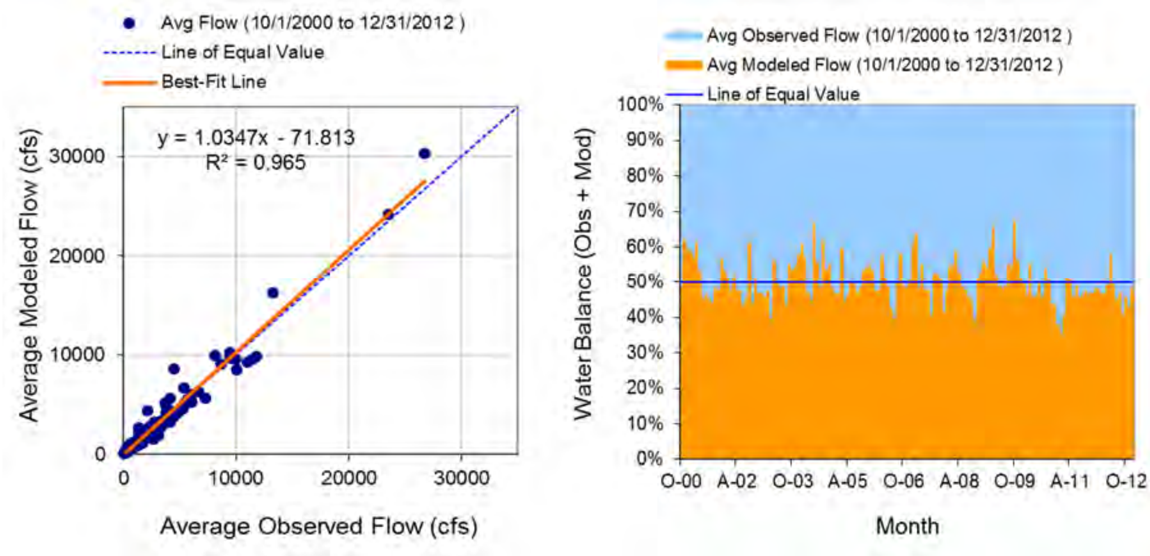

Figure 7. Monthly flow regression and temporal variation at USGS 05316580 Minnesota River at Morton, MN

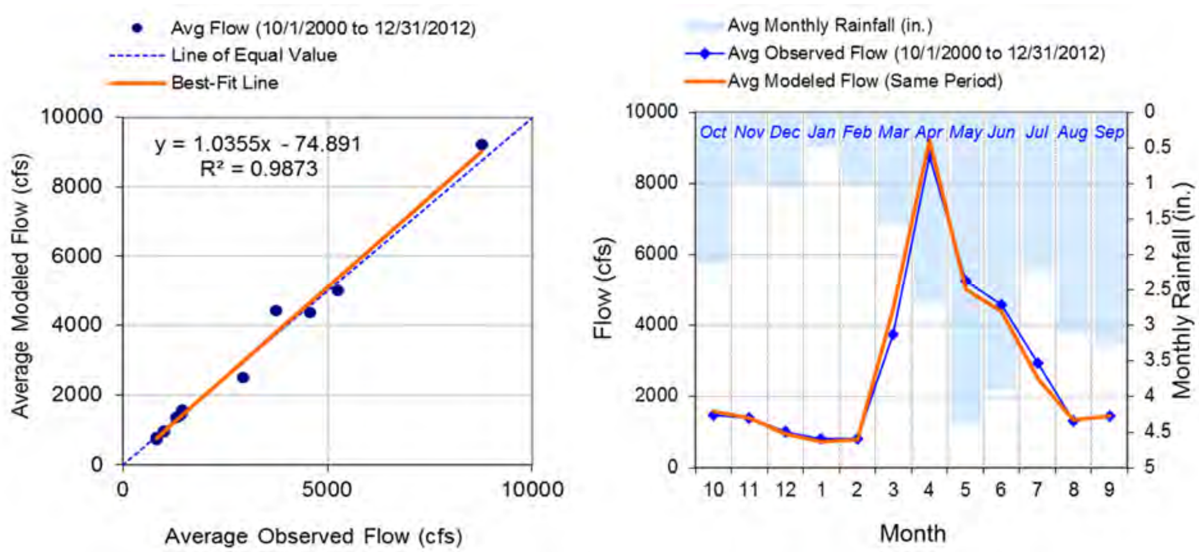

Figure 8. Seasonal regression and temporal aggregate at USGS 05316580 Minnesota River at Morton, MN

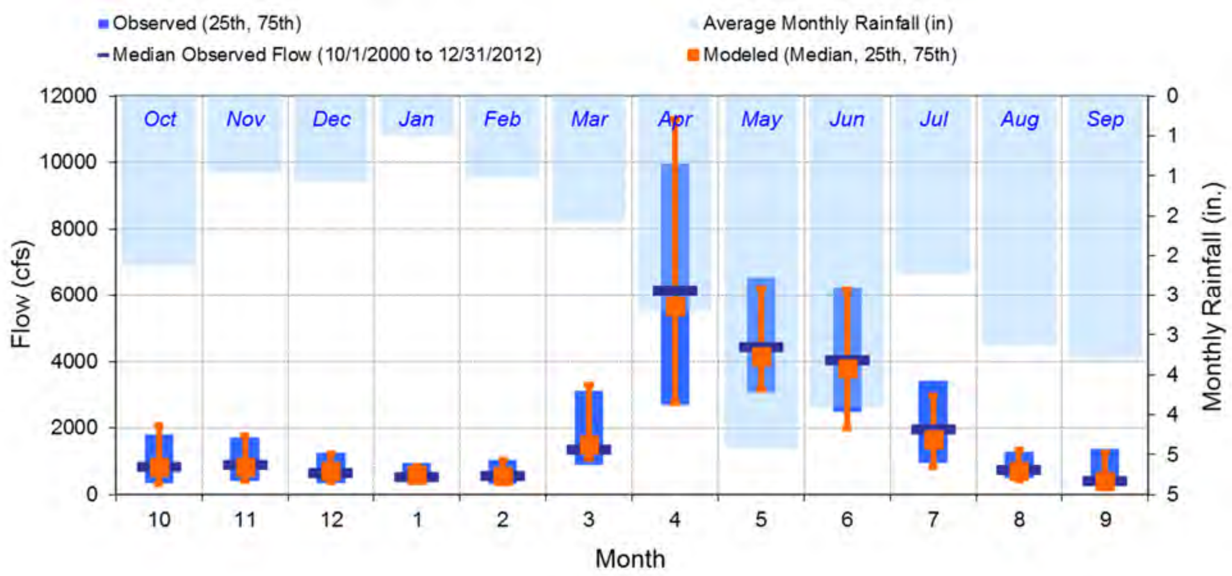

Figure 9. Seasonal medians and ranges at USGS 05316580 Minnesota River at Morton, MN

