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MINNEHAHA CREEK WATERSHED DISTRICT

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Baseflow Restoration in Minnehaha Creek Watershed with Stormwater Infiltration

MWMO Watershed Bulletin: 2014-3

Prepared for the MWMO by:
University of Minnesota

Minnehaha Creek Baseflow and Stormwater Infiltration: Interim Report II

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Front Cover:

(Left Photo) Upstream view from below Minnehaha Falls within Minnehaha Falls Park. Minneapolis, MN. *Photograph by T. Moore of the University of Minnesota.*

(Right Photo) University of Minnesota undergraduate student Laina Breidenbach collecting a piezometer measurement at the Blake Cold Storage Site. Hopkins, MN. *Photograph by T. Moore of the University of Minnesota.*

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Abstract

Minnehaha Creek ranks among the Twin Cities' most valued natural resources. However, frequent drought periods – which have left the creek and its falls dry in 9 of the last 14 years – impair both the ecological and cultural value of the creek. Rapid fluctuations in stream flow due to stormwater runoff exacerbate flow-related impairments in Minnehaha Creek.

Given interest in both improving flow conditions in the creek and managing stormwater runoff, we have posed the following question: Can stormwater runoff be infiltrated and stored in the shallow aquifer to contribute to stream baseflow in Minnehaha Creek? To answer this question, we adopted a "weight of evidence" approach in which current groundwater contributions to Minnehaha Creek were quantified and gaining and losing reaches of the stream were identified. On an annual basis, baseflows provide about 1.5 inches, or 33%, to the total stream flow in Minnehaha Creek. Baseflows are identified here to be composed of both groundwater and contributions from lakes and wetlands. Using isotopic separation techniques, we determined that only about 20% of this baseflow is comprised of groundwater; lakes and other surface water sources make up the remainder. Groundwater-surface water interactions at specific points within the stream were quantified through corroboration of seepage meter, temperature profile, and piezometer measurements. In general, streambed fluxes were upward upstream of Browndale Dam (0.1 to 1.9 cm/d), but downward downstream of Browndale Dam (0 to 0.4 cm/d). When extrapolated to the reach scale, we obtained an estimate of net streambed fluxes on the order of 0.3 in/yr upward, which is in close agreement with isotope-based approximations (0.25 in/yr).

Underlying hydrologic conditions likely play a key role in controlling the quantity of groundwater available for discharge to Minnehaha Creek. Of the estimated 6.7 inches of average annual of recharge to the surficial aquifer, about 6.5 inches is "lost" via deep seepage to underlying bedrock aquifers. While these conditions limit baseflow benefits from infiltration practices distributed

throughout the watershed, we have identified locations along the creek where underlying geology could support baseflow discharge through focused stormwater recharge to the creek's riparian aquifer. These areas are coincident with continuous extents of the Platteville formation, a limestone and shale complex believed to act as an aquitard to prevent vertical losses to underlying bedrock aquifers. Such conditions exist upstream of Browndale Dam. Opportunities for stormwater infiltration-baseflow augmentation could be created downstream as well, but would likely require more engineered approaches such as impermeable liners in the streambed and in the riparian aquifer to prevent vertical seepage losses.

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Executive Summary

Flowing nearly 22 miles from its origin at Grays Bay to its confluence with the Mississippi River; Minnehaha Creek ranks among the Twin Cities' most valued natural resources. The storied Minnehaha Falls are perhaps the creek's most popular feature and attract over a half million visitors each year. Frequent drought periods – which have left the creek and its falls dry in 9 of the last 14 years – impair both the ecological and cultural value of the creek. Rapid fluctuations in streamflow due to stormwater runoff exacerbate flow-related impairments in Minnehaha Creek.

Given interest in both improving flow conditions in the creek and managing stormwater runoff, we have posed the following question: Can stormwater runoff be infiltrated and stored in the shallow aquifer to contribute to stream baseflow in Minnehaha Creek? To answer this question, we must first understand the following:

- What is the existing contribution of groundwater relative to other sources of flow in Minnehaha Creek across a spectrum of flow conditions?
- What is the existing status of groundwater-surface water interactions in Minnehaha Creek? How do groundwater contributions vary spatially along the creek? Can we identify specific locations suitable for artificial recharge (and subsequent stream discharge) through focused stormwater infiltration?
- What are the underlying factors that drive observed groundwater-surface water interactions in the Minnehaha Creek system (e.g., geology, altered hydrology and groundwater residence time, etc.)?

We have combined analyses of existing hydrologic and geologic datasets with new isotopic data (^{18}O and ^{2}H isotopes) collected from the Minnehaha Creek system to understand baseflow sources and their relative contribution to flow in Minnehaha Creek at the watershed-scale. General conclusions from this watershed-scale perspective include:

- Surface waters (e.g., lakes, wetlands) are the predominant source of flow in Minnehaha Creek, particularly during low flow periods. In late August 2012, less than 10% of flow in the creek (< 1 cfs) was attributed to groundwater based upon the isotopic composition of water in the creek.
- Watershed-wide groundwater fluxes are influenced by strong downward gradients in piezometric head. As reported by Tipping (2011), median travel time through the surficial aquifer to the underlying bedrock aquifer is on the order of one-half year. This means that water infiltrated far from the creek riparian zone is "lost" to deep bedrock recharge rather than discharging to the creek as baseflow.
- Streamflow recession analysis by the method of Brutsaert and Nieber (1977) indicated that about 5% of the watershed is underlain by stream-feeding aquifers. This result corroborates with geologic data indicating rapid vertical travel throughout the surficial aquifer, with the result that very little groundwater is available during drought periods (as demonstrated by isotopic data).

Despite the lack of wide-scale groundwater inputs to the creek, opportunities may exist to augment groundwater-fed stream discharge at locations where upward groundwater fluxes are supported by local hydrogeologic conditions. Such opportunities were investigated through site-specific measurements of groundwater fluxes within the creek (by seepage meters and streambed temperature profiles) and its riparian area (through monitoring of groundwater piezometric head relative to the stream) to identify locations along the creek conducive the groundwater discharge. Findings of site-specific investigations include:

- Groundwater fluxes were generally upward between the creek's headwater wetlands and Browndale Dam. Flux magnitudes ranged from 0.1 to 1.9 cm d^{-1} as determined with seepage meters and temperature profile measurements. Between Browndale Dam and Hiawatha Avenue, groundwater fluxes were generally in the downward direction, and ranged from 0 to 0.4 cm d^{-1}.
- Considering evidence from seepage measurements, groundwater fluxes inferred through streambed temperature profiles, piezometric head measurements, and characterization of subsurface conditions, groundwater discharge could be augmented through focused stormwater infiltration at sites such as:
    - The wetland complex between Minnetonka Blvd and Highway 169 in Minnetonka
    - The Cold Storage site in Hopkins
    - Utley Park in Edina

Based on these analyses, the overall weight of evidence suggests ***groundwater contributions to the creek are limited under existing conditions***, likely due to rapid transit through the shallow quaternary aquifer to underlying bedrock aquifers. ***However, there are locations along the creek at which infiltrated stormwater could be translated to stream baseflow***. These are locations at which local subsurface conditions support upward discharging groundwater. It is apparent that infiltration measures will need to be located at strategic sites where the shallow aquifer system is found to discharge to the creek.

Through the completion of Results 1 (geologic and hydrologic characterization) and 2 (field data collection and interpretation), we have identified several areas of future research need that will help to identify actions that can be taken to increase baseflow in Minnehaha Creek. These include development of a GIS-based decision support tool for evaluating the potential of a site to contribute to stream baseflows through stormwater infiltration, characterization of groundwater flow along subsurface pathways coincident with storm drains and municipal sewer lines, and monitoring of pilot projects designed to enhance groundwater contributions to Minnehaha Creek.

1. Introduction and Scope

This report provides a complete description of the results of the project, "Minnehaha Creek Baseflow & Stormwater Infiltration" funded jointly by the Minnehaha Creek Watershed District and the Mississippi Watershed Management Organization. The objective of the project was to develop a better understanding of the dominant hydrologic processes in the watershed with particular emphasis on interactions between Minnehaha Creek and its riparian aquifer. To reach the goal of developing this better understanding the following tasks were completed:

- Assessment of the volume balance for monitored flows within the watershed,
- Evaluation of baseflow sources through isotope collection and analysis,
- Quantification of site-level groundwater discharge (or surface water loss) through temperature profile and seepage meter measurements,

- Site-level soil/aquifer characterization and aquifer storage dynamics, and
- Synthesis of existing hydrogeologic data to support interpretation of field data

Through completion of these steps we intended to inform stormwater management strategies for baseflow optimization in the Minnehaha Creek watershed.

This is among one of the first studies to frame surface-groundwater interactions in the context of stormwater management and utilization of stormwater infiltration as a means of improving baseflow conditions. A few modeling studies have been conducted to assess potential effects of stormwater infiltration through low impact development (LID) scenarios on groundwater recharge (Shuster et al., 2007) and stream baseflow (Zimmer et al., 2007). With respect to such modeling activities, Hamel and Fletcher (2013) demonstrated that prediction of baseflow during drought periods improved as with greater complexity in the model's representation of subsurface storage reservoirs. To the best collective knowledge of the authors, field examinations of the impact of LID and stormwater infiltration on stream baseflow have not been attempted. Hamel et al. (2012) suggest that the lack of studies dealing with linkages between stormwater infiltration and stream baseflow may stem from the complexity of groundwater-surface water interactions. This complexity arises from the heterogeneous nature of aquifer systems and development of preferential pathways along which groundwater flows. As reviewed by Vogt et al. (2010), within channel groundwater-surface water exchanges are known to vary in space (for example, due to heterogeneity of streambed materials and their associated hydraulic conductivity) and time (for example, with temporal increases and decreases in streamflow). Groundwater-surface water interactions also vary as a function of the hydrogeologic context of a particular subcatchment, necessitating a case-by-case assessment for ascertaining the potential to impact stream baseflow through stormwater infiltration. This work provides an important step toward a field evaluation of baseflow impacts affected through focused stormwater infiltration.

The organization of this report follows the line of questions investigated in determining the potential to augment baseflows in Minnehaha Creek through stormwater infiltration. These questions included:

- What is the existing contribution of groundwater relative to other sources of flow in Minnehaha Creek across a spectrum of flow conditions?
- What is the existing status of groundwater-surface water interactions in Minnehaha Creek?
- How do groundwater contributions vary spatially along the creek? Can we identify specific locations suitable for artificial recharge (and subsequent stream discharge) through focused stormwater infiltration?
- What are the underlying factors that drive observed groundwater-surface water interactions in the Minnehaha Creek system (e.g., geology, altered hydrology and groundwater residence time, etc.)?

We begin with observations at the watershed scale to lay a framework in which overall source contributions to Minnehaha Creek are identified and quantified. We then focus in on groundwater-surface water interactions at specific locations within the stream channel. We return to the watershed scale to examine hydrogeologic and other factors that may control observed groundwater-surface water dynamics in Minnehaha Creek. Finally, opportunities for baseflow augmentation through focused stormwater infiltration and recharge are discussed within the context of field observations and hydrogeologic controls.

