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Minnehaha Creek Watershed SWMM5 Model Data Analysis and Future Recommendations

by Zhonglong Zhang and Chanel Mueller

INTRODUCTION: The Minnehaha Creek watershed is located west of Minneapolis, Minnesota. It drains approximately180 square miles of land into the Minnehaha Creek and ultimately the Mississippi River (Figure 1). The watershed includes Lake Minnetonka, Minnehaha Creek, the Minneapolis Chain of Lakes, and Minnehaha Falls. The "Upper Watershed" (referenced as UMCW), above Lake Minnetonka, is a region of rolling farmland interspersed with numerous lakes and wetlands. Lake Minnetonka discharges through a control structure, the Grays Bay Dam, into Minnehaha Creek. Lake Minnetonka covers an area of 122.6 square miles and has a maximum depth of 113 ft. It is comprised of numerous interconnected bays. Lake Minnetonka serves as both the recipient of stormwater runoff of the UMCW and as the source of Minnehaha Creek. The "Lower Watershed" (referenced as LMCW) consists of the area east of Lake Minnetonka that is drained by Minnehaha Creek and extends to the Mississippi River. Minnehaha Creek flows eastward for approximately 22 miles and is the physical link that binds the network of urban lakes, parks, and open space that define the western Twin Cities area and south Minneapolis. Some land area within the LMCW does not drain directly or indirectly to Minnehaha Creek, but drains directly or indirectly to the Mississippi River. Within the Minnehaha Creek watershed, approximately 29% of the land area is shown on the National Wetland Inventory as wetland.

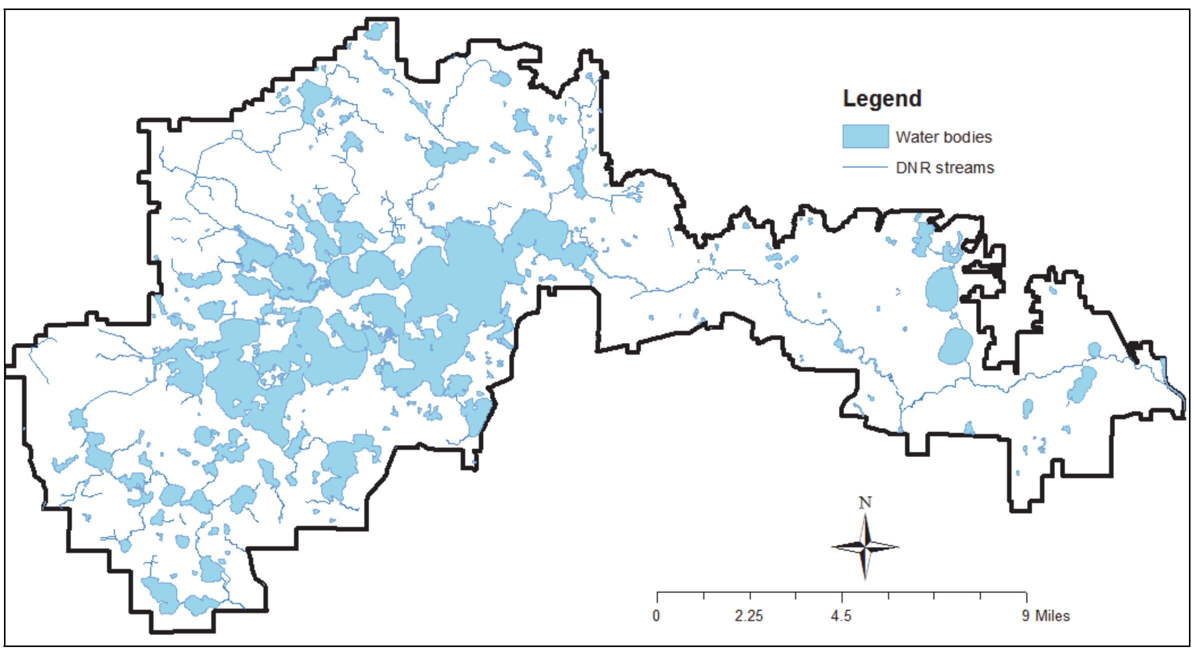

Figure 1. Minnehaha Creek watershed.

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Approximately 10 years ago, the Minnehaha Creek Watershed District (MCWD) had an XP-SWMM (XP Software Storm Water Management Model) model developed for the entire Minnehaha Creek watershed (U.S. Environmental Protection Agency (USEPA) 2010, XP Solutions, Inc. 2011). The XP-SWMM model was developed to simulate the hydrology and hydraulics of the Minnehaha Creek watershed. Due to the size and complexity of the model, the XP-SWMM model was subdivided into two parts identified as the Upper Minnehaha Creek Watershed (UMCW) model and the Lower Minnehaha Creek Watershed (LMCW) model. The divide between the two models occurs at Gray's Bay Dam, which is the outlet for Lake Minnetonka and the headwaters of Minnehaha Creek. The dam is managed to control discharge water from Lake Minnetonka into Minnehaha Creek.

The primary objective of this study is to convert the existing Minnehaha Creek watershed XP-SWMM models into EPA SWMM5 (U.S. Environmental Protection Agency Storm Water Management Model version 5) models. Additional goals of the study are to review available data and to provide recommendations for future data collection/monitoring and modeling efforts. This technical note documents and explains the conversion of the Minnehaha Creek watershed XP-SWMM hydrologic and hydraulic models into SWMM5 models. The document also includes a data inventory, discussions of model calibration efforts and existing model limitations, and recommendations to the MCWD regarding future monitoring and modeling efforts.

CONVERSION OF XP-SWMM MODELS INTO SWMM5 MODELS: This section summarizes Minnehaha Creek watershed XP-SWMM models, model conversion, and resulting EPA SWMM5 models.

XP-SWMM models. MCWD currently runs the UMCW model in XP-SWMM Version 9.14 and the LMCW model in XP-SWMM Version 10.6. Schematics of the UMCW and LMCW XP-SWMM models are illustrated in Figures 2 and 3, respectively. A 100-year, 10-day rainfall event simulation was included within the XP-SWMM models provided by MCWD; however, model results were not compared with measured flows.

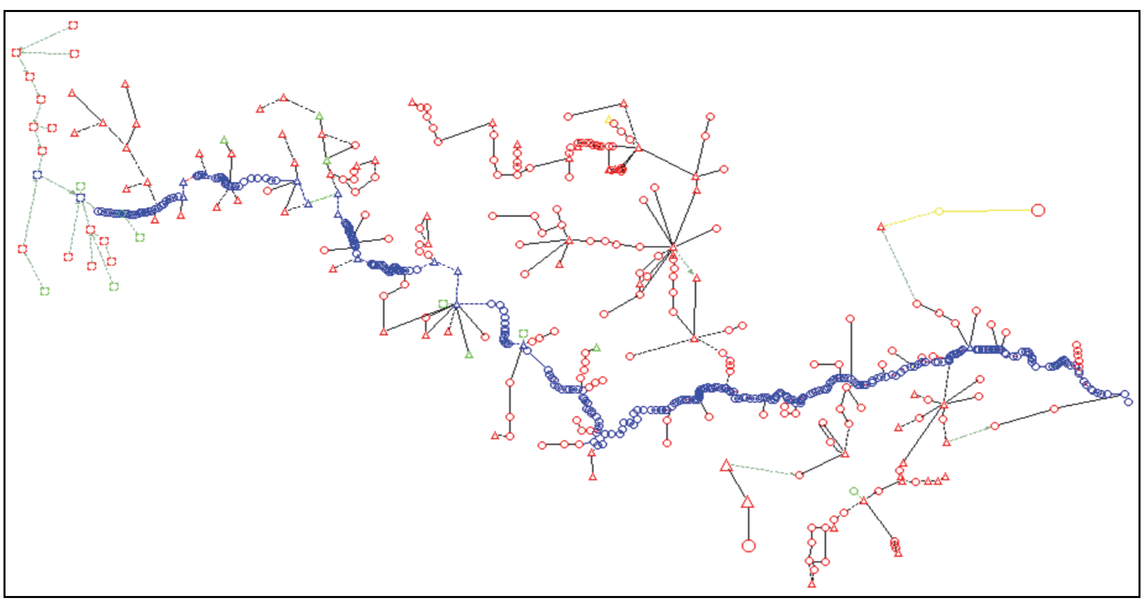


Figure 2. Schematic representation of the LMCW XP-SWMM model.

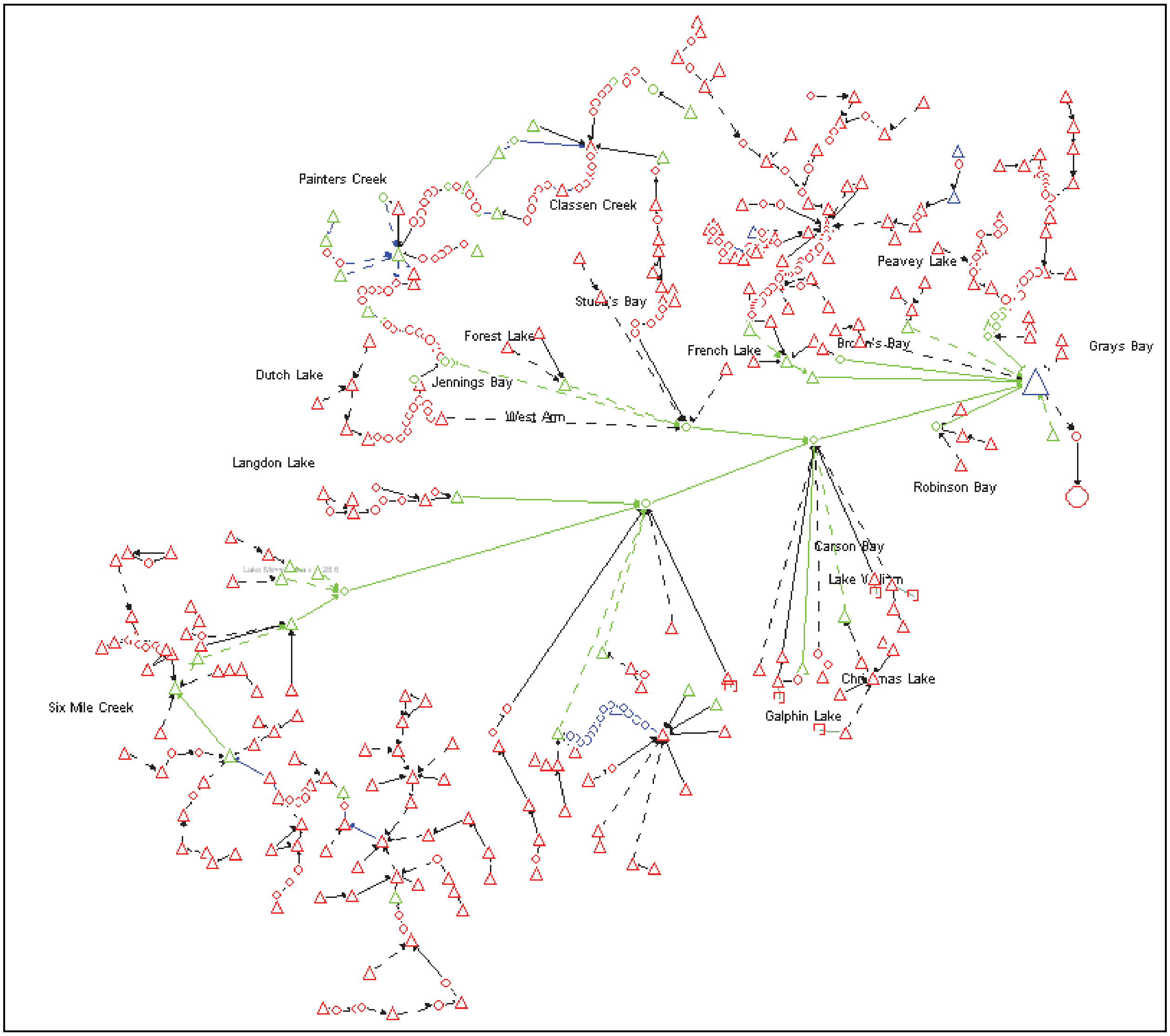


Figure 3. Schematic representation of the UMCW XP-SWMM model.

In the past, several reviews of the XP-SWMM models have been conducted. A brief listing of the problems identified in the two XPSWMM models is as follows:

1) Model setup problems
2) Model instability problems
3) Insufficient model calibration/validation
4) Inadequate documentation of model calibration/validation
5) Failure of modeled simulations to predict observed storm events
6) Lack of necessary documentation of the source data used to set up the XP-SWMM models.

7) Lack of documentation related to the assumptions made for model elements such as special conduits, parameter estimation, etc.

Problems were also encountered in running the UMCW XP-SWMM and LMCW XP-SWMM models using XP-SWMM 2011 software. When the XP-SWMM models are run with the same input data using the latest version of XP-SWMM software, the results are different than those obtained utilizing XP-SWMM version 9.14 and version 10.6. XP-SWMM software updates often result in inconsistencies in model results. It has also been observed that the error statements generated differ depending upon the Windows operating system being used to execute XP-SWMM runs.

The XP-SWMM package was developed by XP Software and is based on EPA SWMM version 4. Three major drawbacks of XP-SWMM are its cost, its out-dated computation engine, and its rudimentary graphical user interface (GUI). The XP SWMM graphing module is "buggy," and does not give users the basic options found in the more recent SWMM5 GUIs.

SWMM5 model. EPA SWMM5 is a complete rewrite of the SWMM4 in C with many bug fixes, enhancements, and additions (James et al. 2010). It provides a new GUI for editing data; running hydrologic, hydraulic, and water quality simulations; and viewing results. SWMM5 is an integrated model–this is a tremendous improvement over the separate SWMM4 and XP-SWMM models. SWMM5 has no limits on number of entities (conduits, nodes). As a result of improvements to SWMM5's computational engine, SWMM5 is more stable and has faster execution times than its predecessors.

SWMM5 is user-friendly freeware that can be downloaded from the US Evironmental Protection Agency (EPA) web site (*http://www.epa.gov/nrmrl/wswrd/wq/models/swmm/*). SWMM5 is appropriately applied to a wide range of project sizes and is widely accepted by regulatory agencies. SWMM5 provides a GUI that allows visual objects to be added to form hydrologic and hydraulic networks. Details of the SWMM5 model are provided in the SWMM5 User Manual (James et al. 2010).