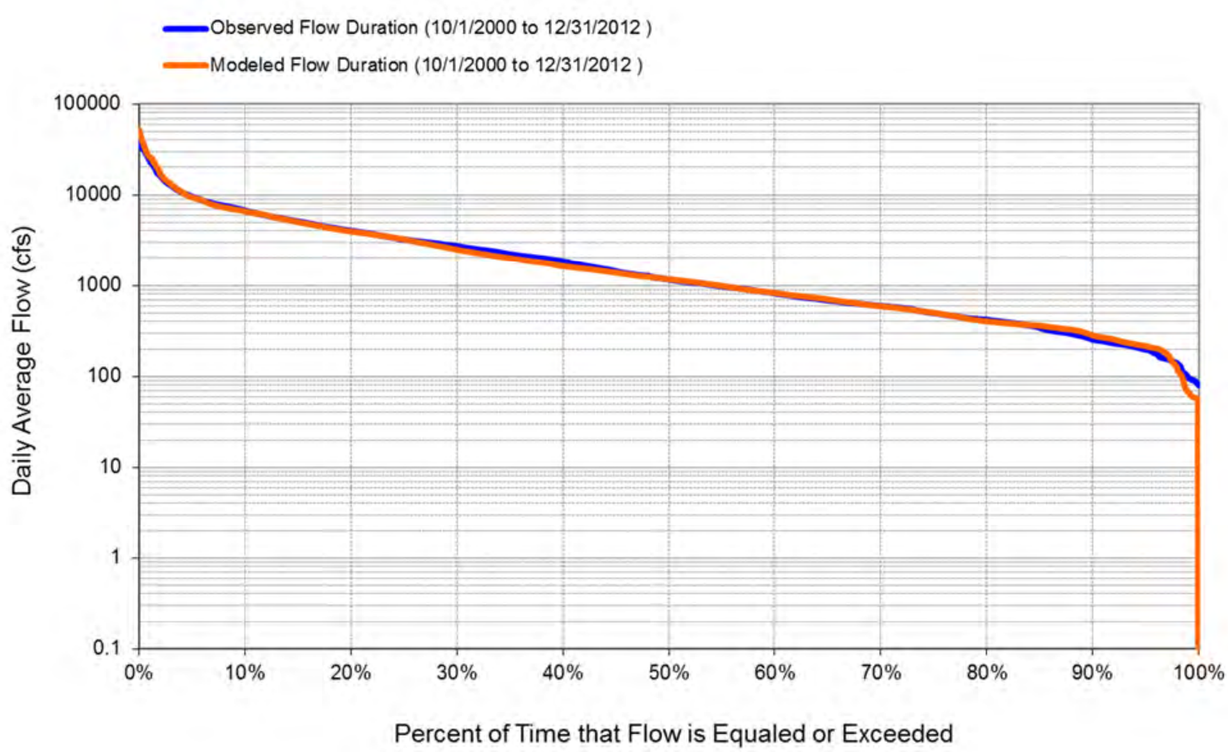

Figure 10. Flow Exceedance at USGS 05316580 Minnesota River at Morton, MN

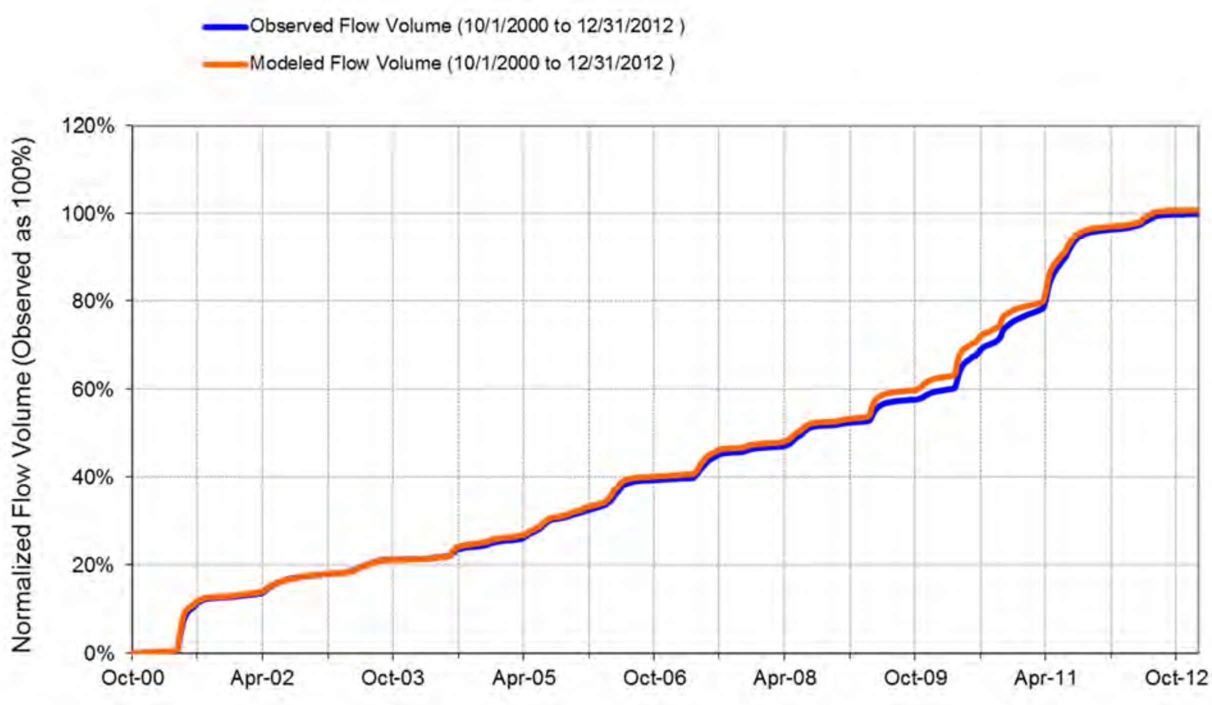

Figure 11. Flow accumulation at USGS 05316580 Minnesota River at Morton, MN

5.2.2 Gage Sites with Long-term, Seasonal Flow Records

The second tier of sites have long-term records, but do not report winter results. Many of these stream gages are operated by MDNR and several have generally poor quality results due to unstable, shifting channels that make calibration difficult. Seasonal statistics for fall (Oct.-Dec.) and winter (Jan.-Mar.) should be discounted as gaging generally stops in October and does not resume until late March. Summary results are provided in Table 9.

The upper Chippewa River gages at Cyrus and Benson were especially challenging, with negative NSE values despite efforts at calibration. Both these gages do not have a fixed control and the channel is noted as not stable with rating curves that are not well developed. Vegetation has an important effect on stage at Cyrus, which may explain the discrepancy between observed and simulated baseflow. Logger malfunctions are also noted, which may result in errors in storm volumes. Garrick's adjusted coefficient is much higher than the NSE, indicating that outliers have an important effect on statistics. Other gages with poor fit statistics also often have poor quality rating curves. Many of these are on smaller streams (e.g., Nicollet CD 13A), where vegetation in the channel has an important effect on flow estimates. Shifting sand also affects the upstream gages on the Cottonwood River. Challenges with the Rush River gages were discussed above in Section 2.

Detailed graphical results are provided, for example, for Cottonwood River near Leavenworth, a site where there is a relatively large volumetric error for 50 percent lowest flows, but a high NSE and a good match on baseflow fraction.

Table 9. Summary Statistics for Gage Sites with Long-term, Seasonal Flow Records

	Chippewa River at Cyrus	Chippewa River at Benson, MN	Shakopee Creek near Benson	Dry Weather Creek near Watson	East Branch Chippewa River near Benson	Redwood River at Russell CR15	Threemile Creek near Green Valley, CR67
HYDSTRA ID	26003001	26037001	26038001	26078001	26088001	27043001	27039001
USGS ID	05301930	05303500	NA	05304800	05303470	05314973	NA
Error in total volume (%):	-7.14	-10.95	-9.88	3.72	5.58	-5.99	5.56
Error in 50% lowest flows (%):	9.46	-17.48	9.33	5.06	17.13	7.54	28.31
Error in 10% highest flows (%):	-6.69	7.57	-14.12	-14.08	6.30	-10.01	-6.41
Seasonal error – Summer (%):	-11.47	-25.30	-20.43	-20.70	2.11	-10.96	-33.94
Seasonal error – Fall (%):	53.91	-23.73	0.45	49.18	23.29	-25.66	12.60
Seasonal error – Winter (%):	3.25	-25.61	-23.08	-41.57	-14.13	-35.70	-24.69
Seasonal error – Spring (%):	-10.45	3.81	-6.41	19.82	7.85	5.55	40.25
Error in storm volumes:	65.56	-0.62	-5.03	5.75	9.18	-5.85	4.77
Error in summer storm volumes:	58.02	-25.79	-21.97	-31.92	-16.64	-13.06	-46.98
Nash-Sutcliffe Coefficient of Efficiency, E:	-0.230	-0.295	0.730	0.610	0.618	0.714	0.533
Baseline adjusted coefficient (Garrick), E':	0.424	0.354	0.594	0.454	0.514	0.608	0.461
Monthly NSE	0.647	0.145	0.789	0.722	0.835	0.851	0.664
Observed Baseflow Fraction	81.87%	80.68%	76.80%	63.13%	82.63%	75.5%	67.3%
Simulated Baseflow Fraction	89.83%	82.69%	77.99%	63.84%	83.21%	75.5%	67.5%

Note: Summer = Jun, Jul, Aug; Fall = Oct, Nov, Dec, Winter = Jan, Feb, Mar; Spring = Apr, May Jun. Seasonal gages typically report only a few days at the beginning of October for Fall and a few days at the end of March for Spring, so statistics for these seasons should be discounted.