2. Minnehaha Creek Hydrology: Characterizing Flow and Flow Sources

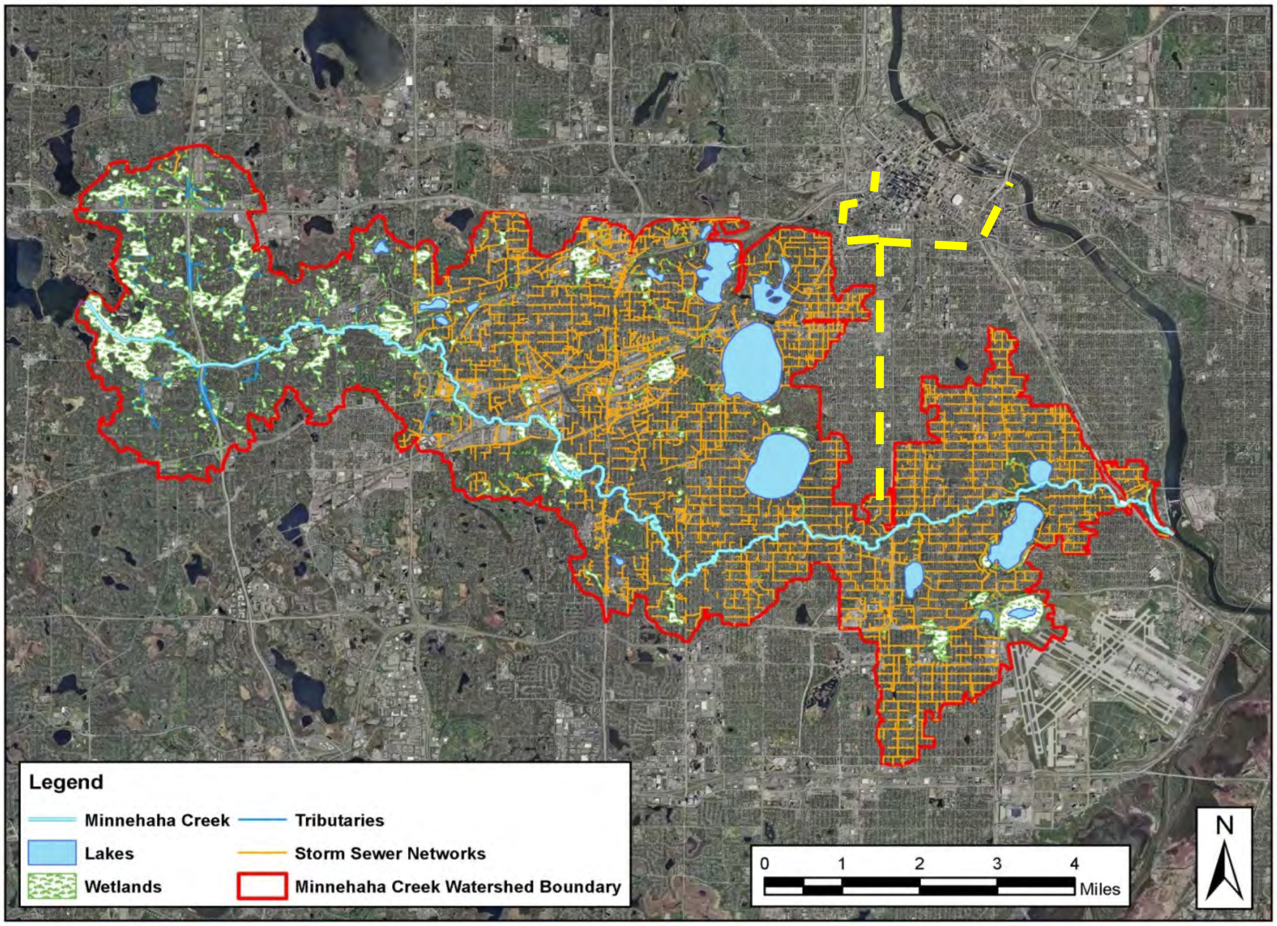


Figure 1. Potential sources and sinks of flow to Minnehaha Creek. Interstate 35W stormwater drainage system indicated by yellow dashed lines. Aerial photograph from MnGeo 2012 and all other data provided by MCWD.

An understanding of the contributions of various flow sources, particularly groundwater, in Minnehaha Creek is foundational to assessing the potential to augment those flows through stormwater infiltration. The Minnehaha Creek Watershed can be conceptualized as a network of sources and sinks of stream flow in Minnehaha Creek (Figure 1). We have used a number of complimentary approaches to quantify the magnitude of these fluxes, including:

- a flow balance approach using available hydrologic data

- analysis of the isotopic composition of the creek and its sources
- field measurements of groundwater fluxes within the streambed

Consideration of each of these data sets, which represent different spatial and temporal scales, improves our interpretation of hydrologic dynamics of the Minnehaha Creek system. Each of these data sets is presented in the following sections, along with conclusions based on these multiple lines of evidence.

2.1 Flow Balance

The U.S. Geologic Survey has maintained a gauging station on Minnehaha Creek at Hiawatha Avenue, approximately one mile upstream of the creek's confluence with the Mississippi River, since 2006. These data were used to calculate the average annual flow in Minnehaha Creek. Contributions from Grays Bay were estimated over the same period of record (2006-2012).

Estimations for contributions from Grays Bay were based on a flow error analysis completed using stage differences and specific D_{calc} (i.e. height of dam opening) values provided by MCWD. Specific stage differences (i.e. hydraulic head differences) were based on the difference between the water level elevation within Grays Bay and the downstream wetland at the dam outlet. Gauges at both of these locations provided a water elevation value every 15 minutes, with the exception of the years 2006 and 2007. D_{calc} values provided by MCWD were based on use of a specific discharge equation for the dam. A discharge value (based on a required discharge level or that required to maintain 'natural' flow conditions within Minnehaha Creek) was entered into the equation, in addition to several specific dam characteristics and a stage difference value, to obtain a D_{calc} value. The stage difference value and values of specific dam characteristics were based on the conditions when altering the height of the dam opening (i.e. calculation of D_{actual} for dam opening changes using D_{calc} value). The dam opening height is generally altered several times throughout the spring, summer, and fall to maintain required and or 'natural' discharge values. Provided D_{calc} values and stage differences values were then re-entered into the dam discharge equation used by MCWD to calculate discharge values relative to discharge values provided by MCWD. In general, discharge values matched the discharge values provided by MCWD at the time of dam opening height changes. This finding makes sense because in both cases all values used in the discharge equation were the same. However, after dam opening height alterations and between successive dam opening height alterations, the actual discharge out of the dam varied considerably relative to the values provided by MCWD. This finding is not completely unexpected due to natural variances observed in flow from changing environmental conditions (temperature, precipitation, etc.). In addition, MCWD actively manages the dam opening to prevent large variances in flow level. However, this finding is critical for determination of contributing flow from Gray's Bay because small errors in flow level can have large effects on calculations of groundwater contributions to Minnehaha Creek. As a result of this, the flow error analysis was critical in determining the best possible estimates for groundwater contributions within the flow balance. Results for the flow error analysis and all provided MCWD dam discharge equation information is provided in Appendix I.

Runoff contributions from the lower watershed were estimated by applying a baseflow filter (Nathan and MacMahon, 1990) to the Hiawatha Avenue stream flow record (after subtracting flow from Grays Bay) to separate the stormflow component of the hydrograph. The resulting average annual contribution from each of these sources is presented in Table 1. The volume remaining after Grays Bay and runoff volumes are subtracted from the total flow measured at Hiawatha Avenue is assumed to represent baseflow. The resulting volume (1.7×10^8 ft^3, or 1,500 MG) is equivalent to approximately 1.5 inches of runoff over the lower watershed, and may be comprised of flow from wetlands, other lakes, and groundwater. Flow data is not available for these sources; however, the relative contribution of these sources may be estimated through the isotopic analysis described in the next section.

Table 1. Average annual flow contributions of Lake Minnetonka via Grays Bay, stormwater runoff, and other baseflows to average annual stream flow in Minnehaha Creek for the period 2006-2012

Flow Source	Annual Volume (ft^3)	Annual Contribution (%)	Runoff Depth (inches)
Grays Bay	8.8E+08	69%	3.09*
Storm flow	2.4E+08	18%	2.06
Baseflow	1.7E+08	13%	1.46
Total flow, Minnehaha Creek	**1.3E+09**	**100%**	---

*Grays Bay runoff depth calculated over upper Minnehaha Creek watershed area (123 mi^2); storm and baseflow calculated over lower Minnehaha Creek watershed area (47 mi^2).

2.2 Separation of Baseflow into Source Components based on Isotopic Evidence

The use of isotopes to separate a mixture (in this case, Minnehaha Creek) into its source components (for example, water from Lake Minnetonka, the Chain of Lakes, wetlands, stormwater runoff, and groundwater) is based on the premise that each of these sources has a unique isotopic composition. In water, unique oxygen and hydrogen isotopic compositions may arise through fractionation processes. In natural waters, evaporation is the primary fractionation process through which heavier isotopes are concentrated in waters with higher rates of fractionation (such as surface water) relative to waters in which fractionation processes are not as dominant (such as groundwater). For this study, samples were collected from potential sources of flow to Minnehaha Creek – including Lake Minnetonka, Lake Harriet, stormwater runoff, summer rainfall, snowmelt, and riparian groundwater – and analyzed to determine the concentration of ^{18}O and ^{2}H relative to the lighter, and more prevalent, ^{16}O and ^{1}H isotopes. Sampling sites were also selected along the length of the creek to represent the mixture of these source waters (Figure 2). Samples were collected during high and low flow periods to capture variation in flow sources across a spectrum of flow conditions (Figure 3). Figure 4 presents isotopic signatures of samples collected from Minnehaha Creek and its potential flow sources during a runoff-dominated period (May 28 and June 6, 2012) and a low flow period (Aug. 22, 2012). Samples collected on May 28 followed a series of storms that produced a total of 4 inches of rainfall between May 23 and 28. Samples collected on June 6 represented the falling limb of the hydrograph following these storms during which there was no precipitation. Grays Bay dam was opened shortly after the May 28 sampling event and was discharging 12 cfs on June 6. The dam was closed for the season two days prior to the Aug. 22 sampling event. Additional samples were collected during the 2013 spring melt to characterize the isotopic composition of snowmelt inputs to shallow groundwater and the creek channel.

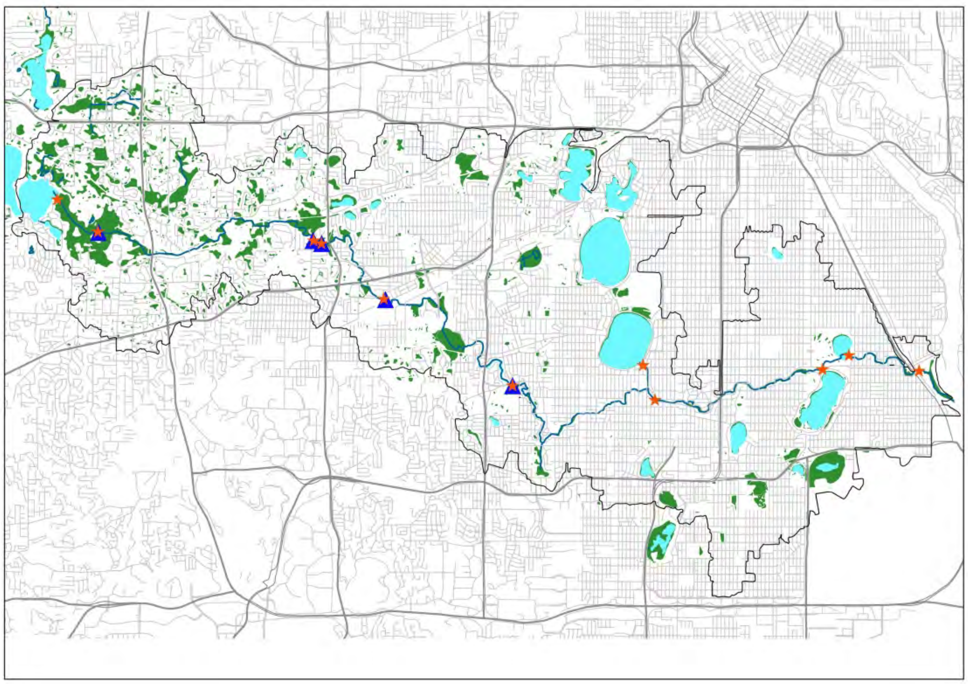


Figure 2. Sample locations for ^{18}O and ^{2}H isotope analysis. Surface water sample sites are marked with a star symbol; groundwater samples were collected from locations marked with triangles. Samples were collected across a range of seasonal flow conditions.