SWMM5 was recommended by the US Army Corps of Engineers (USACE) as the preferred modeling platform for the Minnehaha Creek watershed. The MCWD accepted USACE's recommendation. Consequently, the latest SWMM5, version 5.0.022, was adopted for this project.

Model conversion processes. XP-SWMM is based on SWMM4, so the data in the XP-SWMM model can be translated into SWMM5 using a three-step process:

1) Convert the XP-SWMM ".dat" file to a SWMM 4 file using a XP-SWMM to SWMM4 conversion program.

2) Convert the SWMM4 file to a SWMM5 input file using the SWMM4 to SWMM5 converter.

3) Manually fix the errors in the SWMM4 file and then reconvert the model to SWMM5.

The original XP-SWMM models for the UMCW and LMCW were provided by MCWD. The two XP-SWMM models were key resources for developing the SWMM5 models. The UMCW's XP-

SWMM and LMCW's XP-SWMM models were converted into UMCW's SWMM5 and LMCW's SWMM5, respectively. Based on review of the watershed properties input in the UMCW and LMCW models, USACE recommends that MCWD keep the SWMM5 models separated instead of combining them into one comprehensive SWMM5 model for the entire watershed. The subcatchments, infiltration parameters, streamflow network, and hydraulic structure data included in UMCW and LMCW SWMM5 models are directly derived from the existing XP-SWMM models.

The drainage areas adopted in the network system in SWMM5 are represented by subcatchments. Within the SWMM5 model, the Minnehaha Creek watershed is divided into subcatchments based on the subcatchment delineations from the original XP-SWMM model. Subcatchments are defined as hydrologic units of land whose topography and drainage system elements direct surface runoff to a single point. The watershed delineation represented in the existing models was performed 10 years ago. If significant land use changes have occurred in the basin or the MCWD stormwater system has been modified, USACE recommends a review of the subbasin delineation. The principal input parameters include identification of an assigned rain gauge and outlet node, imperviousness, slope, characteristic width or flow length (width can be calculated from flow length), Manning's roughnesses (n) for impervious and pervious areas, depressional storage (impervious and pervious areas), and impervious area with no depressional storage.

Subcatchment characteristics utilized in the SWMM5 models were adopted from the original XP-SWMM models. Subcatchment characteristics that are specified in SWMM5 include subcatchment width (based on the travel length), percent imperviousness, slope, depression storage depths, and Manning's n values for pervious and impervious surfaces. The subcatchment width is computed by dividing the subcatchment area by the travel length. This is an abstract basin parameter and is commonly used as a "tuning parameter" for model calibration. Land use data were used to develop the percent imperviousness.

Green-Ampt has been selected as the infiltration method for the SWMM models. The Green-Ampt methodology is the most appropriate infiltration method to select, because it uses physically based parameters and is designed for continuous simulations. The Green-Ampt soil infiltration method and its parameters were adopted from the original XP-SWMM models. Soil data are required to develop Green-Ampt infiltration parameters. The Green-Ampt methodology requires the specification of three parameters for each subcatchment: initial moisture deficit (IMD), suction head (Su), and the saturated hydraulic conductivity of the soil (K_s). The hydraulic conductivity value is based on the SCS hydrologic soil group of soil (i.e. A, B, C, D), and the moisture deficit and suction head are based on the soil type (e.g. silt, loam, clay, sandy loam, etc.). These parameters apply only to pervious surfaces. The typical values of these parameters were included in SWMM5. Some of these parameters need to be adjusted within a reasonable range during the model calibration step.

The hydraulic network in the watershed is represented using a system of junctions and conduits. Junctions in SWMM5 are defined as drainage system nodes that can represent the confluence of natural channels or manholes and pipe connections in a storm sewer network. The principal input parameters include invert elevation, height to ground surface, and ponded area when flooded (if allowed). Conduits are channels or pipes that convey water between nodes and represent the stream channel or storm sewer pipes. The principal input parameters of conduits include length, Manning's roughness, cross-sectional geometry, and entrance/exit losses (optional). Conduit slope is calculated using elevations of inlet and outlet nodes and channel length. Geometric data from the XP-SWMM models were used to develop the SWMM5 geometry.

SWMM5 offers three routing methods: steady flow, kinematic wave, and dynamic wave. Each method offers advantages and disadvantages and each is particularly suited to certain types of applications. The original UMCW and LMCW XP-SWMM models used dynamic wave routing techniques (which are based on the Saint Venant equations). The routing method adopted within the SWMM5 models is also dynamic wave routing. Dynamic wave routing is the most theoretically accurate methodology available. It routes unsteady flows and has the ability to model backwater effects, flow reversals, pressurized flows, and entrance/exit energy losses. It is also the most data-intensive and computationally time-consuming routing methodology to execute. However, run times in SWMM5 have been significantly reduced when compared to the run times observed using the XP-SWMM model. SWMM5 allows for dynamic wave routing to be utilized, while maintaining reasonable computation times.

Observed data inconsistencies. After converting the model from XPSWMM to SWMM5, the plan view of the SWMM5 model was reviewed to determine any connectivity data gaps. Similarly, the profiles were also reviewed to identify any questionable network system attribute data or data gaps. Some of the potential issues identified are listed below:

1) Improper pipe inlet/outlet offsets; for example, MC-71MLnT, MC-133LAvT, etc. These pipes have very high offsets (> 100 ft). High offsets cause network discontinuity.

2) Duplicate conduits are present in the model, consisting of two pipes (one on top of the other) transitioning from the same upstream node to the same downstream node.

3) Network discontinuity; for example, outfall MC-158FN1, outfall N4, and MR-3SS, etc.

4) Fixed outfall N13 has "0" stage in it.

5) Numerous storage sites are present in the network. These storage sites may have different functions. They play an important role in the hydraulics/hydrology of the network.

6) Inverts of the storage areas were not available.

Additionally, there was some confusion regarding the special conduits included in the XP-SWMM models. The invert elevations for some of the ponds were based on interpolation and top-of-rim elevations, so exact elevations would need to be verified. Also, losses within the Minnehaha Creek and stormwater pipes would need to be evaluated and added to the model. Due to limited groundwater information throughout the watershed, some assumptions were required with regard to aquifer depth, water table elevations, and stream stage elevations. It is suggested that future studies be carried out to gather data to better characterize the hydrogeology of the watershed. These data gaps, along with the issues listed above, include examples of model inconsistencies and shortcomings. However, this report should not be considered a comprehensive inventory of data inconsistencies in the model.

When such data problems are found, the GIS system attribute data should be reviewed to resolve data discrepancies and identify further issues related to the network system. If the discrepancies cannot be explained by referencing a GIS database, then paper records or field investigations are required. Unfortunately, the source data used to develop the original XP-SWMM model is no longer available. Pipe network, pond, and open channel geometry data used in the XP-SWMM models are not available for verification. Additionally, the XP-SWMM models were constructed using 10-year-old data. These data need to be updated to reflect current basin conditions. The data included in the SWMM5 models should be verified with the latest source data.

It is impossible to develop a comprehensive inventory of data inconsistencies without a source data inventory. To solve this problem, MCWD needs to develop a detailed, georeferenced, GIS-based database that can serve as a baseline. The data gaps outlined in the following sections can then be resolved. In order to ensure that the model is up-to-date, the baseline database needs to be updated regularly. The lack of source data made verifying and updating the converted LMCW and UMCW SWMM5 models impossible. Changes to observed geometry that are made to improve model stability or for calibration purposes also need to be documented.

LMCW SWMM5 Model. Figure 4 is a schematic representation of the LMCW SWMM5 model. The model currently contains climatological and precipitation data for the period of record from April 2010 through April 2012. This period contains many significant events.

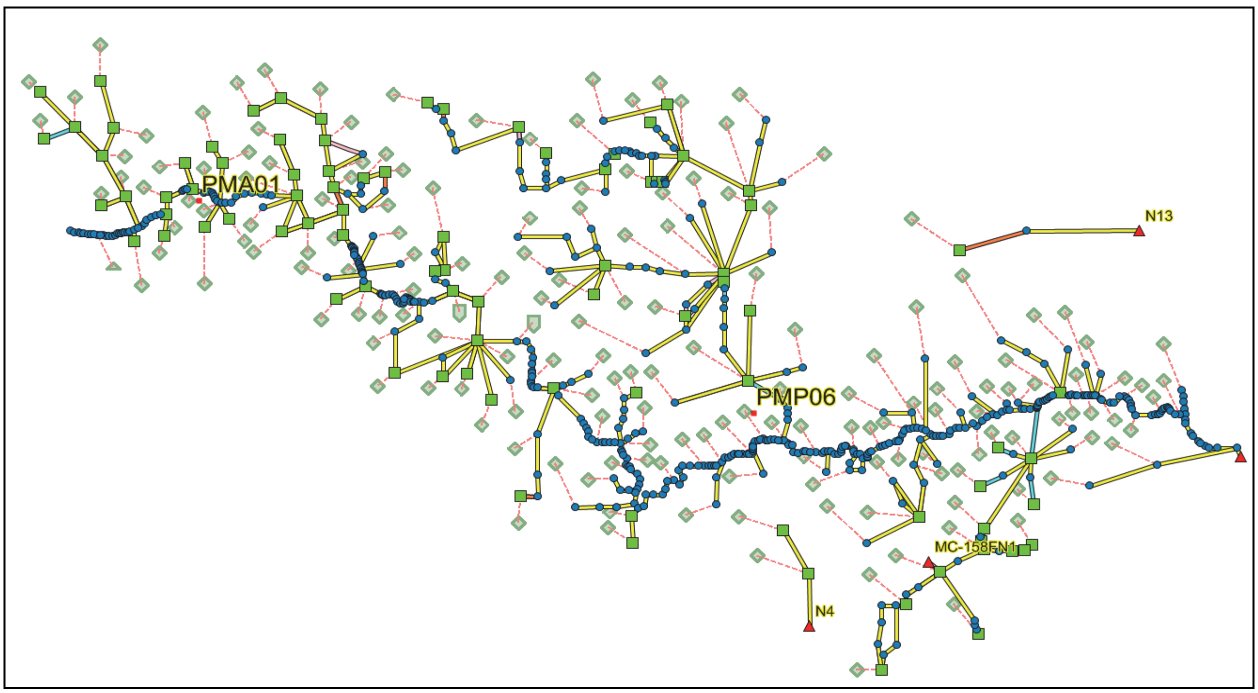


Figure 4. Schematic representation of the LMCW SWMM5 model.

LMCW's subcatchments, junctions, conduits, and special hydraulic structures modeled in SWMM5 are summarized in Table 1. Detailed geometric data including subcatchment delineations; locations, dimensions, and elevations of stormwater pipes; open channel cross sections; storage-area-depth relationships; and locations and dimensions of weirs and other hydraulic structures can be found within the SWMM5 input file (lowerswmm5.inp).

Table 1. Summary of Minnehaha Creek watershed SWMM5 Model.		
Components	**Upper SWMM5 Model**	**Lower SWMM5 Model**
No. modeled subcatchments	249	173
No. modeled conduits	698	676
No. modeled junctions	249	474
No. modeled storage units	260	90
No. modeled outfalls	1	4
No. modeled weirs	31	20
No. modeled orifices	16	16
No. modeled pumps	0	11

UMCW SWMM5 Model. Figure 5 is a schematic representation of the UMCW SWMM5 model.

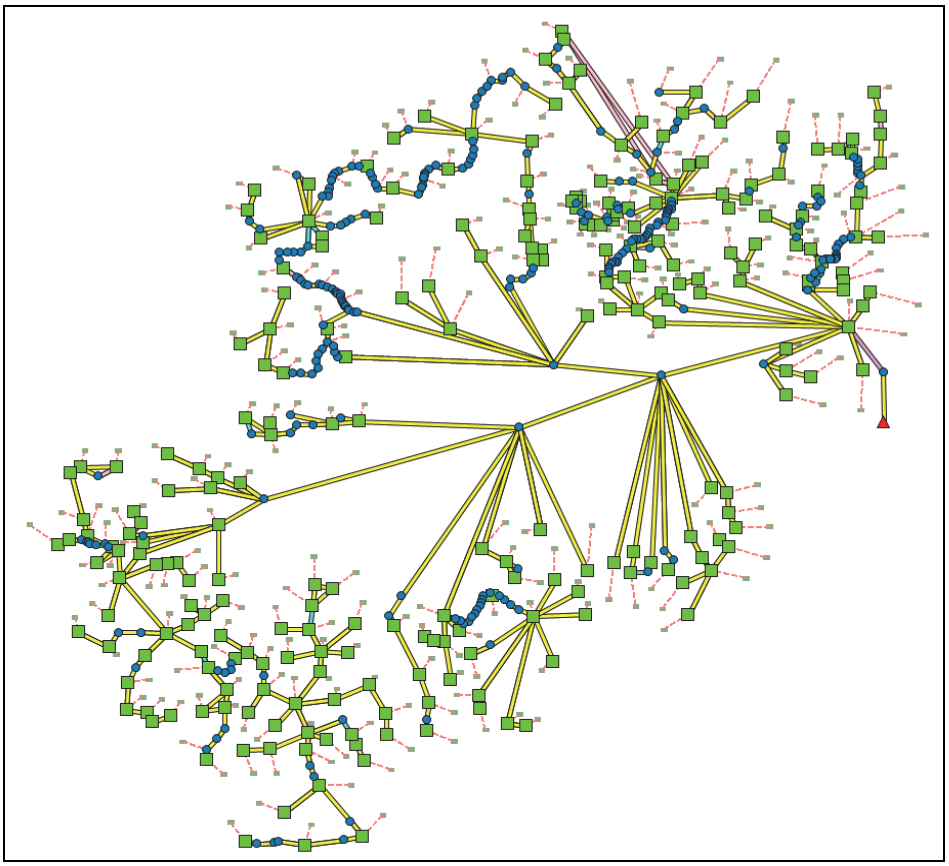


Figure 5. Schematic representation of the UMCW SWMM5 model.

UMCW's subcatchments, junctions, conduits, and special hydraulic structures simulated in the SWMM5 model are summarized in Table 1. Detailed geometric data that includes subcatchments; locations, dimensions, and elevations of stormwater pipes; cross sections of open channels, storage area depth relationships, and locations and dimensions of weirs and other hydraulic structures can be found within the SWMM5 input file (upperswmm5.inp).