(Table 9 continued, part 2)

	Clear Creek near Seaforth, CR56	Nicollet CD46A near North Star, CSAH13	Seven Mile Creek near North Star	Nicollet CD13A near North Star, MN99	Cottonwood River near Lamberton, US14	Cottonwood River near Springfield, CR2	Cottonwood River near Leavenworth, CR8
HYDSTRA ID	27030001	28066001	28063001	28062001	29062002	29015001	29022001
USGS ID	NA	NA	NA	NA	NA	05316950	05316970
Error in total volume (%):	-9.86	-34.12	-16.69	19.46	-15.90	-0.39	-7.34
Error in 50% lowest flows (%):	8.16	-13.88	23.42	186.60	45.69	42.14	38.59
Error in 10% highest flows (%):	-9.39	-30.51	-30.36	3.53	-18.09	0.38	-11.42
Seasonal error – Summer (%):	-33.91	-42.36	-10.05	7.39	-7.12	-3.04	-9.67
Seasonal error – Fall (%):	-12.47	-70.10	-44.29	-22.36	-11.33	-6.10	-5.41
Seasonal error – Winter (%):	-18.48	-34.14	-45.06	49.59	-24.73	-18.48	-17.39
Seasonal error – Spring (%):	0.31	-29.59	-4.71	22.02	-17.03	5.22	-4.49
Error in storm volumes:	-11.54	-28.84	-21.33	3.37	-12.38	1.12	-8.86
Error in summer storm volumes:	-43.96	-45.88	-10.49	4.26	-29.23	-18.94	-27.66
Nash-Sutcliffe Coefficient of Efficiency, E:	0.623	0.336	0.552	0.560	0.719	0.752	0.839
Baseline adjusted coefficient (Garrick), E':	0.568	0.353	0.528	0.388	0.630	0.612	0.671
Monthly NSE	0.722	0.677	0.604	0.658	0.848	0.671	0.838
Observed Baseflow Fraction	66.2%	82.9%	66.9%	78.2%	66.6%	66.7%	68.4%
Simulated Baseflow Fraction	66.8%	81.5%	68.9%	81.5%	65.2%	66.2%	68.9%

Note: Summer = Jun, Jul, Aug; Fall = Oct, Nov, Dec, Winter = Jan, Feb, Mar; Spring = Apr, May Jun. Seasonal gages typically report only a few days at the beginning of October for Fall and a few days at the end of March for Spring, so statistics for these seasons should be discounted.

(Table 9 continued, part 3)

	Sleepy Eye Creek near Cobden, CR8	Center Creek near Huntley, CR1	Elm Creek near Huntley, CR159	Maple River near Rapidan, CR35	Little Beauford Ditch near Beauford, MN22	High Island Creek near Arlington, CR9	Buffalo Creek near Jessenland, 270th St.	Rush River near Henderson, MN93
HYDSTRA ID	29011001	30028001	30051001	32072001	32073001	33075001	33092001	33096001
USGS ID	05316992	NA	NA	05320408	NA	05326700	05326900	05326400
Error in total volume (%):	-8.41	-9.49	-6.37	-10.39	-13.95	-8.41	-11.17	-41.91
Error in 50% lowest flows (%):	58.93	8.92	37.62	-2.23	-53.23	25.48	4.36	18.32
Error in 10% highest flows (%):	-14.50	-7.82	-11.80	-10.32	-10.99	-3.09	-9.43	-52.38
Seasonal error – Summer (%):	-19.37	8.79	18.38	-13.00	-28.04	-28.13	-51.47	-58.54
Seasonal error – Fall (%):	-24.41	3.33	-27.03	-25.56	-28.34	-26.83	-40.00	-55.66
Seasonal error – Winter (%):	-23.83	-12.48	-46.80	-18.09	-10.28	-31.21	-29.55	-59.03
Seasonal error – Spring (%):	0.10	-16.42	-4.60	-3.82	-8.72	0.69	2.32	-32.06
Error in storm volumes (%):	-23.08	-2.27	1.81	-1.42	-17.52	12.73	-19.69	-42.26
Error in summer storm volumes (%):	-48.92	8.96	19.04	-14.09	-37.79	-36.26	-69.65	-70.11
Nash-Sutcliffe Coefficient of Efficiency, E:	0.757	0.840	0.803	0.771	0.066	0.560	0.638	0.413
Baseline adjusted coefficient (Garrick), E':	0.627	0.649	0.647	0.638	0.433	0.571	0.553	0.525
Monthly NSE	0.788	0.871	0.875	0.885	0.806	0.812	0.787	0.429
Observed Baseflow Fraction	60.3%	77.8%	72.4%	57.9%	60.0%	83.4%	68.8%	63.8%
Simulated Baseflow Fraction	66.6%	76.0%	69.9%	53.7%	61.6%	79.1%	71.4%	63.6%

Note: Summer = Jun, Jul, Aug; Fall = Oct, Nov, Dec, Winter = Jan, Feb, Mar; Spring = Apr, May Jun. Seasonal gages typically report only a few days at the beginning of October for Fall and a few days at the end of March for Spring, so statistics for these seasons should be discounted.

USGS 05316970 Cottonwood River near Leavenworth, CR8

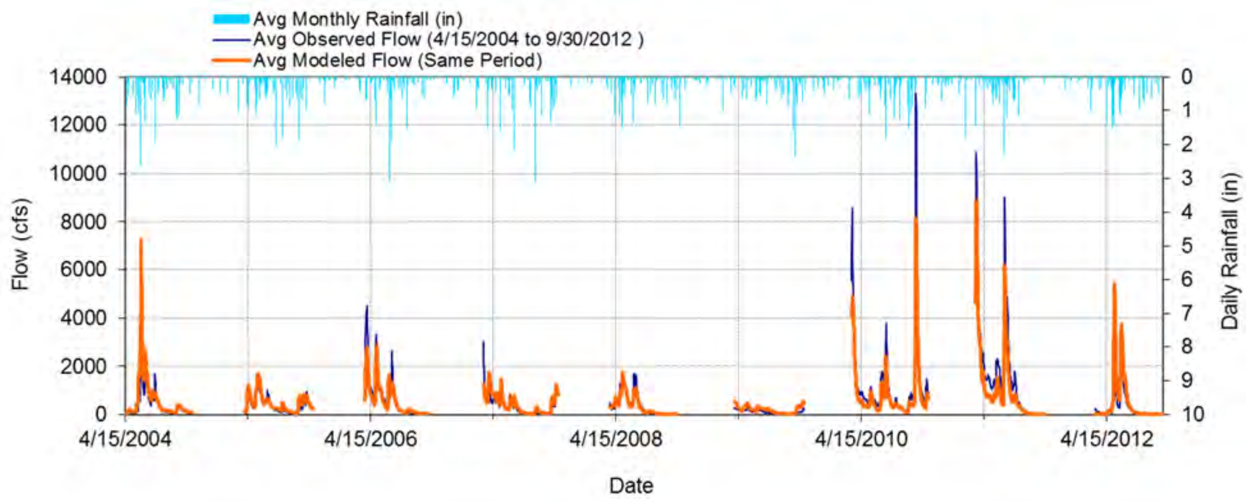

Figure 12. Mean daily flow at USGS 05316970 Cottonwood River near Leavenworth, CR8