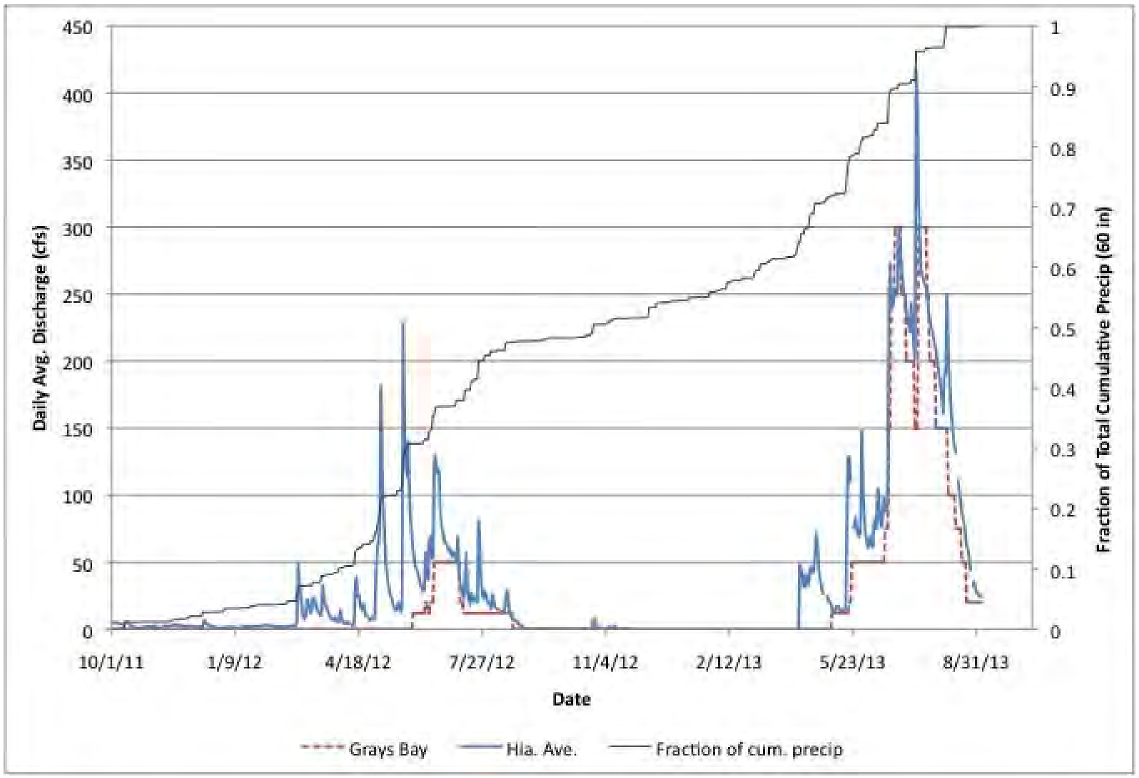


Figure 3. 2012-2013 flow hydrograph of Minnehaha Creek at Hiawatha Ave (solid blue line) with discharge from Lake Minnetonka via Grays Bay (dashed red line). Isotope collection times are highlighted. Samples were collected during high flows following rainfall (May 27 and 28, 2012), snowmelt (March 30, 2013), and interceding drought periods (August 22, 2013; Nov 5, 2013).

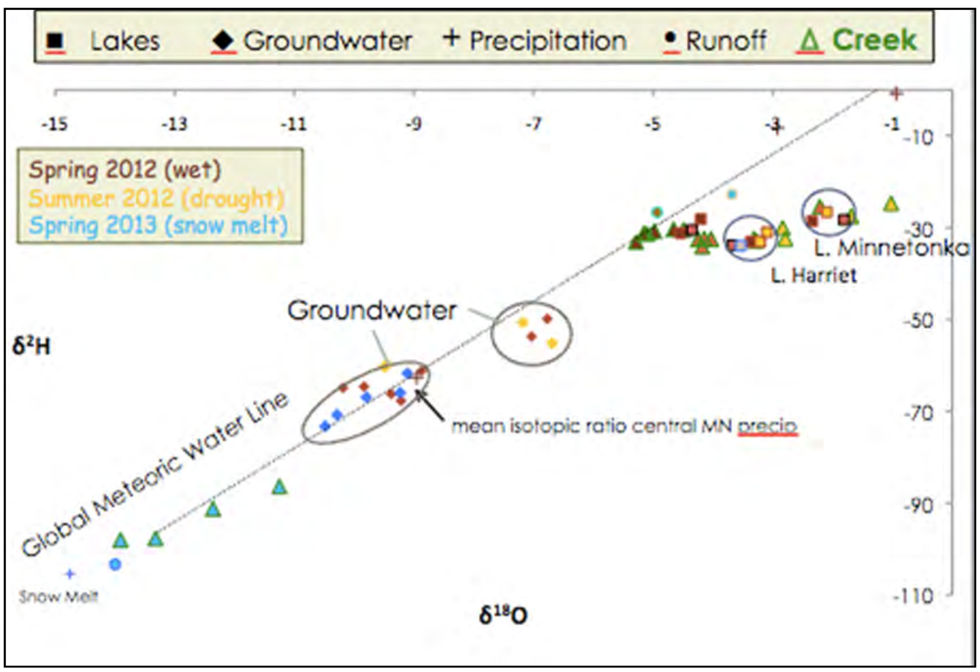


Figure 4. Plot of [18]O (δ^{18}O) and [2]H (δ^{2}H) isotope ratios relative to the established standard of mean ocean water. Increasing δ values indicated increasing concentration of heavier isotopes. Symbols designate sample type (rectangles = lake samples; circles = stormwater runoff; astrix = precipitation; diamonds = groundwater; triangles = creek) while color designates sample time (blue = high flow on May 28, 2012; green = June 6, 2012 recession; maroon = Aug 22, 2012 drought; light blue = March 2013 snowmelt). As indicated by the relative position of the points, the creek's isotopic signature aligns more closely to that of its surface water sources (e.g., Lakes Minnetonka and Harriet) than to its adjacent riparian groundwaters, particularly during the transition from high to low flow conditions.

Figure 4 illustrates the clear distinction between surface and groundwater samples on the basis of their ^{2}H and ^{18}O isotopic compositions. The extent to which water is enriched with ^{2}H and ^{18}O isotopes is reflected by the δ value, which increases (or becomes less negative) with enrichment of heavier isotopes. Precipitation inputs in the Minnehaha Creek watershed fall along the Global Meteoric Water Line (MWL), the solid line in Figure 4 that describes the ratio of ^{2}H to ^{18}O isotopes in waters that have not undergone excessive fractionation, such as precipitation. As described in other studies (e.g., Harvey and Welker, 2000; Brooks et al., 2012), the relative isotopic composition of precipitation in the Minnehaha Creek watershed is dependent upon temperature, with rainfall originating from the Gulf of Mexico (e.g., May 25, 2012 rainfall sample) typified by larger δ values and winter snow having smaller δ values. The degree to which the isotopic ratio of samples stray from the MWL indicates higher rates of fractionation. For example, Lakes Minnetonka and Harriet, from which lighter isotopes selectively evaporate to results in a relative enrichment of heavier ^{2}H and ^{18}O isotopes, plot to the right of the MWL. In contrast, groundwater samples collected from the shallow aquifer underlying the riparian area (see Section 3.3 for piezometer locations) cluster near to the MWL, reflecting the meteoric origin of groundwater through recharge of rainfall and snowmelt. The majority of groundwater samples cluster around the mean O^{18} and H^{2} ratio of precipitation in SW Minnesota, as reported by Magner et al. (2004). The isotopic composition of a subset of well samples, all taken from piezometers located near the channel (within 25 meters) at the Jidana Park wetland, form a second cluster positioned between meteorically-derived groundwater and surface water samples, indicating water from Minnehaha Creek likely moves into the bank at this site. Monitoring of hydraulic heads in piezometers located at this site also suggest creek-to-groundwater flow occurs (Section 3.3.1).

The isotopic composition of samples collected from the creek is the product of the mixture of the various source waters. Samples collected from the creek on May 28 are strongly influenced by precipitation and stormwater runoff as evidenced by their relative similarity with samples collected from a stormwater retention pond and tendency to cluster along the MWL. The creek's isotopic signature shifts toward a greater abundance of heavier isotopes during the falling limb of the storm hydrograph on June 6 and, even more so, during low flow conditions on August 22. In effect, the creek's isotopic signature becomes more "lake-like" as discharge shifts from high to low flow conditions. The apparent influence of Lake Minnetonka waters are strongest at the Jidana wetland site, located about 1 mile downstream of Grays Bay dam and, during the Aug. 22 low flow period, at the Lahti-Gaynor wetland site, located an additional 4.5 miles downstream. A key observation from these isotopic data is the separation between the isotopic ratios observed in Minnehaha Creek and adjacent riparian groundwaters. This separation suggests that **groundwater contributes very minimally to flow in Minnehaha Creek, even during low flow conditions when the creek is no longer receiving inputs from Lake Minnetonka**.

Based on these analyses we can make some preliminary estimates of the relative contribution of lake, precipitation, and groundwater sources in Minnehaha Creek. Each of these sources, also known as end-members, can be quantified through simultaneous solution of two (for two contributing sources) or three (for three contributing sources) equations relating the ^{18}O and/or ^{2}H isotopic ratios with the fraction of flow contributed by each source. Details of the end-member analysis are provided in Appendix II. Results of the isotopic end-member analysis are summarized in Table 2. The percent contribution of groundwater to both total flow and baseflow is reported. The digital filter developed by Nathan and MacMahon (1990) was used to separate stream flow into storm- and baseflow components (Figure 5). As indicated in Figure 5 and Table 2, groundwater comprises a larger portion of stream baseflow (nearly 20%) during wet periods in Spring 2012. During drought of August 2012, the contribution of groundwater to baseflow dwindles to about 5% (Figure 6). Figure 6 contrasts the groundwater component of baseflow during these two periods. If the isotopic "snapshots" collected during wet and dry periods of this study were representative of the rest of the flow record, then of the approximately 1.5 inches per year of baseflow, about 0.2 to 0.25 inches is contributed by groundwater.

