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Streamflow Modeling of Miller Creek, Duluth, Minnesota

by

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Abstract

A Storm Water Management Model (SWMM) was constructed to model flow in the Miller Creek watershed using readily available data. Miller Creek is an urban trout stream flowing through Duluth/Hermantown, Minnesota. Miller Creek starts near the Duluth Airport, flows south through Duluth and discharges into the St. Louis River estuary of Lake Superior. In 2008 and near its mouth, Miller Creek had a mean annual flow of 9.1 cfs, a recorded peak flow of 291 cfs, and base flow of less than 0.1 cfs. Despite extensive commercial and some residential development in the Miller Creek watershed over the past 30 years, Miller Creek has still a naturally reproducing Brook Trout fishery. The urban development included the filling of wetlands to create parking lots, the removal of riparian tree cover, and the introduction of storm water runoff from impervious surfaces (SSWCD, 2001). These changes have lead to elevated stream temperatures, and consequently Miller Creek was put on the list of impaired waters by the Minnesota Pollution Control Agency (MPCA) in 2007. The Minnesota Pollution Control Agency (MPCA) has mandated a temperature Total Maximum Daily Load (TMDL) study. This report summarizes the development of a Storm Water Management Model (SWMM) for Miller Creek in support of the TMDL study.

The model simulates continuous time series of stream flow at 15-minute time intervals in Miller Creek using observed precipitation, stream bathymetry, watershed hydrogeology, and tributary and storm sewer characteristics as input. The model was calibrated and validated against flow data from 2008, and is able predict mean flows, peak flows, base flows, and storm runoff volumes. The SWMM was also used to simulate the effect of a a few stream alteration scenarios on the streamflows in Miller Creek/

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1. Introduction

Miller Creek is an urban trout stream flowing through Duluth/Hermantown, Minnesota. Miller Creek starts near the Duluth Airport, flows south through Duluth and discharges into the St. Louis River estuary of Lake Superior. Despite flowing through a highly urbanized watershed, Miller Creek has a naturally reproducing Brook Trout fishery. Over the past 30 years the Miller Creek watershed has experienced extensive commercial and some residential development, including the filling of wetlands, removal of riparian cover, and the introduction of storm water runoff from impervious surfaces (SSWCD, 2001). These changes have lead to elevated stream temperature and Miller Creek has been put on the list of impaired waters by the Minnesota Pollution Control Agency (MPCA). The Minnesota Pollution Control Agency (MPCA) has mandated a temperature Total Maximum Daily Load (TMDL) study.

Several previous studies conducted have included information and/or analyses of the geomorphology and hydrologic characteristics of Miller Creek (Fitzpatrick et al. 2006, South St. Louis SWCD 2001, 2002) including a SWMM model developed by the Natural Resources Research Institute (NRRI) of the University of Minnesota-Duluth (Schomberg et al. 2000) in 2000. This model was constructed using data from 1997-98 and is no longer viable for Miller Creek, because substantial development has occurred since its development.

In this report we will describe the development of an updated stream flow model for Miller Creek based on the U.S. EPA SWMM (Storm Water Management Model). We will use current watershed land uses and 2007-2008 climate and stream flow measurements to develop the updated SWMM model. The new model will incorporate the changes in land use and development that have occurred in the watershed over the last decade. An extensive study was conducted to understand the hydrology of the watershed, including an analysis of available flow and precipitation data, several site visits, and a literature review.

The flows simulated by the new SWMM model will be used to study the effects of urban development in the watershed on stream temperatures in Miller Creek. The development of a heat transport and stream temperature model of the watershed in support of the temperature TMDL of Miller Creek will be described in a separate report (Herb et al. 2009). The SWMM model described in this report synthesizes the complex hydrology in the watershed and the resulting stream flow in Miller Creek. It can be used to identify what remediation measures might effectively counteract adverse influences of urban development on flows in Miller Creek.

2. The Storm Water Management Model (SWMM)

The Environmental Protection Agency (EPA) Storm Water Management Model (SWMM) is described as a dynamic rainfall-runoff simulation model used for single event or long-term (continuous) simulation of runoff quantity and quality from primarily urban areas (James et al. 2008). SWMM is widely used throughout the world for the planning and the analysis of urban stromwater runoff and drainage systems (Gironas et al. 2009).

2.1 Background

SWMM was first developed by the EPA in 1971 and since then has undergone several major upgrades (Gironas et al. 2009). The EPA, agencies, universities, and engineering firms have all contributed to the evolution of SWMM in its many different versions (REFERENCES). Most recently, in 2002, the EPA's Water Supply and Water Resources Division partnered with the consulting firm Camp, Dresser, and McKee (CDM) to develop a completely rewritten version of SWMM using modern software engineering techniques to produce a more maintainable, extensive, and easier to use model (James et al. 2008). The result was SWMM 5, a platform independent model with a new graphical user interface (GUI). The EPA offers a free version of SWMM 5 at: www.epa.gov/ednnrmrl/models/swmm/index.htm (Sept, 2009). Links to other SWMM versions are also available at the EPA's SWMM website along with literature references and examples. SWMM is also commercially available with different add-ons and graphical interfaces in the form of PCSWMM developed by Computational Hydraulics International (CHI) (www.computationalhydraulics.com) and XPSWMM developed by XP Software, Inc (www.xpsoftware.com).

2.2 Conceptual model

SWMM conceptualizes a drainage system as a series of water flow conduits between several environmental entities. The atmosphere supplies the rainfall that falls on the land surfaces generating runoff. Infiltrated water either returns to the atmosphere by evaporation or flows to an aquifer generating groundwater flow. The surface runoff is funneled to channels that drain the watershed to an outlet. Each of these processes is represented in SWMM.

The SWMM model developed for Miller Creek consists of five main objects: subcatchments, junctions (nodes), conduits, aquifers, and rain gauges. A definition of each object and their respective input parameters follows.

The drainage basins in Miller Creek are represented by **subcatchments**. Subcatchments are defined as hydrologic units of land whose topography and drainage system elements direct surface runoff to a single point (James et al. 2008). The principle input parameters include an assigned rain gage, 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. The drainage network in Miller Creek is represented by junctions and conduits. **Junctions** are defined as drainage system nodes that can represent the confluence of natural surface channels or manholes and pipe connections in storm sewer networks (James et al. 2008). The principle 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) (James et al. 2008). Conduit slope is calculated using elevations of inlet and outlet nodes and channel length. **Rain gauges** provide the data that drive the hydrologic cycle and can be provided either for a single design storm or as a time series of rainfall data for continuous simulation.

2.3 Previous model for Miller Creek

The NRRI (Natural Resources Research Institute) at the University of Minnesota, Duluth, developed a SWMM model for Miller Creek in 1999/2000 (Schomberg et al. 2000). The model was developed to simulate flow and nutrient loading. The model used a version of PCSWMM with the computational engine of SWMM4.4. The primary goal of the NRRI project was to model the water quality of storm water runoff and the model performed quite well for the prediction of peak flow rates and storm volumes. The model was developed with data from 1997 and 1998.

Updating the NRRI SWMM model to current conditions (2008-09) was one objective of our study; another was to make adjustments commensurate with the simulation of runoff and stream temperatures instead of nutrients. The NRRI model worked fine for the purposes it was designed for, using 1-hour time steps. When shorter time-steps were used, flow rates became dependent on the length of the time step (Figure 2.1). With shorter time-steps used, the peak flows generated by the model would become larger. This is not ideal for a temperature simulation which uses 15-min time-steps or smaller. We also encountered some problems in converting the NRRI SWMM 4 model to the new 2002 SWMM 5 model. When the converted NRRI model was run in the SWMM 5 platform using the same 1997-98 flow and precipitation data, the peak flows and storm volumes could not be reproduced. The inability to properly convert the SWMM 4 model to the new platform and the time-dependency in the original model, lead to the creation of a new SWMM model using the SWMM 5 platform.

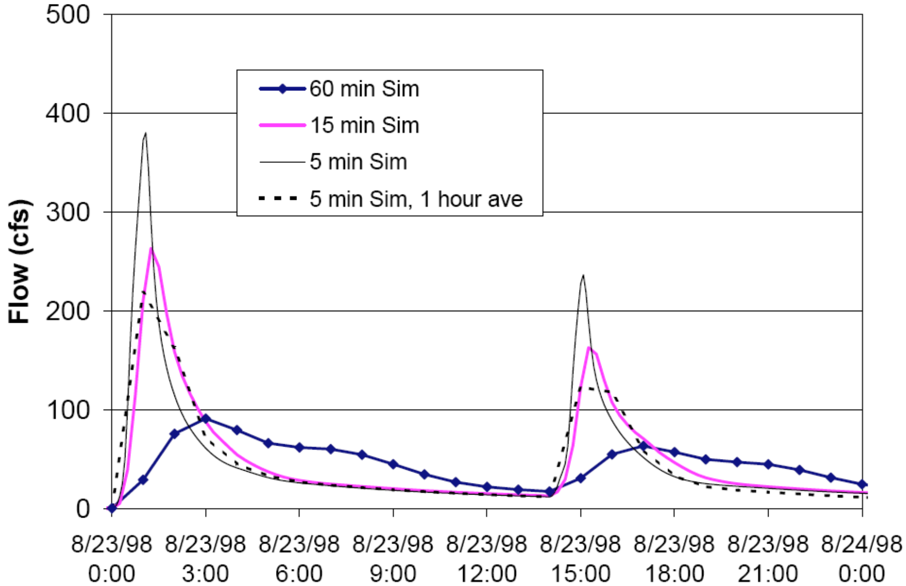


Figure 2.1 Example of time-step dependent flow from the NRRI SWMM 4 model.

To develop the new SWMM model, we decided to uses PCSWMM.NET, the latest version of PCSWMM from CHI. PCSWMM.NET uses the SWMM computational engine and was relatively inexpensive. It has a stand-alone GIS software package, better graphical features than the EPA SWMM 5, and a Sensitivity-based Radio Tuning Calibration (SRTC) tool to help with calibration of the model.

3. Miller Creek Watershed

3.1 Geomorphology, hydrologic features, and land cover

The geomorphology of Miller Creek is typical of North Store streams. The low-gradient headwaters consist mostly of wetlands and saturated shrub-lands (Figure 3.1). The stream becomes incised as it nears the ridge line, then rapidly descends across exposed bedrock to the St. Louis River estuary of Lake Superior. The low gradient channels flow for approximately 6 miles before descending rapidly to Lake Superior, dropping about 500 ft over 2 miles (Fitzpatrick et al, 2006).

The Miller Creek watershed covers approximately 9.3 square miles, with a main channel length of just over 8 miles. The creek drops in elevation about 800 ft from the headwaters to the outlet in the St. Louis estuary. Bedrock is found near or at the land surface in the Duluth area and is composed of mainly Proterozoic volcanic and igneous rock, intrusions, and sedimentary rocks. Quaternary surficial deposits can be found in the upper reaches of most Duluth area streams but they are thin or are absent from the middle and lower reaches where bedrock is exposed at the land surface (Fitzpatrick et al., 2006).

The predominant hydrologic features in the watershed include extensive wetlands in the upper reaches (Figure 3.1) and a relatively dense urban development in the lower reaches (~60% of the watershed area) (Figure 3.2) with a high level of imperviousness (~22%). Approximately 188 wetlands have been identified within the Miller Creek watershed, covering about 1040 acres of land (SSSWCD, 2002). Most of these wetlands are located in the upper half of the watershed (Figure 3.1). The importance of these wetlands will be discussed further.

Little is known about the detailed hydrogeology of the watershed. Many Midwest trout streams are fed by groundwater discharged from large aquifer systems thus providing the coldwater habitat required by trout. The bedrock geology of the areas makes it unlikely that a substantial volume of groundwater is stored in aquifers in the Miller Creek watershed. The shallow and exposed bedrock prohibits such storage. Because of this, Miller Creek is highly depended on rainfall, snowmelt, and storage in wetlands to supply its base flow. This can be seen in the flow record: low flows of less than 0.1 cfs can occur in mid- to late-summer when rainfall can be sparse, snowmelt is absent, and wetlands are low. The wetlands in the upper reaches of the watershed seem to be very important to the water budget of Miller Creek. The importance of the wetlands will be discussed below.

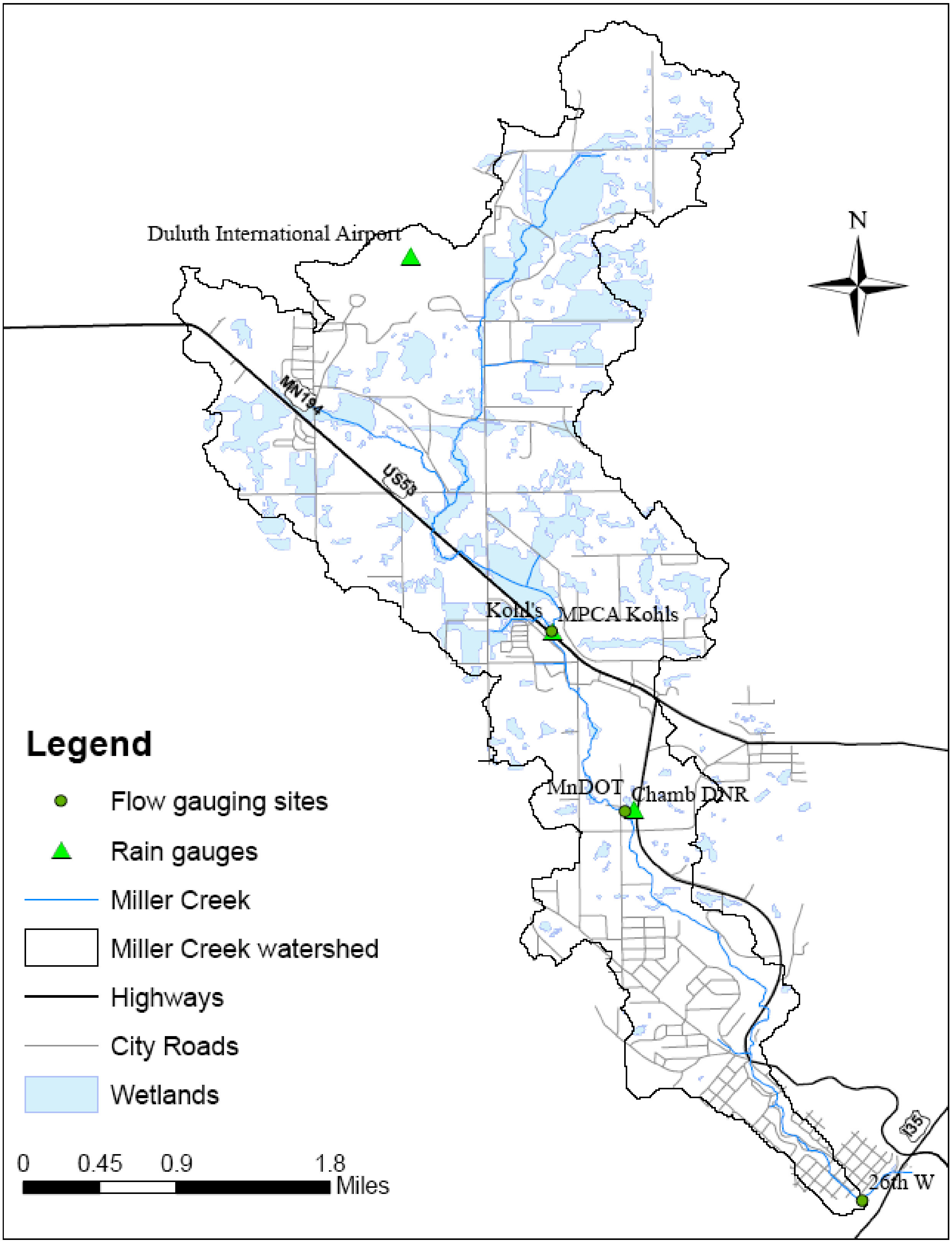


Figure 3.1 Miller Creek watershed with wetlands (blue areas), rain gauges (triangles), and flow gauging stations (circles).

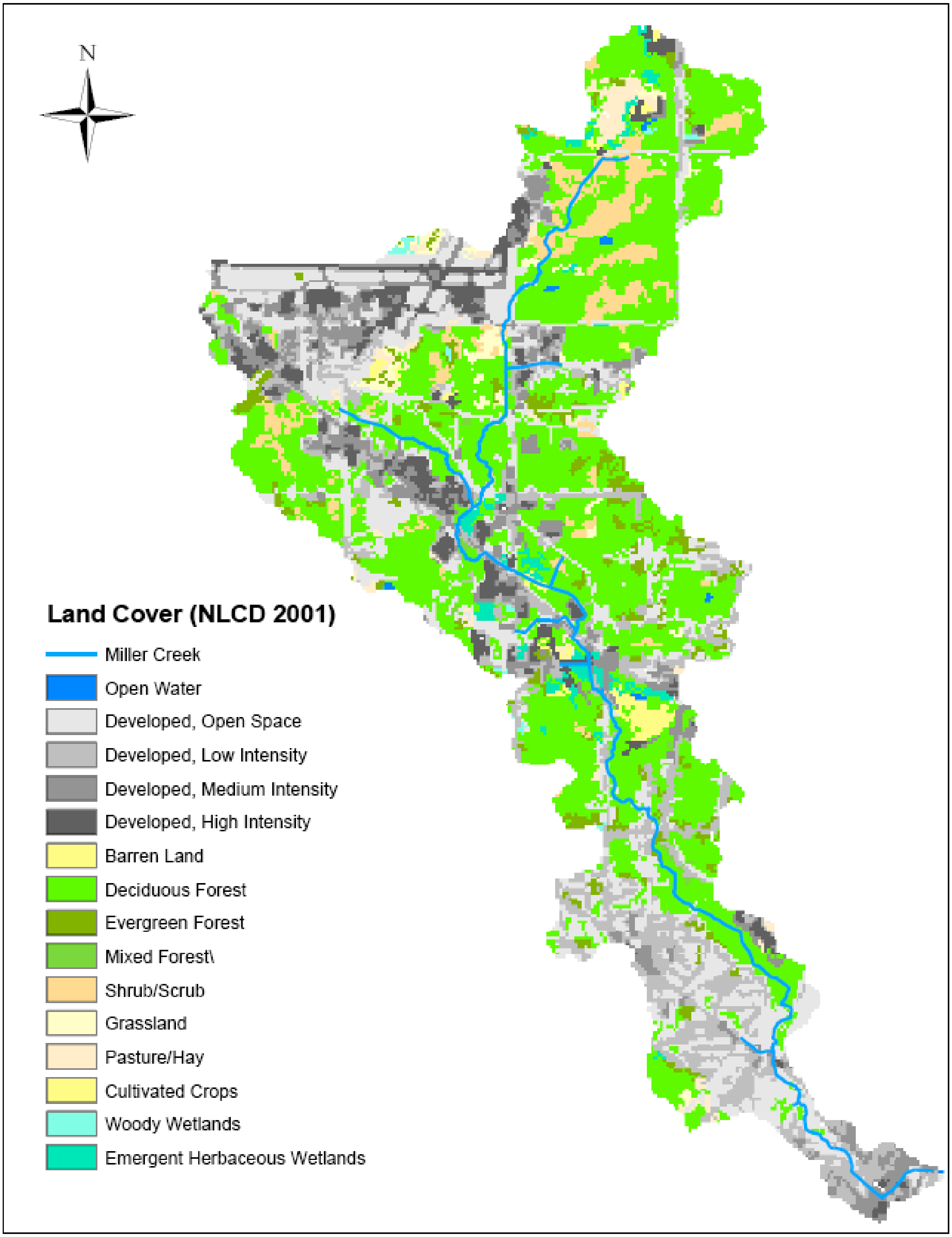


Figure 3.2 Land cover map from the 2001 NLCD dataset for Miller Creek. (DNR data deli, August, 2009).

3.2 Functionality of wetlands

A most important hydrologic feature in the Miller Creek watershed is the presence of numerous wetlands in the headwaters (Figure 3.1). 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 for the stream, (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 maybe independent of the surface hydrology but may be connected thought groundwater seepage.

Since it most likely that large storage aquifers do not exists in the watershed because of its bedrock geology, the wetlands are an important source of water supplying baseflow to Miller Creek. Because little is known about the underlying hydrogeology of the watershed, a hypothesis of the functionality of the wetlands was formed using the topography, known bedrock geology of the area, and the flow record. The authors' hypothesis on the wetlands and how they relate to groundwater and baseflow is as follows. The groundwater system in the Miller Creek watershed is essentially controlled by a system of inter-connected wetlands that are formed in bedrock depressions. Infiltrated water flows along the bedrock to these low-lying areas forming saturated zones or wetlands. Some may be independent of the stream and just store water that will eventually evaporate while others are connected to the stream either as in-line wetlands that the stream flows through, or by supplying groundwater through groundwater interflow between wetlands or through fissures in the bedrock.