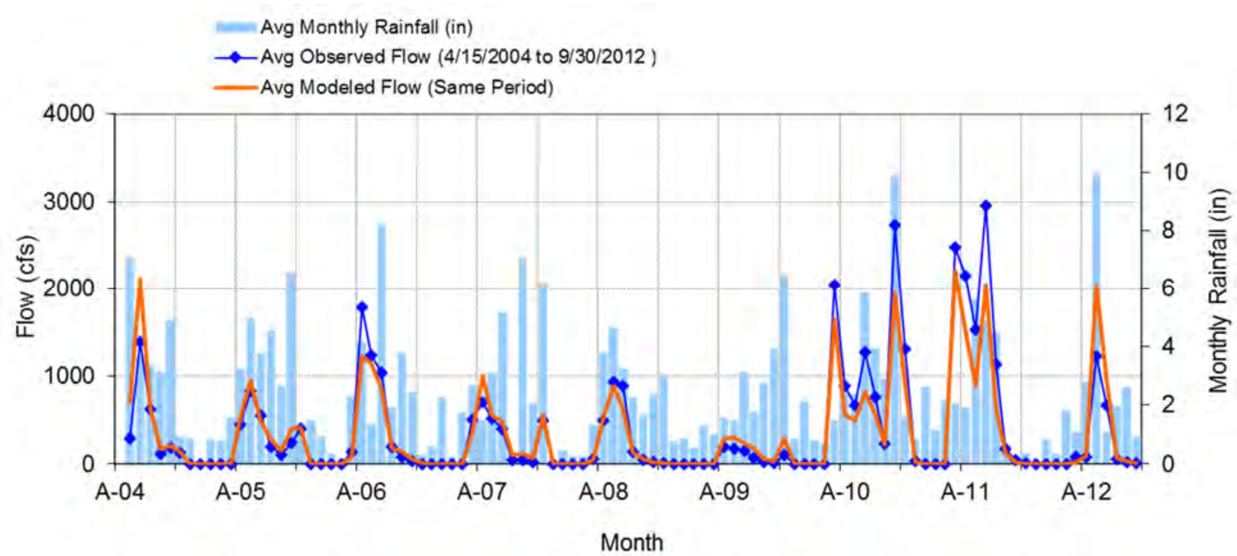

Figure 13. Mean monthly flow at USGS 05316970 Cottonwood River near Leavenworth, CR8

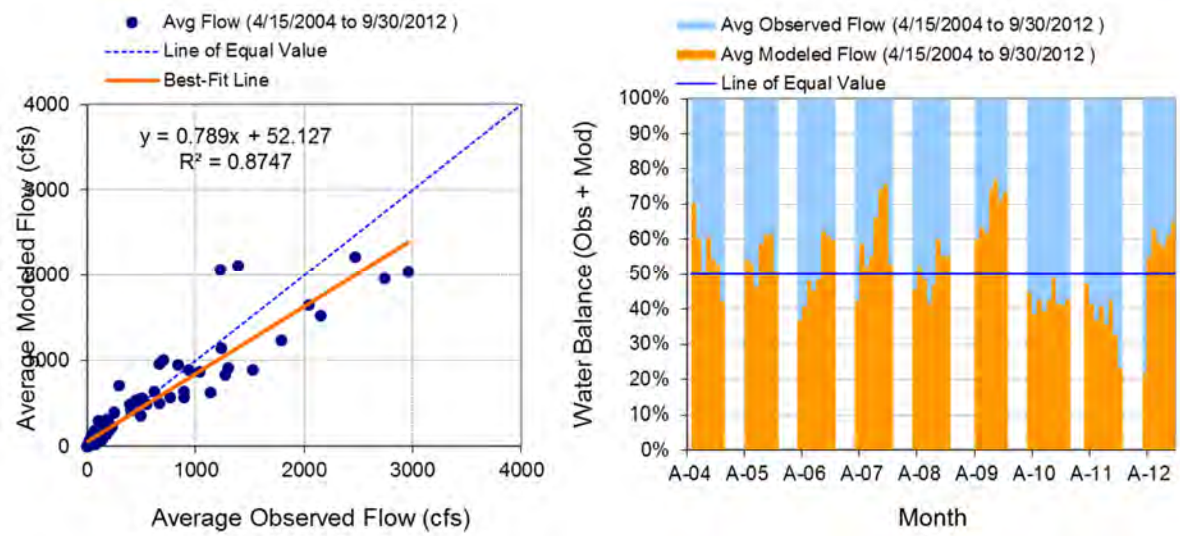

Figure 14. Monthly flow regression and temporal variation at USGS 05316970 Cottonwood River near Leavenworth, CR8

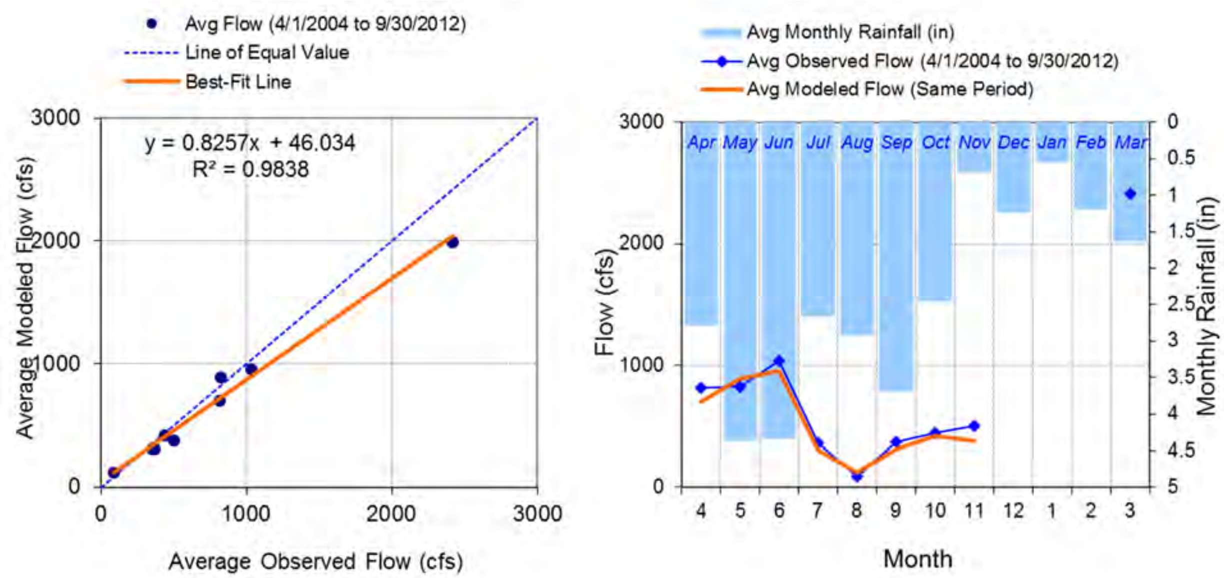

Figure 15. Seasonal regression and temporal aggregate at USGS 05316970 Cottonwood River near Leavenworth, CR8

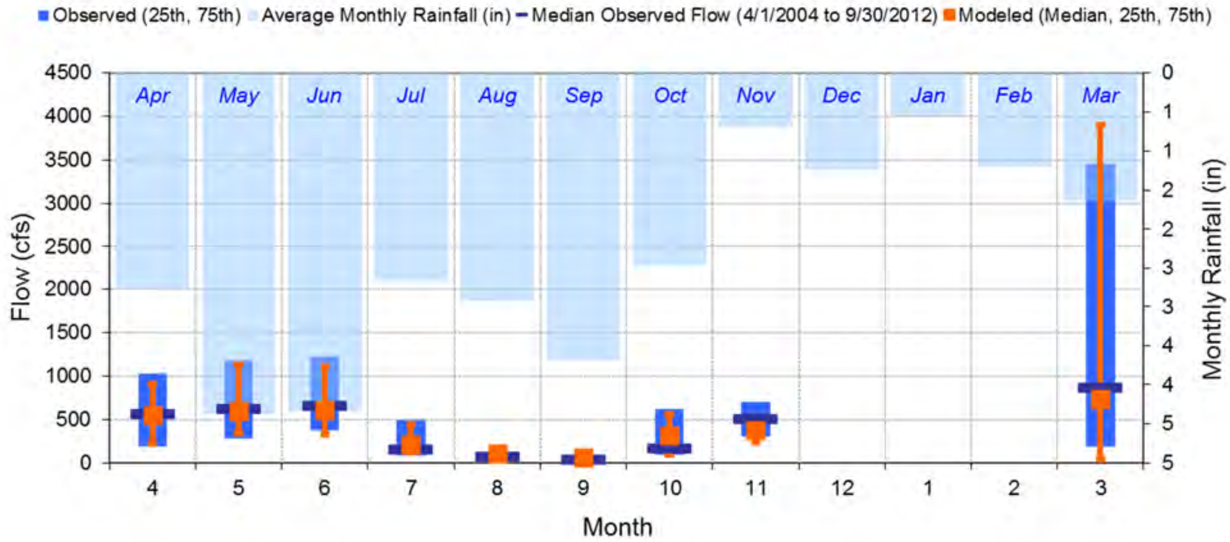

Figure 16. Seasonal medians and ranges at USGS 05316970 Cottonwood River near Leavenworth, CR8