Table 2. Results of end-member analysis using ^{18}O and/or ^{2}H isotopic compositions of Minnehaha Creek and its source waters. The percent contribution of flow sources relative to total flow (as measured at Hiawatha Avenue) and to baseflow (as determined by applying the baseflow filter of Nathan and MacMahon (1990) to the total stream flow record) is presented

	% Total Flow in Minnehaha Creek			**% Baseflow in Minnehaha Creek**	
Sample event	**Runoff**	**Lakes**	**Groundwater**	**Lakes**	**Groundwater**
Spring 2012 (wet)	60	34	6	81	19
Spring 2012 (recession period)	--	90	10	84	16
Summer 2012 (drought)	--	>95	<5	95	5
Spring 2013 (snowmelt)	70	30	<1	**	**

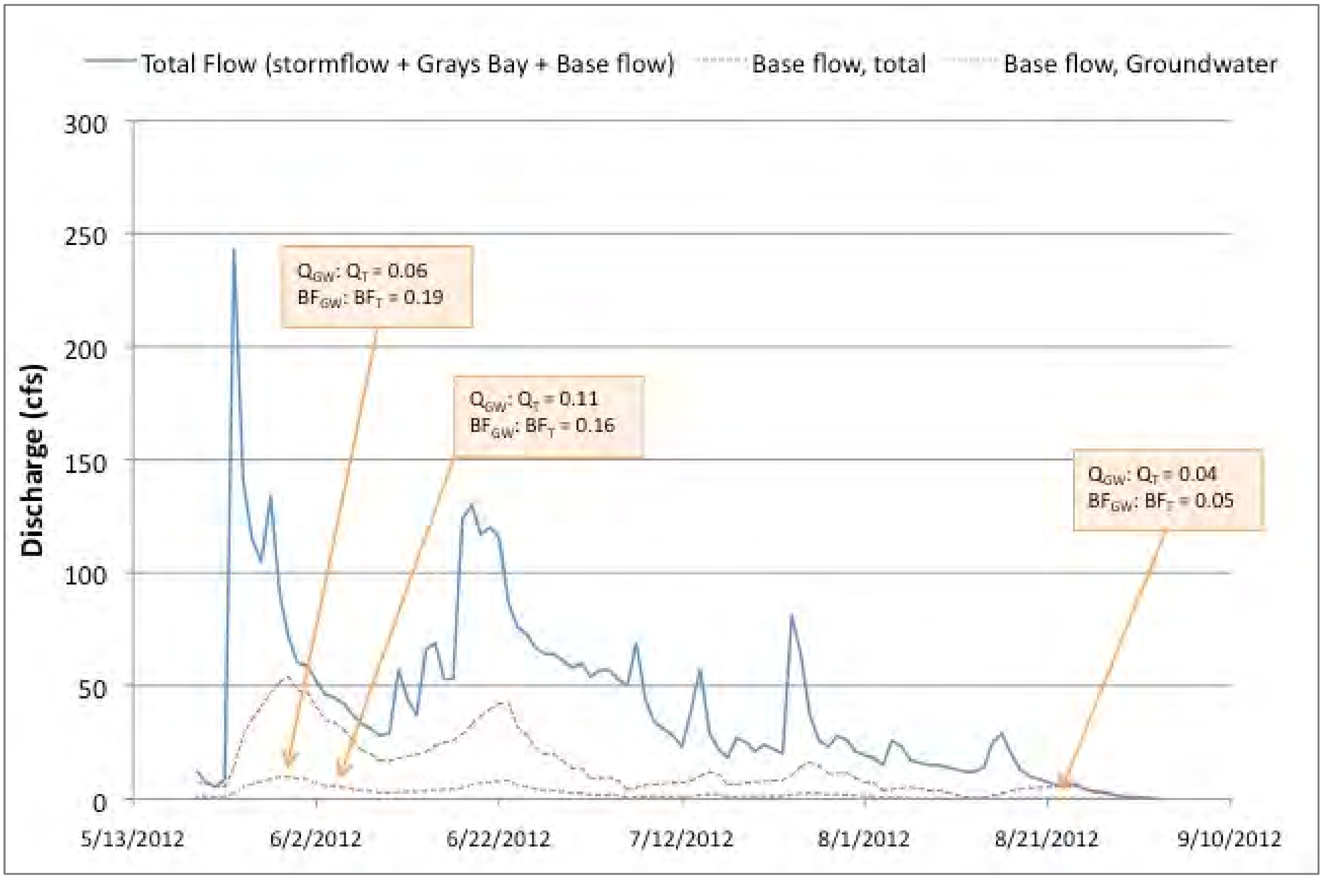


Figure 5. Separation of total flow (solid blue line) into baseflow (dashed red line) and storm flow (area between baseflow and total flow lines) using the baseflow filter of Nathan and MacMahon (1990). Isotopic-based estimates of the groundwater component of total flow (Q_T) and baseflow (BF_T) are highlighted for the May 28 (storm peak), June 6 (recession), and August 22 (drought flow) samples.

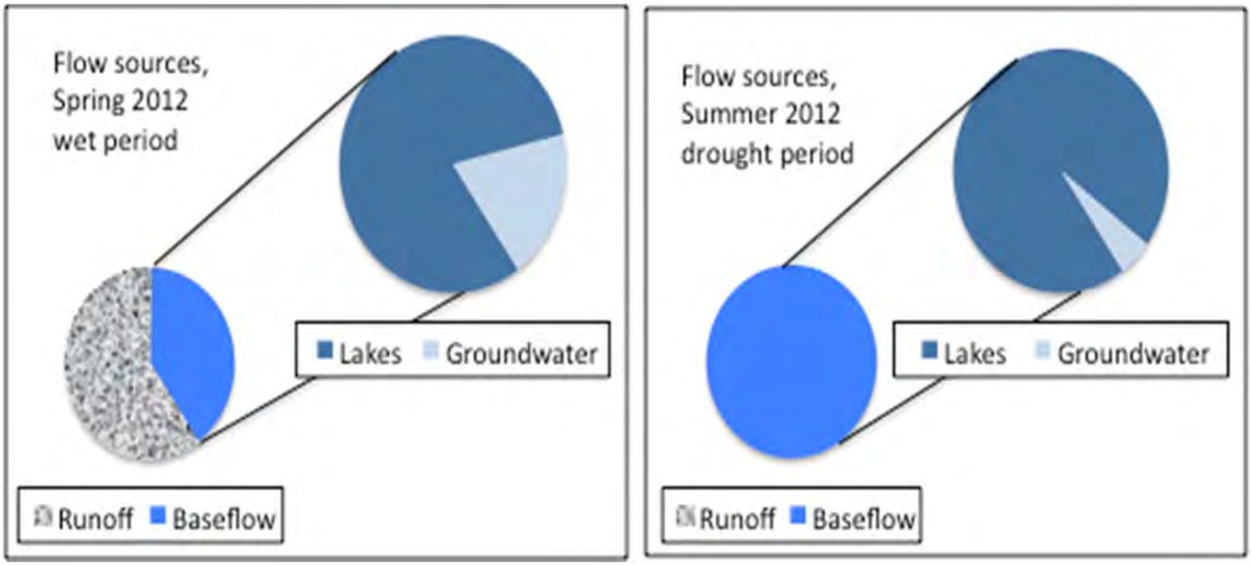


Figure 6. Relative fraction of stream baseflow originating from lakes/surface waters (dark blue sliver) versus groundwater (light blue sliver) during wet conditions (Spring 2012) and drought conditions (Summer 2012).

3. Groundwater-Surface Water Interactions within Minnehaha Creek

The water balance and isotopic analysis provide a high-level view of groundwater contributions to Minnehaha Creek. However, it does not provide a site-level understanding of groundwater-surface water dynamics, which is crucial to assessing the potential for baseflow augmentation via stormwater infiltration. The following sections present results and interpretation of field data collected to quantify interactions between Minnehaha Creek and the shallow aquifer at the site-level. As reviewed by Vogt (2009), groundwater-surface water exchanges are known to vary in both space and time due to variables such as heterogeneity of streambed materials and subsurface flow paths, deposition and subsequent erosion of clogging layers, and spatial and temporal variation in hydraulic gradients. These factors contribute to uncertainty in quantifying groundwater fluxes along the length of a stream. Additional uncertainty arises through the measurements themselves, none of which is without error. In light of these uncertainties, we adopted multiple methods by which to determine groundwater contributions to Minnehaha Creek. These methods include direct measurement of streambed fluxes with seepage meters, indirect estimates obtained through streambed temperature profile measurements, assessment of near-stream hydraulic gradients with shallow piezometers. Measurements were taken at locations along the length of the stream to examine how groundwater-surface water interactions may vary longitudinally (Figure 7). The results of these point measurements are then extrapolated to the reach scale to produce an estimate of total groundwater contributions to compare to isotope analysis presented in Section 2.

3.1 Seepage Meter Measurements

Seepage meters allow direct measurement of fluxes into (groundwater discharge) or out of (surface water loss) the streambed (Rosenberry and LaBaugh, 2008). We constructed meters out of 1-gallon plastic buckets, 8-inches in diameter each, to which a plastic bag was attached through a series of garden hose fittings (Figure 8). The base of the bucket is inserted into the streambed and the plastic bag attached containing a known initial volume of water.

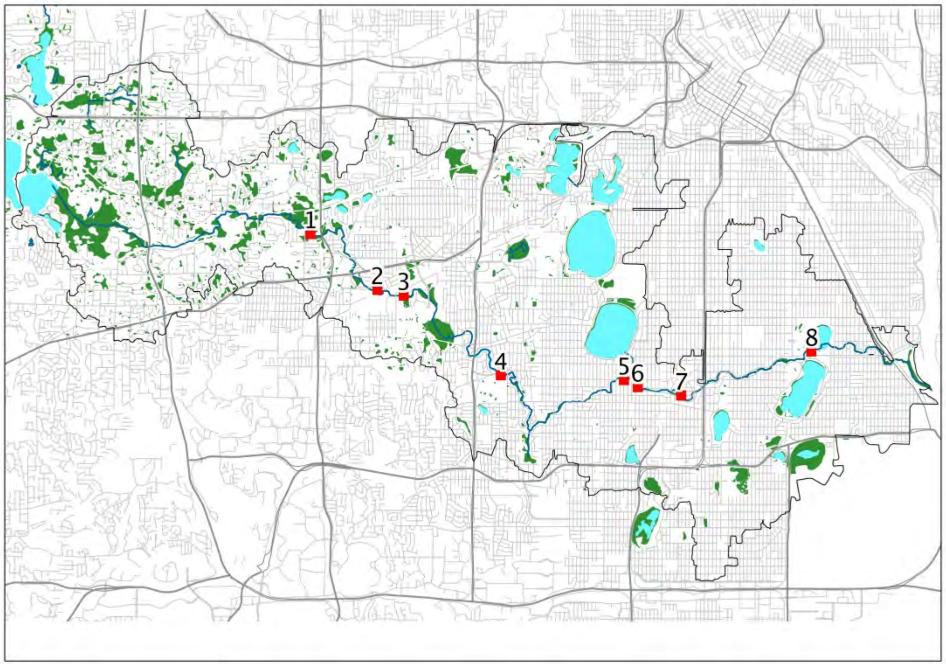
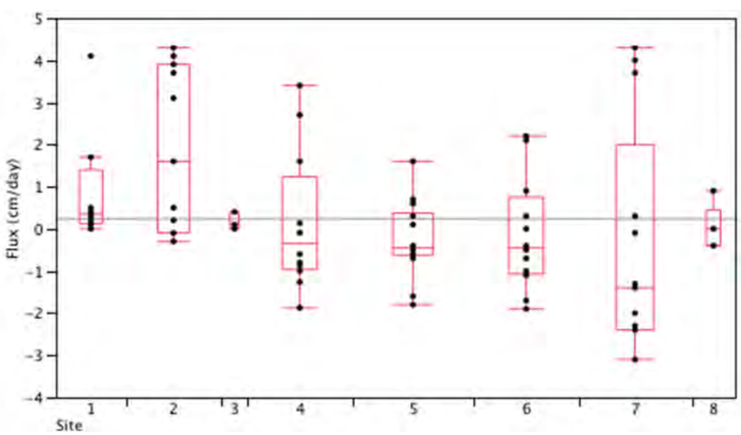


Figure 7. Locations of seepage meter measurements on Minnehaha Creek.

Figure 8. Seepage meters used to measure fluxes into or out of the streambed. (a) Close-up of hose-fittings used to attach the seepage meter to a plastic bag in which the change in volume of water over a set period of time is known. The valve is closed when the bag is being removed or being attached to avoid losing water. (b) Seepage meter deployed in streambed. (c) Measuring the volume of water in seepage meter bags 24 hours after deployment.



Location	Flux (cm/d)	Direction
1. Lahti Lane	0.5	upward
2. Blake	1.9	upward
3. Reach 20	0.2	upward
4. Utley Park	0.1	upward
5. James	0.3	downward
6. Humboldt	0.2	downward
7. Pleasant	0.1	downward
8. Hiawatha	0	neutral

Figure 9. Box plots of seepage meter measurements at 8 locations along Minnehaha Creek. Sites are presented in order from upstream to downstream; numbers correspond to site names in the right panel table and to numbering in Figure 7. The gray horizontal line denotes the average flux rate across all sites (0.2 cm/day upward); average flux rates by site are listed in the table in the right panel. Flux rates less than 0 signify seepage of surface water into the streambed.