The in-line wetlands were formed in low-lying areas where a flow restriction due to topography has occurred. Groundwater flow is funneled to these areas most likely because of the bedrock geology. Flow restriction can be seen on a hillshade topography map (Figure 3.3). Hillshade topography maps are created using the hillshade function in ArcGIS on a digital elevation model (DEMs) map. These hillshade topography maps show topography exaggerated and shaded relative to azimuth, representing the sun, and therefore give a vivid 3-D image of the topography. Three examples of large inline wetlands and topographical flow restriction points can be seen in Figure 3.3. If we assume that the groundwater cannot pass under the hills that form these restrictions, all the infiltrated water should flow into the wetlands and then discharge to the stream in these areas. If this hypothesis is correct, the baseflow in Miller Creek is generated by the slow release of the water stored in the wetlands, and not by slow groundwater inflow that is the classical source of baseflow water.

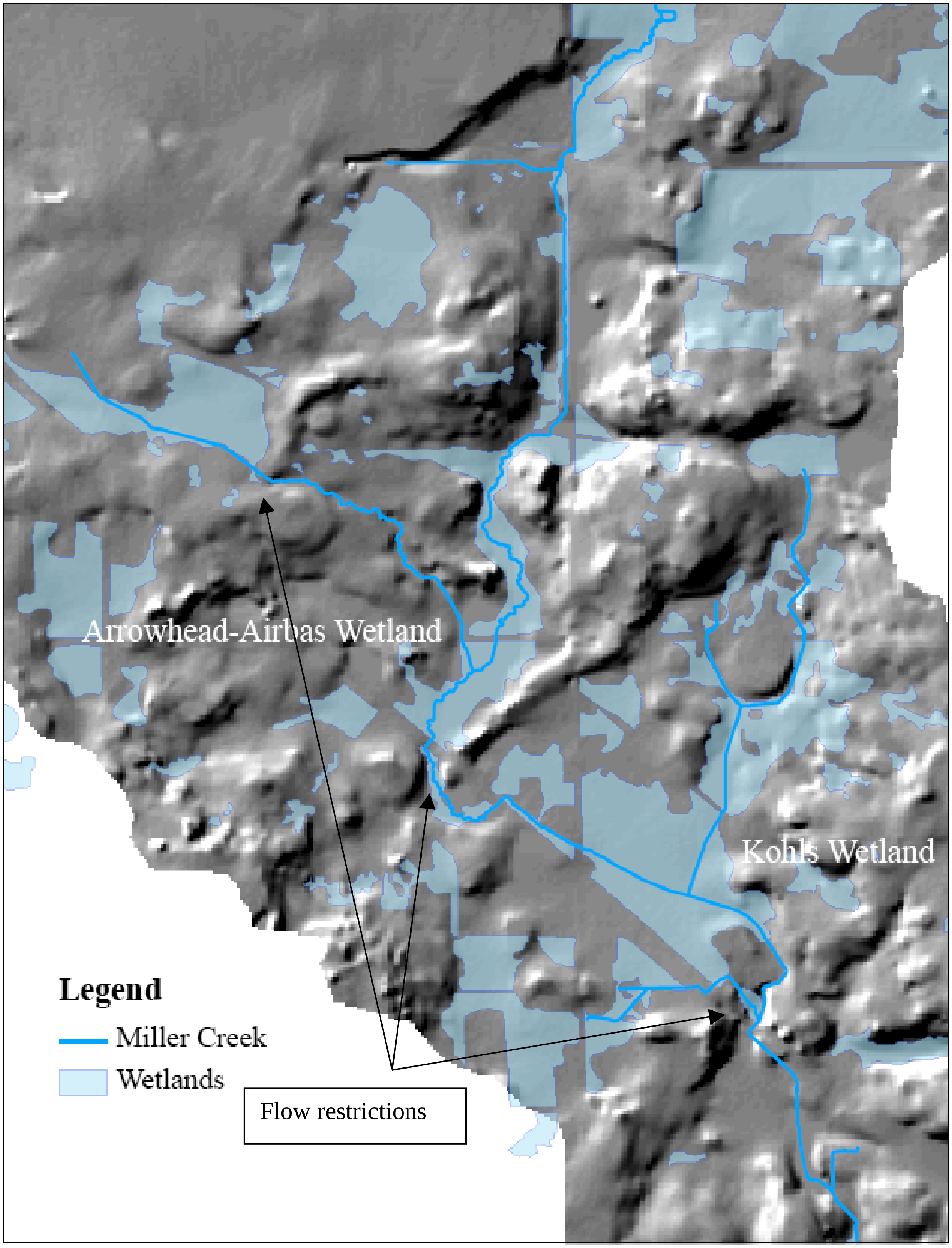


Figure 3.3 Hillshade topography map of Upper Miller Creek watershed showing flow restrictions at downstream ends of wetlands.

3.3 Climate

The climate in the Miller Creek watershed and the surrounding Duluth area is characterized by cool or moderate warm summers, cold snowy winters, and fairly evenly distributed precipitation (Eichenlaub 1979; Fitzpatrick 2006). The 800ft difference in elevation between the mouth of Miller Creek and its uplands causes differences in both climate and weather. Rapid variations in weather can occur due to the proximity of Lake Superior. Average precipitation is 29-30 inches/year (730-760 mm/year); average annual evapotranspiration is 18 inches (450 mm), and annual average runoff is 10-12 inches (250-300 mm) (Young & Skinner, 1974; Fitzpatrick, 2006). Mean maximum air temperature ranges from 22°F (-5.5°C) in January to 78° F (25.5°C) in July (Eichenlaub, 1979; Fitzpatrick, 2006). Some differences in air temperature and humidity can be observed from the lower to upper portions of the watershed (Herb and Stefan 2009).

4. Hydrologic Data for the Miller Creek watershed

Before the SWMM model was constructed, hydrologic data for Miller Creek were assembled and analyzed by Herb and Stefan (2009). A fairly detailed analysis of the limited amount of streamflow data from three Miller Creek gaging stations is given. The reader may refer to that report for a general description of what is known about Miller Creek flow. For the development of the SWMM 5 model we had to determine (1) the best time period in the 2007-2008 hydrologic record to test and calibrated the model, and (2) the quality of data for that period.

4.1 Precipitation data

Precipitation data was available and obtained from 3 rain gages within the watershed:

(1) daily precipitation data from the Duluth International Airport for 1997 – 2008 through the State Climatology Office (climate.umn.edu/doc/historical.htm),
(2) 10 minute precipitation data from a MnDOT roadside weather station (RWIS) on Highway 53 at Anderson Road, very close to the Chambersburg stream flow gaging station, for April – November 2007 and June-August 2008 (www.d.umn.edu/~tkwon/RWISarchive/RWISarchive.html), and
(3) hourly precipitation data from a tipping bucket rain gage at the upper Miller Creek flow gaging station at Kohl's for 1997 and 1998, and 15-minute precipitation data from the same gage for 2008.

It was decided to examine the precipitation data from the year 2008 because it is the only year when measurements were available at all 3 rain gages. To test the uniformity of the rainfall across the watershed, differences in hourly precipitation measured at any two stations were plotted as shown in Figure 4.1 for July and August 2008. Figure 4.1 gives an idea of the spatial variability in rainfall in the Miller Creek watershed in the summer of 2008. The differences are moderate but not insignificant, except for the rainfall event at the end of August 2008, when the differences are very large.

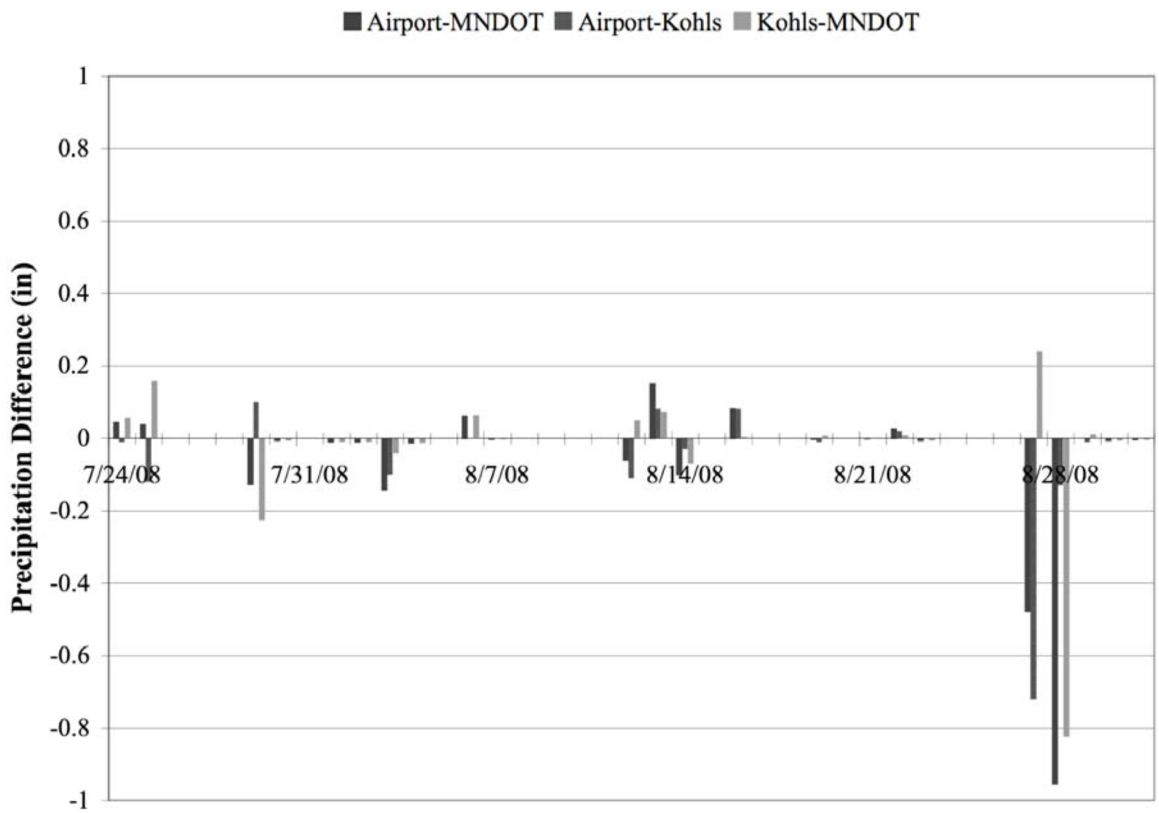


Figure 4.1 Differences in hourly precipitation measurements at the three rain gages (Duluth Airport, MNDOT and Kohl's) in the Miller Creek watershed.

The precipitation data from Duluth International Airport and the Kohl's flow gaging site were compared at daily time scales by Herb and Stefan (2008). Good correlation was found between the two rainfall measurements, with r^2 varying from 0.70 to 0.89 for the five years of data available from the Kohl's site. For the two years (2007, 2008) of available precipitation data from the MnDOT station at Anderson Road, the correlation was somewhat lower (r^2=0.56, 0.71). Both the Duluth Airport and the Kohl site appear to provide good precipitation data. The airport has a much more complete daily precipitation record, however, the Kohl site provides some 15 minute precipitation data as needed for the SWMM.

4.2 Stream flow data

A statistical analysis of Miller Creek stream flow data by Herb and Stefan (2008) gave the histograms of daily flows at the lower site reproduced in Figure 4.2. The skew of the flow data towards low flows (1 to 2 cfs) is evident in the plots.

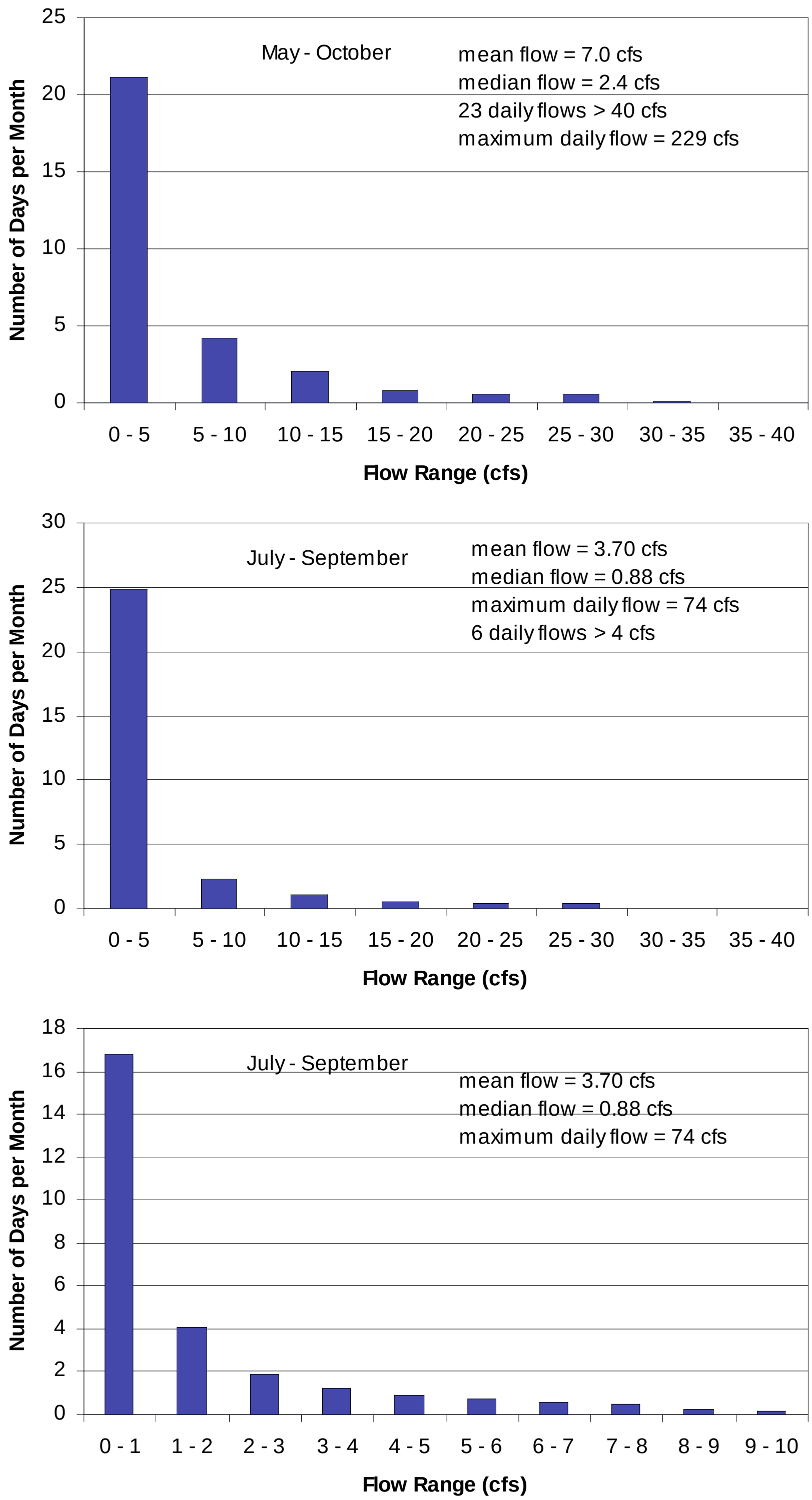


Figure 4.2. Histograms of daily stream flows at the Miller Creek lower stream gaging site for four years of data: 1997/98 and 2007/08. (from Herb and Stefan 2008).

The stream flow data analysis by Herb and Stefan (2008) led to several important conclusions:

1) Based on 1997 and 1998 data, weekly-averaged flows at the middle and upper gaging sites are, on average, 82% and 77% of the lower site, respectively. This suggests that a large fraction of the flow in Miller Creek originates from the upper portion of the watershed, upstream of the Kohl's Department Store site.

2) A statistical analysis of five years of flow data from the Miller Creek lower site indicates that low flows in the range of 1 to 2 cfs are quite common at weekly time scales. Therefore a rainfall event of moderate magnitude may be expected to have a significant impact on stream flow and temperature at the lower site.

3) Although the flow record is relatively short (5 years), the results of a frequency analysis suggest that weekly mean flows near zero are possible with a 10 year return period.

4) 1997-1998 data for the upper stream gaging site (Kohl's Department Store) have lower average weekly flow than the data for the middle and lower stream gaging sites and are therefore considered consistent. Since a good rating curve has not been established for the upper site, stream gage data from 2003 through 2005 are currently not usable for flow studies.

4.3 Relationships between stream flow and precipitation

Monthly averages of precipitation and flow for 1997-1998 and 2007-2008 show significant month to month variations in precipitation and in stream flow (Figure 4.3 from Herb and Stefan 2008). August and September, on average, have the lowest flows. Average precipitation for the full 12 year record (1997-2008) shows less month to month variation than the 4 year partial record.

Because of the scarcity of rainfall data, questions about the reliability of the data, and the variability in rainfall between stations, the relationship between precipitation and stream flow was investigated. The rain gage that provided the precipitation data with the best correlation to stream flow would be considered the most representative for the entire watershed.

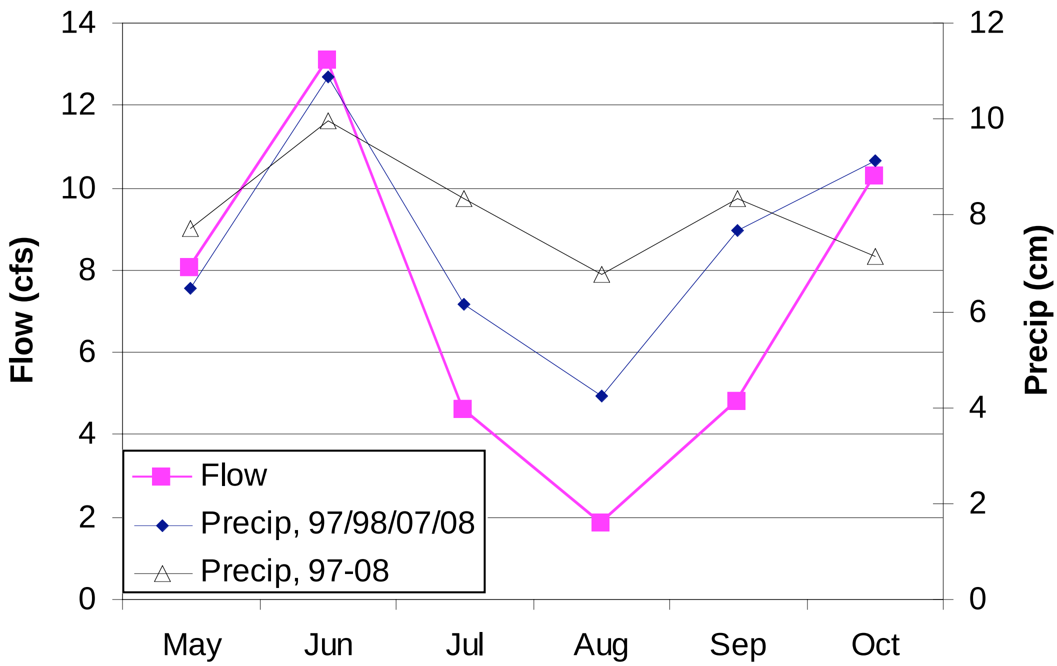


Figure 4.3. Average monthly flow at the lower stream gauging site in Miller Creek and average monthly precipitation at the Duluth Airport. Monthly average precipitation is given for a partial record corresponding to the flow record (1997-1998 and 2007-2008) and for all years 1997-2008.

To investigate the relationship between streamflow and precipitation, daily precipitation for each station was plotted against daily average flow at the 26th Ave. gaging station at the lower end of the watershed (Figure 4.4). A polynomial fit between daily-averaged stream flow (Q) and total daily precipitation (P) was calculated in the form: $Q = a \cdot P^2 + b \cdot P + c$. Although the fit was relatively poor for all three rain gages, the most meaningful relationship was obtained with the precipitation data from Kohl's rain gage site. That rain gage happens to be located near the center of the watershed. Because the rainfall measured at the Kohl's site had the best correlation with stream flow measured at the lower stream gaging station at 26th Ave. it was decided to use the rainfall data from the rain gage at the Kohl's site to create and validate the SWMM model.

This finding is in agreement with the conclusions from the analysis of weekly flow and precipitation data by Herb and Stefan (2008). Relationships between stream flow at the lower site and precipitation were established at weekly timescales, with r^2 of 0.57 for precipitation data from the airport and 0.82 for precipitation from the Kohl's site (Figure 4.5). However, RMSE of the relationships (3.0 and 5.5 cfs for airport and Kohl's, respectively) are similar in magnitude to the mean flows (3.7 cfs for the lower gaging sites). Precipitation data from the upper gaging site (Kohl's) were found to be a slightly better predictor of flow at the lower site, however, the airport has a much more complete data set.