CURRENTLY AVAILABLE DATA AND SWMM5 MODEL CALIBRATION EFFORTS: Model calibration and validation are critical steps to ensure that the SWMM5 model will properly simulate the Minnehaha Creek watershed system for a range of storm events. SWMM5 hydrologic and hydraulic model calibration and validation involve the collection of rainfall data and flow rates/elevation data and development of an initial model input dataset. This is followed by successive model runs and the adjustment of model calibration parameters until the model results are in agreement with the observed data. The calibration parameters are prioritized according to their influence on model results. The influence that the various calibration parameters have on model results can vary from one watershed system to another.

Summary of previous calibration efforts. Emmons and Olivier Resources Inc. (2003) reported that the LMCW XP-SWMM model was calibrated for three locations (CMH-07, CMH-03, and CMH-17) using 2000 and 2001 single storm event data. The UMCW XP-SWMM model was calibrated as follows: the Painter Creek flow was calibrated using two storm events (4/10/1999-6/9/1999, 3/30/2001-7/18/2001) and the Lake Minnetonka water elevation was calibrated for the 6/3/2000-9/23/2000 and 5/19/2001-10/6/2001 periods. However, observed precipitation and flow data used for model calibration were not available. Thorough evaluation of the methods utilized to calibrate the original models is impossible without access to the original calibration data and run results.

Currently available data. To support the SWMM5 model calibration and validation, MCWD has monitored rainfall and streamflow at several locations throughout the basin. After reviewing the currently available data provided by MCWD, it was determined that the UMCW is data poor. Continuous water level monitoring is only available on Painter Creek in the UMCW. Flow monitoring data available from the LMCW for SWMM5 model calibration and validation are also limited. In the LMCW, continuous discharge and water level monitoring is conducted on Minnehaha Creek at Grays Bay Dam (Lake Minnetonka Outlet) in Minnetonka, at the I-494 crossing, Browndale Avenue Dam in Edina, MN, and Minnehaha Creek at 32nd Avenue S. The LMCW SWMM5 model needs input flows from the UMCW SWMM5 model; otherwise, observed flows below the Gray's Bay Dam should be provided.

Flow gauges and observed data-Lower Minnehaha Creek Watershed (LMCW). Flow rate and water depth monitoring data are available in electronic format at four sites on Minnehaha Creek (Figure 6). CMH07 is located at the outlet from the UMCW and its flows can be used as an input for the LMCW SWMM5 model. Three flow gauges, CMH19, CMH03, and CMH06, can be used for LMCW SWMM5 model calibration and validation.

Table 2 lists the gauges in the LMCW and the period of 15-minute flow record associated with each gauge. Flow rates through the cross sections were estimated based on estimated depth of flow in the cross section. The reliability of the flow monitoring data is assessed as part of the model calibration and validation process.

Flow gauges and observed data-Upper Minnehaha Creek Watershed (UMCW). Observed flow data are available for Painter Creek. Table 3 lists the gauge locations and the period of 15-minute flow record associated with each gauge. One seasonal flow measurement is available for each year. The Painter Creek gauges are only representative of one of the subcatchments in the UMCW (Figure 7). The Painter Creek gauge provides the only observed flow data available for UMCW SWMM5 model calibration and validation.

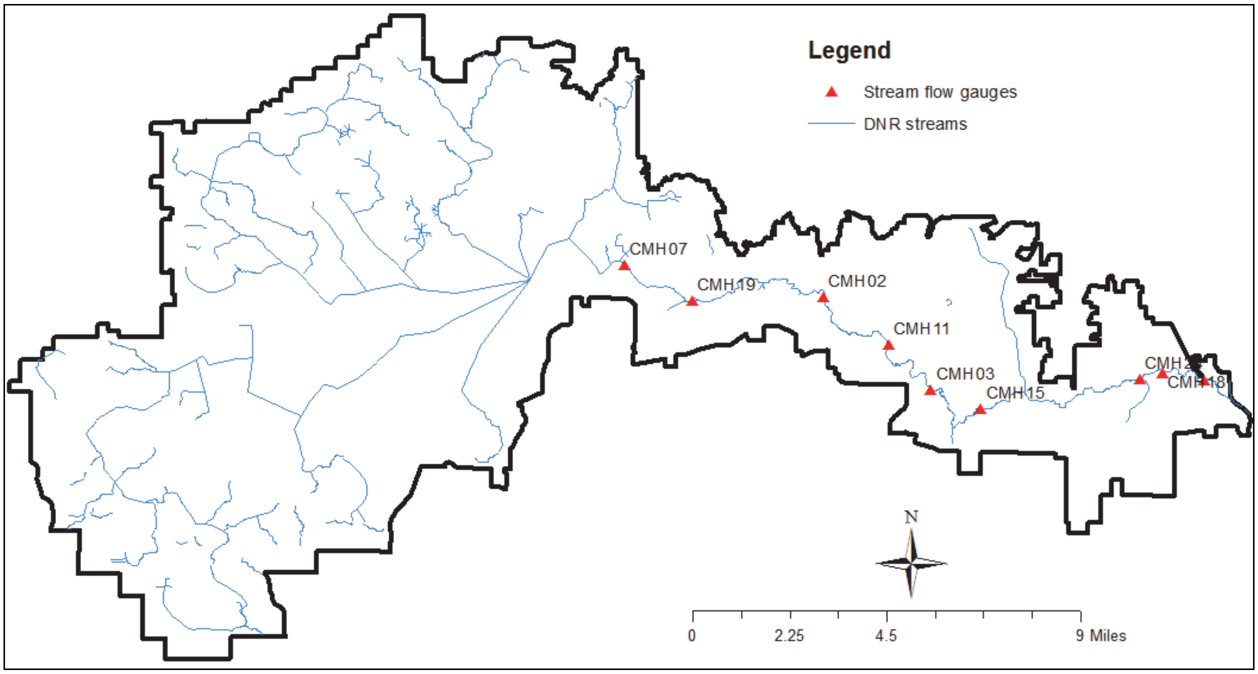


Figure 6. Stream flow monitoring gauge locations on Minnehaha Creek.

Table 2. Observed 15-minute flow discharge and head data.

Gauge	Gauge Location	Record (Head)	Record (Discharge)	Note
CMH07	Minnehaha Creek, Grays Bay Tailwater		4/12/2010-7/10/2012	Computed from the rating curve
CMH19	Minnehaha Creek, I-494 Crossing	4/7/2010-11/12/10 5/19/11/2011-11/15/2011 4/18/2012-8/15/2012	4/7/2010-11/12/10 5/19/11/2011-11/15/2011 4/18/2012-8/15/2012	
CMH03	Minnehaha Creek, Browdale Ave Dam	4/21/2010-10/10/2012 3/30/2012-8/10/2012	4/21/2010-10/10/2012 3/30/2012-8/10/2012	
CMH06/ USGS05289800	Minnehaha Creek, Hiawatha Ave	1/1/2010-11/29/2012	1/1/2010-11/29/2012	

Table 3. Observed 15-minute flow discharge data.

Gauge	Gauge Location	Record (Discharge)	Note
CPA01	Painter Ck W Branch Rd	3/30/1999-8/14/2012	Only sparse, seasonal measurements are available
CPA03	Painter Ck Deborah Dr	5/11/2001-8/28/2012	
CPA04	Painter Ck Painter Marsh Outlet	5/2/2002-7/31/2012	
CPA05	Painter Ck CR110 Jennings Bay	6/26/2003-7/31/2012	
CPA06	Painter Ck Painter Creek Dr	3/30/2005-7/31/2012	

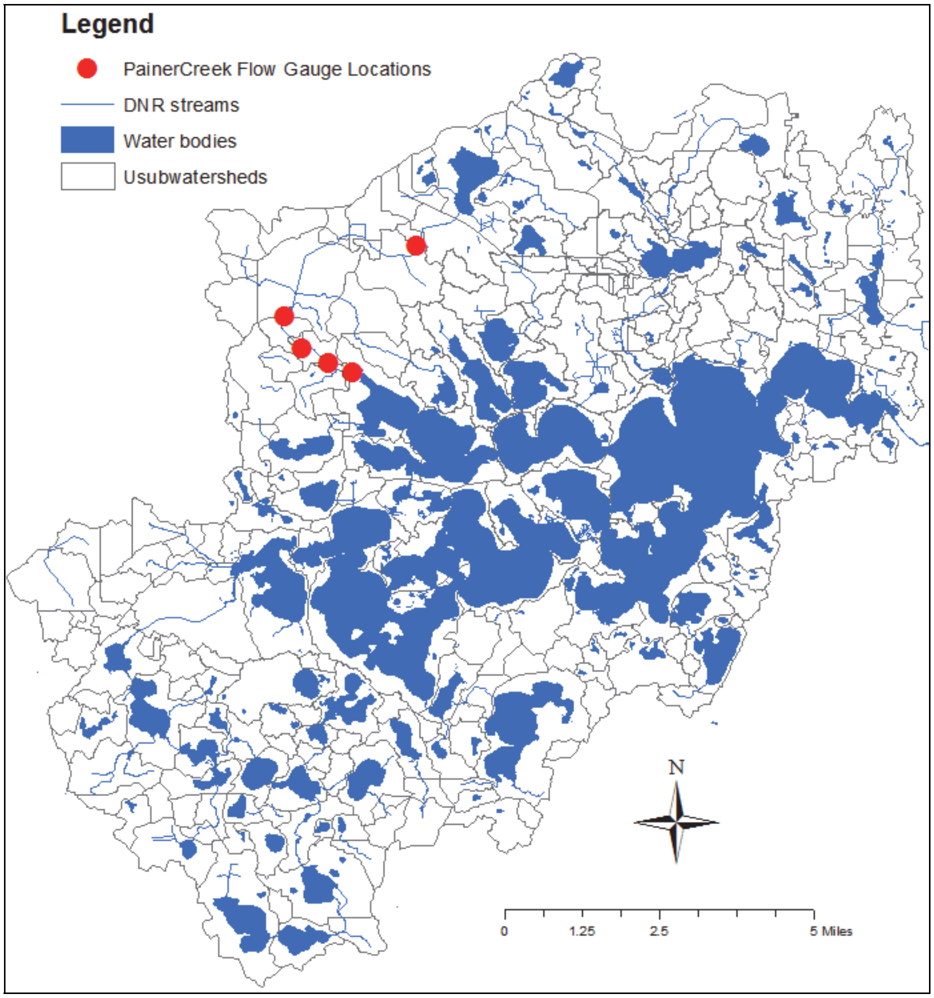


Figure 7. Stream flow monitoring gauge locations on Painter Creek.

*Climatological and rainfall data.*The SWMM5 climatology editor uses temperature, monthly wind speed, snowmelt, and areal depletion data to support surface runoff computations. These climatological data are adopted directly from the XP-SWMM model and imported into the SWMM5 model. USACE recommends that MCWD update climatological data to reflect the current climate conditions.

Rainfall data provide basic time-variable input to the model and are critical to model calibration and validation. Inadequate or erroneous rainfall data introduce calibration errors or misrepresentations of model input, which in turn reduce model accuracy and the reliability of watershed simulations. Rainfall gauging stations operated by the MCWD are displayed in Figure 8.

Aggregate rainfall data are not suitable for SWMM modeling. Fifteen-minute rainfall data are used to develop input hyetographs to the SWMM5 model. Table 4 lists the 15-minute rainfall gauges located within the Minnehaha Creek watershed and their associated period of observation.

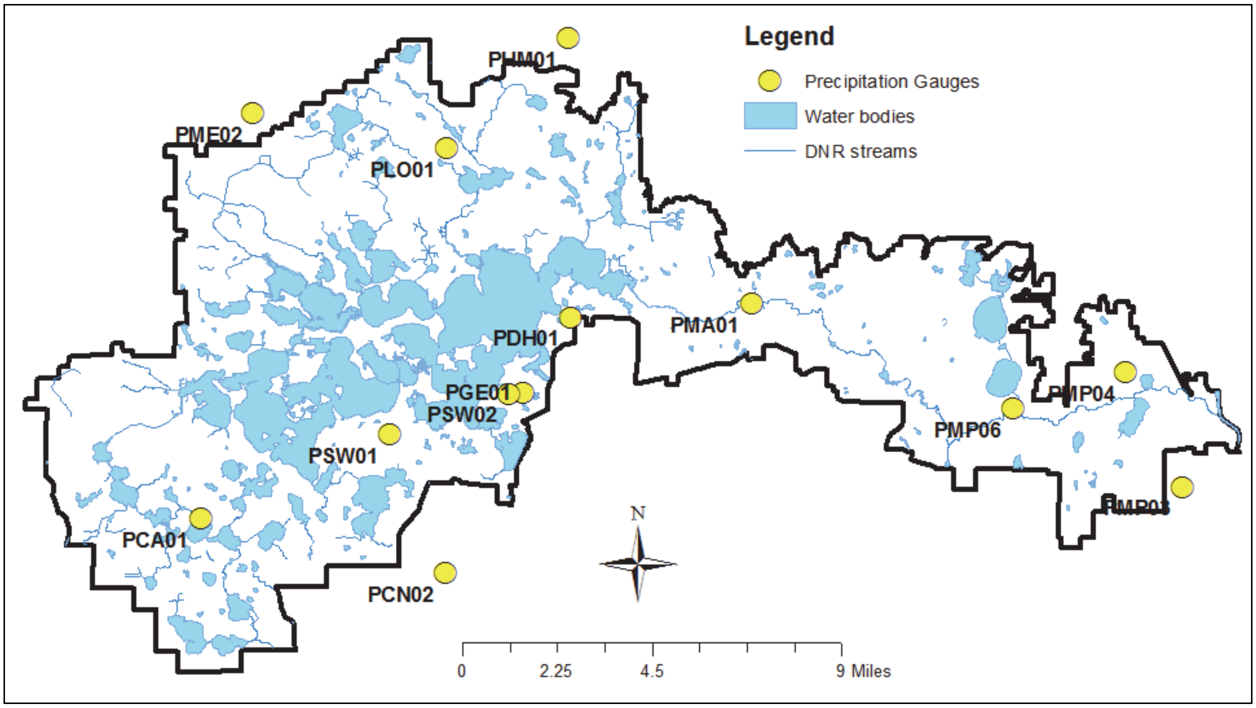


Figure 8. Rainfall monitoring gauge locations in Minnehaha Creek watershed.

Table 4. Observed 15-minute precipitation data.