Following a 24- to 48-hour period, the seepage meter bags are detached and their volume is measured. The change in bag volume over the known period of time represents the rate of seepage into or out of the area of streambed enclosed by the seepage meter. Seepage meter measurements taken at the Blake Cold Storage site during the fall of 2012 indicated upward groundwater discharge ranging from 0.1 to 6.2 cm d^{-1}, with an average of 2.8 cm d^{-1}. Seepage meter measurements were expanded to 7 other sites in 2013, with 4 to 5 meters deployed at each site (Figure 7).

Seepage meters were developed for lentic environments and high flow velocities can cause inaccuracies (Rosenberry and LaBaugh, 2008). For this reason, seepage meter measurements in

Minnehaha Creek were taken when flow in the creek was less than 12 cfs. This requirement limited 2013 measurements to the late fall due to high flow in the first half of the year. Seepage fluxes measured at each site are presented in Figure 9. Negative values result when the volume of water in the seepage bag decreases over time and signify movement of water out of the channel. Positive values indicate rates of upward discharging groundwater. As seen by the spread of data in Figure 9, measured seepage fluxes ranged from positive (groundwater discharge) to negative (groundwater recharge) within single sites. Despite this variability, mean and median seepage rates tend to decrease from upstream to downstream sites. This pattern indicates that (1) the greatest potential for groundwater contributions to stream flow is in the upper half of Minnehaha Creek and (2) lower reaches, particularly below the Chain of Lakes, may have a net loss of surface water to underlying aquifers.

3.2 Temperature Measurements

Streambed temperature profiles compliment seepage meter measurements as an indirect means of estimating groundwater fluxes. As depicted in Figure 10, the degree of curvature of the temperature profile with increasing depth below the streambed can be used as an indicator of the rate of groundwater discharge or recharge, and thus the method is applicable in both gaining and losing streams (Rosenberry and LaBaugh, 2008; Vogt et al., 2010).

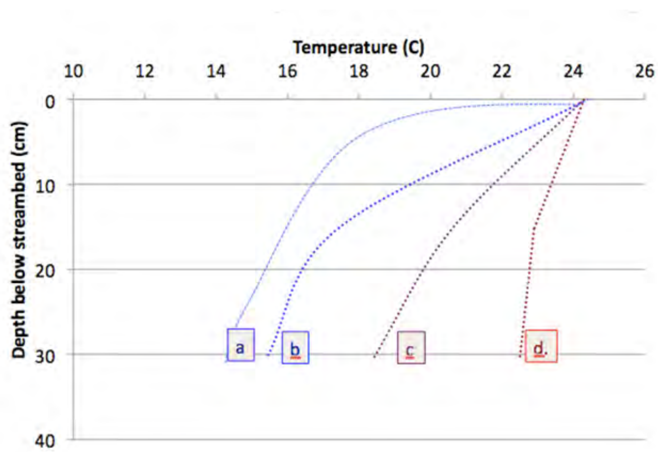


Figure 10. Schematic of temperature versus depth profiles for scenarios in which groundwater is discharged to the stream at a high (a) and medium (b) rates. The linear profile (c) represents a situation in which groundwater is neither discharged nor recharged. The case in which recharge occurs from the surface is represented by (d). *Observed temperature profiles are a result of heat conduction and advection.*

Temperature profiles were measured in Minnehaha Creek by two methods: (1) with a temperature probe (Hannah Instruments) manually inserted into the streambed at 15 cm (6 in) intervals at a discrete point in time and (2) as a continuous time series using temperature data loggers (Solinst Level Logger) placed at the surface and at a depth of 30 cm (1 ft) below the streambed. The majority of temperature profiles were measured with the temperature probe due to the ability to obtain measurements from a large number of locations, to better capture the spatial variability in groundwater discharge along the length and width of the stream. However, since groundwater flux models based on continuous data are expected to be more accurate, continuous data were also collected at a single site (site 2 in Figure 7) and paired with temperature probe measurements to compare results. The magnitude and direction of groundwater fluxes were estimated by solving the 1-dimensional heat flux model under the assumption of steady state conditions for point measurements with the temperature probe (Arriaga and Leap, 2006). For the continuous dataset, the equation was solved for transient conditions following the numerical methods presented by Gulliver (2010) and Lapham (1989). A description and sample calculation for both approaches is presented in Appendix III. Unlike seepage meter measurements, our temperature probe method was not limited by high flow conditions so that data could be collected throughout the flow season. Probe measurements were taken at 20 sites, with repeated measurements during the summer of 2012 and 2013. Within each site, 8 to 10 temperature profiles were measured across the width of the channel. The results of temperature profile measurements are summarized in Figure 11. The points in the box plot represent average seepage rates calculated for profiles measured at the right bank, thalweg, and left bank of the channel. A more detailed summary table including sampling dates is included in Appendix II. Two observations to be made from temperature-based flux approximations are (1) the magnitude and direction of groundwater fluxes can vary substantially within the same site across the width of the channel and (2) despite within site variability, groundwater fluxes tend to decrease or become negative (indicating downward flow of surface water) from upstream to downstream. The majority of sites below Browndale Dam (site 9 through 20 in Figure 11) were characterized by downward groundwater fluxes.

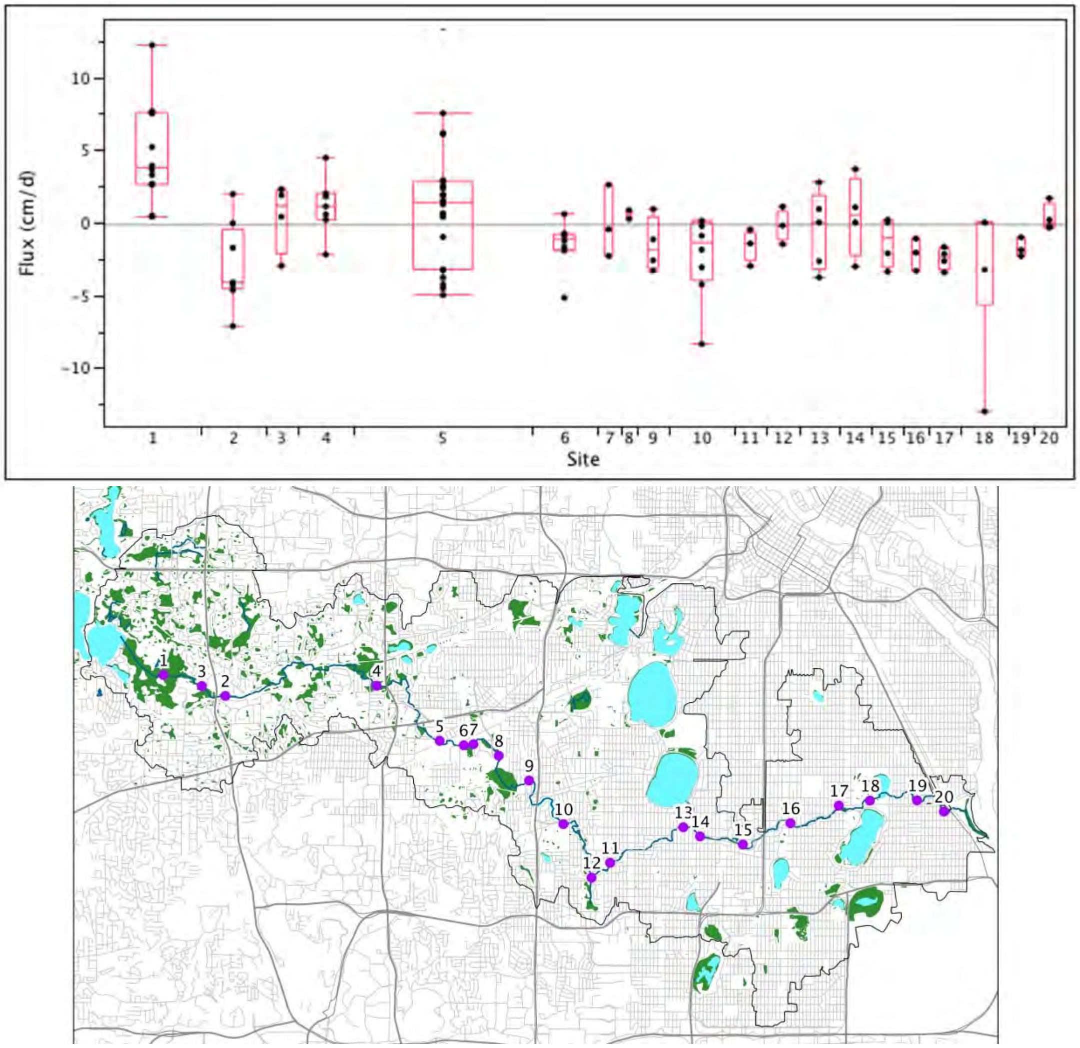


Figure 11. Box plot of groundwater flux as calculated from measured streambed temperature profiles at 20 sites along the length of Minnehaha Creek. Numbered labels in the box plot correspond to numbered locations of temperature probe sites in the map. Within each site, temperature profiles were measured at 8 to 10 locations across the width of the channel 2 or more times during the summer of 2012 and 2013. The gray horizontal line represents the mean of all measurements (-0.1 cm/day). Positive flux values represent upward groundwater movement; negative flux values denote downward groundwater flux.

3.3 Piezometer Measurements

Piezometers were installed to support interpretation of seepage meter and temperature data at four sites of interest, including within the wetland complex in the creek's headwaters (Jidana Park), a wetland five miles downstream (Lahti Lane), at the Cold Storage site in Hopkins, and at Utley Park immediately downstream of Browndale Dam (Figure 12). Details regarding piezometer installations are included in Appendix IV. Piezometric heads that are greater than the surface water elevation in the channel indicate horizontal flow through the aquifer to the stream. Sites at which the groundwater piezometric head is greater than surface water elevations in the creek could support groundwater discharge and, therefore, may be candidate sites for stormwater recharge efforts. Piezometric head measurements at each of the four locations are presented in the following sections. Corroboration with seepage meter and temperature profile data are highlighted, as is the application of these results to interactions between the creek and its riparian aquifer system.

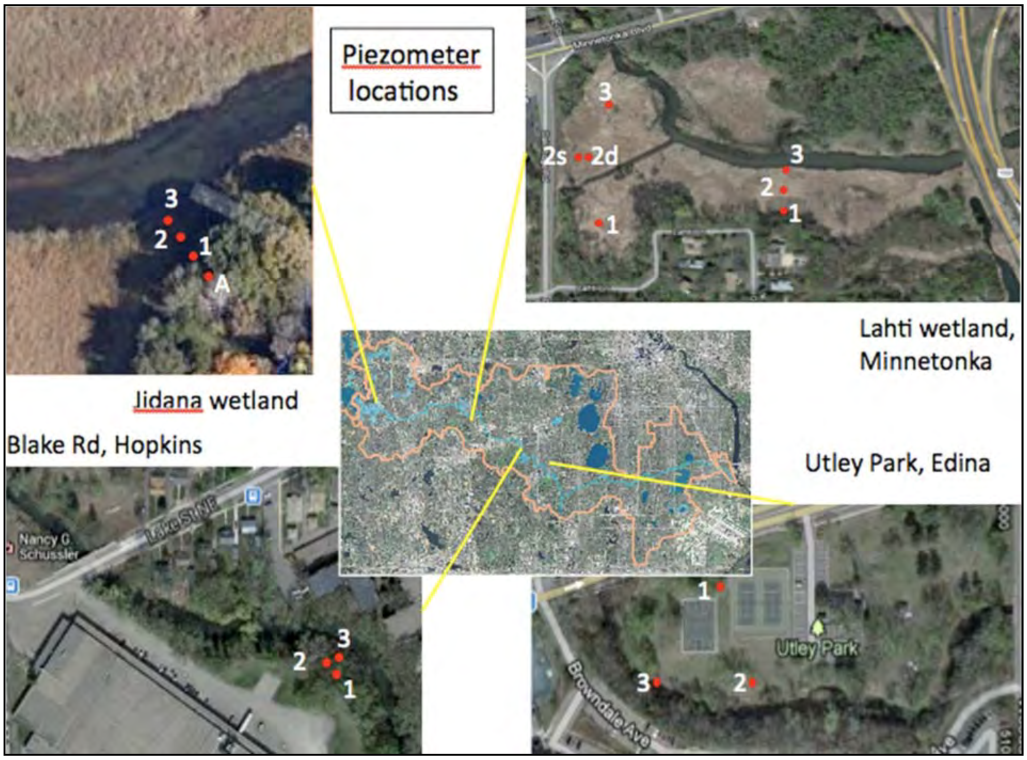


Figure 12. Location of piezometer installations along Minnehaha Creek. Filled circles denote approximate location of piezometers. Numbers correspond to numbering of piezometers in Figures 13 – 16.