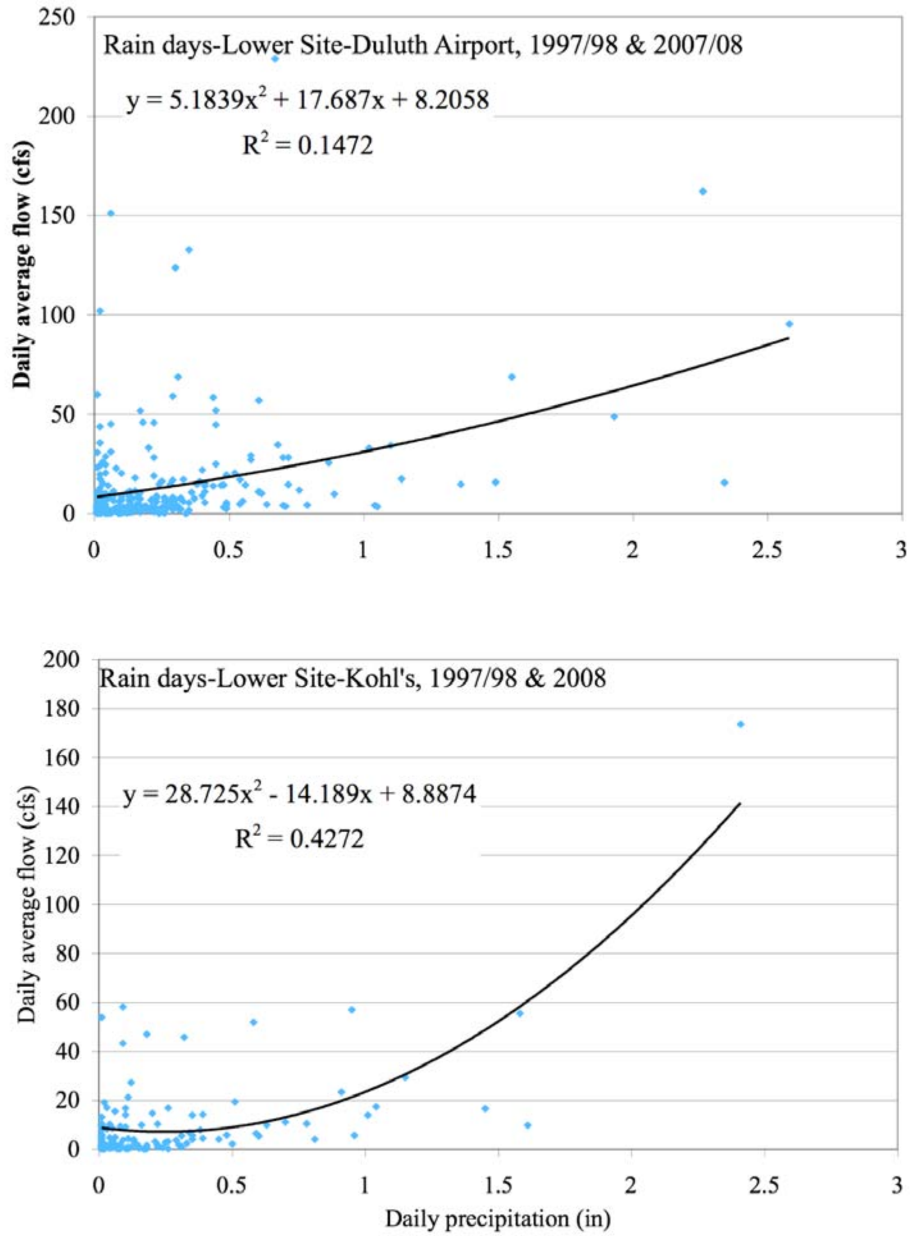


Figure 4.4 Average daily stream flow in Miller Creek on rainy days at the lower (26th Ave) stream flow gage vs. daily precipitation from Duluth Airport (upper panel), and from Kohl's site (lower panel).

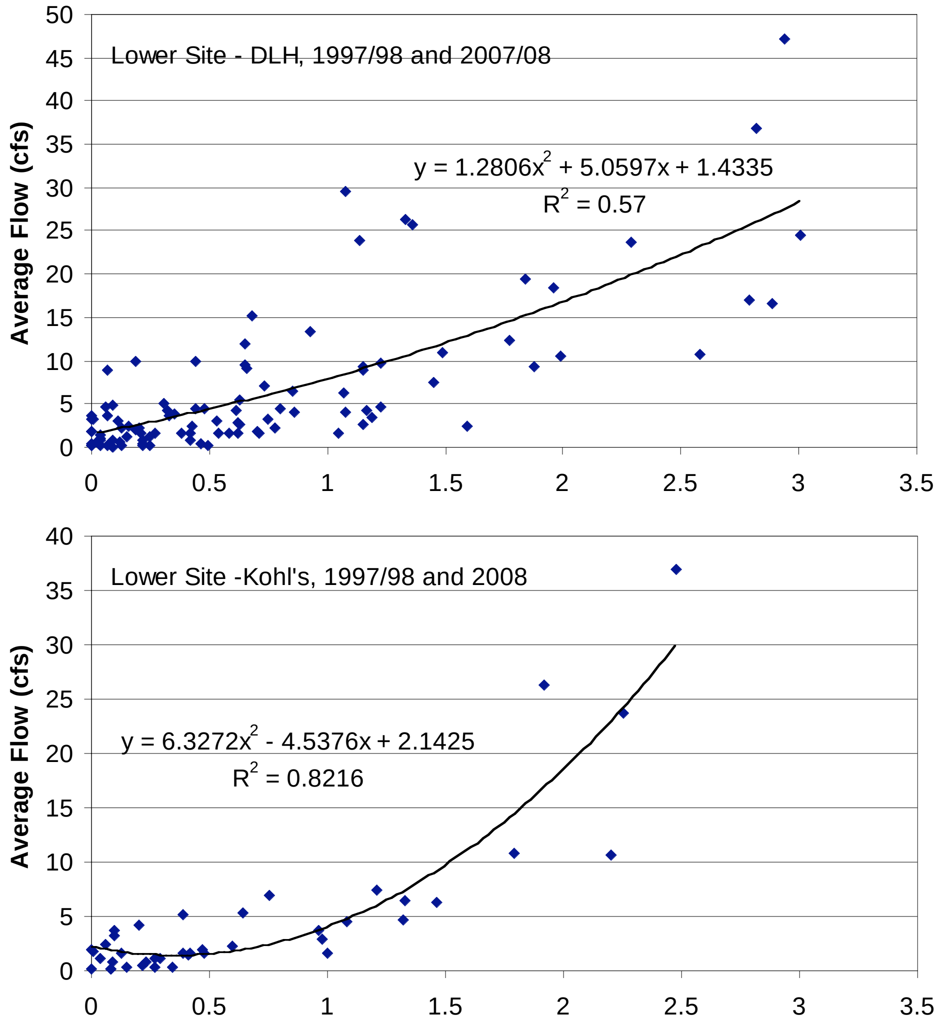


Figure 4.5. Average weekly stream flow in Miller Creek at the lower flow gaging site (26th Ave), 1997/1998 and 2007/2008, vs. weekly precipitation from Duluth Airport (upper panel) and from Kohl's site (lower panel).

4.4 Evapotranspiration data

Since the SWMM 5 model is not intended to simulate winter months, i.e. months with snowfall, evapotranspiration depth is the only other required climate variable needed in the SWMM model. Evapotranspiration can be specified either as a constant value, or a monthly average, or as a daily time series. It was decided that daily ET estimates would be used to incorporate climate variability in ET. No measurements of ET or pan evaporation were available in the Miller Creek watershed. Daily potential ET was estimated using the FAO-56 PM ET equation (Allen et al. 1992). Results are plotted in Figure 4.6. Estimated (2007) or measured (2008) solar radiation and other measured climate variables from the Duluth Airport were used as input to the equation. Estimated solar radiation values for 2007 came from the Minnesota Climate office at the University of Minnesota and the measured solar radiation values for 2008 can from the weather station at Lincoln Park Elementary School, located in the southern end of the Miller Creek watershed.

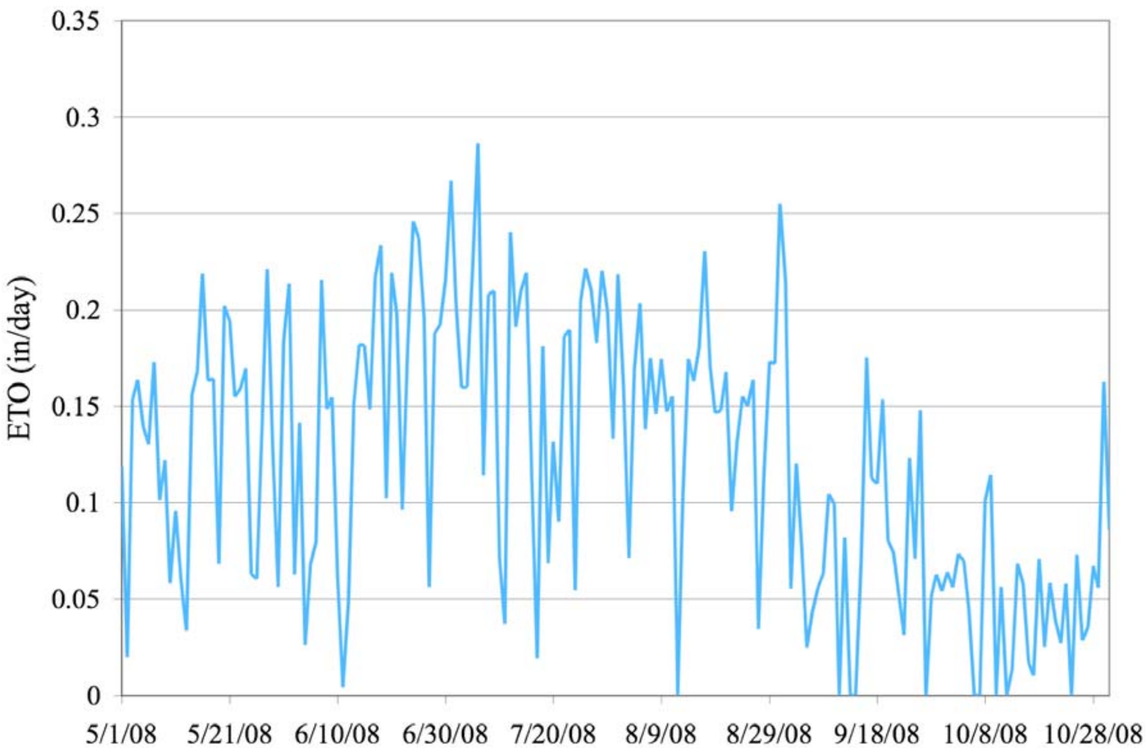


Figure 4.6. 2008 Evaporation estimates using FAO-56 PM

5. SWMM Construction for Miller Creek

The physical input parameters required by SWMM are numerous. They are used in the equations that describe and estimate the hydrologic processes in the watershed. Numerous data sources were used to estimate the parameters required in the SWMM model. Many of these data sources were analyzed using a Geographic Information System (GIS) program, either using the GIS functions in PCSWMM or using ArcGIS. Digital maps of topographic elevations (DEMs), roads, wetland delineations, the storm sewer network, soils, rivers, and imperviousness and aerial photos were used. In areas where no data was available or the data quality was suspect, parameters from the previous NRRI SWMM model were used as a starting point. These data sources were utilized extensively to construct the SWMM model. A full list of the input parameters, as they are given in the input file, and their sources is provided in the Appendix Table A.1.

To start, the watershed was divided into several drainage basins using a basins map developed using HydroCADD with a 10-meter digital elevation model (DEM) map and 30 drainage points. These basins were adjusted and further divided to accommodate the storm sewer pipes, e.g. where pipes cross the natural land divides, using a map of the Duluth storm sewer system, or the basins were divided into more homogenous entities to increase model efficiency. During this process, the basins were divided in a way to preserve the previous NRRI SWMM so that data could be more easily mined in areas where data was limited. Overall, the watershed was divided into 41 drainage basins (compared to 36 in the NRRI SWMM model) that make up the sub-catchments in the SWMM model (see Figure 5.1).

SWMM can use three different infiltration models (Horton, SCS, and Green-Ampt methods). We used the Green-Ampt method for estimating infiltration. SWMM also can handle multiple rain gauges in the program but since reliable rainfall data do not seem to exist at multiple sites in the Miller Creek watershed (see Section 4.1), the use of a single rain gauge (at the Kohl site) was chosen.

Stream channels made up of nodes and links were constructed for SWMM. Nodes are points of interest, e.g. the intersection of two streams, places where temperature sensors were placed, or points where basins discharge to the stream. Links represent the physical channel and link the nodes together. To construct the channel network, nodes were first placed at all the stream channel intersections, including storm sewer outlets shown on Duluth's storm sewer map. For the thermal modeling of Miller Creek, 26 stream temperature gauging stations were added, so that the modeled stream flow at those sites could be extracted from the model. Invert elevation for each node was estimated using a 10-ft contour map provided by the City of Duluth, and the 10-meter DEM elevation map. The invert elevation and the ground elevation for nodes that represent manholes and storm sewer outlets were taken from the Duluth storm sewer map, if the data was available. A total of 89 junctions were incorporated into the model.

Links were added connecting the nodes and following the stream path on a stream route map provided by the city of Duluth. To keep the model manageable, only the larger storm water collector pipes were added to the model. There was no good information source for channel geometry of the mainstem and tributaries, except where the channel was a storm sewer pipe. Channel geometry was therefore taken from the previous NRRI SWMM except for the areas where data was available, i.e. from the Duluth storm sewer map. The channel length between the nodes was automatically estimated by PCSCMM.net. The channel lengths were used as a calibration parameter to account for small scale meandering that might not be picked up by the digital stream map. The slope of channel sections was estimated using the node elevations and length between them. The channel roughness was initially taken from the NRRI SWMM model and then recalibrated to fit the observed flows.

Finally, aquifers were added to the model. Because little is known about the hydrogeology in the Miller Creek watershed, it was assumed that the lower half of the watershed has no groundwater interaction; the outcrops of rock that exist in this area indicate that the bedrock reaches all the way to the surface. Groundwater aquifers were added only to the upper and middle reaches of Miller Creek. Since there is no available information on the hydrogeology, aquifer parameters in Table 5.1 were initially assigned the values from the NRRI SWMM and then adjusted during calibration to match observed base flow conditions. Seventeen aquifers were used in the SWMM model; some had more than one subcatchment draining to them (see Figure 5.1).

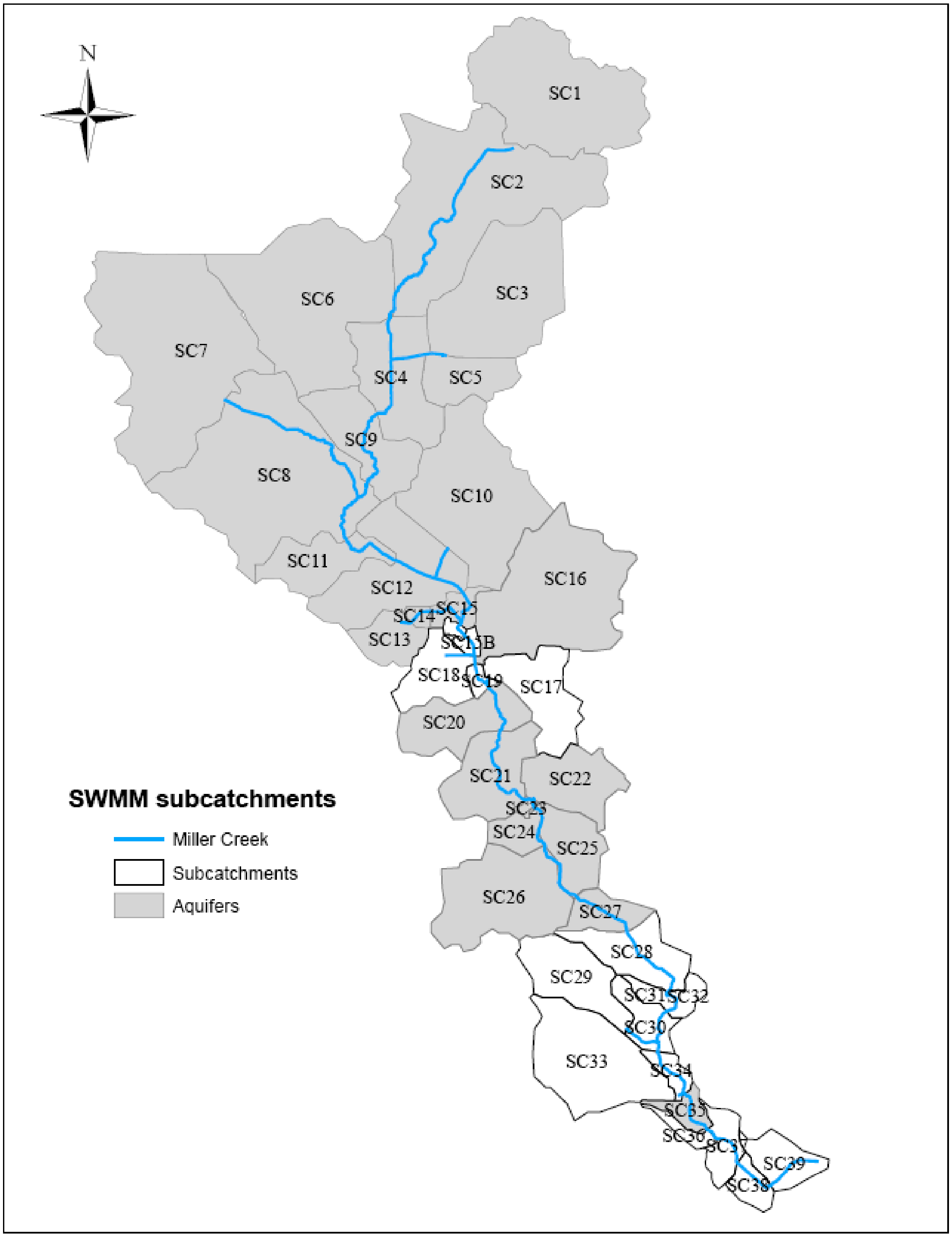


Figure 5.1 Subcatchments and aquifers used in the SWMM of Miller Creek

6. SWMM Calibration for Miller Creek

The model calculates runoff at a 15-minute time step and does flow routing at a 30-second time step, then reports the flow every hour. Using rainfall data from the Kohl site for the period June 1 to October 10, 2008 as input, the SWMM 5 constructed for Miller Creek was used to simulate stream flows at the lower stream gaging station (26th Ave). The modeled flows were compared to observed flows at the 26th Street gauging station. Flow data for 2008 were only available at the lower 26th Ave. station.

A perfect match between simulated and observed stream flow time series is not realistically achievable - even with calibration - given the spatial heterogeneity and time variability in precipitation and the short record (77 days) of good precipitation data. During model calibration several model parameters were adjusted in a trial and error calibration process until differences between simulated and observed stream flows were considered to be at a minimum. Most of the calibration was guided by visually comparing plots of simulated and observed stream flow time-series. Adjustments were made to the model parameters depending on the type of flow discrepancies. The process used is described in Schomberg et al. (2000). Volume discrepancies were remedied through changes in impervious surface area and percent imperviousness with zero depressional storage, and sub-routing of flow from impervious area to pervious areas within the same subcatchment (representing disconnected impervious areas in the upper watershed). Peak flow discrepancies were changed through subcatchment depressional storage depths (both impervious and pervious). Peak flow timing was corrected by altering subcatchment and channel roughness, and channel lengths (mostly for natural channels). Discrepancies in the ascending and receding limb of the hydrograph were adjusted by changing channel and subcatchment roughness, subcatchment width, and certain individual channel characteristics associated with the wetland areas. Base flow or low flow discrepancies were remedied by changing groundwater flow and aquifer parameters in the upper and middle watershed.

PCSWMM.net has a Sensitivity-based Radio Tuning Calibration (SRTC) tool to help with calibration. To use this tool, an uncertainty percentage is assigned to each calibration parameter. Then, two scenarios are simulated for each calibration parameter, using an adjusted maximum and minimum value according to the uncertainty assigned. Finally, the simulated flow is plotted along with the observed flow, and "tuning" levers can be turned, adjusting the calibration parameters to match the observed flows. The SRTC tool was not helpful in gross adjustments, but was helpful for the fine-tuning of the model.

Two storms were used particularly to calibrate SWMM 5: storm hydrographs that occurred on August 27-30, 2008 (Figure 6.1) and on September 11-20, 2008 (Figure 6.2). In addition, base flow over the whole simulation period (July 24 to October 10, 2008) was used for model calibration.