Station	Station Location	Observed Record	Note
PMA01	City of Minnetonka Public Works	1/5/2006 – 4/18/2012	Included in SWMM5
PMP06	Burrough Elementary School	1/5/2006 – 4/18/2012	Included in SWMM5
PMP04	4423 Cedar Ave S Minneapolis	4/1/2010 - 12/14/2011	
PCA01	TRPD Maintenance Garage	7/28/2006 - 5/23/2012	
PDH01	MCDW office	6/22/2006 - 5/23/2012	
PLO01	Long Lake City Works Building	1/6/2006 - 5/23/2012	
PME02	Wenck Office	1/6/2006 - 4/19/2012	
PSW01	Michael Pressman's Home	6/1/2006 - 4/19/2012	

After reviewing all rainfall gauge data, it was determined that records from the PMA01 and PMP06 gauges can be used for calibration and validation of the LMCW. Rainfall data from the PMA01 and PMP06 gauges were acquired from the MCWD and included in the LMCW SWMM5 model. Rainfall data collected from the PCA01, PDH01, PLO01, PME02, and PSW01 gauges can be used in calibrating the model and validating the UMCW model.

LMCW SWMM5 model calibration. Rainfall and discharge/depth data were only available concurrently for the period of record from 2010 to 2012; therefore, this time period was adopted as the calibration/validation period for the LMCW SWMM5 model. The two rainfall gauges and three streamflow gauges operated in the LMCW provide observed 15-minute rainfall and corresponding streamflow measurements for the calibration/validation period. However, there are gaps in the streamflow record.

Storm characteristics were reviewed for a number of storms throughout the calibration period and the nature of the rainfall and the flow response were evaluated. After this analysis, the 2010 and 2011 storms were selected for model calibration. The 2012 event was selected for model validation. The 2010, 2011, and 2012 rainfall datasets were included in the LMCW SWMM5 model. To test rainfall uniformity across the LMCW, differences in 15-minute precipitation measurements at rainfall stations PMA01 and PMP06 were plotted, as shown in Figure 9.

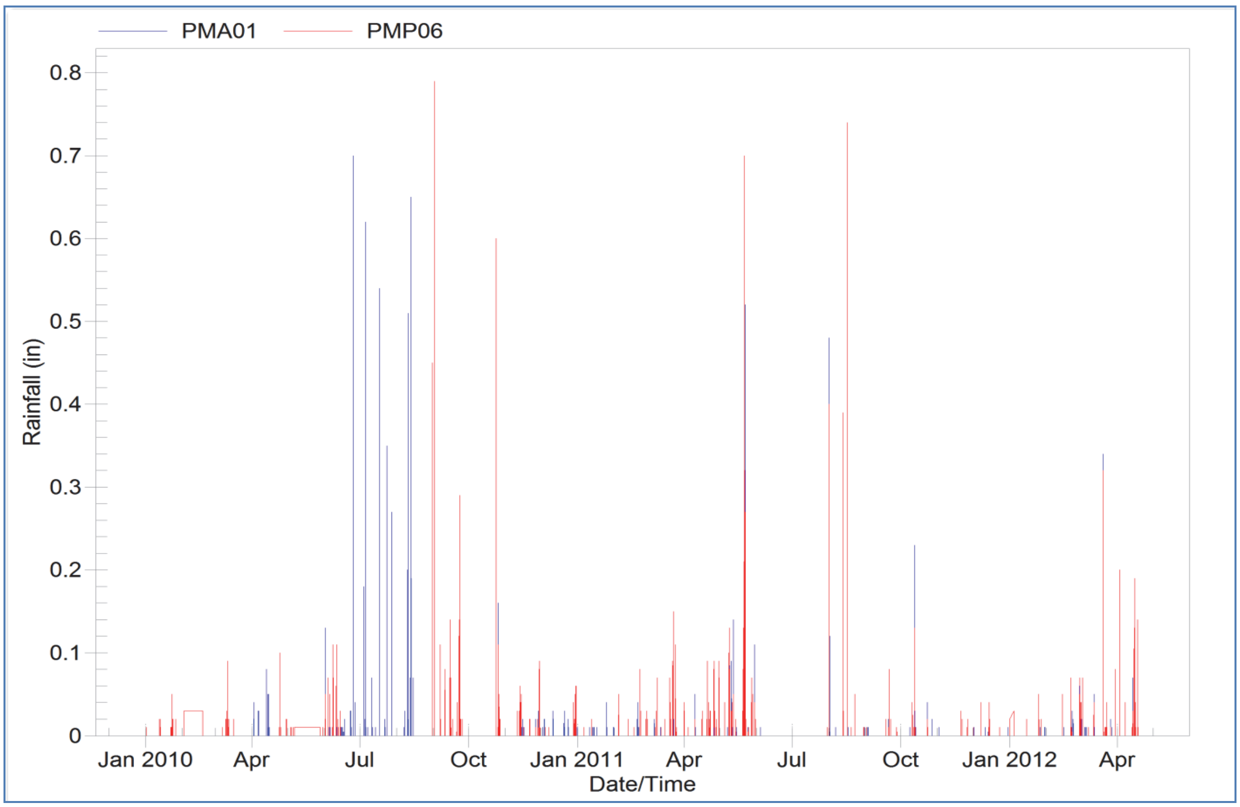


Figure 9. Differences in 15-minute precipitation measurements at gauges PMA01 and PMA06.

Figure 9 indicates the spatial variability in rainfall in the LMCW. For the majority of rainfall occurrences, the spatial variability in rainfall is moderate, but not insignificant. During the July 2010 and September 2010 rainfall events, spatial variability was great. Gauge PMA01 indicated a large storm event in July 2010 that was not observed at gauge PMP06. Gauge PM06 indicated a large storm event in September 2010 that was not observed at gauge PMA01. The precipitation reported at the gauges could be inaccurate or the density of the rainfall gauges in the LMCW may not fully characterize the spatial variability of the rainfall throughout the basin. It is recommended that the MCWD apply quality assurance/ quality control (QA/QC) checks to these records and install additional rainfall gauges throughout the basin to capture the spatial variability in rainfall within the LMCW.

The LMCW SWMM5 model was intended to run continuously in 2010; however, measured flow data were only available from April through December, so the model was run only for this period. The initial run of the SWMM5 model using the 2010 dataset revealed significant data issues. Gauge CMH07, which represents the inflow from the UMCW, is located approximately 2,300 ft upstream of gauge CMH19. As shown in Figure 10, the average difference between the two locations is significant. The difference in flow between the two sites should not be greater than 60 cfs, without an additional quantity of lateral inflow.

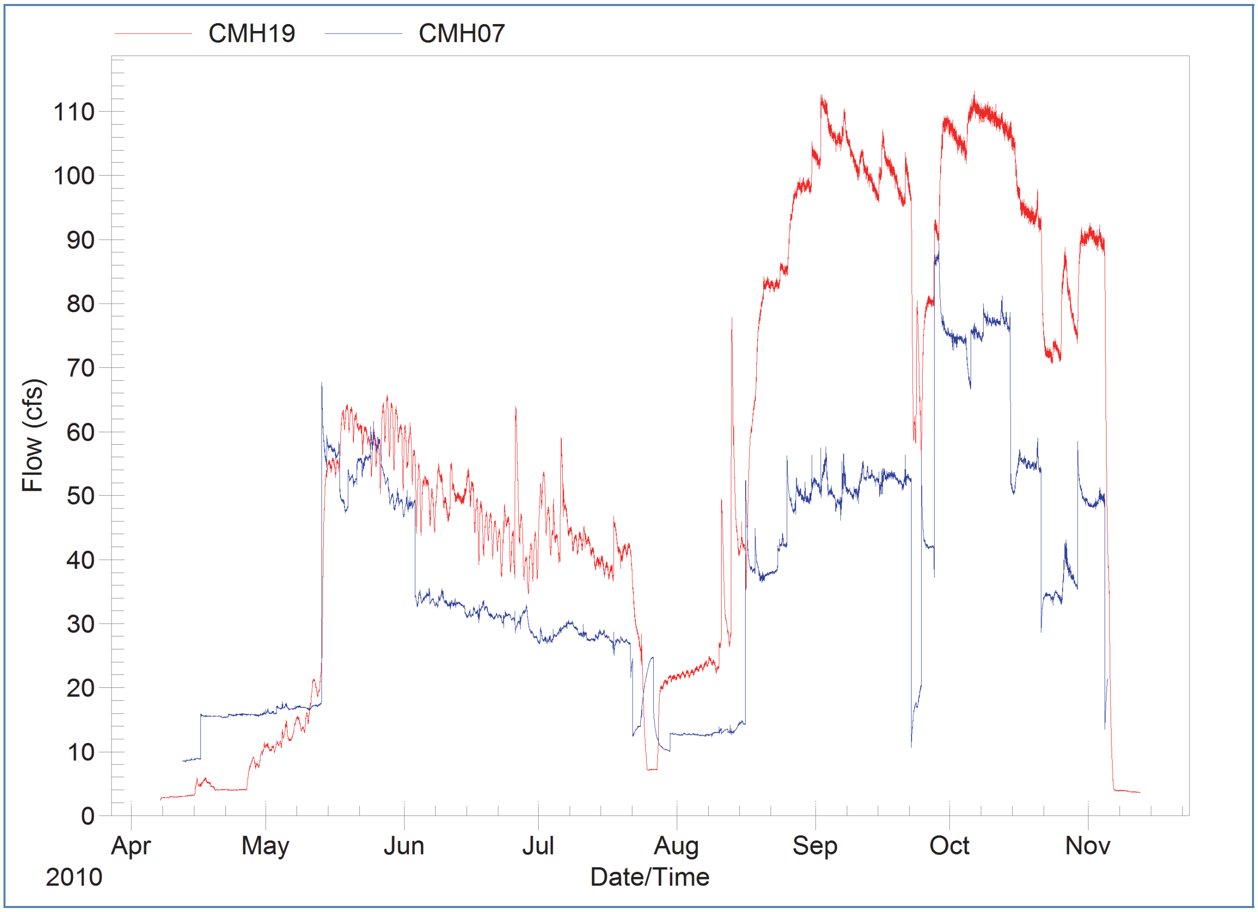


Figure 10. Differences in flow measurements at gauges CMH07 and CMH19.

After an extensive review of hydrographs generated from measurements below the Gray's Bay Dam (the outlet of Lake Minnetonka), it was found that estimated flow was incomplete or failed to satisfy the basic principle of volume balance for the LMCW. The flow rate at gauge CMH19 must be approximately the same as the inflow from gauge CMH07. The volumetric discrepancy indicated in Figure 10 is the result of either groundwater baseflow into Minnehaha Creek between gauges CMH07 and CMH19 that is unaccounted for or by transmission losses. If neither of these options explains the discrepancy, the inflow hydrograph to the LMCW from the UMCW is misrepresented.

Between Gray's Bay Dam and CMH19, there are 17 subcatchments (MC-1 to MC-17) that were not included in the original XP-SWMM models (Figure 11). Consequently, these subcatchments were not included in the SWMM5 models. These subcatchments contain a significant amount of wetland area, as shown in Figure 11. The difference observed between flow measurements at gauges CMH07 and CMH19 is likely due to groundwater flows and/or wetland effects that were not accounted for. Groundwater flow may enter the stream upstream of CMH07, which is why it may be picked up at gauge CMH19.

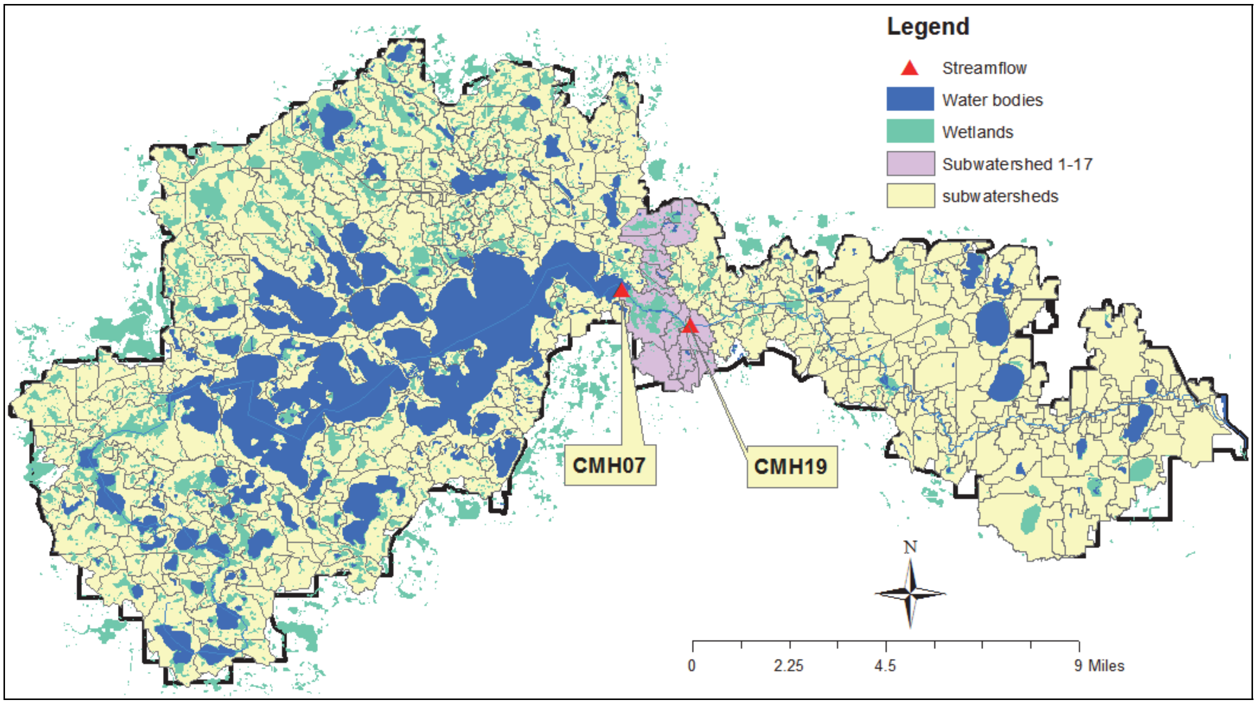


Figure 11. Subwatershed delineation and wetland areas.

Figure 11 also displays wetland areas in the Minnehaha Creek watershed extracted from the national wetland inventory data (http://www.fws.gov/wetlands/data/). The UMCW above gauge CMH19 has significant wetland area. These wetlands are likely to have multiple hydrologic functions: (1) reduce storm water peak flows, (2) absorb and slowly release storm water, supplying base flow, (3) provide convergence areas for groundwater flow and discharge the collected groundwater as surface water to the streams, and (4) provide a source for groundwater recharge through bottom leakage, creating springs along the stream. Some of these wetlands may be independent of the surface hydrology, but may be connected through groundwater seepage. Little is known about the detailed hydrogeology and the role of wetlands in the Minnehaha Creek watershed.