3.3.1 Jidana Wetland Site, Minnetonka

The Jidana wetland park is located approximately one mile downstream of Grays Bay. The surficial aquifer at this site lies below approximately two feet of organic/peaty soils. Groundwater head elevations relative to that of surface water were measured on an approximately weekly basis at this site from July 2012 to November 2013 (Figure 13). During this period, both surface and groundwater elevations were highly correlated with Grays Bay discharge. Despite the differences in flow conditions from 2012 (57% below average annual flow) and 2013 (26% above average annual flow), groundwater elevations followed a similar pattern at this site. During periods when Grays Bay discharge was constant or increasing, groundwater elevations tended to be equal to or greater than surface water in the stream channel, indicating the potential for groundwater discharge to the stream. However, during periods when Grays Bay discharge was decreasing or equal to zero, groundwater elevations tended to fall below that of the stream, indicating the potential for recharge from the channel to the riparian aquifer. Streambed temperature profiles taken at this site during June and July of 2012 and 2013, periods during which Grays Bay discharge was *not* receding or equal to zero, indicated upward discharging groundwater in the range of 0.4 to 12 cm/day. Flux measurements taken after Grays Bay was closed in October 2013, however, ranged from 0 to -1 cm/day *downward*. Such movement of water from the creek into the shallow groundwater was also suggested by the isotopic composition of samples collected from the piezometers within 75 ft of the stream channel (Wells 3, 2, and 1 in Figure 13). Isotope mixing analysis indicated a mixture of 70% meteoric waters (i.e., recharge from rainfall and snowmelt) and 30% Lake Minnetonka water (see Appendix II for calculations). These results indicate this site may contribute to losses of water from the channel, at least during drought periods.

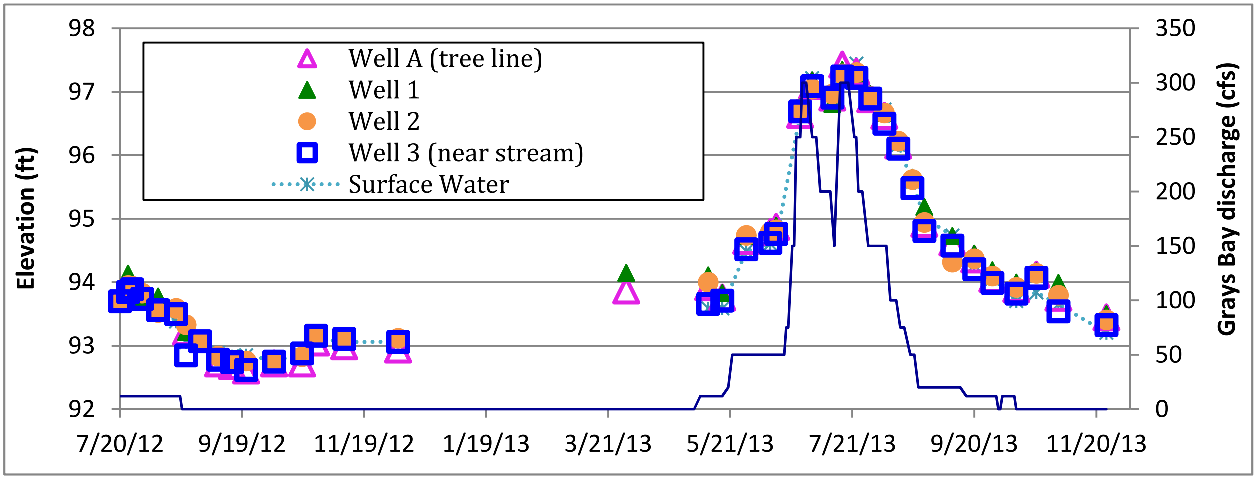


Figure 13. Piezometric head and surface water elevation measurements at the Jidana Park wetland complex located in the creek's headwaters. Groundwater head is highly correlated with Grays Bay discharge.

3.3.2 Lahti Wetland Site, Minnetonka

The Lahti wetland, named after Lahti Lame to which it is adjacent, lies about 5.5 miles downstream of Grays Bay. A 5-6 ft thick layer of organic/peaty soils overlays the surficial aquifer at this site. The surficial aquifer consists of sand and gravel with occasional cobbles. A confining clay layer was discovered at a depth of about 45 ft below the wetland. Two sets of well were installed at this site. On the downstream (east) side of this wetland, a series of three wells were hand-augered in August 2012. On the upstream (west) end of this site, a series of four wells were installed in June 2013. Two of these wells (Wells 2s and 2d in Figure 14) were installed by a drill rig to depths of 12 ft and 25 ft. At both the upstream and downstream ends of this site, the piezometric head of the surficial aquifer was greater than the surface water elevation for the duration of the monitoring period. This included periods in which flows from Grays Bay were receding or equal to zero. This result is in accordance with both seepage meter (average value = 0.9 cm/day) and temperature-based (average value = 1.1 cm/day) flux measurements. It is likely that the confining clay layer encountered at 40 ft serves to perch the water table at this location. Based on seepage meter, temperature, and piezometer measurements, we believe this site (or others with a similar confining layer) hold potential for stormwater recharge and baseflow discharge.

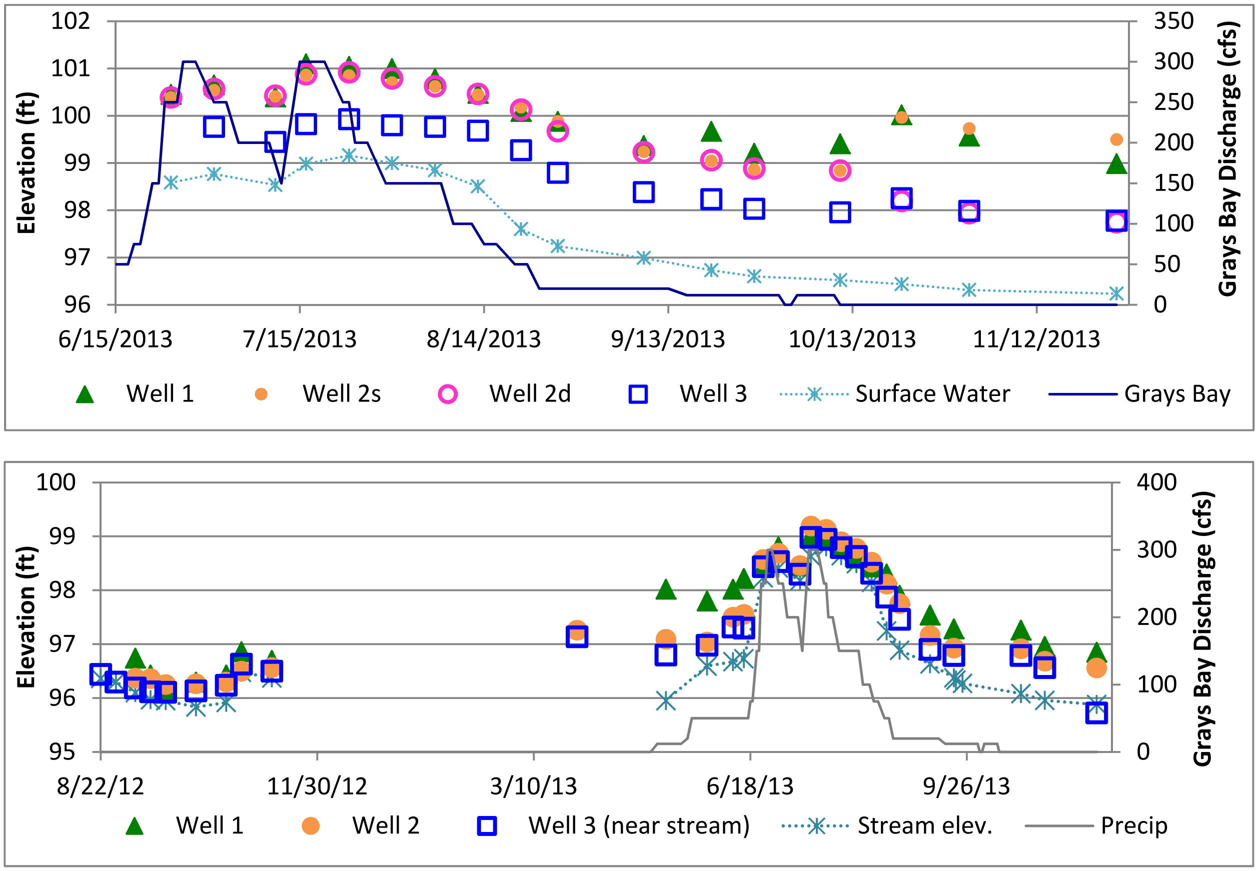


Figure 14. Piezometric head and surface water elevation measurements of the upstream (top panel) and downstream (bottom panel) ends of the Lahti wetland, located along Minnetonka Blvd between Oak Ridge Rd and Highway 169 in Minnetonka. Well 2s and 2d on the upstream end are 12- and 25-ft deep, while the depths of all other wells range from 8 to 5 ft.

3.3.3. Blake Cold Storage Site, Hopkins

Piezometers were installed at the Hopkins Cold Storage site, just downstream of the creek's crossing at Blake Road North. Located approximately 7.5 miles downstream of Grays Bay, this site may be utilized by the MCWD to manage stormwater from a relatively large pipeshed. Thus, it was important to install piezometers here to better characterize groundwater dynamics and subsurface materials. The surficial aquifer at this site is overlain by 0.5-2 ft of organic soil within the wooded riparian area. Soil cores were also taken at a higher elevation in the lawn area adjacent to the riparian buffer with a drill rig (Figure 3.9). The surficial aquifer in this area was overlain by 7-12 ft of sandy clay fill material. The aquifer itself was comprised of sandy glacial outwash material with silt interspersed with gravel. Sandy clay is typically found under perched ponds and lakes in Minnesota (Kersten et al., 2003), suggesting the potential for holding stormwater from being lost directly to the bedrock aquifer on the site.

During the 2012 drought period, piezometric head at this site remained greater than surface water elevations in the creek (Figure 15). This relationship persisted through the spring and early summer of 2013 but, as flows receded and eventually ceased from Grays Bay, a depression developed between the stream surface elevation and the head of the piezometer nearest the stream (Well 3 in Figure 15). This indicates a potential reversal in flow from the channel to the riparian groundwater system.