After visually matching simulated flows to observed flows, two statistics were calculated to quantify the goodness of fit: the root mean square error (RMSE) and the Nash-Sutcliffe coefficient. The Nash-Sutcliffe coefficient is an index showing how well a model performs; it is similar to the coefficient of determination (R^2) in a regression equation. The Nash-Sutcliffe coefficient ranges between negative infinity and 1.0. A perfect model would have a Nash-

Sutcliffe coefficient of 1; if the coefficient is zero, the modeled flows are as good as the average flow of the time period, and if the coefficient is negative, using the average flow would be better than the model.

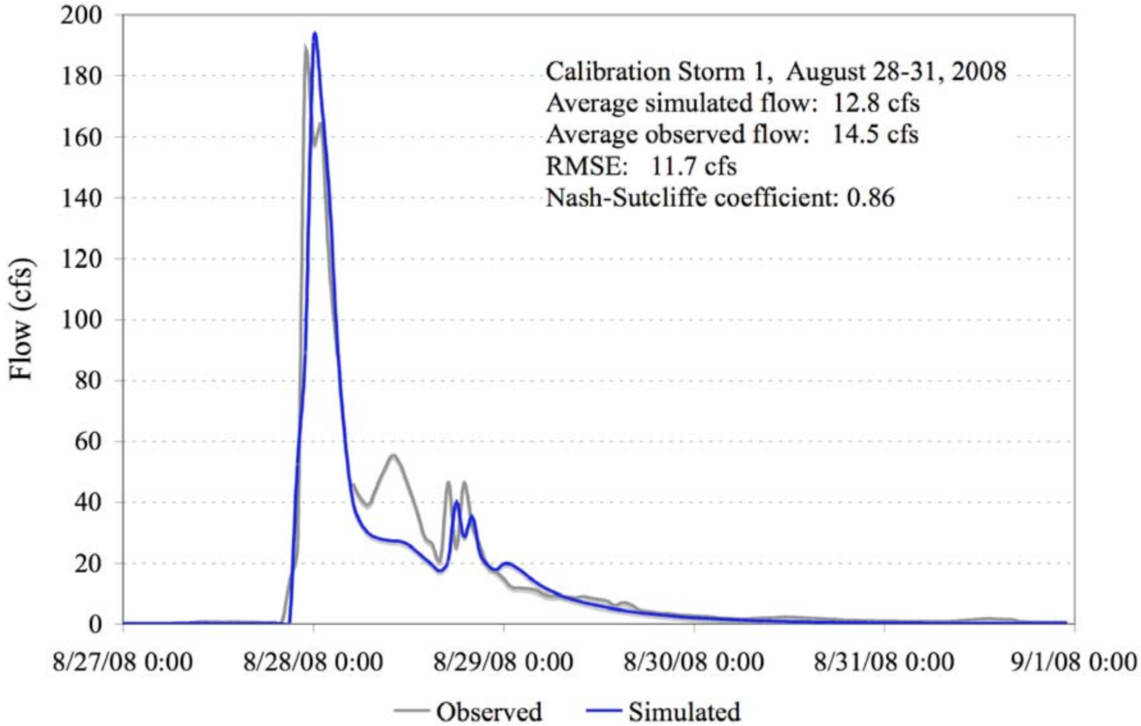


Figure 6.1. Calibration Storm 1 (Aug 27-31) for the Miller Creek SWMM.

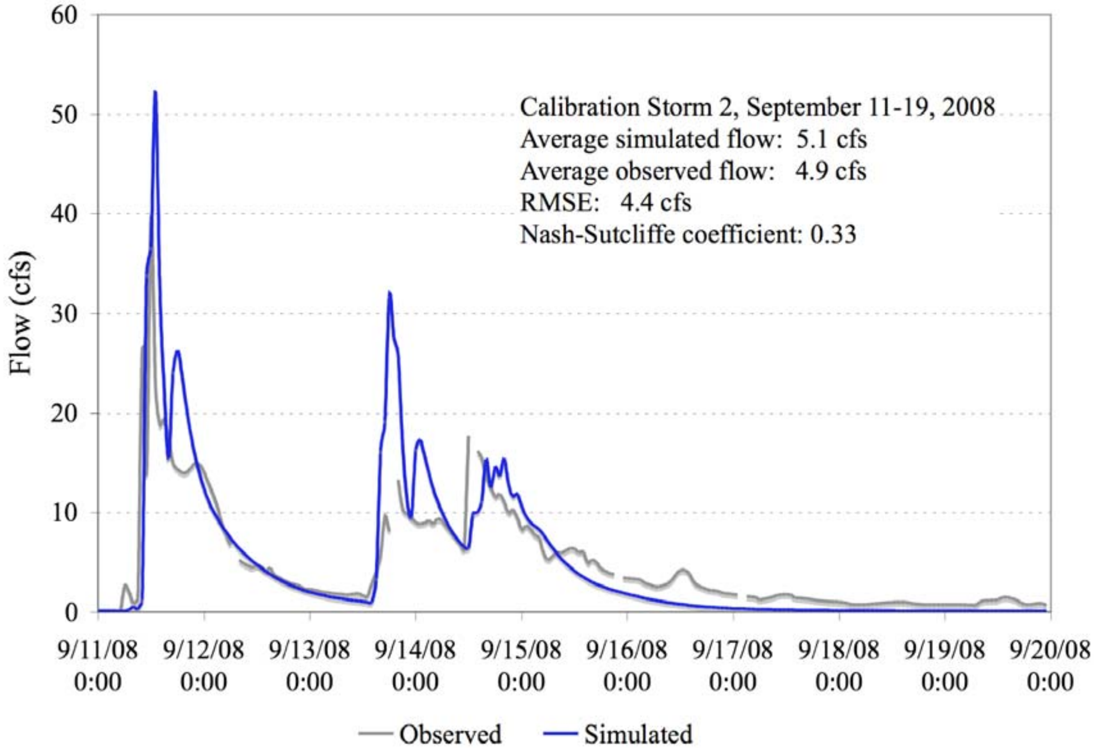


Figure 6.2. Calibration Storm 2 (September 11-19, 2008) for the Miller Creek SWMM.

The model was able to closely reproduce the hydrographs of the calibration periods (Figures 6.1 and 6.2). The average hourly observed flow for calibration storm 1 (August 27 to August 31, 2008) was 14.5 cfs with a peak flow of 185.7 cfs occurring at 11 pm, the night of August 27, 2008. The average simulated hourly flow for the same period was 12.8 cfs with a peak flow of 191.7 cfs occurring 1 hour after the observed flow. The storm hydrograph was simulated fairly well. The RMSE between the modeled and the observe flow was 11.7cfs. The Nash-Sutcliff coefficient was 0.86, i.e. a relatively good model fit. The largest difference between the modeled flow and observed flow is that the model was unable to reproduce a secondary flow peak occurring on August 28. This peak may be caused by a delay in discharge caused by the wetlands.

The calibration storm 2 gave a decent fit. The average hourly, observed flow for the time period of September 11 to September 19, 2008 was 4.9 cfs with two peak flows of 39.5 cfs and 17.7 cfs, respectively. The average simulated hourly flow for the same period was 5.1 cfs with peak flows of 52.3 cfs and 31.7 cfs. The RMSE between the modeled and the observe flow was 4.4 cfs. The Nash-Sutcliff coefficient was 0.33. Overall, the model preformed well simulating the flows in Miller Creek over the time period. SWMM 5 performance will be further discussed in the next section.

7. SWMM Validation for Miller Creek

7.1 Time series plots of stream flows in Miller Creek

Comparisons between the observed and simulated flows for the time period June 1 to October 10, 2008 were made to test the validity of the SWMM model. The summer of 2008 was relatively wet. Normal monthly values of precipitation in the Miller Creek watershed from June to October were shown in Figure 4.3. Values for 2008 are given in Table 7.1.

Table 7.1: Comparison of monthly precipitation at Kohls/MnDOT (2008) and averages for Duluth Airport (1990-2008)

Month	Average precipitation at Duluth Airport (1990 to 2008) (in)	Kohls/MnDOT precipitation (2008) (in)
May	3.2	2.3
June	4.4	5.6
July	4.1	4.6
August	3.5	2.9
September	4.0	4.6

A plot (Figure 7.1) and a log plot (Figure 7.2) show different aspects of the flow time series throughout the 2008 summer season. The linear plot (Figure 7.1) shows that the timing and peak flows are relatively close for most of the storm events. Most of the late summer/ early fall storms were modeled well, but peak flows during the early to mid-summer seem to be overpredicted by the SWMM model. Figure 7.1 also shows that the model under-predicts the volume of the first storm event. A likely reason for these discrepancies is that the SWMM model was calibrated for two storms occurring in late summer or early fall, therefore the model will perform best during this time. Also, the flow during this time (late summer/early fall) showed the best correlation to precipitation data (Section 4). Precipitation data from the three rain gage sites were combined in order to simulate a long time period. The inability to model the first storm peak could be an initialization problem. Flow in the channels needs time to adjust to the precipitation.

Different aspects of the flow can be seen in the log plot (Figure 7.2) of the stream flow time series. First, the base flow periods and hydrograph recessions are easier to see. The model does a fair job simulating base flows for most of the year and the recessions are pretty good. As with the linear plot, problems occur in modeling the early and late storms. Because the model can not do a good job reproducing these early and late storms, the rest of the comparisons between the observed and simulated flows will be conducted on the time period June 20 to September 22, 2008, which is the most critical period for a Minnesota trout stream. Possible reasons why the model cannot reproduce the early or late events will be discussed later.

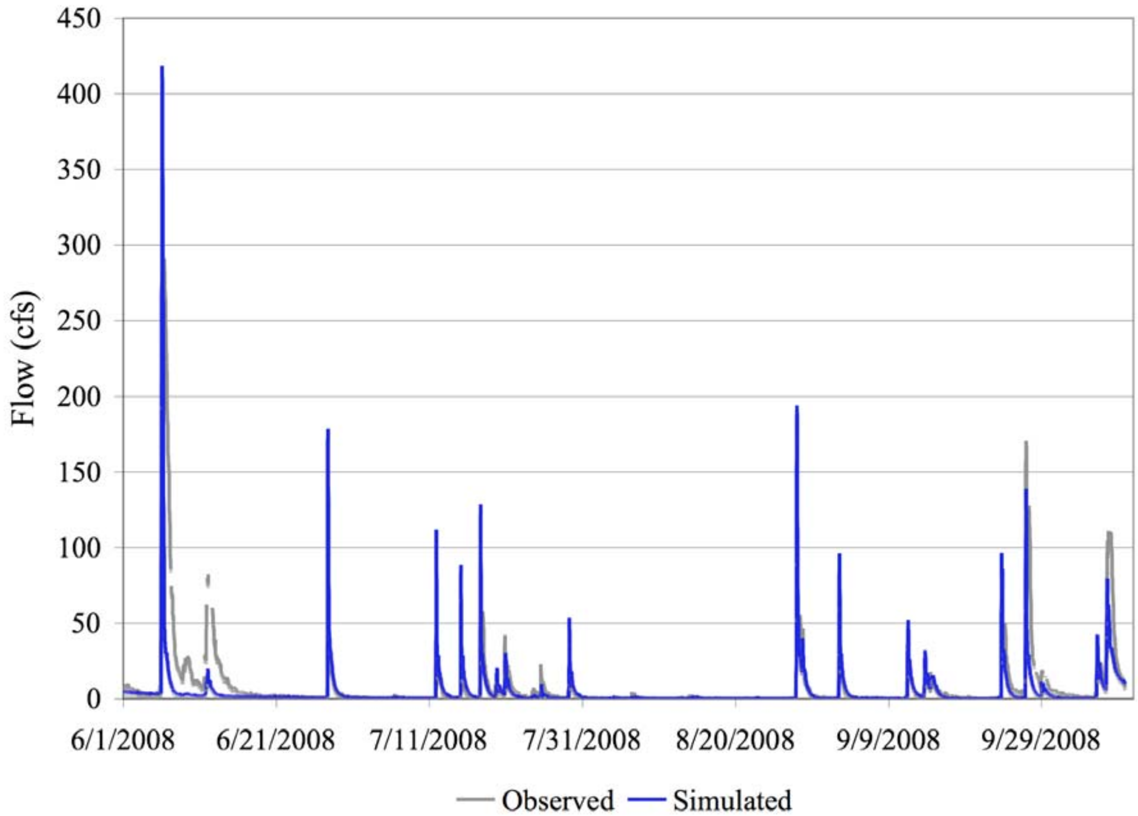


Figure 7.1 Simulated (SWWM) (dark line) and observed (gray line) flows in Miller Creek at the 26th Ave stream flow gage from June 1 to October 10, 2008 plotted as a time series.

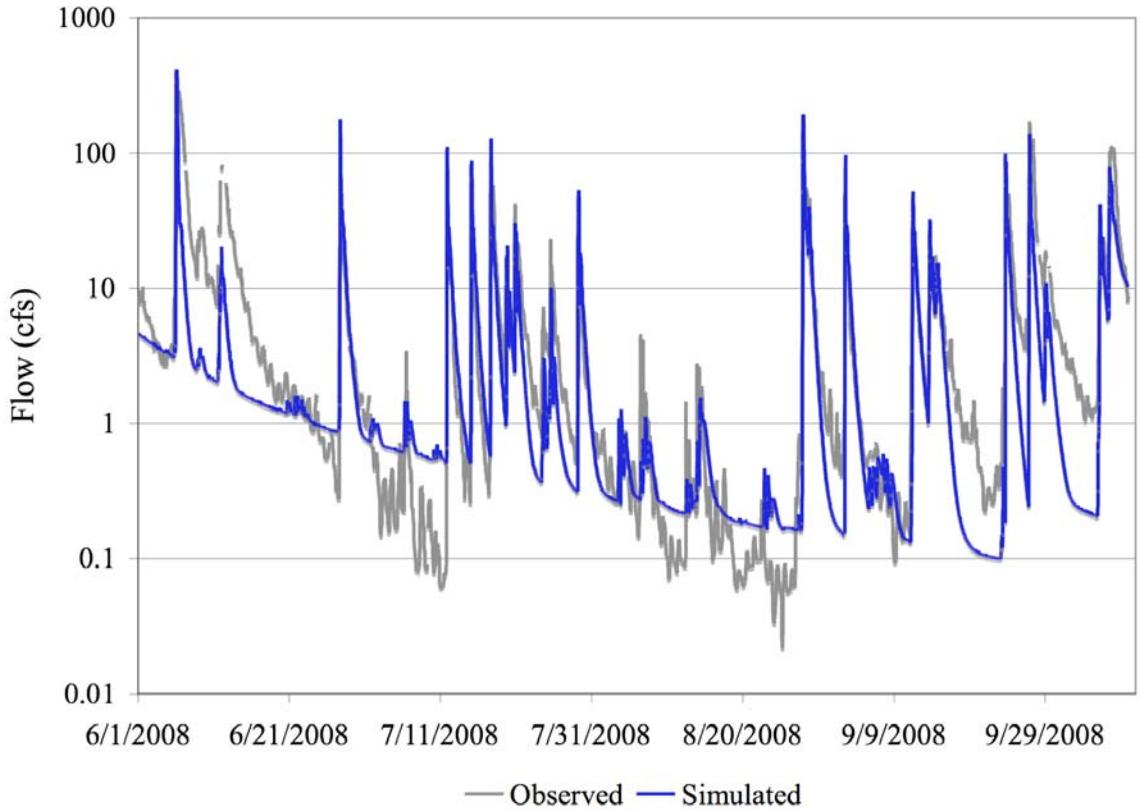


Figure 7.2 Log plot of simulated (SWMM) (dark line) and observed (gray line) flows in Miller Creek at the 26th Ave stream flow gage (gray line) from June 1 to October 10, 2008 plotted as time series.

Multiple procedures were employed to test different aspects of the model: (1) plots of observed flows against simulated hourly, daily, and weekly average flow, (2) correlations of simulated and observed flows for low flows (<1 cfs), medium-range flows (between 1 cfs and 10 cfs), and high flows (>10 cfs), and (3) comparisons of baseflow simulations in the watershed to point measurements taken on two days (July 2 and August 4, 2009).

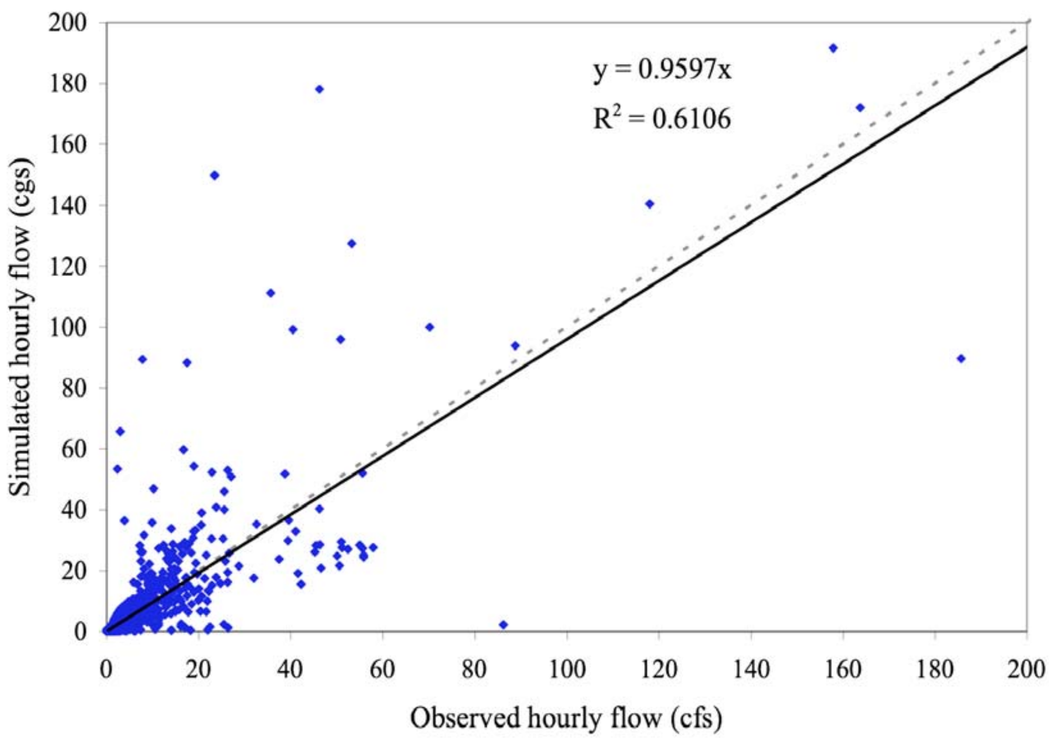
7.2 Regression of simulated against observed stream flows in Miller Creek

To quantify the validity of the model, the simulated flows were plotted against the observed flows and some statistical attributes were calculated. Three plots (Figure 7.3) were created to see how the model performs overall on different timescales: hourly, daily, and weekly. All three plots show a unity line, i.e. if the simulation was perfect all points would fall on this line.

The top panel of Figure7.3 shows the **hourly** average flow comparison. A trend line and unity line were added as references. The trend line is close to unity (slope 0.96, unity is 1) meaning the simulated average hourly flows are close to the observed hourly flows – on average. However the data scatter is tremendous and $R^2 = 0.61$. At the lower flows the model over-predicted as much as it under-predicted the flows, but at the higher flows the model tended to over predict the flows. The average hourly observed flow over the time-period is 3.3 cfs and the average simulated flow is 3.5 cfs. The RMSE for the hourly flows is 7.4 cfs. This means that the hourly flow prediction is not reliable, although on average it is not significantly biased.

The center panel of Figure 7.3 shows the observed **daily** average flows against simulated average daily flows. The plot shows a satisfactory correlation, the slope of the trend-line is close to unity. The observed average daily flow over the whole time period is the same as the hourly flows (3.3 cfs) and the simulated average daily flow is 3.5 cfs. The RMSE for day average flows over the whole period is 3.1 cfs. The Nash-Sutcliffe coefficient is 0.79. These values indicate that the model does a good job – on average - reproducing the average daily flows. The RMSE is not negligible, however.

The bottom panel of Figure 5.4 shows the observed **weekly** average flows against simulated average weekly flows. The average observed weekly flow is 3.4 cfs and the average simulated weekly flow is 3.6 cfs. The RMSE is 1.5 cfs. The Nash-Sutcliffe coefficient is 0.76. The statistics suggest that the model does a good job reproducing average flows on a weekly time scale.