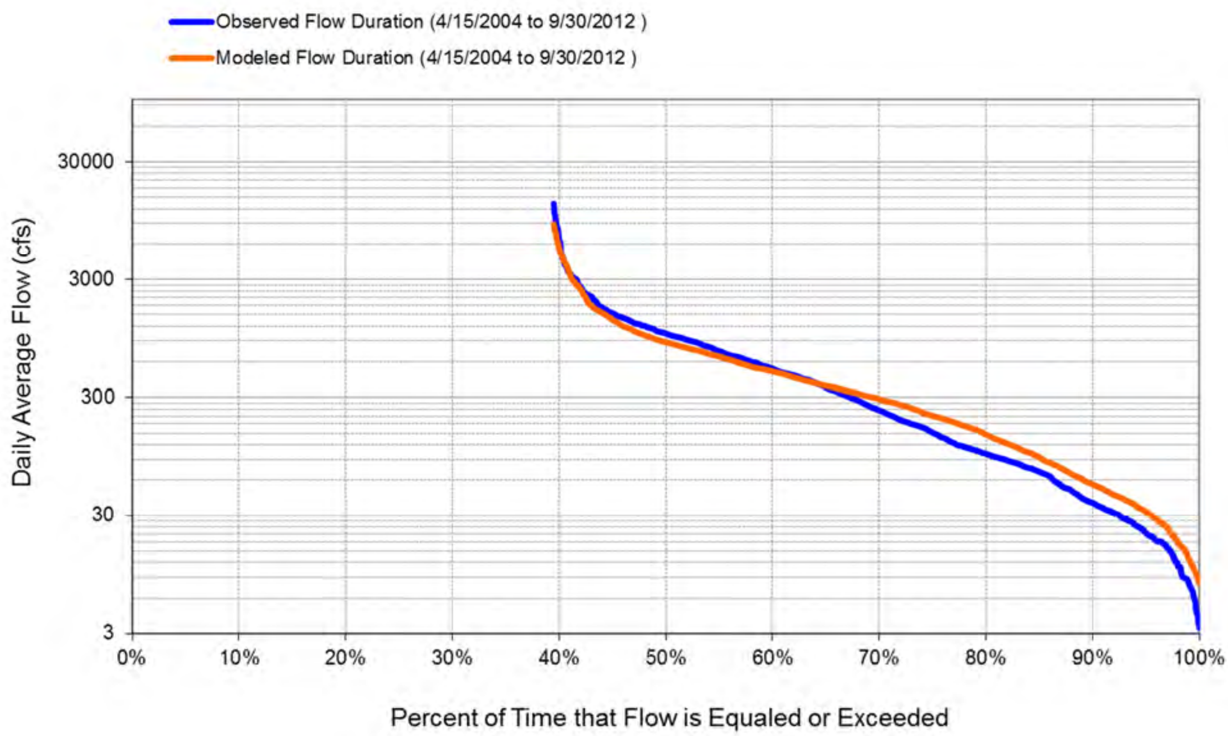

Figure 17. Flow Exceedance at USGS 05316970 Cottonwood River near Leavenworth, CR8

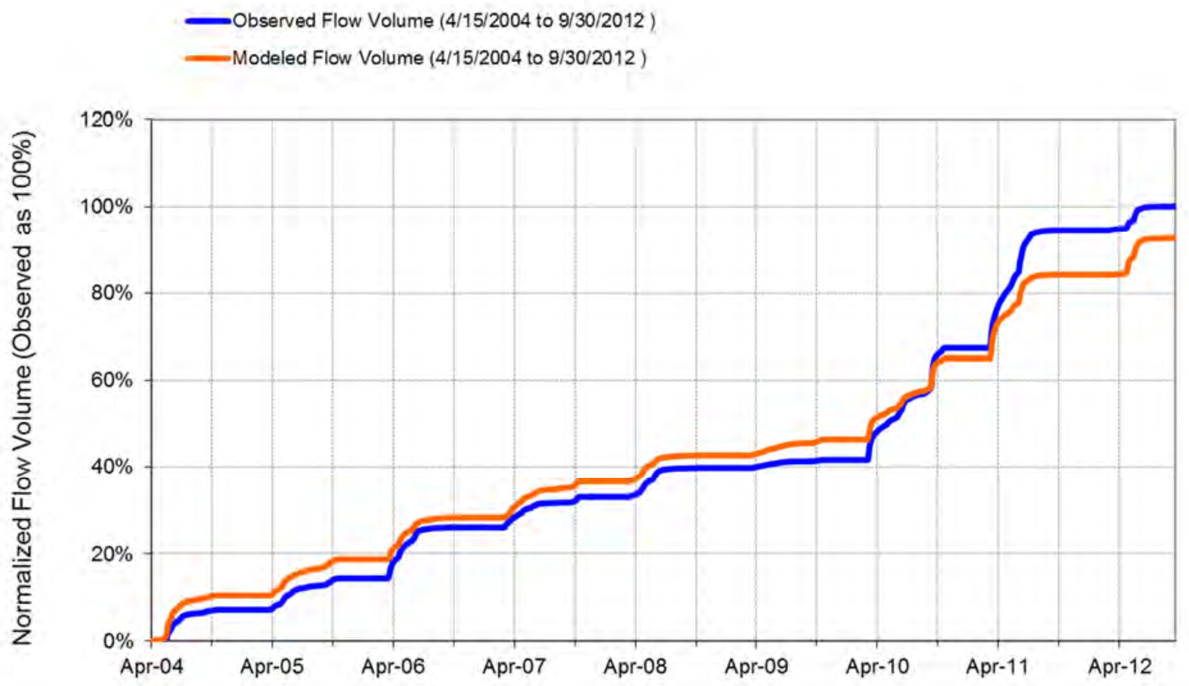

Figure 18. Flow accumulation at USGS 05316970 Cottonwood River near Leavenworth, CR

5.2.3 Gage Sites with Short-term, Seasonal Flow Records

The third tier of sites are also seasonal, but have only one to six years of monitoring. The shorter periods of record present several challenges. The model fit statistics are likely to be influenced by anomalies in the recorded precipitation record, and one poorly fit event will have a major effect on the apparent degree of fit. In addition, short records do not provide enough evidence for reliable site-specific calibration. Finally, the fact that these sites were in use for only a few years increases the degree of uncertainty that is likely to be present in rating curves that convert stage to flow estimates. Results for the short-term gages are summarized in Table 10. Example graphical calibration results are provided in the following figures for Watonwan River at La Salle. As before, complete calibration results are provided in the accompanying electronic files.