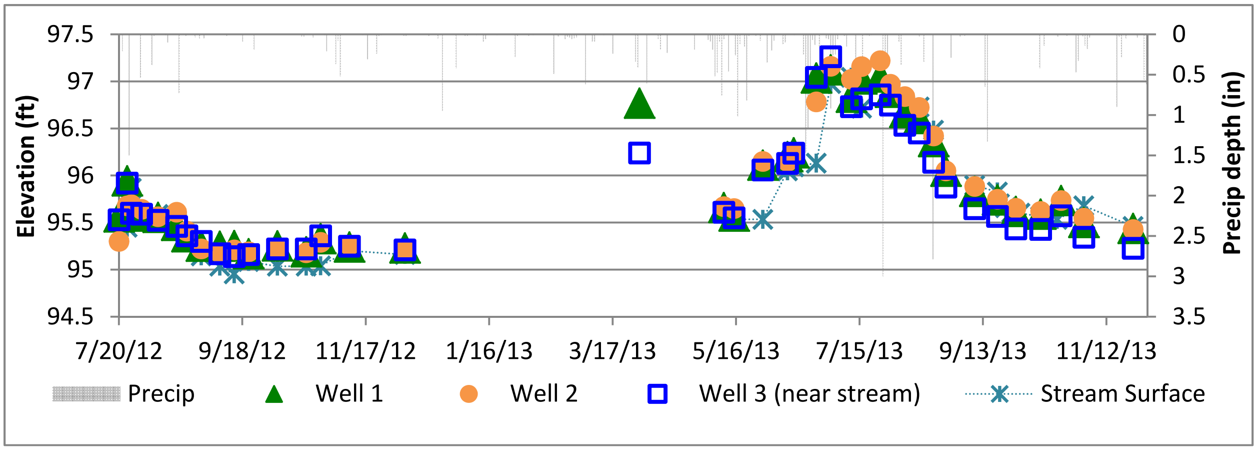


Figure 15. Piezometric head versus precipitation depth at the Blake Cold Storage Site.

Such a relationship is expected during recession periods. The isotopic composition of groundwater within these wells indicated origins through recharge of precipitation rather than surface waters such as Lake Minnetonka, which would suggest that such flow reversals have minimal impact on the overall composition of the groundwater system. Given strong indication of groundwater discharge at points within this reach, this site would likely support discharge of focused stormwater infiltration.

3.3.4 Utley Park Site, Edina

Utley Park is located immediately downstream of the Browndale Dam in Edina, approximately 11.5 stream miles from Lake Minnetonka's outlet at Grays Bay. Like the Blake Road site, Utely Park lies in a strategic location for potentially enhancing stream baseflow in concert with stormwater mangement as it is surrounded by runoff-generating impervious areas and is underlain by the Platteville limestone, a geologic formation which may perch water in the surficial aquifer and prevent vertical losses (see Section 4). As suspected based on observations during site reconnaissance and as revealed by bore holes drilled by Braun Intertech for this study, the surficial aquifer at this site is composed of highly transmissive sands and gravels. It is underlain by a confining layer of clay at a depth of about 50 ft, which could serve to perch the water table and prohibit vertical leakage to underlying aquifers.

Observed piezometric heads within the surficial aquifer remained greater than surface water elevations in the stream, indicating lateral groundwater movement toward the stream during the observation period (Figure 16). While upward discharging groundwater (on the order of 0.1 cm/day) was detected through seepage meter and temperature-based flux calculations at a few points within this reach, the majority of measurement points indicated downward discharging groundwater (on the order of 1 cm/day). Given the geologic conditions underlying this site, it may be possible to promote groundwater discharge to the stream by creating a groundwater mound through focused stormwater infiltration at this site. However, more investigation using an external source water (fire hydrant, tanker truck, etc.)

would be warranted prior to commencing such efforts.

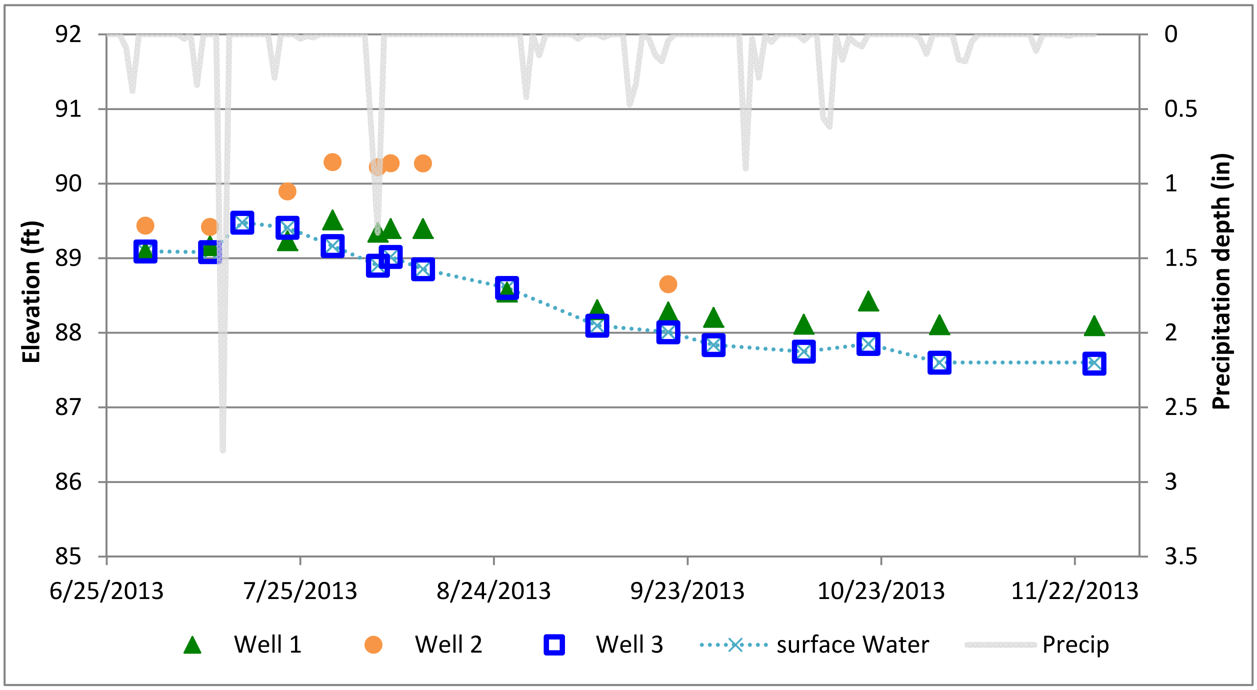


Figure 16. Groundwater piezometric head (Wells 1 and 2) and surface water elevation measurements (Well 3) at Utley Park, immediately downstream of Browndale Dam in Edina.

3.4 Extrapolation of Point Measurements to Reach Scale

The field measurements described in the preceding sections quantify groundwater fluxes at discrete points along the stream channel. While these measurements are useful for characterizing the spatial heterogeneity of groundwater-surface water interactions along the length of the stream, one cannot get a sense of overall groundwater contributions and/or losses without extrapolating from these point measurements to the reach scale. In the following sections, we describe how the point measurements were used to approximate reach wide groundwater fluxes on an annual basis. The results of this approach are then compared to the estimate of net groundwater discharge obtained through isotope analysis (0.2-0.26 inches/year).

3.4.1 Channel Width Analysis

A channel width analysis for length of Minnehaha Creek was initially completed to determine historic changes in channel width due to straightening and narrowing of the creek over the course of increasing urban development within the channel corridor. Representative reach channel areas and channel center lines were first created using 1892 and 1912 geo-referenced survey maps (C.M. Foote & Co., 1892; Wirth & Vitrud, 1912, respectively) and 2012 aerial photos and LiDAR (MnGeo, 2012; MnGeo, 2011, respectively) within ArcGIS. Channel width was then determined by dividing representative reach channel areas by channel center lines for each of the three years. Initial results for comparison of current aerial photo and LiDAR-derived channel width conditions to the 1892 and 1912 geo-referenced survey maps did not yield results suggesting significant changes in channel width for the majority of reaches. In addition, it was not possible to locate survey notes for either survey map and as a result it was not possible to determine whether the channel conditions were drawn anatomically correct. Based on this, changes in channel conditions were mainly used to infer potential old channel locations and sinuosity changes and the representative reach channel areas instead were used to calculate reach scale groundwater fluxes. Details of the results from this analysis are presented in Appendix V.

3.4.2 Reach Groundwater Fluxes

For each reach identified in the width analysis, an average groundwater flux rate was assigned. This flux rate corresponded to the average rate measured via seepage meters and/or temperature profiles across points within that reach. If field measurements were not taken within a reach identified in the width analysis, then the rate from the reach nearest in proximity and channel characteristics (e.g., similar bed material, slope, channel geometry) was assigned. If the average rate observed across points in a given reach was downward in direction, then a negative flux value was assigned. The assigned flux was then multiplied by the length and width of the channel to obtain a volumetric, daily flux. This flux was then multiplied by 365 days per year to produce an annual volume of groundwater discharge or recharge. The net groundwater discharge obtained by this method was 0.31 inches per year. While this can only be considered as a rough approximation, it compares very favorably with isotope-based estimates of groundwater contributions to baseflow (0.2-0.26 inches per year). Results are presented in Table 3.

Table 3. Net groundwater discharge estimated on reach basis by applying average of point measurements (via seepage meter and/or temperature-based flux calculation) taken within a given reach to the total streambed area within that reach.

Reach	2012-Length (ft)	2012-Area (ft^2)	*Seepage measurement - Location(s)*	*Flux: cm/d (+ UP)*	*Volume loss (-) or gain (+) (ft^3/yr)*	
1	4,456	156,891	estimate	0	0.00E+00	
2	765	26,089	estimate	0	0.00E+00	
3	3,638	291,940	Hiawatha Ave; S. 38th Ave	-0.9125	-3.19E+06	
4	3,651	143,349	L. Hiawatha	-0.805	-1.38E+06	
6	1,898	64,088	L. Hiawatha	-0.805	-6.18E+05	
7	3,002	100,751	L. Hiawatha, 49th-Cedar	-1.7275	-2.08E+06	
8	4,929	162,230	49th-Cedar	-2.65	-5.15E+06	
9	3,752	123,370	50th-Minnehha	-2.36	-3.49E+06	
10	4,185	131,831	Pleasant	-0.76	-1.20E+06	
11	4,892	176,668	Girard, James	-0.3825	-8.09E+05	
12	6,061	200,902	Girard, James	-0.3825	-9.20E+05	
13	4,655	147,602	James	-0.425	-7.51E+05	
14	4,069	141,071	Arden Park, Edina res	-0.835	-1.41E+06	
15	4,884	185,157	Arden Park, Edina res	-0.835	-1.85E+06	
16	1,169	37,557	Utley/mill	-0.49	-2.20E+05	
17	5,506	851,447	Yosimite	-2.62	-2.67E+07	
18	1,852	85,148	Yosimite	-2.62	-2.67E+06	
19	4,429	1,491,623	Excelsior	0.38	6.70E+06	
20	6,061	212,472	Schloff, Meadowbrook bridge, Reach 20, Excelsior, Methodist	0.80375	2.05E+06	
21	3,022	124,965	Blake	1.92	2.87E+06	
22	1,956	170,836	DQ wetland	1	2.05E+06	
23	3,493	350,682	Lahti	1	4.20E+06	
24	4,934	172,431	Hopkins Xroads	0.7	1.45E+06	
25	4,809	377,872	Big Willow, Civic Center	0.7	3.17E+06	
26	1,664	43,866	Big Willow	0.7	3.68E+05	
27	6,352	231,812	Big Willow	0.7	1.94E+06	
28	3,799	139,195	Big Willow	0.7	1.17E+06	
29	3,512	106,250	Burwell	-3.02	-3.84E+06	
30	9,998	1,412,332	Jidana, wetland opposite	3.8	6.43E+07	
Total	76,164	6,282,318	**Sum, *net* annual groundwater discharge:**		**3.39E+07**	**ft^3/yr**
					0.31	**in/yr**

4. Factors Driving Observed Groundwater-Surface Water Interactions within Minnehaha Creek

The weight of evidence provided by seepage meter measurements, temperature profiles, and isotopic composition of the creek and its source waters indicates annual groundwater contributions on the order of 0.2 to 0.3 inches per year. This represents less than 7% of total annual flow in Minnehaha Creek, and only 3-4% of the 6.7 inches of annual recharge estimated for the watershed (Barr, 2008). A natural question follows: why the paucity of groundwater in Minnehaha Creek? This is not merely a question of curiosity; understanding the underlying factors driving observed groundwater-surface water interactions can provide important insights to potential to manage stormwater for baseflow augmentation. We posit that geologic factors exert important controls, though anthropogenic influences such as groundwater pumping and subsurface drainage may also contribute. In the following sections, we discuss these controls within the context of baseflow augmentation in Minnehaha Creek.