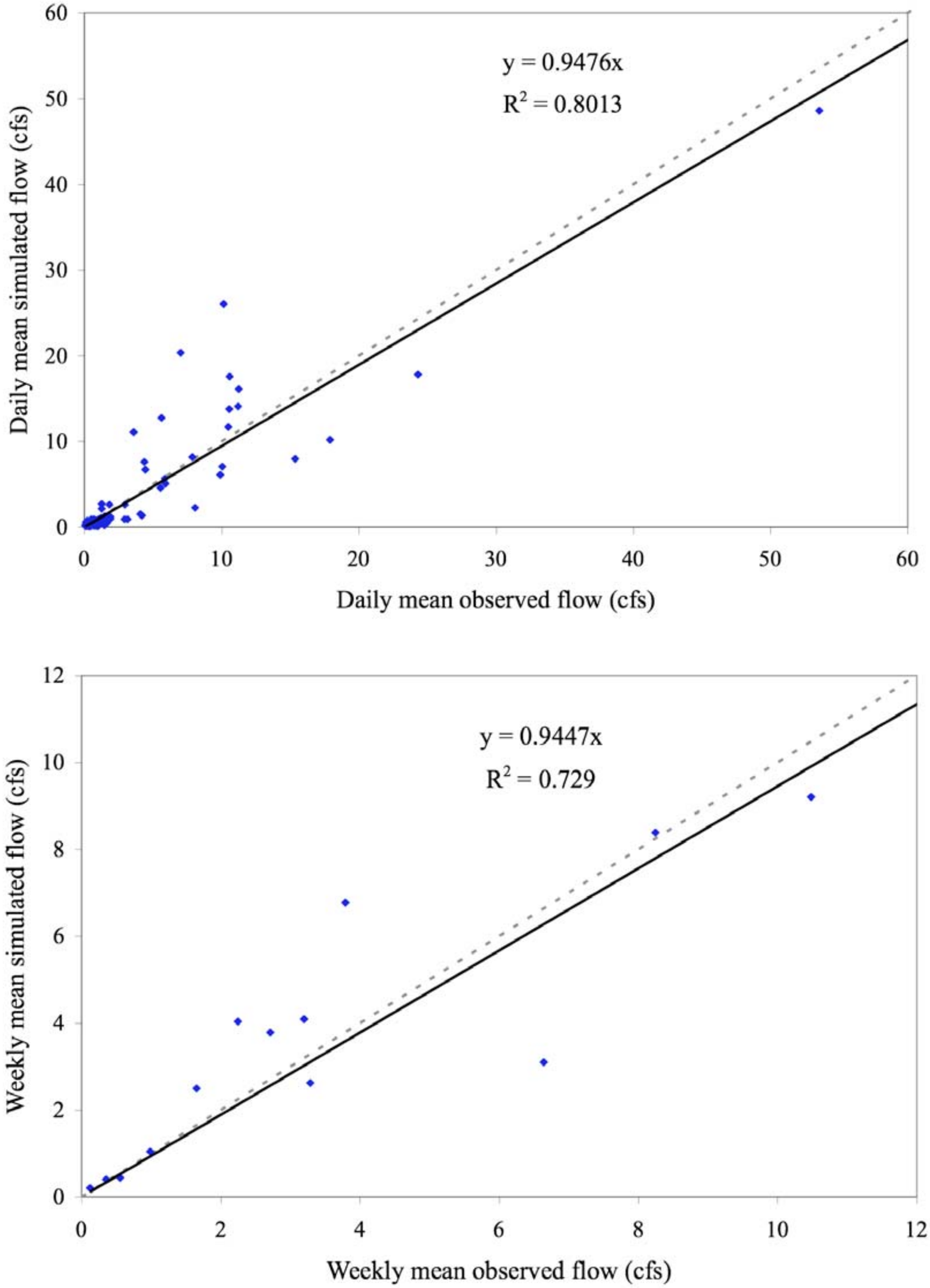


Figure 7.3 Hourly (top panel), daily (center panel), and weekly (bottom panel) average SWMM flows plotted against observed flows in Miller Creek for June 20 to Sept 22, 2008 for Miller Creek.

7.3 Stream flow regressions in three flow ranges for Miller Creek

Next, the flows were broken into three flow ranges to see how well the model performs reproducing high or low flow regimes. The three flow regimes are Q<1cfs (baseflow), 1< Q <10 cfs (average flows), and Q > 10cfs (storm flows). This analysis was conducted on hourly flow rates. The partitioning of flows is with respect to observed flows. Figure 7.4 shows the correlation between observed and simulated hourly flows when they are divided into three flow ranges.

The top panel of Figure 7.4 is for the.low flows (less than 1 cfs), the center panel is for intermediate flows (between 1 and 10 cfs), and the bottom panel is for high flows (greater than 10 cfs). Trend lines and R^2-values were added to test how well the model performs for each flow regime. The model does not do a good job reproducing the hourly flows within each of the three flow regimes. The low flows tended to be under predicted (slope of trend line is less than unity), the intermediate flows over predicted, and the high flows are slightly under predicted. The high flows had the best correlation coefficient (R^2) the medium flows and low flows. The correlation seems to decrease with the increase of hourly in each group. Low flows occurring the most, followed by medium flows and then high flows.

The average observed flow for each flow regime was 0.41 cfs for low flows, 3.2 cfs for intermediate flows, and 25.9 cfs for high flows. The number of hours of flow for each regime was 1372, 735, and 175 hours, respectively. The average simulated flow was 0.41 cfs, 3.4 cfs, and 27.0, respectively. The average flows were fairly close and acceptable. The RMSE for the low, intermediate, and high flow regimes were 0.31 cfs, 5.3 cfs, and 24.3 cfs, respectively. Overall, the model performed well for each flow regime.

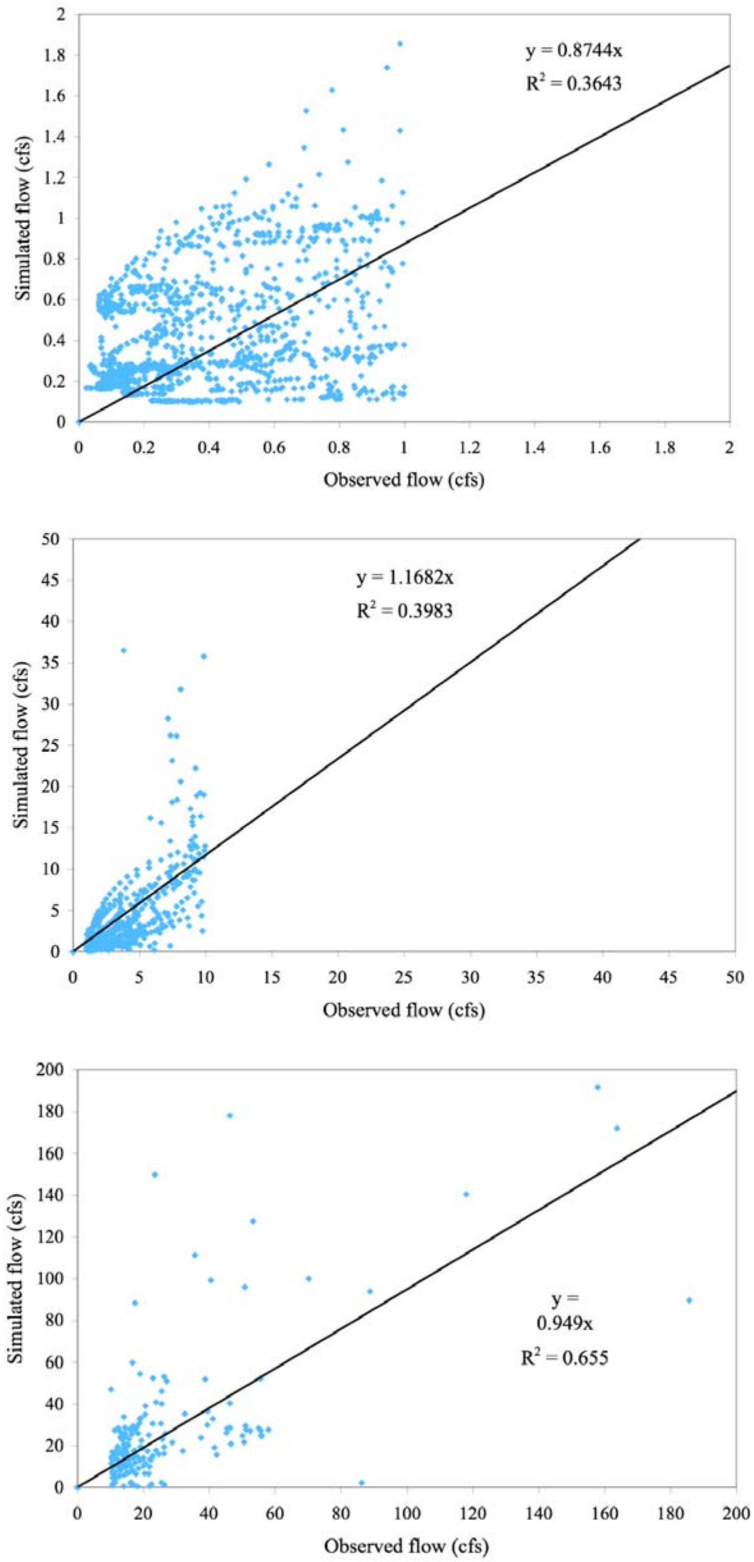


Figure 7.4. Hourly observed flows versus simulated flows for Miller Creek. Flows are partitionned into low flows (less than 1 cfs) (top panel), intermediate flows (between 1 and 10 cfs) (center panel), and high flows (greater than 10 cfs) (bottom panel).

7.4 Modeling of wetlands, groundwater, and baseflow.

Groundwater, wetlands, and baseflow in Miller Creek are closely interconnected. It is most likely that large aquifers do not exist in the watershed, and that subsurface water storage occurs in the wetland areas. SWMM 5 does not have a module to model wetlands directly. Wetlands can be modeled in SWMM 5 by manipulating channel characteristics, such as channel width, slope, length, and roughness, to produce a channel that stores and conveys water like a wetland. Other aspects of wetlands, such as bank storage and channel seepage could not be modeled directly. Instead, wetlands had to be modeled by splitting the functionality into surface processes and sub-surface processes. The surface processes where modeled by manipulating the channel characteristic to slow down the flow of water through the wetland. The sub-surface processes, i.e. storage and discharge of groundwater, were modeled by using the groundwater module in SWMM 5. The problems associated with this type of modeling will be discussed in Section 8.

The groundwater routine in SWMM uses the following equation to estimate groundwater flow (Rossman, 2009):

$$Q_{gw} = A1\left(H_{gw} - H^{*}\right)^{B1} - A2\left(H_{SW} - H^{*}\right)^{B2} + A3H_{gw}H_{SW} \qquad [7.1]$$

where

Q_{GW} = groundwater flow (cfs per acre),
H_{GW} = height of saturated zone above bottom of aquifer (ft),
H_{SW} = height of surface water at receiving node above aquifer bottom (ft),
H^{*} = threshold groundwater height (ft),
A1, A2, A3, B1, B2, B3 = user defined coefficients.

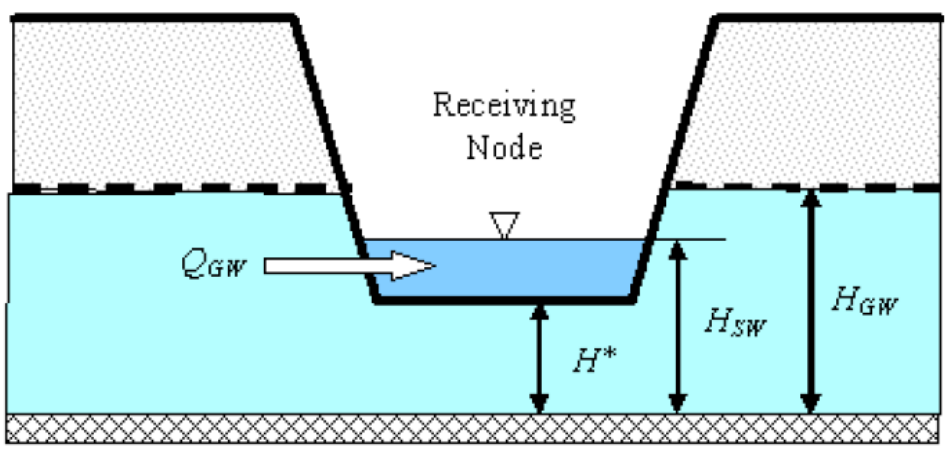


Figure 7.5 SWMM's groundwater equation schematic (From Rossman, 2009).

The groundwater flow equation (eqn 7.1) is robust and can describe a variety of groundwater flows. For example, a uniform flow with uniform infiltration can be described using the Dupuit-Forcheimer approximation given as (James et al., 2008):

$$K\left(h_1^2 - h_2^2\right) = L^2 f \qquad [7.2]$$

where

K = hydraulic conductivity (ft/hr),

h_1 = head of the water table (ft) at a distance (L) from the stream (ft)

h_2 = head of water table at stream (ft)

f = infiltration rate (ft/hr),

.

Since SWMM only calculates an average elevation for the water table throughout the subcatchement, we need to substitute $h_1 = 2*D1 - h_2$, where D1 is the average water table elevation. Assuming that the aquifer and the stream are very shallow at the discharge point, h_2 is equal to zero. By rearranging equation 7.2 and substituting D1, we get:

$$D1^2 \frac{4K}{L^2} = f \qquad [7.3]$$

for uniform flow in an aquifer. Therefore, $A1 = 4K/L^2$, B1 = 2, A2 = A3 = B2 = 0. These values give a good starting point for the parameters in the groundwater equation.

Aquifer parameters of SWMM 5 were calibrated to obtain the best baseflow match with the flow record. Aquifers used in SWMM 5 discharge groundwater to the wetlands or to areas that were identified during two site visits discussed below. Total simulated groundwater discharge to the stream is shown in Figure 7.6.

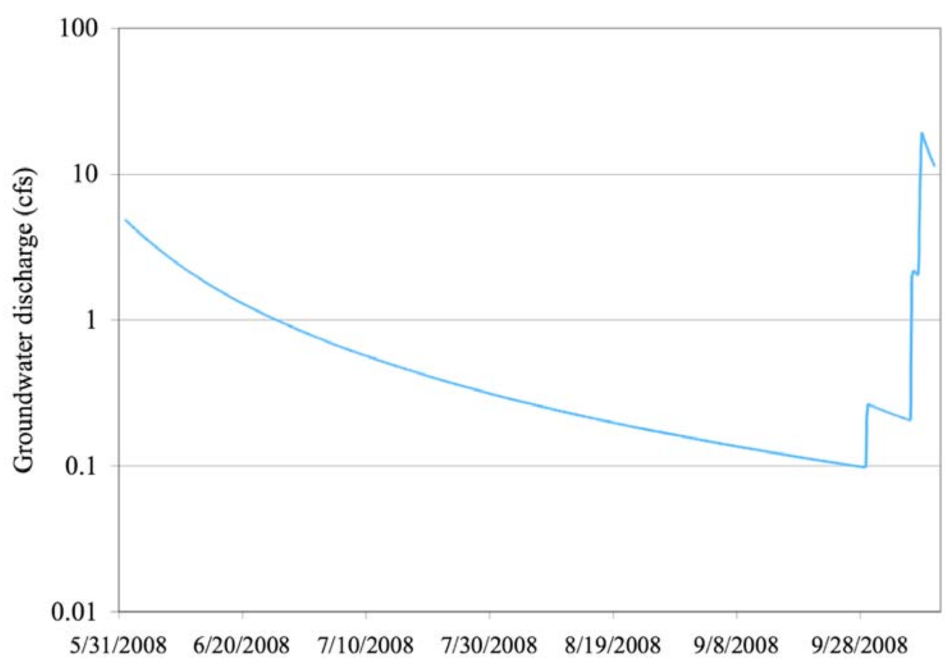


Figure 7.6. Simulated groundwater discharge in the Miller Creek watershed.

The simulated groundwater discharge depends on initial conditions in late spring and decays exponentially during summer until infiltration from rain in early fall appears to recharge the aquifer system. Figure 7.2 shows that the actual baseflow determined from Miller Creek flow records recedes to values below 0.1 cfs, i.e.more than the simulated baseflow. Overall, the simulated baseflows are considered acceptable for the temperature study because measurements of such low flows in Miller Creek have a high level of uncertainty. Groundwater flow will be discussed further in Section 8.

To check the simulated discharge of groundwater along Miller Creek, i.e. to determine if the stream picks up flow in the right stream reaches, simulated base flows were compared to point measurements taken on July 1, 2009 by the senior author and on August 4, 2009 by the South St. Louis SWCD and the MPCA. The locations of the measurements are shown in Figure 7.7 for the July 1 site visit and in Figure 7.8 for the August 4 site visit; stream reaches are highlighted.

The two site visits were preceded by 3 days with little or no rainfall, and with 0.78 in of rain in the two weeks prior to July 1 and 1 inch prior to August 4, 2009.. Figures 7.9a and 7.9b give plots of each point measurement and an average baseflow simulation. Since stream flow data from the three stream gauging stations on Miller Creek were not yet available at the time this report was written, average baseflows during periods of low flow were used. The flows were normalized to the flow at the most downstream point so that comparisons between the measurements and simulation could be easily made. The model was able to add baseflow to the stream in the right areas according to Figures 7.9 a and 7.9 b.

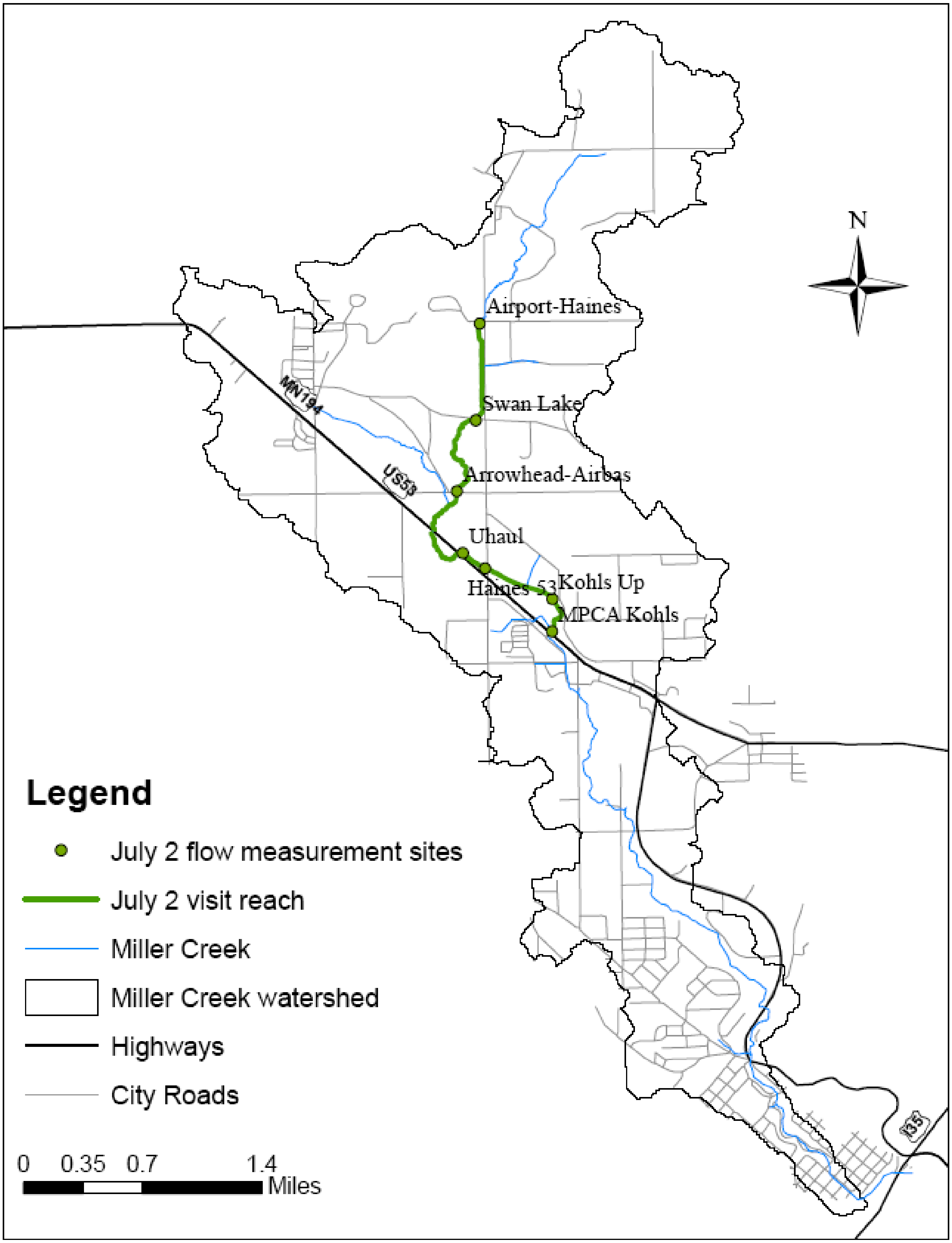


Figure 7.7 Flow measurement sites in Miller Creek on July 2, 2008.