SWMM5 was designed to model urban runoff, but not to effectively model wetland and groundwater interactions. Field studies and additional modeling using an alternate, more appropriate software package may be necessary to learn more about wetland effects and suspected groundwater/water interactions. From communication with a local consultant, USACE also recommends that the MCWD carry out further field investigations and data collection to define the role of these wetland areas and estimate their impacts on Minnehaha Creek.

UMCW SWMM5 model calibration. The streamflow gauge in the Painter Creek subwatershed provided limited flow data. The Painter Creek subwatershed is 8,667 acres in size, and includes

26 subcatchments (PC-1 through PC-26). The area captured by the Painter Creek subwatershed (highlighted in light blue in Figure 12) is very small compared with the total area encompassed by the UMCW (Figure 12). It is inappropriate to utilize the flows observed in the Painter Creek subwatershed to calibrate the entire UMCW. Additionally, wetlands are the most dominant land category in the Painter Creek subwatershed. Thus, the effects of wetland areas and groundwater on Painter Creek need to be assessed through field study of wetland areas, before the data collected at the streamflow stations can be accurately used for calibration purposes.

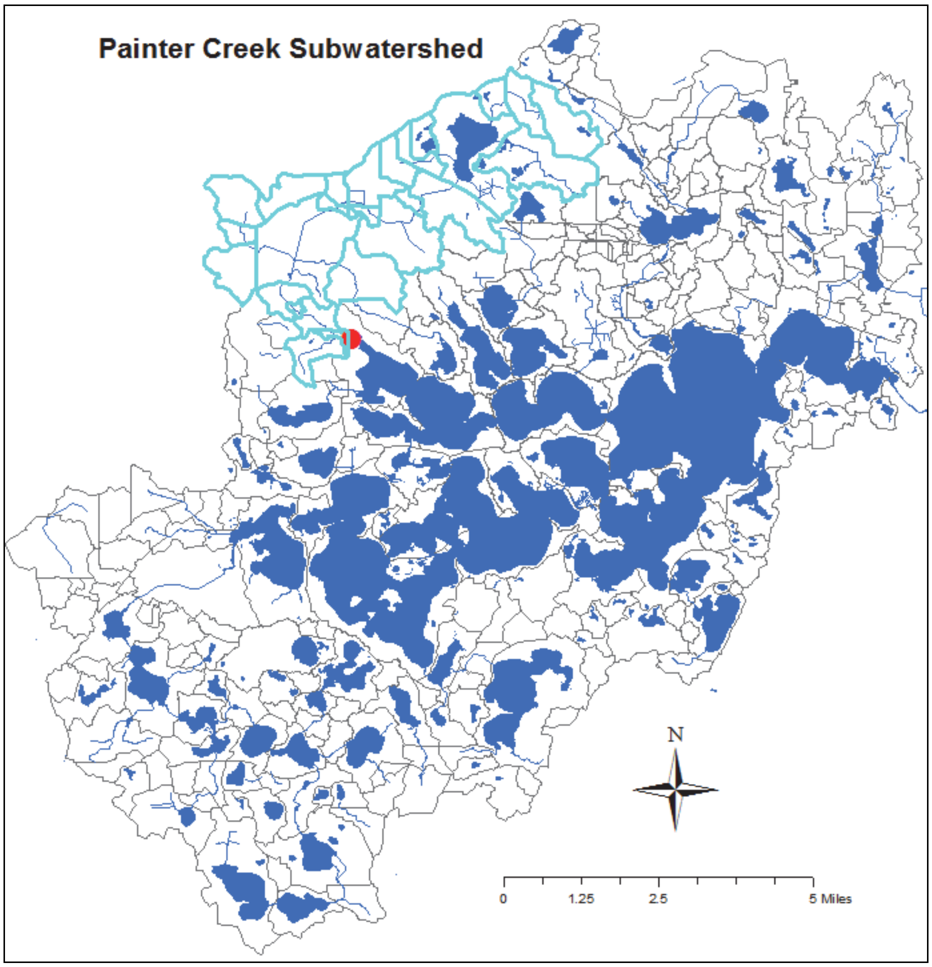


Figure 12. Painter Creek subwatershed within UMCW.

In contrast to the LMCW (which has no significant wetland area downstream of gauge CMH19), the UMCW includes many wetlands, ponds, and lakes. Ponds and lakes cover over 50% of the land area in the UMCW. Some of them were represented in SWMM5 as open channel conduits; however, evaporation rates were not simulated in the SWMM5 model since no observed evaporation data were available. Evaporation rates have a large impact on the volume balance of surface runoff in the UMCW. Omitting dynamic variation in evaporation data for a water body can lead to significant error in predicting lake surface water elevations and hydrographs. Evaporation data for these water bodies is required in order to calibrate the model. Without evaporation data and additional observed flow data, the UMCW SWMM5 model cannot be calibrated.

SWMM5 uses a single monthly value to represent evaporation losses for the whole watershed. One monthly evaporation rate does not represent the variability that can occur across the watershed's land surfaces and large water bodies. It is recommended that additional flow and evaporation data be collected in the UMCW before conducting any SWMM5 model calibration and validation. It is recommended that Lake Minnetonka and its associated open channel tributaries should be modeled using riverine and lake/reservoir models instead of an urban watershed model like SWMM5. An alternative modeling platform that can be utilized to model the UMCW is described in the following section.

RECOMMENDATIONS FOR FUTURE DATA COLLECTION/MONITORING: Data collection is an integral aspect of model development. Quality data leads to quality model output, which allows for informed decision making. Without high-quality data to calibrate and verify model output, the results of a model are not reflective of real world conditions. Reliable data are the foundation of model development.

To further improve the SWMM5 model or to support supplementary model development, additional data are needed. Data needs include the development of a GIS baseline database, synoptic rainfall and flow recordings at numerous inflow sites and stream sites in the Minnehaha Creek watershed, and field data related to wetlands and groundwater interactions.

GIS database. An accurate representation of the physical watershed and stormwater network is fundamental to developing reliable SWMM5 models. The accurate and up-to-date representation of the Minnehaha Creek watershed's physical attributes is necessary in order to ensure that the simulated hydrology, flow rates, and water depths represent real-world conditions. The watershed and stormwater system data in the current SWMM5 models have been directly imported from the XP-SWMM models provided by MCWD.

The data sources utilized to provide inputs into the original XP-SWMM models were not documented. Consequently, the SWMM5 model inputs were not verified utilizing source data. Additionally, the watershed and stormwater system data may have changed since the development of the original XP-SWMM models. The baseline data in the SWMM5 models need to be verified based on current conditions in the watershed. This will require extensive field surveys. The SWMM5 model should also incorporate the changes in land use that have occurred in the watershed over the last decade.

GIS is a powerful tool that can be utilized to develop a geospatially referenced catalog of model inputs. GIS can assist the engineer in analyzing spatial characteristics and in developing input parameters. Much of the data used in hydrologic and hydraulic modeling requires spatially referenced information. USACE recommends that a database be developed to catalogue GIS source data for MCWD's stormwater system, based on the latest information in the basin. The GIS database should include important information such as pipe IDs, pipe diameters, pipe lengths, pipe material, manhole IDs, invert elevations, pipe connectivity, and the locations of hydraulic structures such as weirs, orifices, and pump stations.

With an operative GIS database, information required by the SWMM5 model can easily be extracted from the database. This database should include maps of the MCWD storm sewer network. The map should include points of interest representative of the manholes and conduits located within the basin. A spatially referenced attribute table should also be developed to describe the dimensions, elevations, and location of all conduits and manholes. Weir, orifice, and culvert dimensions and storage pond areas (though not the inverts) should also be included in the database. Certain system features like pump stations and outfalls have flow characteristics, which define system performance. Understanding these features is critical to properly representing the system within the SWMM5 model and these features should be described in detail in the updated database.

Sources are also required in order to understand the subcatchment characteristic data. Subcatchment data inputs required by the SWMM5 model include subcatchment delineations, land use data, zoning boundaries, parcels, population, ground contours, and aerial photographs. Shamsi (1998) discusses several ways that SWMM input parameters may be estimated using GIS. Subcatchment characteristics such as area, width of overland flow, percent imperviousness, and slope may be estimated for the SWMM model. Similarly, land use data acquired from GIS-based datasets may be used to create SWMM input files for water quality simulations.

For the following elements of the SWMM5 model, the database should include the listed attributes:

Subcatchment attributes:

- ID
- inlet node
- area
- impervious area
- width
- slope
- roughness of impervious area
- roughness of pervious area
- storage of impervious area
- storage of pervious area
- infiltration parameters

Node attributes:

- ID
- longitude
- latitude
- ground elevation
- invert elevation
- inflow

- initial depth

Conduit attributes:

- ID
- upstream node
- downstream node
- type
- length
- roughness
- cross-sectional shape
- invert elevation at each end
- side slope if applicable
- initial flow
- initial depth

For lakes, ponds, and open channel networks, cross-section geometry data are required. Geometric data collected throughout the entire channel and floodplain are required to establish the connectivity of the river system schematic for model simulation. Types of information needed to describe the system include river reach network, cross-section geometry, hydraulic structure characteristics, and reach lengths of the channel and overbanks.

Data collection/monitoring in support of model calibration/verification. Measurements and observations are intrinsic and indispensable to the modeling process. The processes of calibration and validation in model application were noted earlier and in both cases, a direct comparison of model simulation to field measurements is required.

Calibration/validation event selection. For the SWMM5 model to function properly over a wide range of storm conditions, model calibration and validation storms must be selected that feature, at a minimum, the following scenarios:

1) Long Duration - Moderate Intensity Rainfall

2) Short Duration - High Intensity Rainfall

3) Long Duration- Low Intensity Rainfall (pervious-dominated)

For scenario 3, the relatively slow and steady rainfall allows for significant infiltration; thus, the model parameters related to pervious areas and infiltration, like specified soil types and initial moisture deficit, have a significant influence on the model results. Conversely, for scenario 2, storms of short duration and high intensity (e.g. thunderstorms) are considered impervious-dominated. Runoff flows quickly over the basin, allowing less infiltration. Thus, the model parameters related to impervious surfaces such as percent impervious, watershed width, and slope are more important.

Evaluating and calibrating model results requires evaluation of both the peak flows during large events and the average flows over longer periods of time. If a flood study is going to be performed, more emphasis would need to be placed on matching the peaks and volumes for large events, rather than the overall average flow for particular months.

Data collection in support of model calibration/verification.

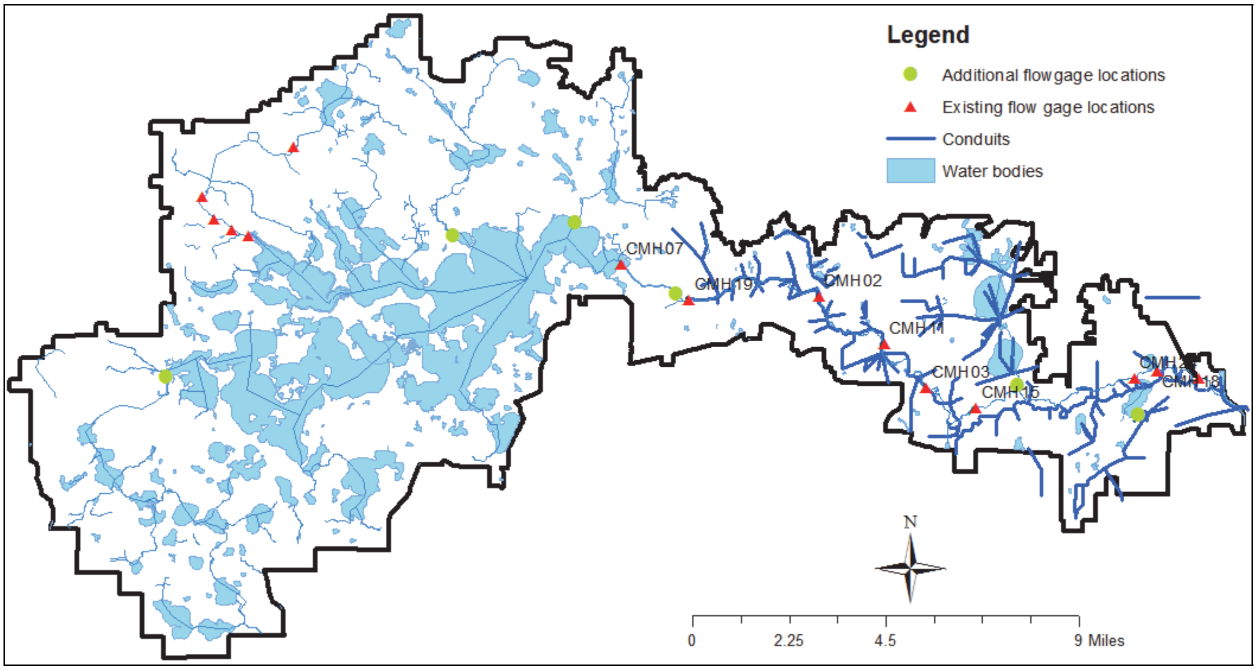
<u>Streamflow data collection network.</u> Besides calibrating the model to flow gauges located on the mainstem of Minnehaha Creek, model calibration should also be performed using observed data representative of major tributary contributions. In order to accomplish this, additional flow data need to be collected and added to the SWMM5 model. There are essentially two basic classes of flow systems in the Minnehaha Creek watershed: 1) closed conduits, and 2) open channels. Flow in a closed conduit may occur as pipe flow. Measuring flow in a pipe requires that special measurement devices (like flow meters) be installed. There are many meters and methods for measuring or estimating pipe flow velocities and volumes. Information needed for flow monitoring should include flow discharge and stream water level.

Figure 13a indicates approximate locations where additional flow monitoring gauges should be installed in the Minnehaha Creek watershed. One should be aware that the proposed gauge locations are representative of the minimum required gauge density necessary to accurately calibrate and validate the UMCW and LMCW models. If funding is available and further investigations are necessary for larger subwatersheds, additional flow monitoring gauges may be required, as shown in Figure 13b. When any of the subwatersheds require further investigation, the model needs to be calibrated for that subwatershed. An additional flow gauge for that subwatershed is required for the model calibration. Gauges have been placed without any consideration of physical suitability or budget constraints. MCWD has the flexibility to install more flow monitoring gauges if resources become available.