Table 10. Summary Statistics for Gage Sites with Short-term, Seasonal Flow Records

	Minnesota River at Judson, CSAH42	Crow Creek near Morton, Noble Ave	Wabasha Creek near Franklin, CSAH11	North Eden Creek near Franklin, CSAH10	Nicollet CD24 near North Star, Timber Ln	Plum Creek near Walnut Grove, CSAH10	North Fork Watonwan River near Sveadahl, MN
HYDSTRA ID	28054001	28098001	28102001	28095001	28063002	29048001	31030001
USGS ID	05317500	NA	NA	NA	NA	NA	NA
Error in total volume (%):	-5.18	1.54	-77.10	-13.40	-35.29	3.79	-3.06
Error in 50% lowest flows (%):	-11.00	-10.72	-6.13	2.85	24.52	86.05	85.58
Error in 10% highest flows (%):	-2.63	-5.41	-83.87	-27.13	-58.54	-9.11	-1.15
Seasonal error – Summer (%):	-10.63	-23.91	-61.39	-20.53	-1.27	69.10	-3.18
Seasonal error – Fall (%):	-7.94	-22.47	4.53	56.76	-86.80	13.36	-0.67
Seasonal error – Winter (%):	0.97	2.16	-88.92	-46.05	-1.83	-29.54	ND
Seasonal error – Spring (%):	-4.67	18.87	-71.16	6.86	-21.48	-2.90	-3.09
Error in storm volumes (%):	19.79	-8.84	-75.13	-19.58	-63.63	-2.27	-1.87
Error in summer storm volumes (%):	9.28	-36.04	-63.71	-22.50	-25.56	36.55	-43.92
Nash-Sutcliffe Coefficient of Efficiency, E:	0.914	0.689	0.069	0.688	0.063	0.866	0.726
Baseline adjusted coefficient (Garrick), E':	0.764	0.608	0.403	0.503	0.255	0.679	0.637
Monthly NSE	0.940	0.908	0.030	0.663	0.347	0.904	0.873
Observed Baseflow Fraction	79.3%	67.2%	71.6%	77.3%	66.2%	71.7%	72.1%
Simulated Baseflow Fraction	73.9%	66.7%	71.7%	76.1%	84.6%	73.4%	71.8%

Note: Summer = Jun, Jul, Aug; Fall = Oct, Nov, Dec, Winter = Jan, Feb, Mar; Spring = Apr, May Jun. Seasonal gages typically report only a few days at the beginning of October for Fall and a few days at the end of March for Spring, so statistics for these seasons should be discounted.

(Table 10 continued, part 2)

	Watonwan River near La Salle, CSAH16	Watonwan River near La Salle, CSAH3	South Fork Watonwan River near Madelia, CSAH13	Maple River near Sterling Center, CR18	Big Cobb River near Beauford, CR16	LeSueur River at St. Clair, CSAH28	LeSueur River near Rapidan, CR8
HYDSTRA ID	31040001	31028001	31021001	32062001	32071001	32079001	32076001
USGS ID	NA	NA	NA	05320450	05320330	NA	NA
Error in total volume (%):	-8.59	9.24	7.36	-14.67	-1.13	0.10	-2.81
Error in 50% lowest flows (%):	57.04	36.74	99.73	-6.08	34.30	12.89	2.45
Error in 10% highest flows (%):	-6.08	16.10	-3.29	-15.06	-3.14	-5.77	-5.78
Seasonal error – Summer (%):	-4.38	1.66	87.22	-10.66	12.19	-0.17	-3.01
Seasonal error – Fall (%):	129.40	-17.66	-13.63	-17.92	-18.32	-14.10	-14.45
Seasonal error – Winter (%):	ND	-3.49	-4.87	-23.00	-17.94	-8.24	-14.10
Seasonal error – Spring (%):	-9.66	11.63	0.95	-12.89	2.00	6.95	3.19
Error in storm volumes (%):	-1.92	8.51	8.41	-6.87	12.08	-0.90	-2.25
Error in summer storm volumes (%):	-31.04	-29.20	26.42	-10.53	7.50	-2.98	-7.03
Nash-Sutcliffe Coefficient of Efficiency, E:	0.877	0.901	0.907	0.735	0.731	0.698	0.739
Baseline adjusted coefficient (Garrick), E':	0.715	0.702	0.702	0.641	0.610	0.582	0.609
Monthly NSE	0.967	0.940	0.968	0.893	0.872	0.899	0.898
Observed Baseflow Fraction	71.0%	62.1%	71.0%	58.0%	67.7%	59.2%	64.6%
Simulated Baseflow Fraction	68.9%	62.4%	70.7%	54.2%	63.3%	59.6%	64.4%

Note: Summer = Jun, Jul, Aug; Fall = Oct, Nov, Dec, Winter = Jan, Feb, Mar; Spring = Apr, May Jun. Seasonal gages typically report only a few days at the beginning of October for Fall and a few days at the end of March for Spring, so statistics for these seasons should be discounted.

(Table 10 continued, part 3)

	High Island Creek near Fernando, CSAH7	High Island Creek near New Auburn, CSAH13	Buffalo Creek (County Ditch 59) near New Rome, CSAH17	North Branch Rush River near New Rome, CSAH9	Middle Branch Rush River near New Sweden, CR63	South Branch Rush River near Norseland, CR63	Nicollet Sibley JD1A near Norseland, CSAH3
HYDSTRA ID	33010001	33003001	33092002	33071001	33069001	33065001	33068001
USGS ID	NA	NA	NA	NA	NA	05326189	05326205
Error in total volume (%):	2.51	12.51	16.01	22.46	-5.88	-3.89	-2.81
Error in 50% lowest flows (%):	206.19	275.40	-47.33	84.56	64.03	37.91	24.67
Error in 10% highest flows (%):	-38.02	-31.98	7.91	18.11	-5.74	-1.38	-6.58
Seasonal error – Summer (%):	8.68	41.19	-77.65	28.96	-16.43	-18.15	-28.69
Seasonal error – Fall (%):	ND	ND	ND	62.17	-71.33	-42.62	-26.71
Seasonal error – Winter (%):	ND	ND	ND	-5.39	-13.30	13.87	6.98
Seasonal error – Spring (%):	2.43	12.23	19.02	20.52	2.50	4.69	5.13
Error in storm volumes:	-36.42	-34.16	-10.04	5.97	-25.54	-4.25	-19.51
Error in summer storm volumes:	2.92	85.69	53.20	2.76	-48.03	-21.58	-53.95
Nash-Sutcliffe Coefficient of Efficiency, E:	0.641	0.755	0.827	0.753	0.698	0.624	0.693
Baseline adjusted coefficient (Garrick), E':	0.490	0.507	0.560	0.588	0.545	0.533	0.557
Monthly NSE	0.811	0.827	0.902	0.828	0.709	0.731	0.823
Observed Baseflow Fraction	63.2%	65.2%	57.7%	69.8%	58.4%	63.1%	57.8%
Simulated Baseflow Fraction	78.2%	80.4%	67.2%	73.7%	67.0%	63.1%	64.9%

Note: Summer = Jun, Jul, Aug; Fall = Oct, Nov, Dec, Winter = Jan, Feb, Mar; Spring = Apr, May Jun. Seasonal gages typically report only a few days at the beginning of October for Fall and a few days at the end of March for Spring, so statistics for these seasons should be discounted.