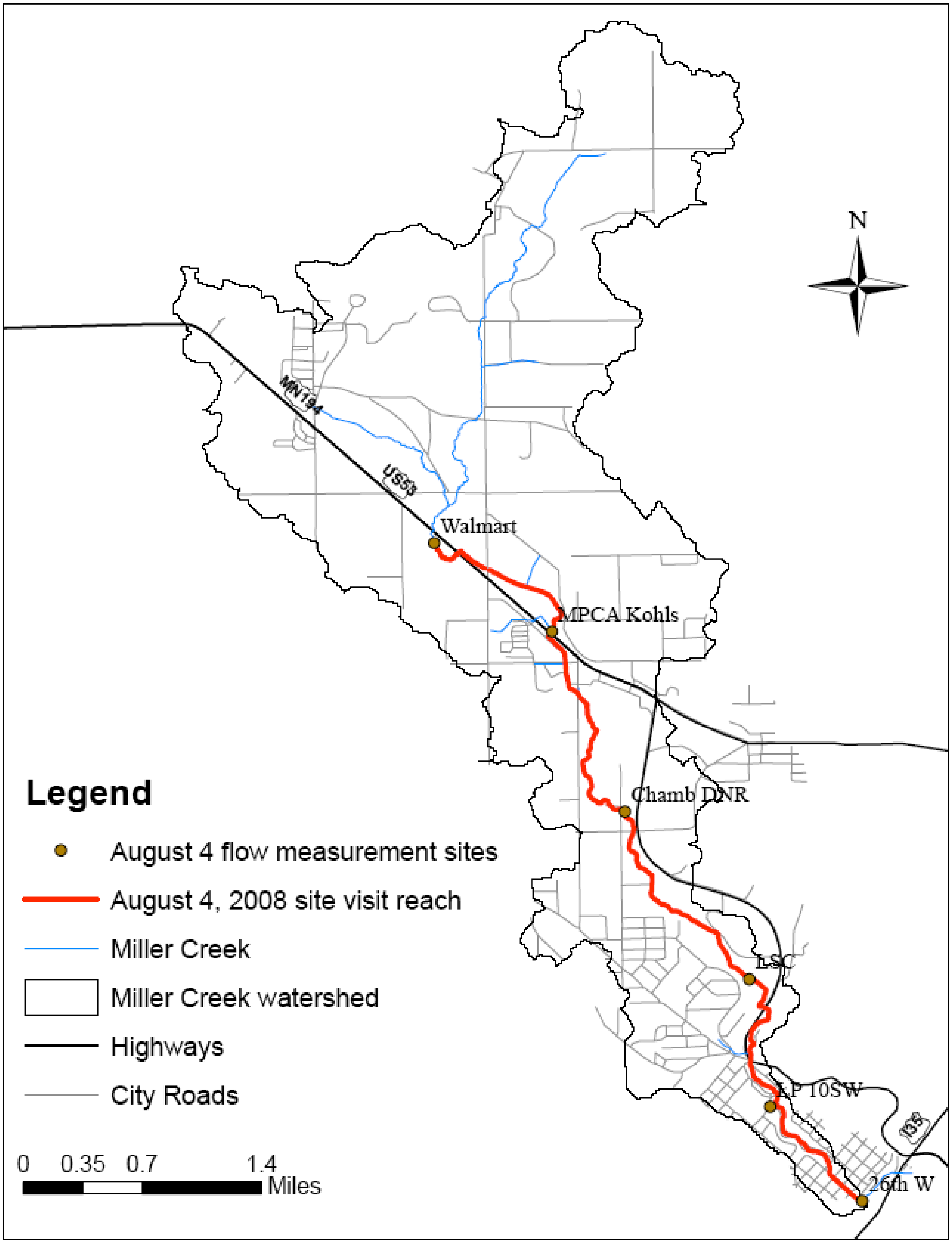


Figure 7.8 Flow measurement sites in Miller Creek on August 4, 2008.

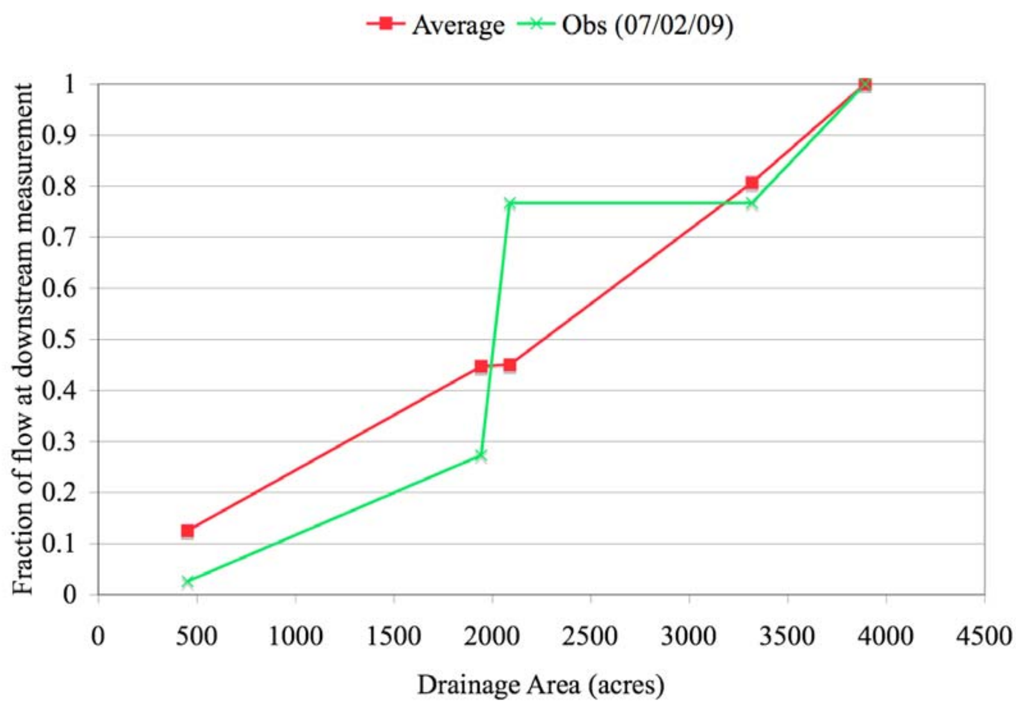


Figure 7.9 a. Streamwise distribution of simulated baseflow in the upper reach of Miller Creek compared to point measurements taken on July 1, 2009.

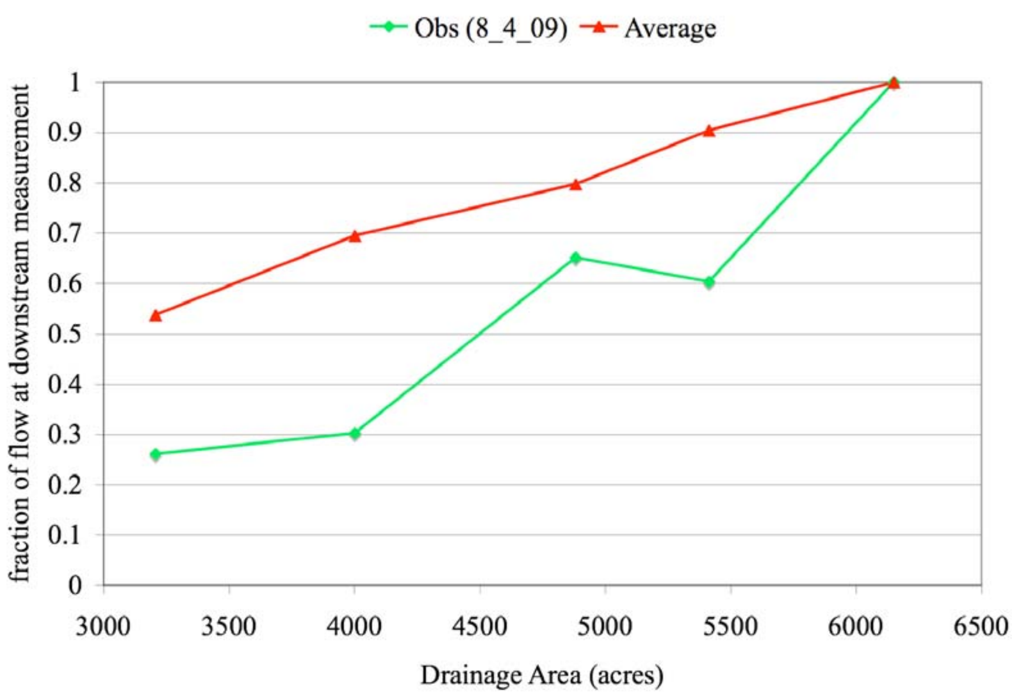


Figure 7.9 b. Streamwise distribution of simulated baseflow in the lower reach of Miller Creek compared to point measurements taken on August 4, 2009.

8. Discussion

Overall the updated SWMM 5 for Miller Creek performed well when compared to the observed flows. The model performed best for late summer/early fall flow because the model was calibrated to storms (rainfall events) in this period. This time period is most important for the thermal study that will use input from SWMM because the stream flows in that period were usually the lowest and the air temperatures the highest. The model was able to reproduce daily average flows the best (R^2=0.8) with Nash-Sutcliffe coefficient of 0.79.

There are several known sources of errors in the model. Some of these errors could be eliminated with a more detailed study of the watershed, including better channel geometry, longer timeseries of precipitation and flow data, and a better understanding of the hydrogeology. Most of the channel geometry was taken from the NRRI SWMM model (Schomberg et al. 2008) and then confirmed in some places with a site visit. A more complete survey of the stream channel could improve the model accuracy.

One of the biggest causes of error in the model simulations was the lack of information on the complex interaction of wetlands and groundwater flow in the watershed. SWMM 5 doe not have a wetland module. Wetlands can be represented only by manipulating and calibrating the channel width, channel roughness and by adding an outlet restriction to match the outflow. The hydrology of the wetlands in the SWMM 5 model for Miller Creek was represented by calibrating channel roughness, channel length, and slope to reproduce the slow release of surface flow. In addition, the groundwater module was utilized to model the groundwater flow to the wetlands, and the discharge of groundwater from the wetlands.

Wetlands play a large role in the hydrology of Miller Creek. They are likely to 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.

The surface flow through the wetlands was modeled fairly well, and the model reproduced the peak flows and the receding arms of the storm hydrographs (Figure 7.2). The streamwise distribution of groundwater discharge to Miller Creek is also represented fairly well (Figures 7.8a, b) but the groundwater discharge recedes more slowly in the model than is observed (Figure 7.2).

Very little appears to be known about groundwater flow in the Miller Creek watershed and the sub-surface properties of the Miller Creek watershed. Parameters in the groundwater flow module of SWMM 5 had to be estimated or calibrated from minimal data. Because data on the hydrogeology of the watershed were lacking, coefficients in the groundwater equation were calibrated to match base-flow, and their link to the physical world is unknown. Most groundwater-related coefficients came from the NRRI SWMM and model calibration to match base flow or low flow periods. The groundwater flow coefficients should range from 10^{-4} to 10^{-6} (Zarriello & Barlow, 2002). In order to match the observed low flow conditions in Miller Creek, the calibrated groundwater coefficient had to be 0.05, two orders of magnitude higher than the expected value. It is unknown if a substantial portion of the baseflow comes from groundwater. It is likely that the groundwater component of baseflow is minimal. This can be shown in the recessions of baseflow with flows receding to less than 0.1 cfs (see Figure 7.2). The modeled groundwater discharge decays slowly throughout the summer without any variability (Figure 7.5). The variability in the modeled streamflow between storms stems from channel storage slowly moving from the upper reaches and wetland areas. The low flow observations suggest that baseflow in Miller Creek stems from the drawdown of wetland areas and from channel storage instead of the draining of aquifers as is the case in coldwater streams of other regions.

SWMM does not allow for flow from channels into the sub-surface as is likely to occur in wetlands. Because bedrock in the Miller Creek watershed is found at shallow depths, it is likely that the hydrogeology includes groundwater recharge from the wetlands; wetlands most likely also supply the source water for springs that exist in the watershed. Overall, the SWMM model was able to reproduce the streamwise distribution of flow in Miller Creek. In the model simulations Miller Creek picks up flow in the right places along its stream length.

Errors in model results are associated with the limitations in the SWMM assumptions and SWMM formulations themselves, especially in the SWMM's ability to effectively model the wetlands and groundwater in Miller Creek. SWMM was originally developed to model storm water runoff and pollutant loading in urban areas with storm sewer systems. The fate of infiltrated water was originally considered to be insignificant (James et al. 2008) and no groundwater component was included at its inception. A groundwater component has since been added, but is fairly simplistic and robust. SWMM was developed for the typical hydrologic urban watershed. Wetlands were not specifically addressed in SWMM, so that it has trouble with modeling areas with a significant area of wetlands contributing to the hydrology of a stream.

Because of the numerous wetlands in the Miller Creek watershed and their influence on the hydrology of the stream, SWMM may not be the best model type for the Miller Creek watershed. A model with the ability to effectively model wetland hydrology and flow processes in greater detail may add a better understanding of the importance of wetland modifications. If further investigation into the watershed or similar watersheds on the North Shore is needed, a different model should be considered. For a greater understanding of the surface-groundwater interaction, a model capable of modeling wetlands and complex groundwater flow is needed. Detailed field investigations e.g. dye studies will also be needed.

Another limitation is that SWMM cannot represent changes due to the growing season. The effect of this shortcoming was seen during the time periods for which the model was not calibrated, e.g. early summer. Early summer storms are not modeled as effectively as late summer/early fall storm events. Parameters such as channel and subcatchment roughness can change during the year but SWMM keeps them constant.

In SWMM, evaporation rates seem to have a large impact on the volume of runoff generated and on channel losses (Schomberg et al 2000). This large dependence is due to the way SWMM handles evaporation. It uses an "off the top" approach meaning that evaporation is subtracted during a rainfall event before infiltration and runoff are estimated (James et al. 2008). This can lead to underestimating of the runoff volume and infiltration depths during storm events.

Evaporation during rainfall events is small or non-existent. The sun is blocked by clouds, lowering solar radiation, and the air is close to saturation, i.e. there is little difference between the dew point and air temperature. Along with the wind, these main drivers of evaporation are therefore not very effective during rainfall/runoff events.

SWMM also uses one value for evaporation for the whole watershed. Variations in vegetative cover can lead to spatial and temporal varied evapotranspiration rates. For example, the heavily vegetated upper reaches of the Miller Creek watershed have a variety of trees and shrubs, whereas the lower, more urban areas are covered mostly with lawn grasses and few trees. Plants use different amounts of water at different times as they grow throughout the year. One daily evapotranspiration rate does not represent the variability that can occur in the watershed.

9. Simulations of Baseflow Augmentation Scenarios

Baseflows in Miller Creek can get very low. The effects of wetland restoration and increased storage in Miller Creek on baseflow in Miller Creek was therefore simulated using the SWMM. Low baseflow (less than 0.1 cfs) during summer months contributes to the impairment of Miller Creek (this report and Herb and Stefan 2009). Increasing the baseflow may reduce stream temperatures, and provide better habitat for trout.The restoration of the wetland near Kohl's (Figure 9.1), or impounding water in the wetlands using hydraulic structures such as weirs were simulated..

Four scenarios were test using the SWMM model: (1) Increases in channel roughness in the wetland, (2) increases in channel length in the wetland, (3) increased water storage in the wetland using weir structures, (4) increased storage in the watershed using detention ponds. The first 3 scenarios can be implemented in the Kohl's wetland. Channel length can be increased, and channel slope can be decreased by restoring the stream (channel) meandering. Roughness can be increased by adding woody debris, rock vanes and a pool-riffles system to the channel. Weirs would increase the water residence time and reduce the peak flows in the wetland. In the fourth simulated scenario stormwater is captured in stormwater detention basins located in three of the highly developed sub-catchments (near the airport and mall areas) and then slowly released to augment the baseflow. It should be noted that all four scenarios are simplified representations of possible structural modifications They are simplified versions because SWMM is unable to model wetlands in detail. Any future restoration project in the Miller Creek watershed has to include further investigations of the effect it will have on the stream.

The simulations of the stream flow modifications were made for weather and flow conditions that occured from August 27, 2008 to September 11, 2008. This time period gave good agreement of modeled flow and observed flows. The time period is long enough for flows to reach baseflow condition. Rainfall and modeled flows for this period can be seen in Figure 9.1.

Six metrics are used to test the sensitivity of the stream flow to changes in the wetlands or to storage in the watershed: (1) average flow over the time period, (2) maximum peak flow, (3) minimum flow, (4) flow on September 4, 2008 2:00 AM for flows at downstream end of wetland or 10:00 AM for flows at lower gauging station (The original modeled flow reaches 1 cfs at these times), (5) flow on September 11, 2008 at 6:00 AM, and (6) the number of hours after the last peak flow for the flow to reach 1 cfs. These metrics quantify the changes in the streamflow hydrograph recession and the baseflow. The first three are fairly standard and self-explanatory, the last three are described next. The flow on September 4, 2008 at 2:00 AM at the wetland or 10:00 AM at the lower gauging station is the time when the original modeled flow reaches 1 cfs after the second storm flow peak (Figure 9.1). The flow at this time step can be used to describe the magnitude of the hydrograph recession, i.e. how much the altered physical parameter affects the hydrograph recession. The flow on September 11, 2008 at 6:00 AM is the flow right before another rainfall event.This flow shows a restoration scenario's long term effect on baseflow. The number of hours after the second storm peak required by the stream flow to reach 1 cfs describes the length of the recession.

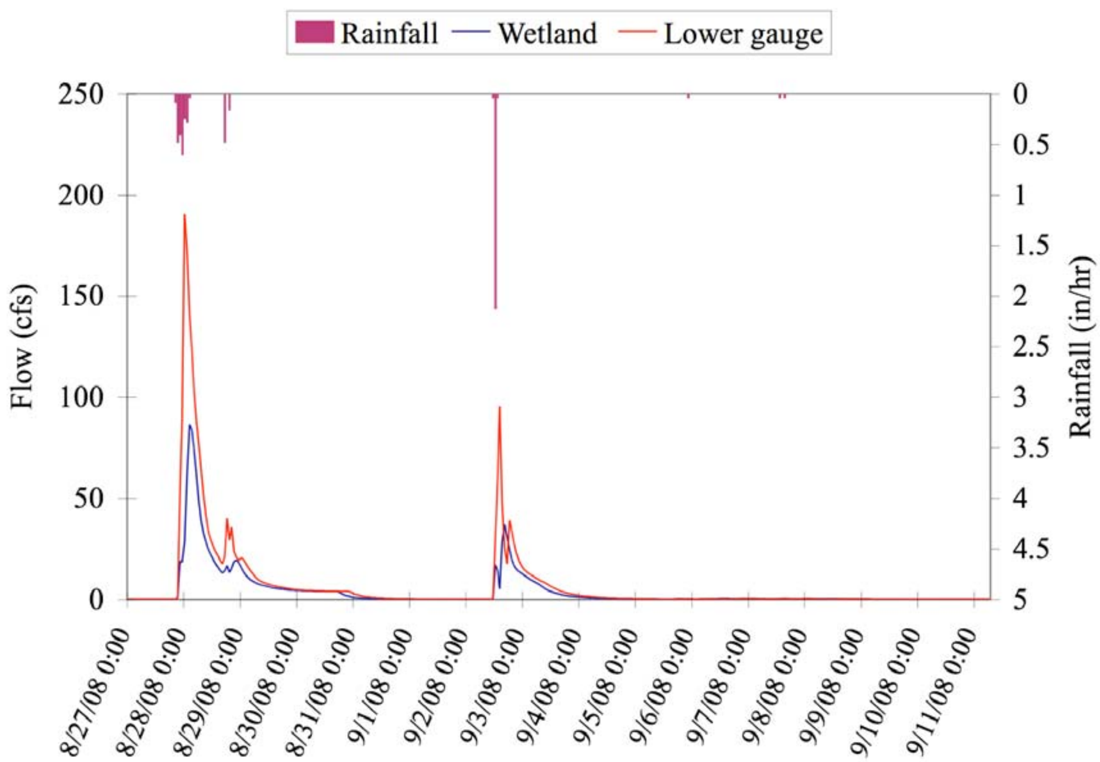


Figure 9.1 Original modeled flows and rainfall for Miller Creek.

The scenarios are divided into two sections: (1) simplified wetland restoration scenarios in Kohl's wetland; and (2) storage increase in the watershed, either in Kohl's wetland or throughout the watershed.

9.1 Wetland restoration

The sensitivity of streamflows to two stream properties (stream length/slope and roughness) of the wetland near Kohl's (Figure 9.2) has been simulated. First, the channel length through the wetland is increased. This will show if re-meandering of the channel will increase the baseflow.

Second, the roughness is modified to see if adding rock structures or wood debris will increase the baseflow.