Observed data are not available for some of the existing flow gauge locations (Figures 13a and 13b), so MCWD needs to ensure that these gauge sites remain operative. In general, streamflow data should be collected utilizing a time interval of less than 1 hr.

<u>Precipitation data collection network.</u> Additionally, as illustrated in Figure 8, the five currently operating rain gauges do not form a rain gauge network dense enough to adequately characterize the spatial variability of rainfall throughout the entire Minnehaha Creek watershed. More rain gauges are needed to solve this problem. Rainfall gauges are used to measure and record the amount of precipitation that falls during a storm. Figure 14a provides proposed additional rainfall gauge locations in Minnehaha Creek watershed for reference. Precipitation may be highly variable within a small area. More precipitation gauges may be needed as shown in Figure 14b if funding is available and precipitation data collected from the these locations cannot provide a reliable estimate of the areal distribution of precipitation throughout the watershed. One should be aware that the proposed gauge locations are representative of the minimum required gauge density necessary to accurately calibrate and verify the UMCW and LMCW models. These gauge locations have been selected without any consideration of physical suitability and budget

constraints. Note that MCWD has flexibility to install more rainfall gauges if it is found that these gauges still cannot capture the spatial distribution of rainfall in the Minnehaha Creek watershed. In general, precipitation data should be collected using a 5- or 15-minute time-step.



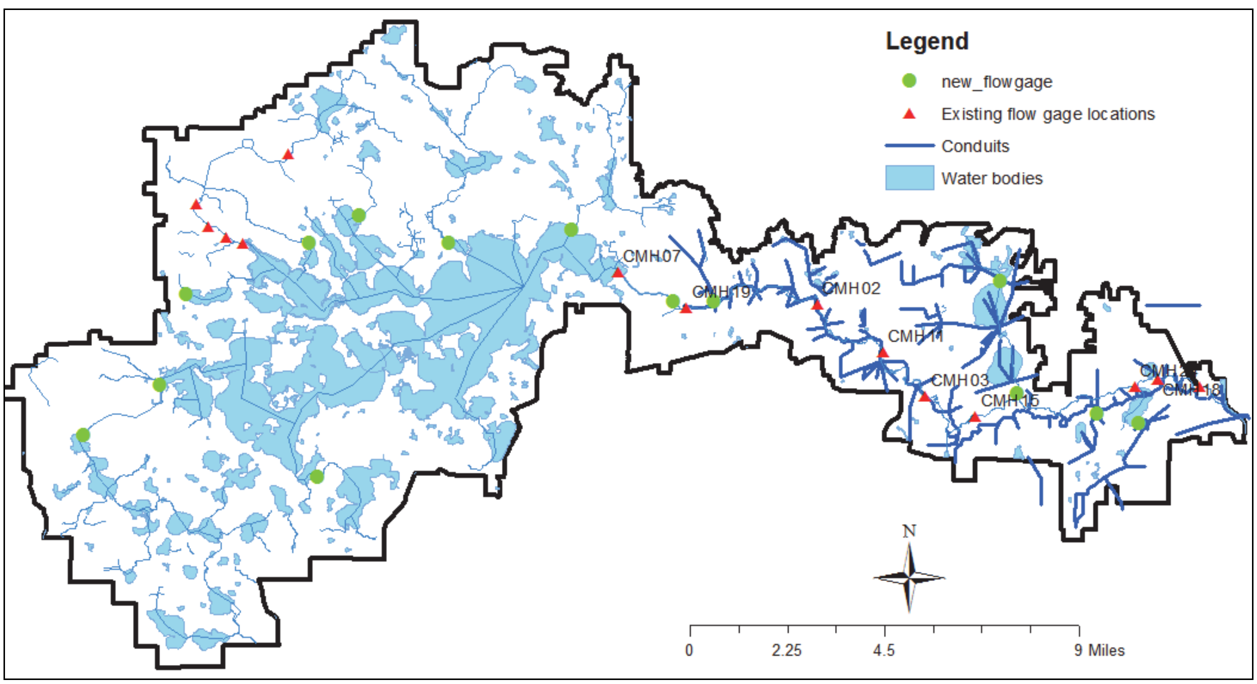


Figure 13. Additional flow gauge locations.

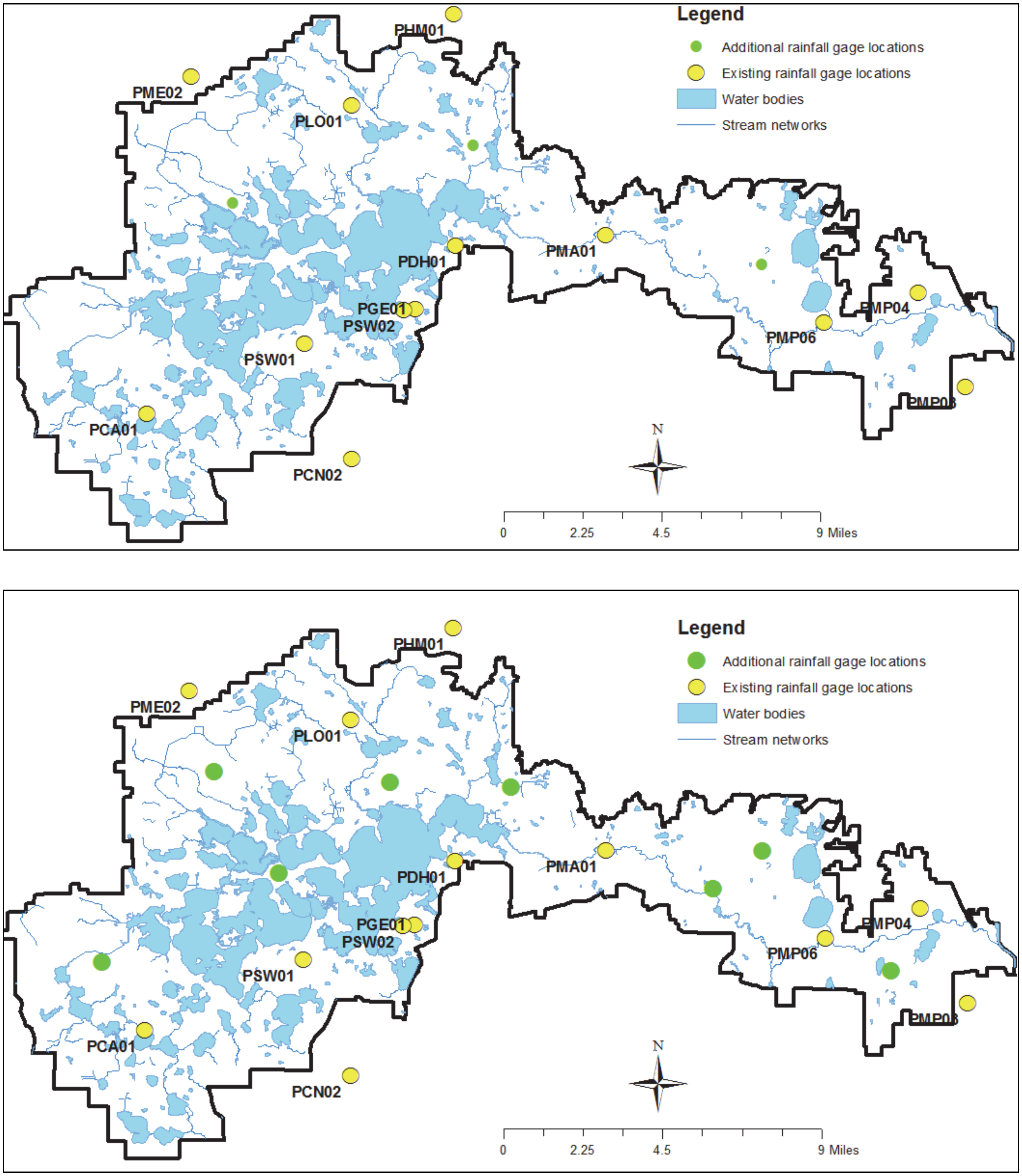


Figure 14. Additional rainfall gauge locations.

The additional precipitation and flow gauges described above should be utilized only as a starting point. The number of gauges installed directly affects the quality of precipitation and flow data. The higher the number of gauges, the better the estimate of precipitation and flow amounts. MCWD should evaluate the topography, climate, and project objectives to determine ideal numbers and locations of gauges. Proper installation and maintenance of the gauge is also important.

Hydrogeology data collection. To better characterize the effects of wetland areas and groundwater on Minnehaha Creek, field work must be done in the wetland areas to take measurements and collect scientific data to assess wetland function and groundwater flow. Groundwater monitoring wells should be installed in wetland areas within the Minnehaha Creek watershed as part of the monitoring program. Groundwater flow, direction, and elevation as well as soil types should be established before monitoring sites are chosen. Observation wells include both those that allow for measurement of the water table and those that allow for measurement of the hydraulic head below the water table. It may be necessary to install multiple sets of wells to obtain an accurate representation of the water table. For example, if the wetland site encompasses two sites of a stream like Minnehaha Creek, each with a different gradient, at least three wells must be installed on each side of the stream.

Snowmelt modeling. The majority of the large events observed in the Minnehaha Creek watershed are snowmelt driven. In order to characterize these events, the Minnehaha Creek Watershed modeling initiative would benefit from better characterizing snowmelt-driven runoff.

To predict snowmelt runoff, a better understanding of the influence of various meteorological parameters is needed. The collection of vapor pressure, wind speed, and air temperature data will be necessary in SWMM5 modeling. Also, a system for measuring the amount of melt water draining from the base of the snowpack is useful in snowmelt runoff model calibration.

RECOMMENDATIONS FOR FUTURE MODELING EFFORTS AT MCWD: The Minnehaha Creek watershed includes highly urbanized areas, non-urban lands, and wetlands. There is a large lake, many ponds, open channels, pressure pipe networks and hydraulic structures in the watershed. It is difficult for a single modeling platform to represent all of the components and natural water processes in the watershed. To better understand the movement of water across the landscape and within engineered systems, an integrated modeling approach utilizing more than one software package is the preferred approach. Individual models can be used to simulate different components of the Minnehaha Creek watershed system to provide the necessary information. From an operational point of view, the formatting and I/O (input/output) options may be important in facilitating the coupling of the watershed model outputs to receiving watershed models. In determining the applicability of a model, there are numerous aspects of that model to be considered, ranging from the processes incorporated in or excluded from the model formulation, the numerical treatment of the basic equations, how the model is coupled to the larger watershed system, which input data are required, and the specifics of the computer program embodying all of the above.

Choosing the best model or suite of models to utilize depends upon modeling objectives and watershed characteristics. Based on the objectives outlined by MCWD and the characteristics of the Minnehaha Creek watershed, USACE recommends that the commonly used hydrologic/ hydraulic and water quality modeling software packages listed in Table 5 be adopted for the stated target applications. Three tiers of models that vary their level of input and degree of complexity are provided. The organization that provides the software is also provided in Table 4. Based on experience with the modeling software packages, a brief discussion is provided that summarizes the advantages associated with the recommended software packages in fulfilling a given project objective for a given portion of the watershed.

Table 5. Alternative models and target applications.			
Tier	**Models**	**Target Watersheds or Water Bodies**	**Organization**
1	SWMM5	LMCW	EPA
1	HEC-RAS	Minnehaha Creek and Lake Minnetonka system	HEC
2	CE-QUAL-W2	Lake Minnetonka system	ERDC Portland State University
3	GSSHA	UMCW	ERDC

All of the recommended models are non-propriety. These models are well-known and widely accepted in the engineering community. The proposed models have a high degree of reliability and flexibility for modeling various, complex scenarios. More detailed discussions for the models provided herein and their target applications are available in the following sections. USACE recommends that the MCWD develop these models using a tiered approach. An increased level of effort and complexity is associated with models in Tier 2 and Tier 3. Models in Tier 1 should be developed first, followed by the development of models in Tier 2 or 3, if needed. Tier 2 and Tier 3 models require more input data than Tier 1 models. Once a modeling platform is selected, MCWD needs to design a monitoring program to support it. The modeling approach should be evaluated and adjusted as needed to adequately address project goals and priorities.

SWMM5 and HEC-RAS are the recommended Tier 1 models. The current SWMM5 model is an appropriate modeling platform for modeling subbasins in the LMCW. HEC-RAS should be used to model Minnehaha Creek and the Lake Minnetonka system. This suite of models can be utilized for flood plain management, hydrologic and hydraulic studies, and basic water quality and pollutant control study. Under the Tier 1 modeling approach, drainage inputs into the Lake Minnetonka system can be provided by monitoring major tributaries. If there is a need for modeling subwatersheds in the UMCW, an alternative modeling platform needs to be considered. Figure 15 shows the Tier 1 modeling study area maps for the two models. Figure 16a shows how the Tier 1 models are integrated into a streamlined modeling approach. HEC-RAS is recommended for modeling Minnehaha Creek and the Lake Minnetonka System in the UMCW. The existing SWMM5 model is the recommended modeling platform for the LMCW subbasins. HEC-RAS is the recommended modeling platform for Minnehaha Creek open channel flow in the LMCW.

CE-QUAL-W2 is a Tier 2 model that may be used to better characterize hydrodynamics and water quality conditions in Lake Minnetonka. GSSHA modeling in the UMCW is proposed as a Tier 3 modeling platform. The GSSHA model may be used to clarify the following issues: surface water and groundwater interactions, the effect of wetland area and subsurface hydrology in the UMCW. If all models are developed and implemented, their integration plan is illustrated in Figure 16b.

Improvement of current SWMM5 model. SWMM5 is well suited for modeling the LMCW below gauge CMH19, downstream of the wetland areas currently not included in the model. Most of the pipe network and channel geometry was taken directly from the XP-SWMM model.