MN 31040001 Watonwan River near La Salle, CSAH16

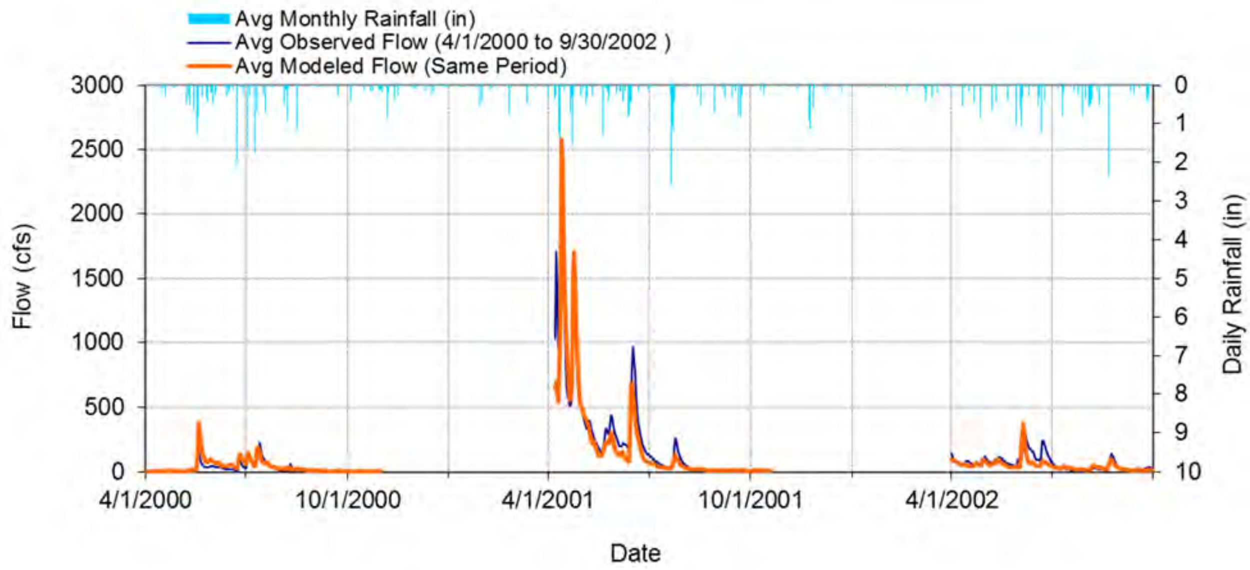

Figure 19. Mean daily flow at MN 31040001 Watonwan River near La Salle, CSAH16

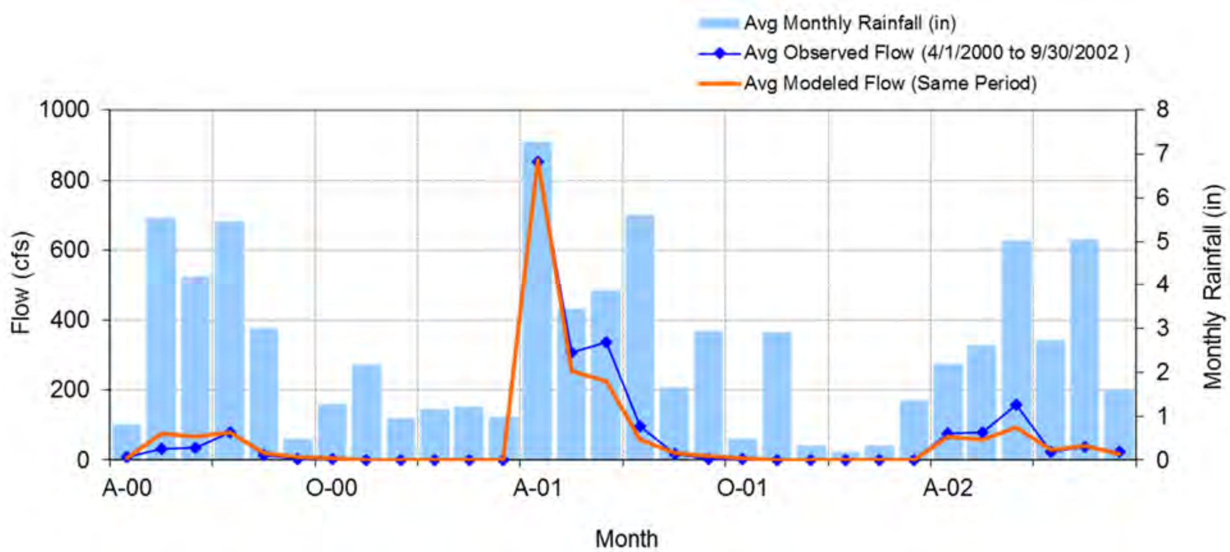

Figure 20. Mean monthly flow at MN 31040001 Watonwan River near La Salle, CSAH16

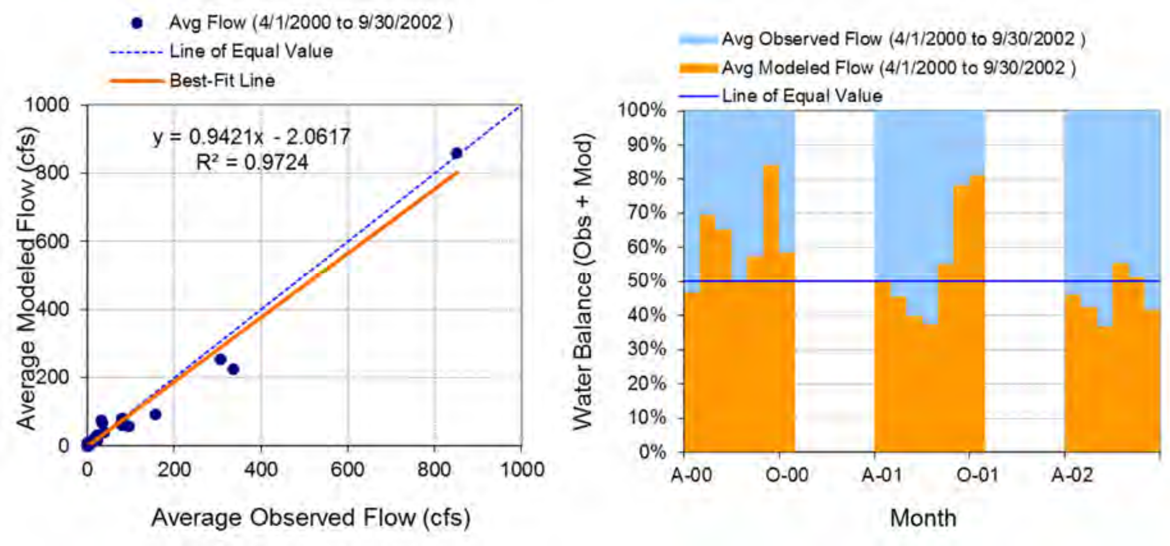

Figure 21. Monthly flow regression and temporal variation at MN 31040001 Watonwan River near La Salle, CSAH16

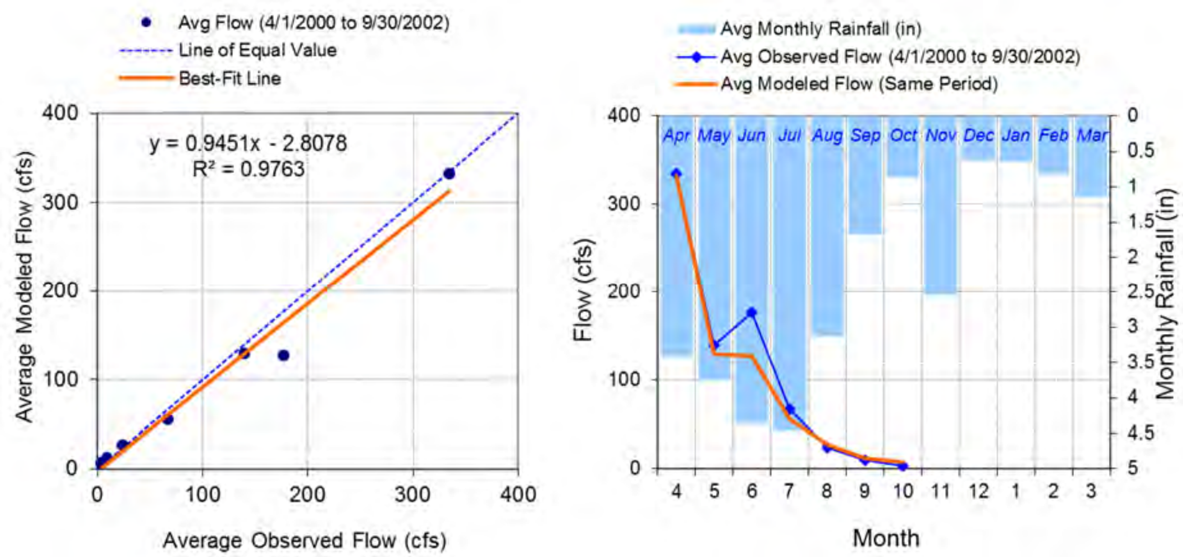

Figure 22. Seasonal regression and temporal aggregate at MN 31040001 Watonwan River near La Salle, CSAH16