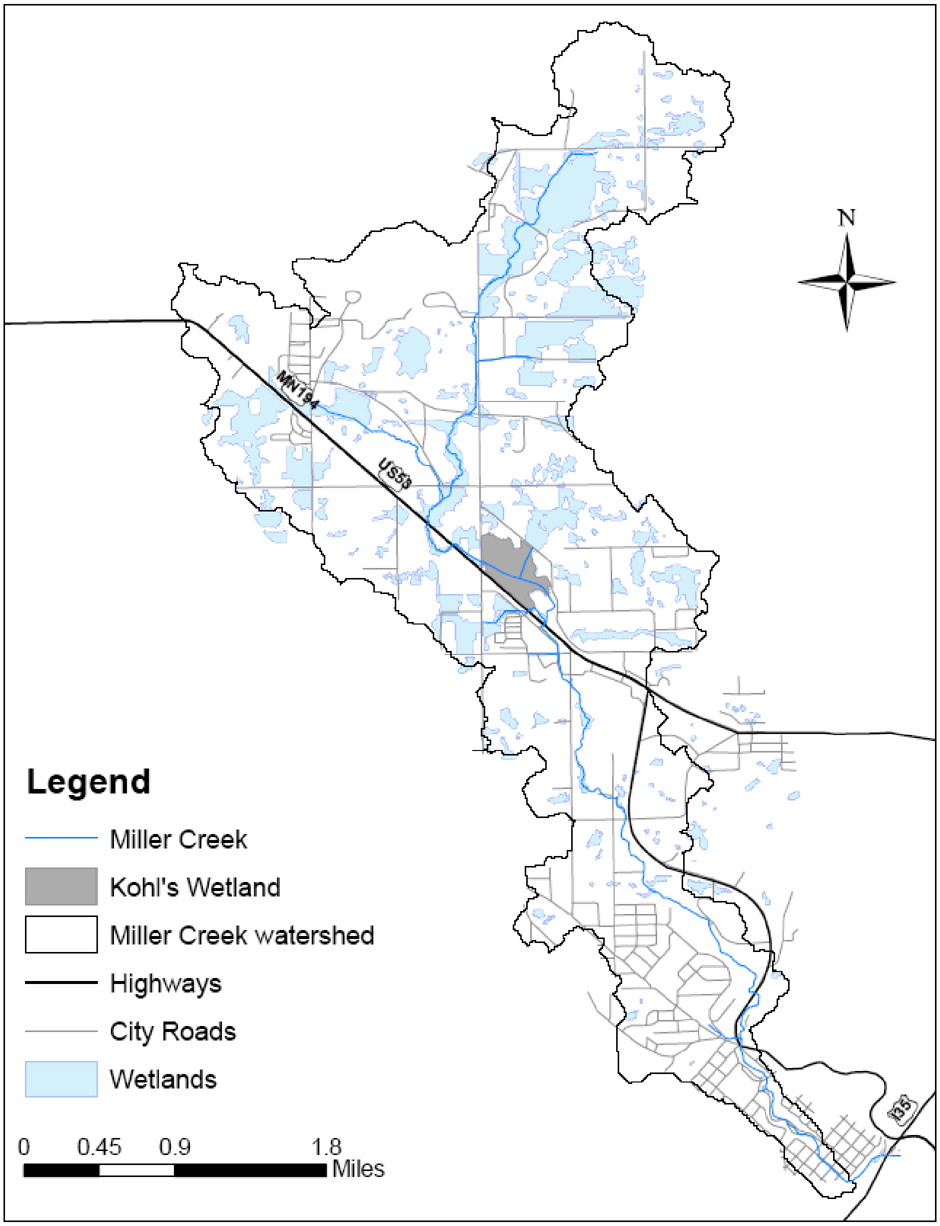


Figure 9.2 Location of Kohl's wetland in the Miller Creek watershed.

Change of channel length in Kohl's wetland

In the first wetland restoration scenario the sensitivity of streamflow to increased channel length through the Kohl's wetland was tested. The channel would meander to represent a more natural stream. Increasing the channel length would decrease its slope, and increase the residence time of

the water. According to the SWMM some of the baseflow is from channel storage, and hence increasing the residence time and channel storage would increase the baseflow.
The current channel length through Kohl's wetland was adjusted by factors of 0.5, 2, 4, and 8 of length. The two channel sections adjusted in the model were main 25 and main 26 (Appendix B) Streamflows simulated with different channel lengths as input were compared to the original modeled flows. The original lengths of the manipulated channel sections are 1710 ft and 992 ft for a total channel length through the wetland of 2802 ft. The linear distance between the inlet and outlet of the wetland is approximately 2250 ft. The ratio of channel length to linear length shows that the stream is currently fairly straight and channelized through the wetland; a meandering stream would have a ratio much greater than one.

Table 9.1 Flow metrics for modified channel lengths through Kohl's wetland.

Flow at downstream end of wetland					
Length multiplier	0.5x	1x (original)	2x	4x	8x
Mean flow (cfs)	4.1	4.1	4.2	4.4	5.1
Max flow (cfs)	91.6	86.6	79.6	68.2	46.5
Min flow (cfs)	0.11	0.11	0.11	0.12	0.15
Flow on 9/4/08 at 2:00am (cfs)	0.91	1.01	1.29	2.15	5.55
Flow on 9/11/08 at 6:00am (cfs)	0.11	0.11	0.11	0.12	0.18
Time from peak flow to 1cfs flow (hrs)	35	35	37	42	57

Flows at the lower gauging station					
Length multiplier	0.5x	1x (original)	2x	4x	8x
Mean flow (cfs)	7.1	7.1	7.1	7.4	8.0
Max flow (cfs)	192.1	190.6	188.6	186.7	186.2
Min flow (cfs)	0.13	0.13	0.14	0.15	0.18
Flow on 9/4/08 at 2:00am (cfs)	0.93	1.01	1.22	1.88	4.45
Flow on 9/11/08 at 10:00am (cfs)	0.13	0.13	0.14	0.15	0.24
Time from peak flow to 1cfs flow (hrs)	44	45	48	56	85

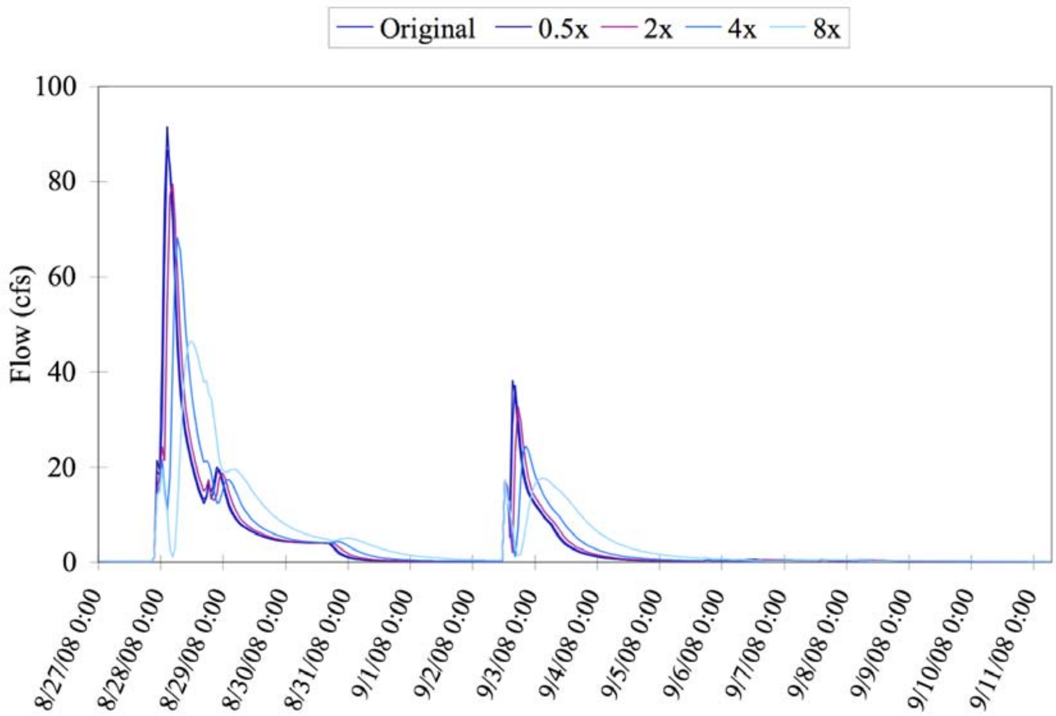


Figure 9.3: Modeled streamflow in Miller Creek at the downstream end of Kohl's wetland for channel lengths in the wetland that are 0.5, 2x, 4x, and 8x the current existing length (2802ft).

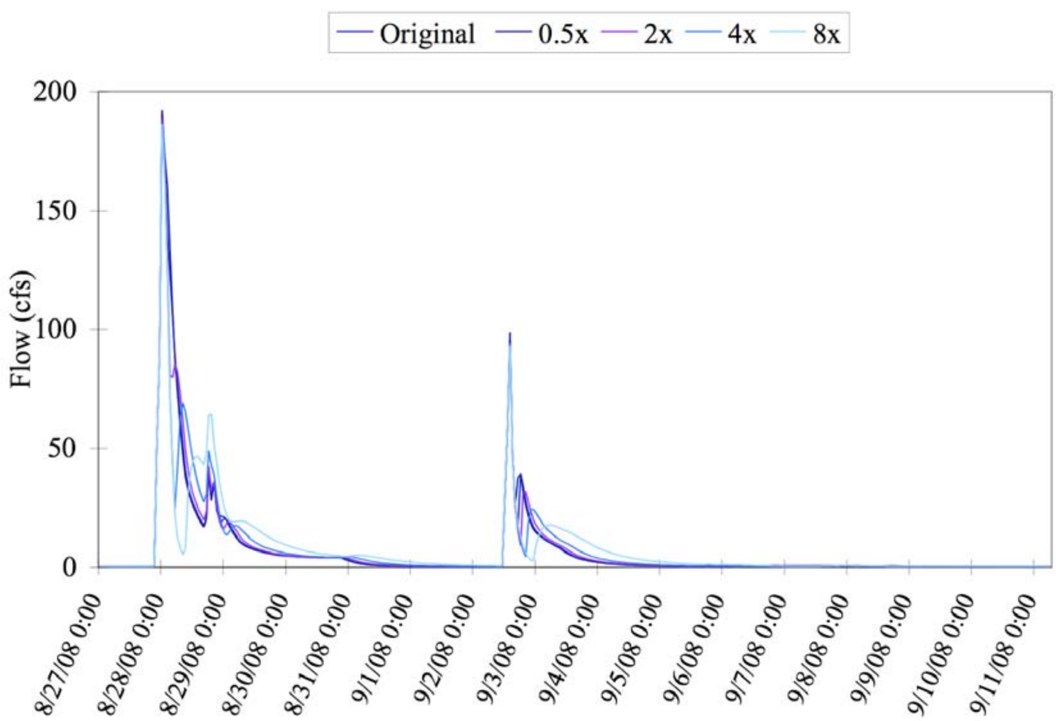


Figure 9.4: Modeled streamflow in Miller Creek at the lower gauging station for channel lengths in the wetland that are 0.5, 2x, 4x, and 8x the current existing length (2802ft).

Figures 9.3 and 9.4 give the modeled flows in Miller Creek downstream of the wetland and at the lower gauging station, respectively, for four channel length scenarios. Table 9.1 illustrates how the flow metrics change with channel length. The modeled flows, especially at the end of the wetland show some sensitivity to the channel length of the wetland. The average flow increases from 4.1 cfs to 5.1 cfs. Lengthening the channel reduces the peak flow and extends the storm flow recession as expected. Downstream of the wetland the peak flow is reduced from 91.6 cfs for the 0.5xlength to 46.5 cfs for the 8xlength scenario but at the lower gauging station the effect is much smaller. The recession period is extended from 35 hours after peak flow to reach 1 cfs for the original channel to 57 hrs for the 8xlength scenario. The delayed storm flow recession does translate downstream: the recession from peak flow to 1cfs is 45 hours for the original channel length and 85 hours for the 8xlength scenario. The increase in baseflow due to the increased channel length is, however, short-lived; the long-term baseflow is unaffected by the changes, i.e. baseflow at the end of the time period is only slightly higher (0.11 cfs compared to 0.18 cfs). This may lead us to believe that re-meandering the stream channel will decrease the peak flows and extend the storm flow recessions but will not affect baseflow during extended periods without rainfall. However, since the SWMM model does not consider subsurface flow in the wetland, the full benefit of increasing the channel length may not be represented by the model results.

Change of channel roughness in Kohl's wetland

An alternative for the Kohl's wetland restoration is to increase the roughness of the channel in the wetland. This can be achieved by adding rock structures or vegetation or pool-riffle sections. Manning's n is used to describe channel roughness in SWMM. Five roughness scenarios were tested using the SWMM model. The five scenarios are 0.25x, 0.5x, 1.5x, 2x and 4x the current existing roughness. The two lower roughnesses were tested because the original roughness of the channel through the wetland was already very high (n = 0.149).

In Figures 9.5 and 9.6 the modeled streamflows downstream of the wetland and at the lower gauging station, respectively, are presented for all roughness scenarios. Table 9.2 gives the flow metrics of the five roughness scenarios. The modeled flows are fairly insensitive to roughness. Peak flow is reduced slightly from 91.4 cfs for 0.25x roughness to 72.6 cfs for 4x roughness. Most other metrics are even closer to each other. Based on the SWMM model results, it appears that flows through the wetlands are more sensitive to channel length than channel roughness.

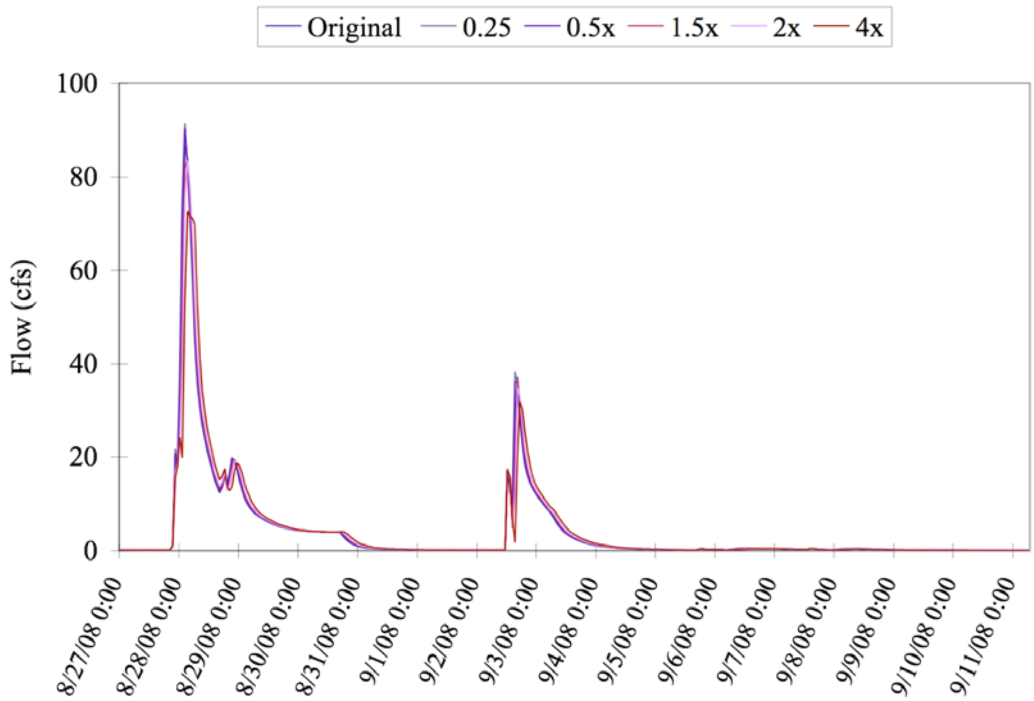


Figure 9.5: Modeled streamflow in Miller Creek at the downstream end of Kohl's wetland for 0.25x, 0.5x, 1.5x, 2x and 4x the current existing channel roughness (n=0.149).

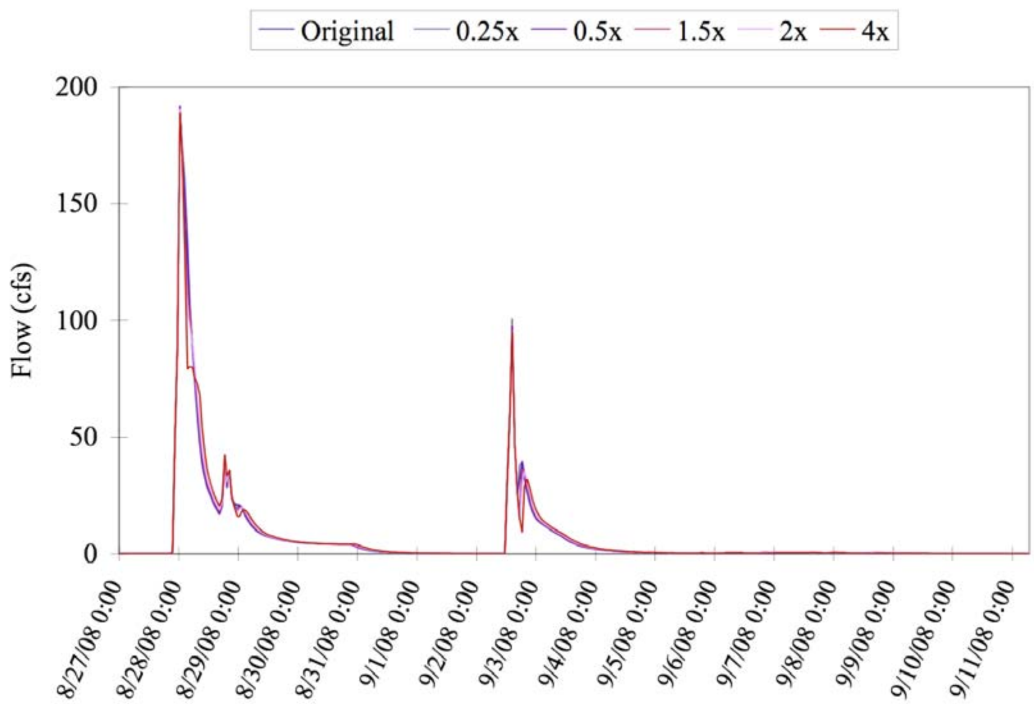


Figure 9.6: Modeled streamflow in Miller Creek at the lower gauging station for 0.25x, 0.5x, 1.5x, 2x and 4x the current existing channel roughness (n=0.149).

Table 9.2 Flow metrics for modified channel roughness (Manning's n) through Kohl's wetland.

Flows at downstream end of wetland						
Roughness multiplier	0.25x	0.5x	1x (original)	1.5x	2x	4x
Manning's n	0.0373	0.0745	0.149	0.224	0.298	0.596
Mean flow (cfs)	4.1	4.1	4.1	4.2	4.2	4.2
Max flow (cfs)	91.4	90.4	86.6	83.9	83.5	72.6
Min flow (cfs)	0.11	0.11	0.11	0.11	0.11	0.11
Flow on 9/4/08 at 2:00am (cfs)	0.92	0.96	1.01	1.07	1.11	1.28
Flow on 9/11/08 at 6:00 am (cfs)	0.11	0.11	0.11	0.11	0.11	0.11
Time from peak flow to 1 cfs flow (hrs)	35	34	35	35	36	37

Flows at the lower gauging station						
Roughness multiplier	0.25x	0.5x	1x (original)	1.5x	2x	4x
Manning's n	0.0373	0.0745	0.149	0.224	0.298	0.596
Mean flow (cfs)	7.1	7.1	7.1	7.1	7.1	7.2
Max flow (cfs)	191.9	192.0	190.6	190.6	190.3	188.8
Min flow (cfs)	0.13	0.13	0.13	0.13	0.13	0.14
Flow on 9/4/08 at 2:00am (cfs)	0.93	0.96	1.01	1.05	1.08	1.22
Flow on 9/11/08 at 6:00 am (cfs)	0.13	0.13	0.13	0.13	0.13	0.14
Time from peak flow to 1 cfs flow (hrs)	44	44	45	45	46	48

9.2 Additional water storage in the watershed

Adding water storage in the watershed can also serve to augment baseflow. Two storage options were considered: The first is to place two weirs in Kohl's wetland, creating two miniature reservoirs; the second is to add storage at three locations throughout the watershed.

Weirs added to the channel in Kohl's wetland

It has been suggested that hydraulic structures could be added to the channel in Kohl's wetland to increase water storage. To test the usefulness of this idea, two weirs that create identical storage units were added to the SWMM model in the wetland. The storage units cover a total surface area SA (ft^2) = 50,000 ft *h + 850,000 ft^2 and have a storage volume V (ft^3) = 25,000 ft* h^2 + 850,000 ft^2*h where h(ft) is the water depth at the weir. Together they cover the entire wetland area (roughly 2,400,000 ft^2). Two weir lengths were tested, 1ft and 6ft. The 1ft weirs might not be realistic but were used to test an extreme scenario. The discharge coefficient used for the weirs was 3.33 (sharp crested weir). The weirs were placed in a channel cross-section such that the water level could rise 7ft above the channel bottom without overflow. In the simulations the water depth never exceeded 4 ft.