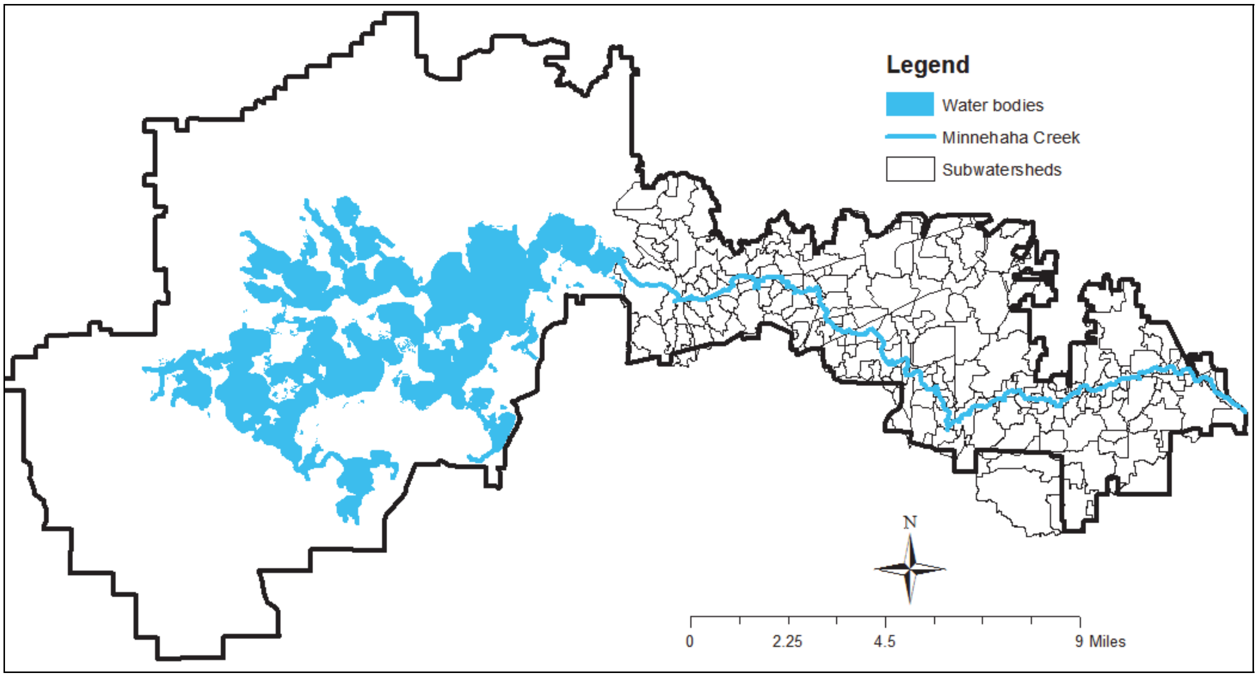


Figure 15. Tier 1 SWMM5 and HEC-RAS modeling domains.

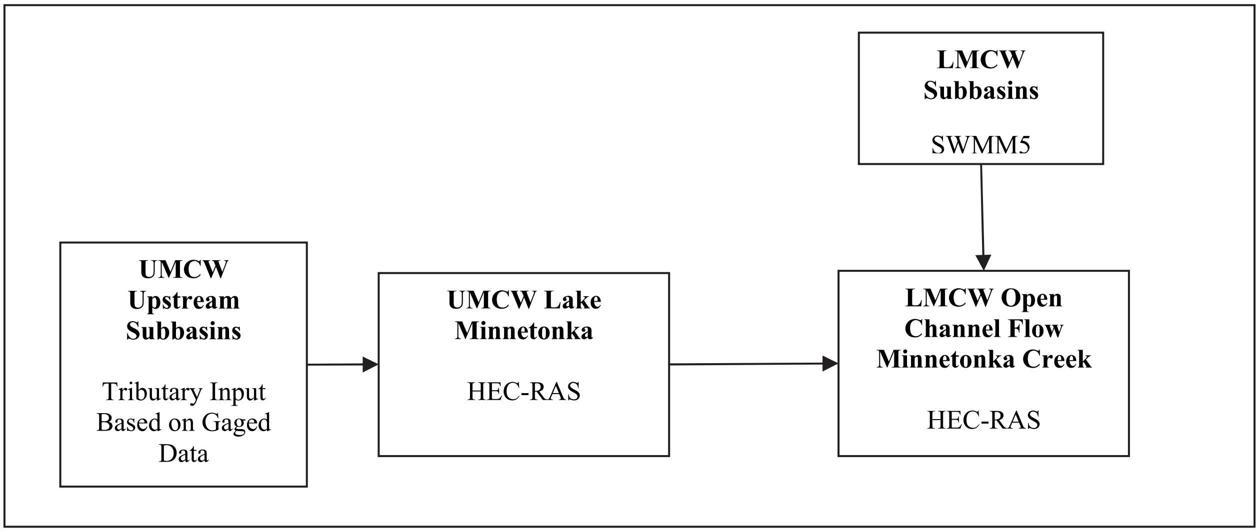
There are some potential sources of errors in the current LMCW SWMM5 model. Some of these errors could be eliminated with a more detailed study of the watershed, including updated pipe networks and hydraulic structures, better channel geometry, and a better understanding of the hydrogeology. A more complete survey of the stormwater system and stream channel could improve model accuracy.

One significant source of error in the SWMM5 model simulations is the area upstream of the LMCW. This area consists of a significant amount of wetland area and is currently excluded from the LMCW model and the UMCW model. The lack of information related to the effects that wetland and groundwater interactions have on the hydrology of the Minnehaha Creek watershed makes it difficult to calibrate the LMCW model.

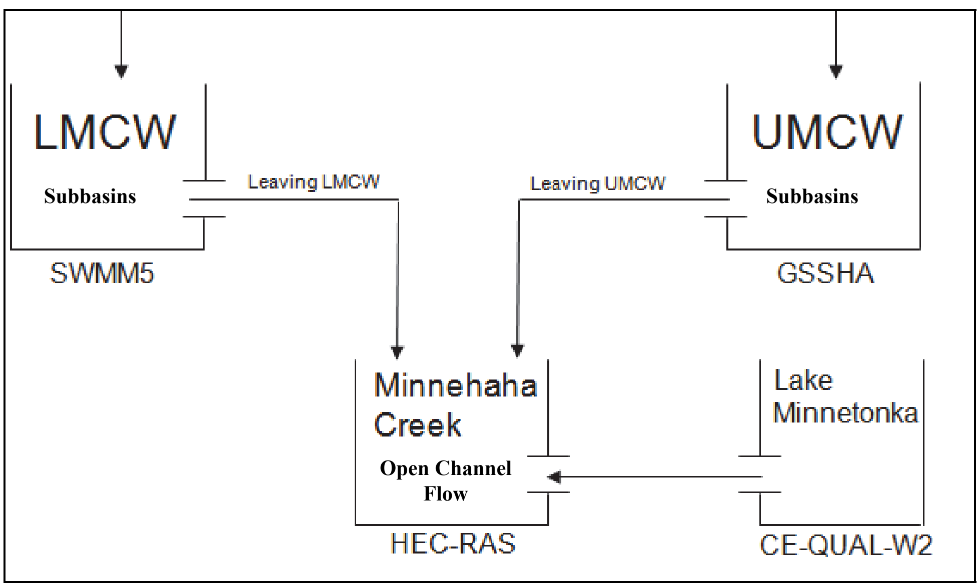
SWMM5 does not simulate wetlands effectively because it does not allow for channelized flow to contribute to groundwater flow via seepage and recharge, and vice versa. It is likely that the hydrogeology of the Minnehaha Creek Watershed includes groundwater recharge from the significant wetland areas. Wetlands are likely a supply source of water to Minnehaha Creek. SWMM5 is not well suited for modeling the UMCW and the intervening area between the UMCW and the LMCW that is characterized by substantial wetland area. An alternative modeling platform needs to be considered to address these issues.

Floodplain management. Floodplain and floodway evaluations are the basis for flood management programs. Management personnel wish to know when (time) a stream will reach its peak flow rate, how high (elevation) the peak water surface elevation will be, how much flow (quantity) will occur at the peak, and where (spatial location) the peak will arrive. The objective is to develop a reliable Minnehaha Creek hydraulic model, acceptable to FEMA, that adequately supports flood plain management. The Hydrologic Engineering Center-River Analysis System

(HEC-RAS) model is recommended for modeling open channel flow throughout the Minnehaha Creek watershed. This model uses physical field measurements of stream and floodplain cross sections to estimate flow values (rate, velocity, energy, water surface elevation) from one section to another.



a. Tier 1 models and model integration.



b. Tier 2 and 3 models and modeling integration with Tier 1 models.

Figure 16. Models and model integration.

HEC-RAS is designed to perform one-dimensional hydraulic calculations for a full network of natural and constructed channels (HEC 2010). It is non-proprietary and can be downloaded from U.S. Army Corps of Engineer Hydrologic Engineer Center's website (http://www.hec.usace.army.mil/software/hec-ras). The HEC-RAS system contains four one-dimensional river analysis components for: (1) steady flow water surface profile computations, (2) unsteady flow simulation, (3) movable boundary sediment transport computations, and (4) water quality analysis (via NSM).

A key element of the HEC-RAS system is that all four components use a common, physically based representation of the floodway and common geometric and hydraulic computation routines. In addition to the four river analysis components, the system contains several hydraulic design features that can be invoked once the basic water surface profiles are computed.

The Steady Flow Water Surface Profile component of the modeling system is intended for use in calculating water surface profiles for steady gradually varied flow. The system can handle a full network of channels, a dendritic system, or a single river reach. The steady flow component is capable of modeling water surface profiles for subcritical, supercritical, and mixed flow regimes. The basic computational procedure is based on the solution of the one-dimensional energy equation. Energy losses are evaluated by friction (Manning's equation) and contraction/expansion (coefficient multiplied by the change in velocity head). The momentum equation may be used in situations where the water surface profile is rapidly varied. These situations include mixed flow regime calculations (i.e. hydraulic jumps), hydraulics of bridges, and profile evaluations at river confluences (stream junctions).

The effects of various obstructions such as bridges, culverts, weirs, and structures in the flood plain may be considered in the computations. The steady flow system is designed for application in flood plain management and flood insurance studies to evaluate floodway encroachments. Also, capabilities are available for assessing the change in water surface profiles due to channel improvements, and levees. Special features of the steady flow component include: multiple plan analyses; multiple profile computations; multiple bridge and/or culvert opening analyses; and split flow optimization.

The HEC-RAS steady flow system is designed for application in flood plain management and flood insurance studies to evaluate floodway encroachments. HEC-RAS has the capability to perform inundation mapping of water surface profile results directly from HEC-RAS. Using the HEC-RAS geometry and computed water surface profiles, inundation depth and floodplain boundary datasets are created through the RAS Mapper.

Hydrologic and hydraulic study. If MCWD is concerned with all aspects of the water environment, including urban infrastructure, water supply, water resources, and environmental compliance, both hydrologic and hydraulic models are required. In general, hydrologic models are used to determine the amount of stormwater runoff that will be generated from a subbasin during a storm or series of storms. Hydrologic models simulate flow values based on topography, land use characteristics, soil types, and meteorological parameters. Hydraulic models are then used to route the flows generated by the hydrologic model through the conveyance system, such as pipes or natural channels, to evaluate the performance of the watershed system during different storm frequencies. In the Minnehaha Creek watershed, the conveyance systems consist of natural channels, wetlands, enclosed storm drain systems, and hydraulic structures.

Several models can be used to accurately model the hydrologic and hydraulic components of the Minnehaha Creek watershed. For UMCW hydrology modeling, the ERDC GSSHA (Gridded Surface Subsurface Hydrologic Analysis) model is recommended to model surface runoff. For LMCW hydrology modeling, SWMM5 is recommended. For Minnehaha Creek and Lake Minnetonka hydraulic modeling, the HEC-RAS unsteady state model is recommended.

GSSHA. SWMM5 is not the best modeling platform for the UMCW. Applying SWMM5 to the UMCW imposes limitations due to the numerous water bodies and wetlands that exist in the UMCW. Water bodies, including Lake Minnetonka, cover a significant area of the UMCW. SWMM5 was designed to model urban runoff and is not designed to model large water bodies, wetlands, or groundwater interactions effectively. This is a significant issue in the UMCW. Additionally, it is not possible to accurately model the dynamic evaporation mechanisms that have a considerable effect when attempting to simulate the hydrology and hydraulics of a watershed that contains a significant number of ponds and lakes in the SWMM5 model.

In addition, wetlands play a large role in the hydrology of Minnehaha Creek. Wetlands have multiple functions in the watershed: (1) reduce storm water peak flows, (2) absorb and slowly release storm water, supplying base flow to the stream, (3) provide convergence areas for groundwater flow, and (4) provide a source for groundwater recharge through bottom leakage, creating springs along the stream. Wetlands processes are modeled differently than overland flow or groundwater processes. A model with the ability to effectively model wetland hydrology and flow processes in greater detail would provide for a deeper understanding of the importance of wetland and baseflow effects on flows in the Minnehaha Creek watershed.

Alternative modeling and further investigation of the wetlands and their impacts on the hydrology of Minnehaha Creek are recommended by USACE. GSSHA is one of the few watershed models capable of modeling wetlands and the interactions between surface water and groundwater flow (Downer and Ogden 2006). GSSHA is a physically-based, distributed-parameter, structured-grid, hydrologic model that simulates the hydrologic response of a watershed subject to given hydro-meteorological inputs. The watershed is divided into grid cells that comprise a uniform finite difference grid. GSSHA is a reformulation and enhancement of the CASC2D (Figure 17). The model incorporates 2D overland flow, 1D stream flow, 1D unsaturated flow, and 2D groundwater flow components. The GSSHA model employs mass conservation solutions of partial differential equations and closely links the hydrologic components to assure an overall mass balance. GSSHA had already been tested and applied for hydrologic response in several watersheds and achieved satisfactory results. A brief introduction follows; details of the GSSHA model can be found at the web site (*http://www.gsshawiki.com*). Application of GSSHA to the UMCW and the 17 subcatchments (MC-1 to MC-17) between Lake Minnetonka and the LMCW will enable the complex interactions between groundwater and surface water in the Minnehaha Creek watershed to be simulated.

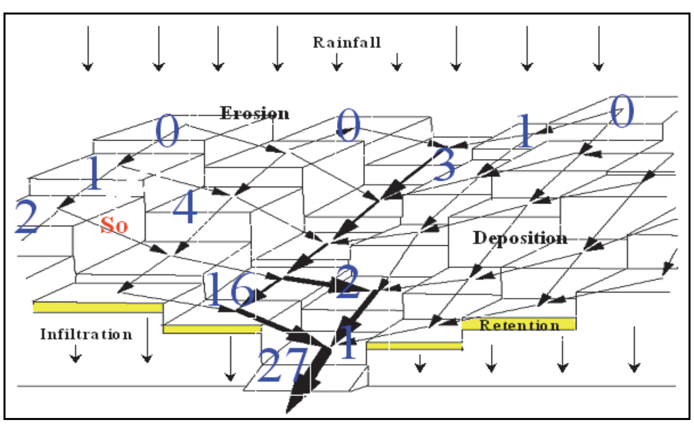


Figure 17. Topographical representation of overland flow and channel routing schemes within a watershed.