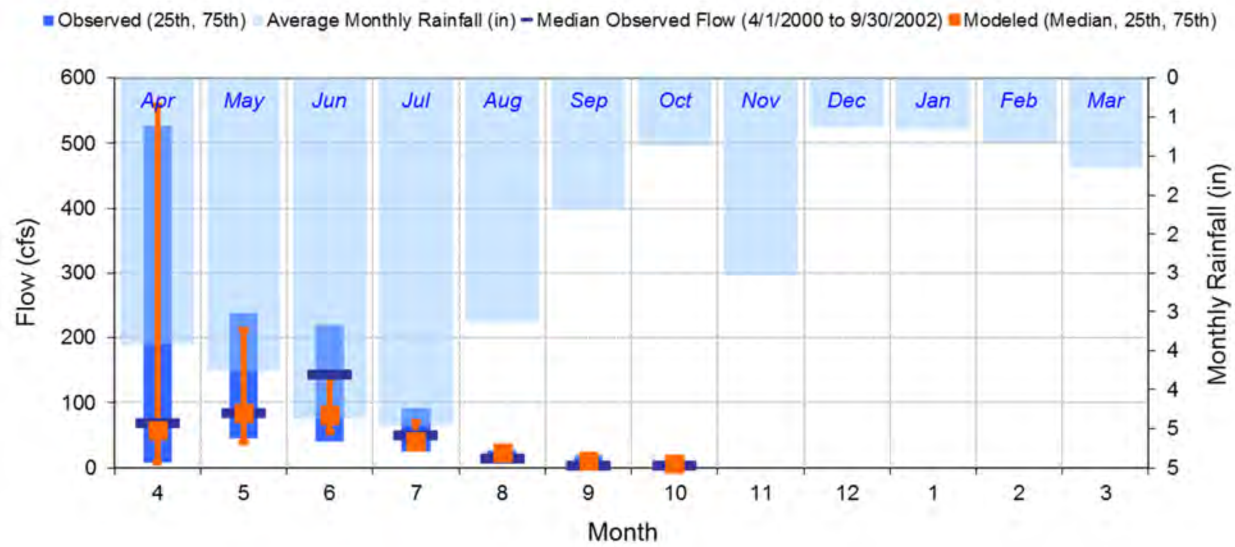

Figure 23. Seasonal medians and ranges at MN 31040001 Watonwan River near La Salle, CSAH16

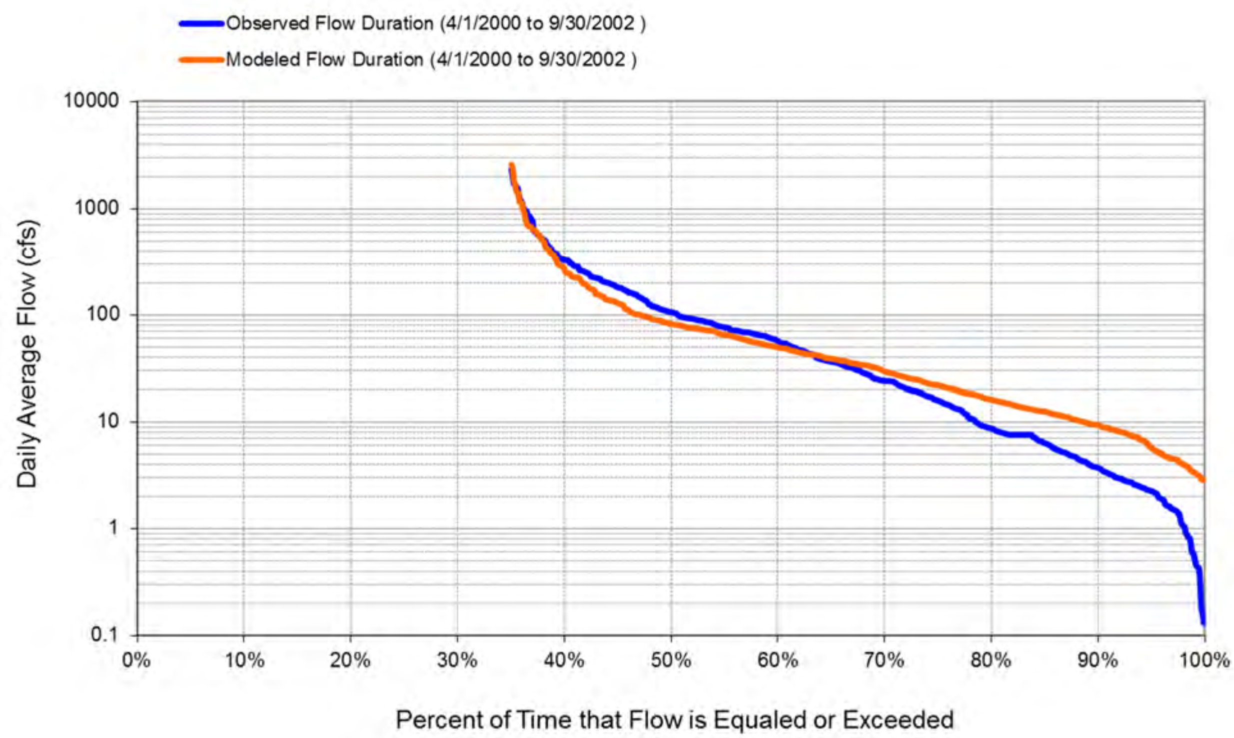

Figure 24. Flow Exceedance at MN 31040001 Watonwan River near La Salle, CSAH16

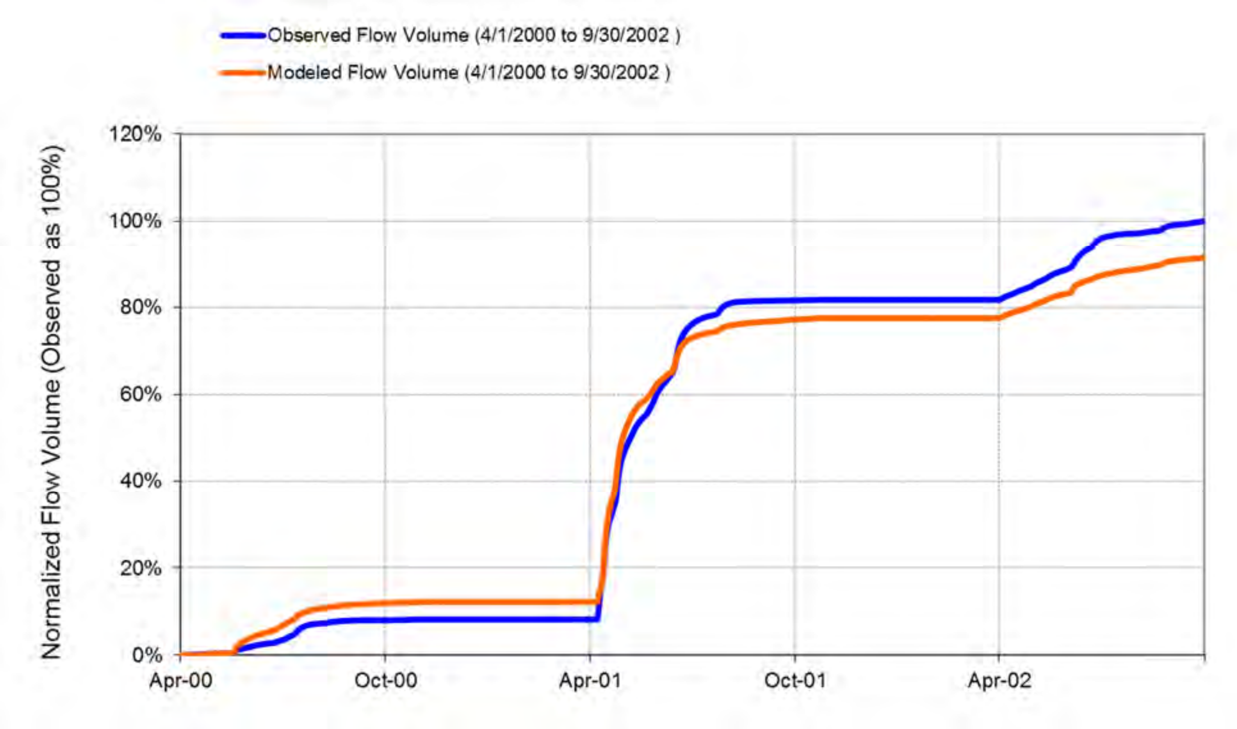

Figure 25. Flow accumulation at MN 31040001 Watonwan River near La Salle, CSAH16

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