According to the model results, adding weirs has a drastic effect on flows through the wetland and at the lower gauging station (Figures 9.7 and 9.8). Peak flows through the wetland are reduced from 86.4 cfs to 25 cfs for 1ft weirs and to 19.8 cfs for 6 ft weirs. On the recession leg of the hydrograph storm flows are still at 4.75 cfs for the 1 ft weirs and 5.96 cfs for the 6 ft weirs at the time the original modeled flows without weirs had already dropped to 1 cfs downstream of the wetland. This increased recession flows extend to the lower gauging station where the flows are 4.76 cfs and 6.42 cfs, respectively, at the time when the original flow was 1cfs. The storm flow recessions are extended from 30 hours to 210 hours for the 1ft weirs and to 107 hours for the 6ft weirs. The peak flow reductions are not present at the lower gauging station but the extended recessions are.

Adding weirs to the Kohl's wetland is an extreme measure and requires additional study of temperature effects. Weirs increase the baseflow by increasing the retention of water in the wetland. This increased storage would result in a standing pool of water after the high flows. The pool may trap large amounts of undesirable heat from solar radiation unless sufficient emergent vegetation is maintained to shade the retained water. Without shading of the pool, the stream temperatures may rise to unacceptable levels.

Table 9.3 Flow metrics when two weirs are added to the channel in Kohl's wetland.

Flows at downstream end of Kohl's wetland			
	Original	1ft weirs	6ft weirs
Average flow (cfs)	4.1	3.7	4.1
Max flow (cfs)	86.4	25.0	19.8
Min flow (cfs)	0.11	0.24	0.15
Flow on 9/4/08 at 2:00/10:00am (cfs)	1.01	4.75	5.96
Flow on 9/11/08 at 6:00am (cfs)	0.11	1.47	0.29
Time from peak flow to 1cfs flow (hrs)	35	210	107

Flows at the lower gauging station			
	Original	1ft weirs	6ft weirs
Average flow (cfs)	7.1	6.6	7.1
Max flow (cfs)	191.9	186.0	186.6
Min flow (cfs)	0.13	0.27	0.18
Flow on 9/4/08 at 2:00/10:00am (cfs)	1.75	4.76	6.42
Flow on 9/11/08 at 6:00am (cfs)	0.13	1.56	0.34
Time from peak flow to 1cfs flow (hrs)	41	209	115

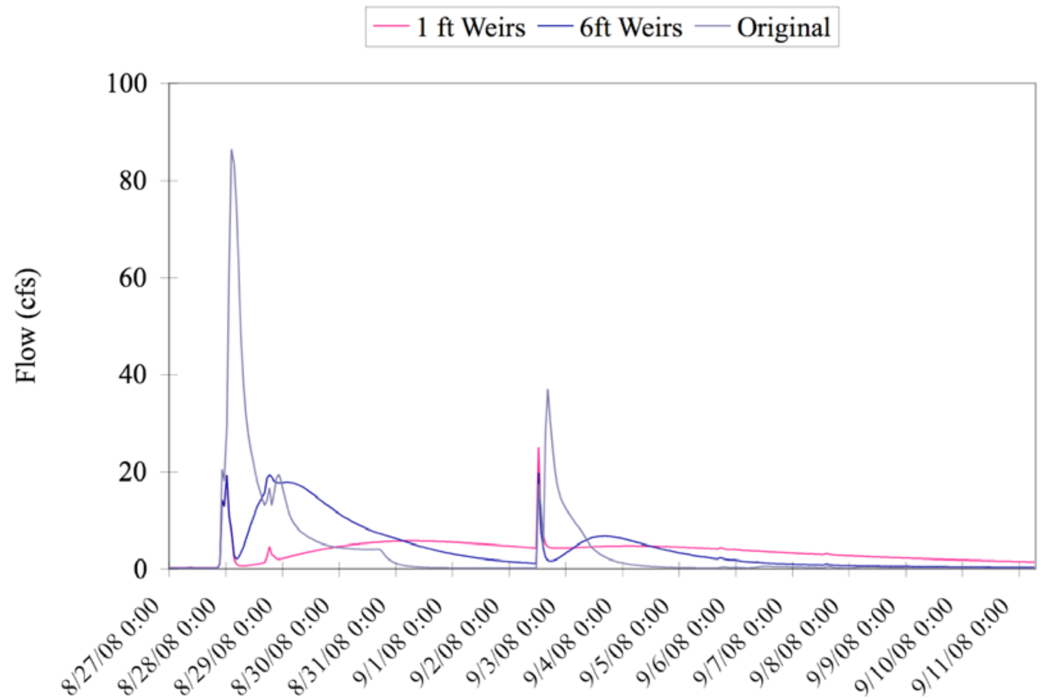


Figure 9.7 Modeled streamflows in Miller Creek downstream of Kohl's wetland when two weirs are added to the channel in Kohl's wetland.

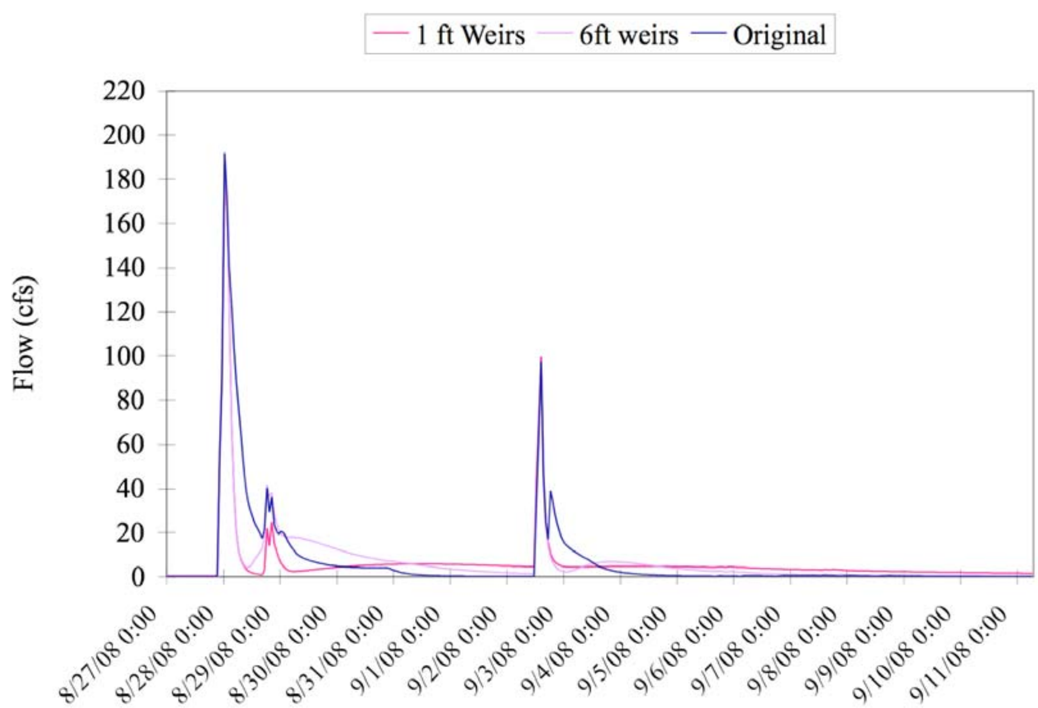


Figure 9.8 Modeled streamflows in Miller Creek at the lower gauging station when two weirs are added to the channel in Kohl's wetland.

Storage added throughout the watershed

The final scenario for increasing baseflow is to add storage (stormwater detention) throughout the watershed. In this case stormwater runoff is captured, and slowly released to the stream, thus adding to the baseflow. This scenario is similar to the previous one except it does not transform a wetland into a reservoir. Instead, multiple "retention" ponds would be installed throughout the watershed. A "retention" pond would be similar to a detention pond except that it would have to be designed to augment baseflow instead of reducing peak flows. A detention pond is designed to release the stormwater within 12 to 24 hours after an event to make room for the next rainfall event. The retention ponds would impound stormwater, much like a reservoir, and slowly release it over a design period of perhaps two weeks, sustaining higher baseflows during the release time.

Three "retention" ponds were place in the watershed and their impact was simulated with SWMM. The three ponds collect runoff from highly impervious sub-catchments near the airport and in the Mall area near the middle of the watershed. The three simulated ponds are virtual ponds. In reality, multiple retention ponds spread throughout the watershed may be better. Figure 9.9 shows the locations (dots) of the three assumed ponds and the sub-catchments (gray areas) that drain into them. The ponds were sized to 1-3% of the drainage area (typical detention pond size). Pond 1 drains subcatchment SC7 (Appendix B), which covers 571.8 acres of land and has 35.1% impervious area. In the model, pond 1's shape is defined by the surface area equation SA (ft^2) = 10,000 ft*h + 400,000 ft^2, where h is the depth of the pond. The maximum depth reached for the 0.5 ft outlet was 3.4 ft. Pond 2 drains subcatchments SC15a, SC15b, SC18, which cover 7.2, 12.0, and 91.8 acres and have a 100%, 97,8%, 59.4% impervious areas, respectively. Pond 2's shape is defined by SA (ft^2) = 10,000 ft*h + 40,000 ft^2. The maximum depth needed for pond 3 was 8.5 ft. Pond 3 drain subcatchment SC 17 with an area of 128.55 acres and 69.2% impervious areas. The pond is defined by SA (ft^2) = 10,000 ft*h + 40,000 ft^2. The maximum depth needed for pond 3 was 8.4 ft.

The outlets were assumed to be concrete (Manning's n of 0.016) and were 50 ft in length. Three outlet sizes were modeled to test the sensitivity to pipe size in the ponds: 6 inch, 12 inch, 18 inch pipes. These outlets are relatively small because the ponds need to retain the water for a long period.

Figure 9.10 is a plot of the flows from the three pipe sizes. Table 9.4 gives the flow metrics in Miller Creek for the three pipe sizes. Adding the three ponds reduces the peak flow from 191.9 cfs for the original modeled flows to 152.8 cfs for the 12-inch outlet pipes. The pipe diameter for the outlet seemed not to effect the reduction in peak flow (Table 9.4). The stormflow recessions are extended over a longer time than fore any other baseflow improvement scenario. The number of hours to reach 1 cfs after the peak flow is extended from 45 hours for the original modeled flows (without the retention ponds) to at least 153 hours for the flows with the three ponds and 12-inch outlet pipes. With a 6 inch outlet the recession is extended further such that baseflow above 1 cfs is maintained until the next rainfall event.

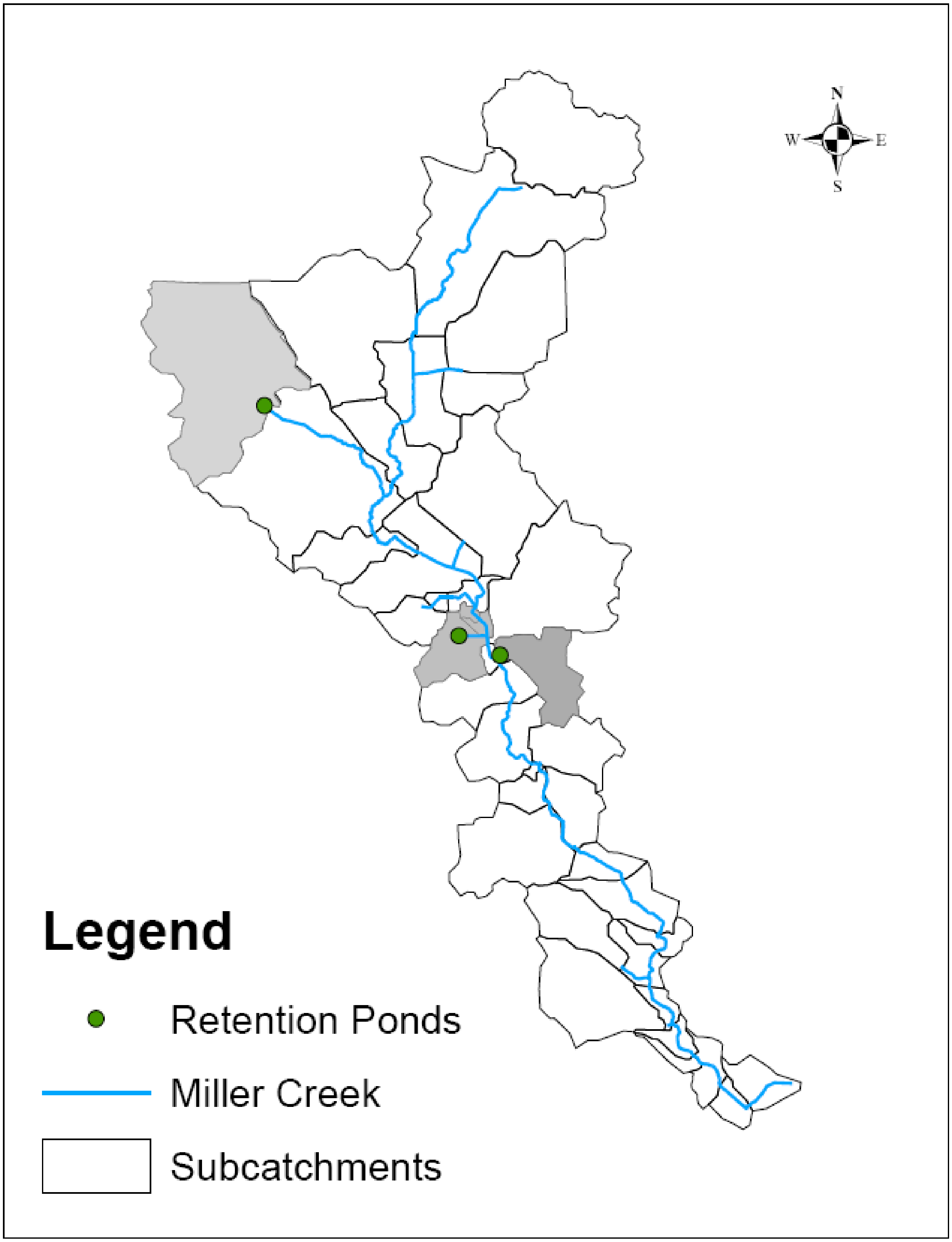


Figure 9.9 Locations and subcatchment areas of added retention ponds in the Miller Creek watershed.

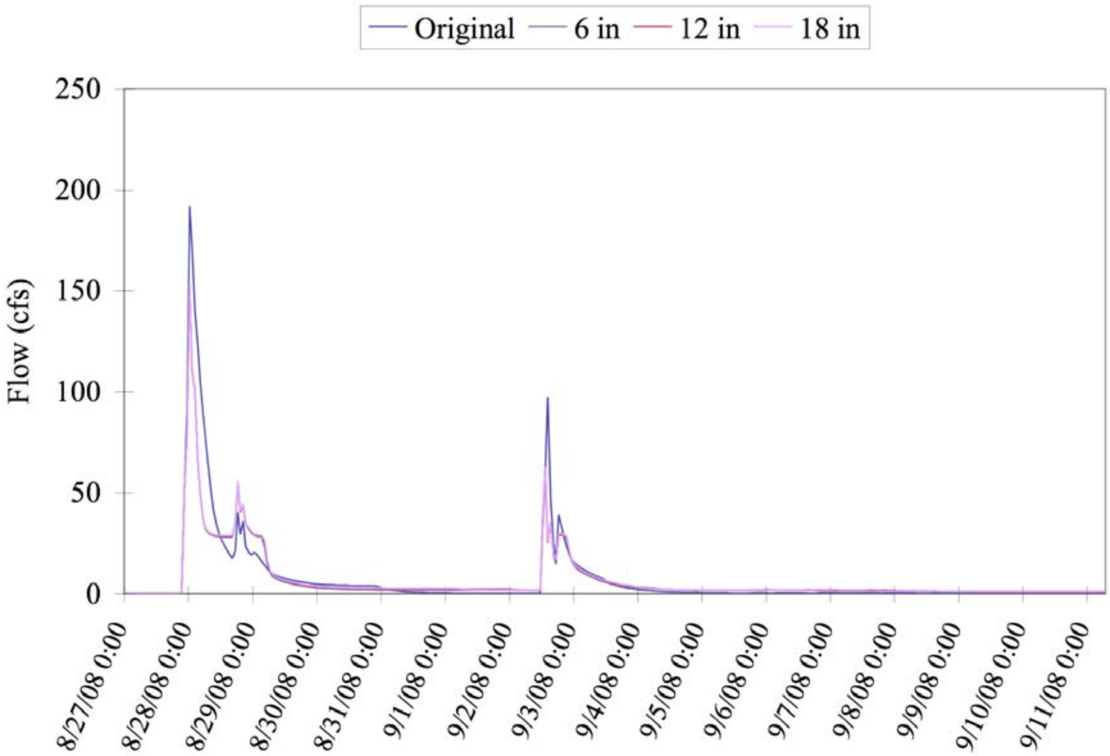


Figure 9.10 Modeled streamflows in Miller Creek at the lower gauging station when three retention ponds are added in the watershed (Figure 9.9).

Table 9.4 Flow metrics at the lower gauging station in Miller Creek when three retention ponds are added in the watershed (Figure 9.9).

Added Detention Ponds in Selected Areas				
Outlet pipe size	Original	6 in	12 in	18 in
Average flow (cfs)	7.1	6.6	6.8	6.9
Max flow (cfs)	191.9	152.4	152.8	153.1
Min flow (cfs)	0.13	0.18	0.17	0.17
Flow on 9/4/08 at 10:00am (cfs)	1.00	2.18	2.21	2.25
Flow on 9/11/08 at 6:00 am (cfs)	0.13	1.13	0.82	0.97
Time from peak flow to 1cfs flow (hrs)	45	210+	153	157

9.3 Summary of simulation results

Four potential base flow augmentation options were investigated using the SWMM model: (1) increasing channel length in Kohl's wetland, (2) adding channel roughness in Kohl's wetland, (3) impounding runoff in Kohl's wetland by installing weirs, (4) adding retention ponds in the watershed. All four options reduced the peak flows and slowed the flow recession in the runoff hydrograph. The SWMM results showed that adding roughness to the wetland channel segments affected the storm hydrographs the least. Adding weirs to the Kohl's wetland augmented the baseflows significantly. However, this measure turns a wetland into a reservoir, and measures to reduce undesirable water heating in the wetland would have to be studied. Retention ponds in the watershed delayed runoff and augmented baseflow for the longest time. Re-meandering the channel in Kohl’s wetland and adding storage retention ponds could greatly increase long-term baseflows in Miller Creek. Since the SWMM model does not consider subsurface flow in the wetland, the full benefit of restoring Kohl’s wetland on baseflow may not be represented by the model results.

10. Conclusions

A Storm Water Management Model (SWMM) was constructed to model streamflow in the Miller Creek watershed. The model was developed in support of a thermal study conducted for an MPCA mandated temperature TMDL. The model was able to predict peak flows, base flows, and storm water runoff volumes. Compared to measurements, the model performed best during the late summer and early fall. This period is most important for a coldwater stream due to the low flows and high air temperatures.

The application of SWMM to the Miller Creek watershed imposes some limitations. SWMM was designed to model urban runoff but not to model wetlands and groundwater interactions effectively. Even with these limitations, the SWMM constructed for Miller Creek shows good ability to model observed base-flows, and can be used to investigate the relative benefits of wetland improvements to Miller Creek.

Despite the limitations discussed in the report SWMM is valuable for the thermal modeling of the Miller Creek watershed. Because SWMM was able to reproduce observed flows it will be valuable to develop the temperature TMDL for Miller Creek and can help identify areas where thermal mitigation efforts could be utilized.

To further improve the model, additional data and measurements are needed. These include synoptic temperature recordings at numerous inflow sites and stream sites during a summer season. The streamwise distribution of low flows in Miller Creek needs to be documented in greater detail to identify the sources of water that produce the coldwater habitat.

This study confirms the importance of wetlands in the hydrology of Miller Creek. Although the model was unable to reproduce the quick storm hydrograph recessions and the lowest of low flows, a good understanding of the wetlands and hydrogeology in the watershed was developed in the modeling process. The most important role of the wetlands is to supply the baseflow to the stream. The rapid recession in the storm hydrographs points to channel storage and surface storage in wetlands rather than in aquifers as the source of water during low flow periods. The wetlands in the upper reaches of Miller Creek therefore need to be protected because they play a key role in the hydrology during low flow periods.

The modeling efforts also showed that the rain gage at the Kohl site gives representative precipitation data for predicting stream flow in Miller Creek. It is recommended that this station be maintained in the future to help assess changes in stream flow due to climate change and watershed restoration efforts.

To provide trout habitat and to mitigate the thermal impact of commercial and residential development, it will be important to increase the baseflow in Miller Creek. This might be possible by restoring some of the impacted wetlands or by providing additional water detention and delayed release of water to increase baseflow in Miller Creek as shown in the scenarios simulated in Section 9.

Acknowledgements

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