The modeling of hydrologic processes begins with rainfall being added to the watershed, some of which is intercepted by the canopy cover, and then evapotranspirated or infiltrated. Hydrologic processes that can be simulated and the methods used to approximate these processes within the GSSHA model are listed in Table 6.

Table 6. Processes and approximation techniques in the GSSHA model.

Process	Approximation
Precipitation distribution	Thiessen polygons (nearest neighbor) Inverse distance-squared weighting
Snowfall accumulation and melting	Energy balance
Precipitation interception	Empirical two parameter
Overland water retention	Specified depth
Infiltration	Green and Ampt (GA) Multi-layered GA Green and Ampt with Redistribution GAR) Richard's equation (RE)
Overland flow routing	2-D diffusive wave
Channel routing	1-D diffusive wave, 1-D dynamic wave
Evapo-transpiration	Deardorff Penman-Monteith with seasonal canopy resistance
Soil moisture in the vadose zone	Bucket model RE
Lateral groundwater flow	2-D vertically averaged
Stream/groundwater interaction	Darcy's law
Exfiltration	Darcy's law

Water quality and pollutant control study. From a water quality standpoint, for the Minnehaha Creek watershed, the most important watercourses are Minnehaha Creek and the Lake Minnetonka system. Water quality conditions in Minnehaha Creek and Lake Minnetonka affect allowable waste loads, thus impacting activities such as future development and changes in land use practices. Generally, more spatial detail is necessary in these receiving watercourses than in the contributing watersheds, because it is in the receiving watercourse that the target water quality criteria must be met in the Environmental Protection Agency's (EPA) TMDL (Total Maximum Daily Load) program and pollution control studies. Minnehaha Creek is an open channel and thus HEC-RAS can be utilized to model sedimentation and water quality issues in Minnehaha Creek. Lake Minnetonka hydrodynamics and water quality can be modeled most accurately using the two-dimensional (2D) CE-QUAL-W2 model.

HEC-RAS. To evaluate Minnehaha Creek water quality, the primary variation is considered to be in the longitudinal direction (upstream to downstream). Consequently, a cross-sectional mean is an adequate approximation of the constituent concentration at any position along the watercourse. The need for water quality modeling to also consider time-dynamic flows means that the hydrodynamic part of the model will have to be given more careful consideration. The Unsteady Flow component of the HEC-RAS modeling system is capable of simulating one-dimensional (1D) unsteady flow through a full network of open channels. The model is able to simulate backwater flow effects and a variety of hydraulic structures. The hydraulic calculations for cross sections, bridges, culverts, and other hydraulic structures that were developed for the steady flow component were incorporated into the unsteady flow module. The latest HEC-RAS systems also have capabilities for sediment and water quality analysis (Figure 18).

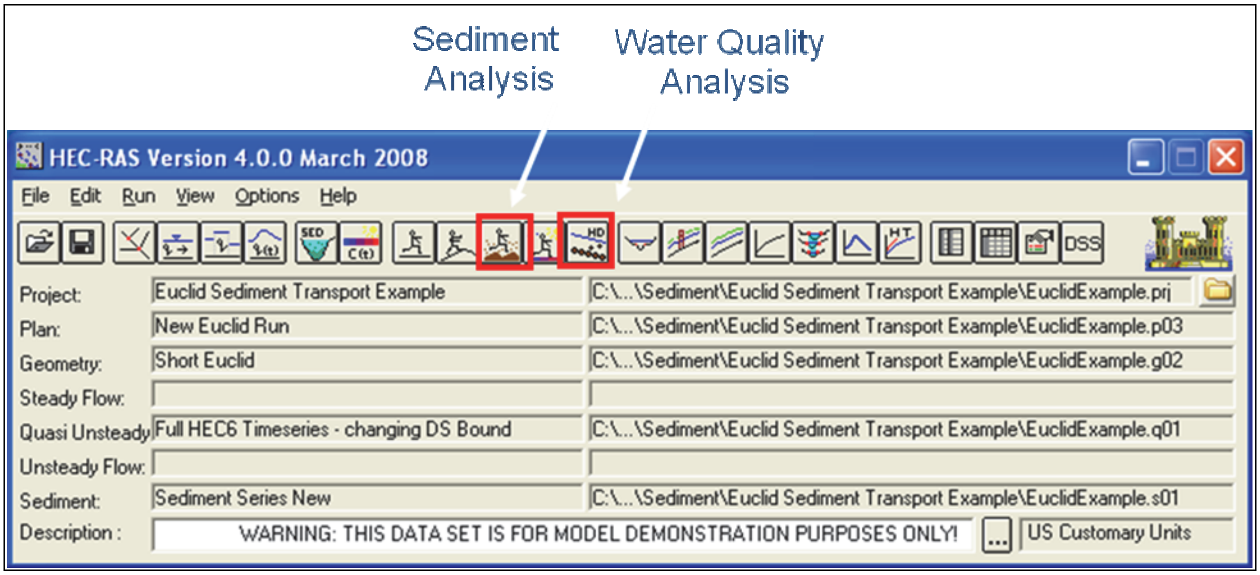


Figure 18. HEC-RAS main user interface.

Sediment transport/movable boundary computations in HEC-RAS. This component of the modeling system is intended to simulate 1D sediment transport/movable boundary calculations resulting from scour and deposition over moderate time periods (typically years, although applications to single flood events are possible). The sediment transport potential is computed by grain size fraction, thereby allowing the simulation of hydraulic sorting and armoring. Major features include the ability to model a full network of streams, channel dredging, various levee and encroachment alternatives, and the use of several different equations to compute sediment transport.

The model is designed to simulate long-term trends of scour and deposition in a stream channel that might result from modifying the frequency and duration of the water discharge and stage, or modifying the channel geometry. This system can be used to evaluate deposition in reservoirs, design channel contractions required to maintain navigation depths, predict the influence of dredging on the rate of deposition, estimate maximum possible scour during large flood events, and evaluate sedimentation in fixed channels.

NSM (Nutrient Simulation Module). NSM is a set of nutrient kinetic libraries developed by U.S. Army Engineer Research and Development Center (ERDC) for HEC-RAS (Zhang and Johnson, in preparation). Riverine water quality simulation can be conducted with the chosen complexity level using NSM. NSM I computes riverine algal biomass, nitrogen and phosphorus cycling, and dissolved oxygen (DO) concentrations. NSM II has the capability of simulating up to the twenty-third state water quality variable and computes multiple algal biomass, nitrogen, phosphorus, and carbon cycling, DO, pH and pathogen, as well as numerous additional constituents and processes. In addition, NSM III incorporates a dynamic bed sediment diagenesis component, which simulates the chemical and biological processes undergone at the sediment-water interface after sediments are deposited. Incorporating NSM water quality capabilities in

HEC-RAS provides a fully integrated riverine hydraulic, sediment, and water quality model that encompasses diagnostic, predictive, and operational applications that greatly aid in Total Maximum Daily Load (TMDL) development and implementations required by the Clear Water Act.

The HEC-RAS model uses physical field measurements of stream and floodplain cross sections to estimate flow (rate, velocity, energy, and water surface elevation), transport, and fate of pollutants from one section to another. Developing and applying the HEC-RAS model for Minnehaha Creek will provide tools not only for flood management, but also for pollutant/ sediment load allocation studies.

CE-QUAL-W2. The key defining property that differentiates a lake from the riverine watercourses is the long detention time that is a result of the large ratio of the volume of the lake to its inflow. Because of this property of detention, lakes pose the possibility of retention and accumulation of pollutants, and the resulting effects on water quality can be more problematic than the purely flux-dominated stream or river. An additional consequence of the long detention time is the possibility of warm-season stratification due to receipt and accumulation of heat in the near-surface layers.

The 1D HEC-RAS model or SWMM watershed model cannot capture the details of these flow patterns in Lake Minnetonka because vertical variations are not simulated. The complex flow patterns in Lake Minnetonka result in a wide distribution of residence times there. An increased or decreased travel time has an important effect on water quality because more or less time is available for settling or decay or other processes. A more detailed examination of hydrodynamics and water-quality processes in Lake Minnetonka in the future could benefit from the development of a 2D model. The ability to predict hydrodynamics and water quality under different conditions will allow the MCWD to determine if surface elevation and water quality of the lake will be affected.

CE-QUAL-W2 is a 2D longitudinal/vertical, hydrodynamic and water quality model that has been under continuous development for three decades (Cole and Wells, in preparation). W2 is capable of modeling water elevation, flow, water temperature, and 28 water quality constituents. The model has the following major capabilities:

1) Applicable to sloping rivers, lakes, reservoirs, and estuaries and any combination thereof
2) Applicable to multiple water bodies and branches
3) Provides accurate numerical solution schemes
4) Has the ability to model any number of inorganic suspended solids, algal, periphyton, and CBOD groups and their impacts on algal/nutrient/dissolved oxygen interactions
5) Can accommodate any number of generic constituents defined by a 0 and/or 1st order decay rate and/or a settling rate, which can include conservative tracers, coliform bacteria, water age, and contaminants

CE-QUAL-W2 is a well-tested and utilized code in the government, private consulting, and academic arenas. The model has now been successfully applied to over 400 systems in the

United States and throughout the world for thermal and water quality investigations. It is the reservoir hydrodynamic and water quality model of choice for U.S governmental agencies including the Environmental Protection Agency (EPA), Bureau of Reclamation (USBR), Geological Survey (USGS), Army Corps of Engineers (USACE), and Tennessee Valley Authority (TVA), as well as numerous states, counties, and local agencies. For a list of the model applications, see the CE-QUAL-W2 website*:* *http://www.ce.pdx.edu/w2/*. A typical model grid is shown in Figure 19.

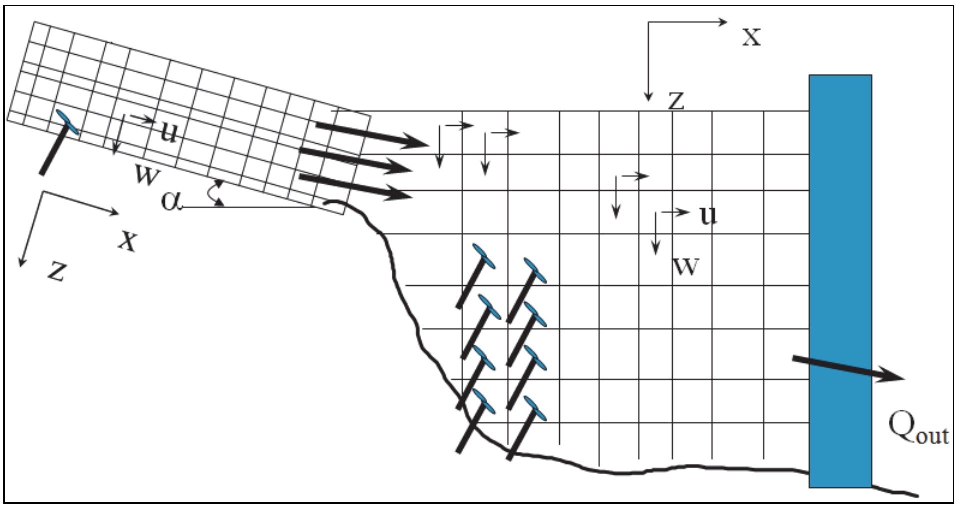


Figure 19. Schematic representation of typical CE-QUAL-W2 model grid.

W2 is appropriate for modeling Lake Minnetonka systems with spatially varying depths. W2 is able to simulate various responses due to changes in flow and loads. W2 can also provide a bridge to other models in the Minnehaha Creek watershed.

Model scaling. The watershed models described above are used to simulate the whole LMCW and UMCW. Both SWMM5 and GSSHA are capable of providing results for each sub-watershed. If MCWD is interested in detailed investigation at a subwatershed level, these models need to be calibrated for that subwatershed without any modification of the model setup. Therefore a flow gauge installed at that subwatershed is necessary. If refined soil, land use, or flow network information needs to be incorporated into the model, then the model must be refined using these localized data.

HEC-RAS and CE-QUAL-W2 are used to simulate the Minnehaha Creek and Lake Minnetonka water bodies. These model set-ups should be good for any level of investigation as long as the geometry information included in these models is anaccurate representation of the systems. Additional calibration may be necessary for a detailed study.

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LIST OF ATTACHMENTS

The following files are attached to the electronic version of this technical note.

- Memorandum for Record Describing Original Source Data Available Source Data Inventory (excel)
- LMCW SWMM5 model input file: lowerswmm5.inp
- Proceeded LMCW streamflow and precipitation data files in PCSWMM format
    - PMA012010-2012.tsf (2010-2-12 precipitation observed at PMA01)
    - PMP042010-2011.tsf (2010-2-11 precipitation observed at PMA04)
    - PMP062010-2012.tsf (2010-2-12 precipitation observed at PMA06)
    - CMH072010.tsf (2010 flow discharge observed at CMH07)

  - CMH072011.tsf (2011 flow discharge observed at CMH07)
  - CMH072012.tsf (2012 flow discharge observed at CMH07)
  - CMH032010H.tsf (2010 water elevation observed at CMH03)
  - CMH032010Q.tsf (2010 flow discharge observed at CMH03)
  - CMH032012H.tsf (2012 water elevation observed at CMH03)
  - CMH032012Q.tsf (2012 flow discharge observed at CMH03)
  - CMH192010H.tsf (2010 water elevation observed at CMH19)
  - CMH192010Q.tsf (2010 flow discharge observed at CMH19)
  - CMH192011H.tsf (2011 water elevation observed at CMH19)
  - CMH192011Q.tsf (2011 flow discharge observed at CMH19)
  - CMH192012H.tsf (2012 water elevation observed at CMH19)
  - CMH192012Q.tsf (2012 flow discharge observed at CMH19)
  - USGS05289800H.tsf (2010-2012 water elevation observed at USGS gauge 05289800)
  - USGS05289800Q.tsf (2010-2012 flow discharge observed at USGS gauge 05289800)

- UMCW SWMM5 model input file: upperswmm5.inp
- Additional rainfall gauge location GIS layer (minimum): rainlocations1.shp
- Additional rainfall gauge location GIS layer (ideal): rainlocations2.shp
- Additional flow gauge location GIS layer (minimum): flowlocations1.shp
- Additional flow gauge location GIS layer (ideal): flowlocations2.shp
- Utility for converting XP-SWMM data files to SWMM4 files: XPtoEPA4.exe Utility for converting SWMM4 data files to SWMM5 files: swmm4to5.exe