4.1 Geologic Controls: the Platteville Limestone and Buried Bedrock Valleys

The lower Minnehaha Creek watershed is underlain by a layer of unconsolidated sediments deposited by glaciers during the Quaternary period. The average thickness of the quaternary deposits across the lower watershed is 100 ft, ranging from complete absence of these deposits in the vicinity of Minnehaha Falls to over 300 ft beneath the Chain of Lakes. This particularly thick region of quaternary deposits coincides with an erosional bedrock valley created by glacial and pre-glacial fluvial processes that was then filled by glacial outwash. These deposits form the quaternary, or surficial, aquifer, the mean saturated thickness of which is 100 ft. Interactions between the creek and this surficial aquifer have been the primary interest of this study. As shown in Figure 17, the surficial aquifer surface is more or less coincident with the creek channel from Grays Bay outlet to the upstream end of the impoundment formed by Browndale Dam. Below Browndale Dam, the water table surface diverges from the streambed, indicating the potential for losses from the channel to the underlying aquifer.

Below the unconsolidated materials of the surficial aquifer lie a series of bedrock formations, the uppermost of which is the Platteville-Glenwood limestone formation. The Platteville is present throughout about 60% of the lower watershed (Figure 18). This formation has been described as a discrete aquitard with very low vertical conductivity (Runkel et al., 2011). The next bedrock unit in succession is the St. Peter Sandstone, which is the uppermost bedrock unit across 31% of the watershed. Although horizontal conductivities may be as high as 10 ft/day, the lower portion of the St. Peter is characterized by low permeability and acts as a hydraulic barrier between the St. Peter and the Prairie du Chien (Runkel, 2003). Below the Chain of Lakes, pre-glacial erosional processed removed both the Platteville and the St. Peter formations, creating the present-day "bedrock window" in which the surficial aquifer is in direct contact with the Prairie du Chien. This condition is restricted to about 9%

of the lower watershed. Figures 17 and 18 illustrate the spatial relationship between the land surface (which coincides with the Minnehaha Creek streambed in Figure 17), the water level in the surficial aquifer, the uppermost bedrock surface, and potentiometric head associated with the Prairie du Chien aquifer.

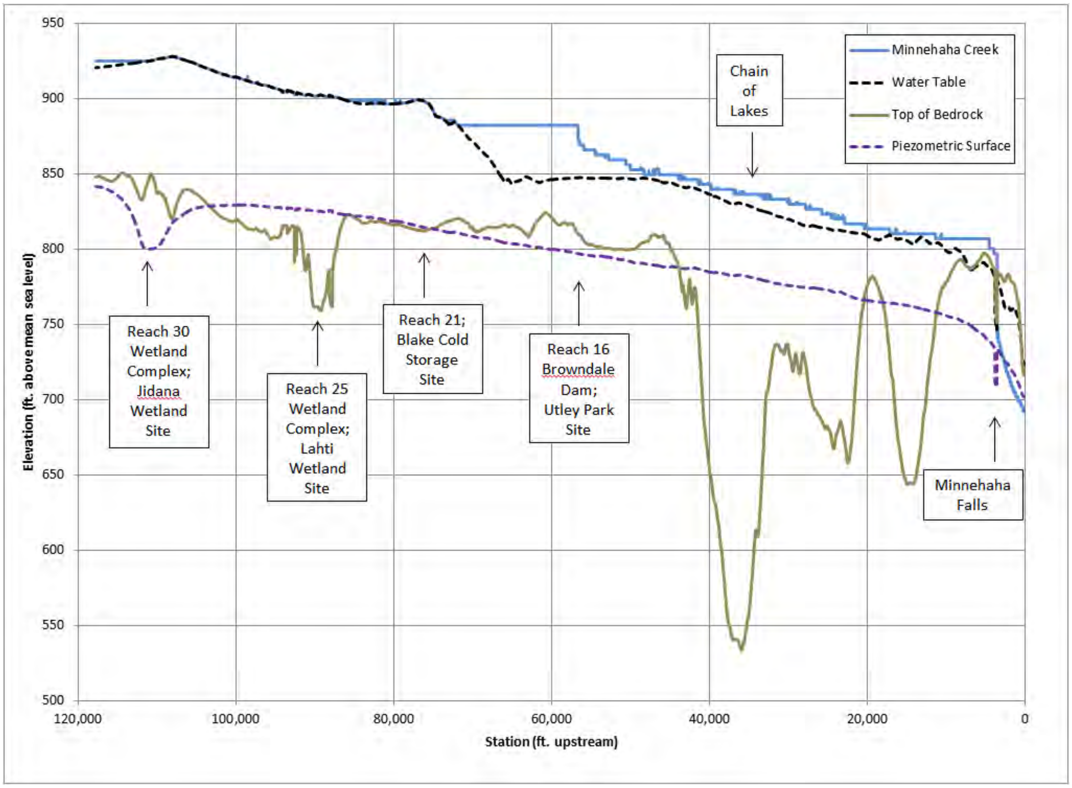


Figure 17. Long profile depicting surficial and bedrock aquifer systems along the length of Minnehaha Creek. Long profile created within ArcScene using 1 M LiDAR surface (MnGeo 2011) and water table, top of bedrock, and piezometric surface data (Tipping, 2011).

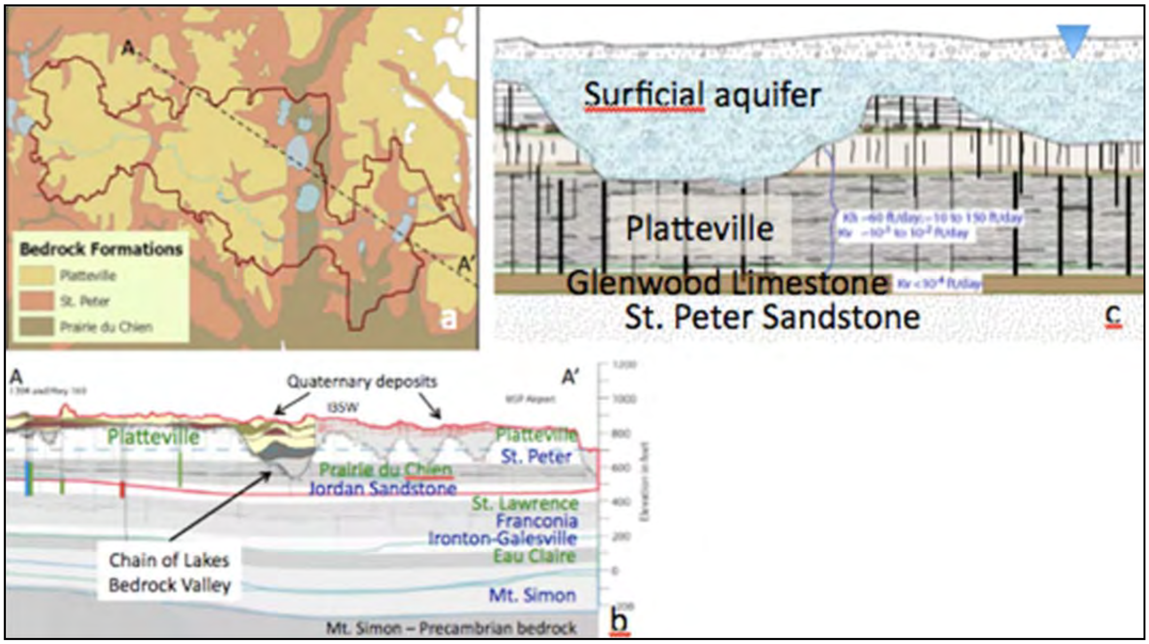


Figure 18. Bedrock geology underlying lower Minnehaha Creek watershed. (a) distribution of Platteville (Yellow), St. Peter (Salmon) and Prairie du Chien (Brown) aquifers. (b) Section A-A', illustrating "Bedrock Valleys" where Platteville and/or St. Peter formations have been eroded, creating direct contact between the surficial and Prairie du Chien aquifers, most notably below the Chain of Lakes (from Tipping, 2011). (c) detail of the Platteville and low-conductivity Glenwood Limestone formation of this unit, which may play an important role in perching the groundwater table and slowing vertical leakage to the underlying bedrock aquifers (from Runkel et al., 2011)

We believe that, where present, the Platteville-Glenwood shale formation plays an important role in perching the groundwater table in the surficial aquifer, supporting groundwater discharge to Minnehaha Creek when aquifer levels are high enough and preventing vertical leakage to underlying bedrock aquifers, most notably the Prairie du Chien. Field measurements of streambed fluxes indicated predominantly upward fluxes above Browndale Dam along the most continuous expanse of Platteville in the watershed. Both our field measurements and the drop in the water table relative to the land surface in Figure 17 indicate strong potential for channel losses below Browndale Dam. Geologically, this region of the watershed is characterized by a discontinuous Platteville layer and direct contact with the Prairie du Chien in some areas. These areas of direct contact likely serve as a conduit from which water from the surficial aquifer (and which is available for discharge to Minnehaha Creek) is lost to the bedrock aquifer system. The series of cartoons in Figure 19 illustrate this concept.

To determine if this hypothesis was tenable in terms of the annual water budget, we calculated aquifer properties required to supply the remaining 6.5 in/year of annual recharge to the Prairie du Chien. This calculation was made using Darcy's law and a hydraulic head dataset developed by Tipping (2011). Darcy flux calculations are described in Appendix IV. The uppermost formation of the Prairie du Chien aquifer is the Shakopee, which is characterized by low vertical conductivities on the order of 0.0003 to 0.3 ft/day (Runkel et al., 2003). In order for leakage from the surficial aquifer to the Prairie du Chien to account for the remaining 6.5 in/year of annual recharge, the effective vertical conductivity between the surficial and Prairie du Chien aquifers would need to be 0.076 ft/day assuming minimal leakage across the Platteville or St. Peter formations. This value falls within the expected range of vertical conductivities for the Prairie du Chien, so the supposition that leakage from the surficial aquifer accounts for over 95% of total recharge is not unreasonable. Furthermore, it helps explain the lack of groundwater available for discharge to Minnehaha Creek.

Data compiled by Tipping (2011) pertaining to groundwater age provides another line of evidence to support our hypothesis of significant leakage to bedrock aquifers. Figure 20 illustrates tritium concentrations detected in groundwater from a series of wells across the lower Minnehaha Creek watershed. Tritium concentrations have been related to groundwater age, with lower concentrations (less than 1 Tritium unit) generally corresponding to waters that were recharged over 50 years ago. Groundwater within two wells located in the upper end of the watershed was characterized as such. Tritium concentrations in the bedrock aquifer tended to increase with distance downstream along Minnehaha Creek, suggesting that recharge rates are higher and/or hydraulic residence time in the surficial aquifer is lower in this region. Rapid transit of water from the surface to underlying bedrock aquifers suggests leakage from the surficial aquifer is occurring, with the effect of a loss of recharge available for discharge to Minnehaha Creek.

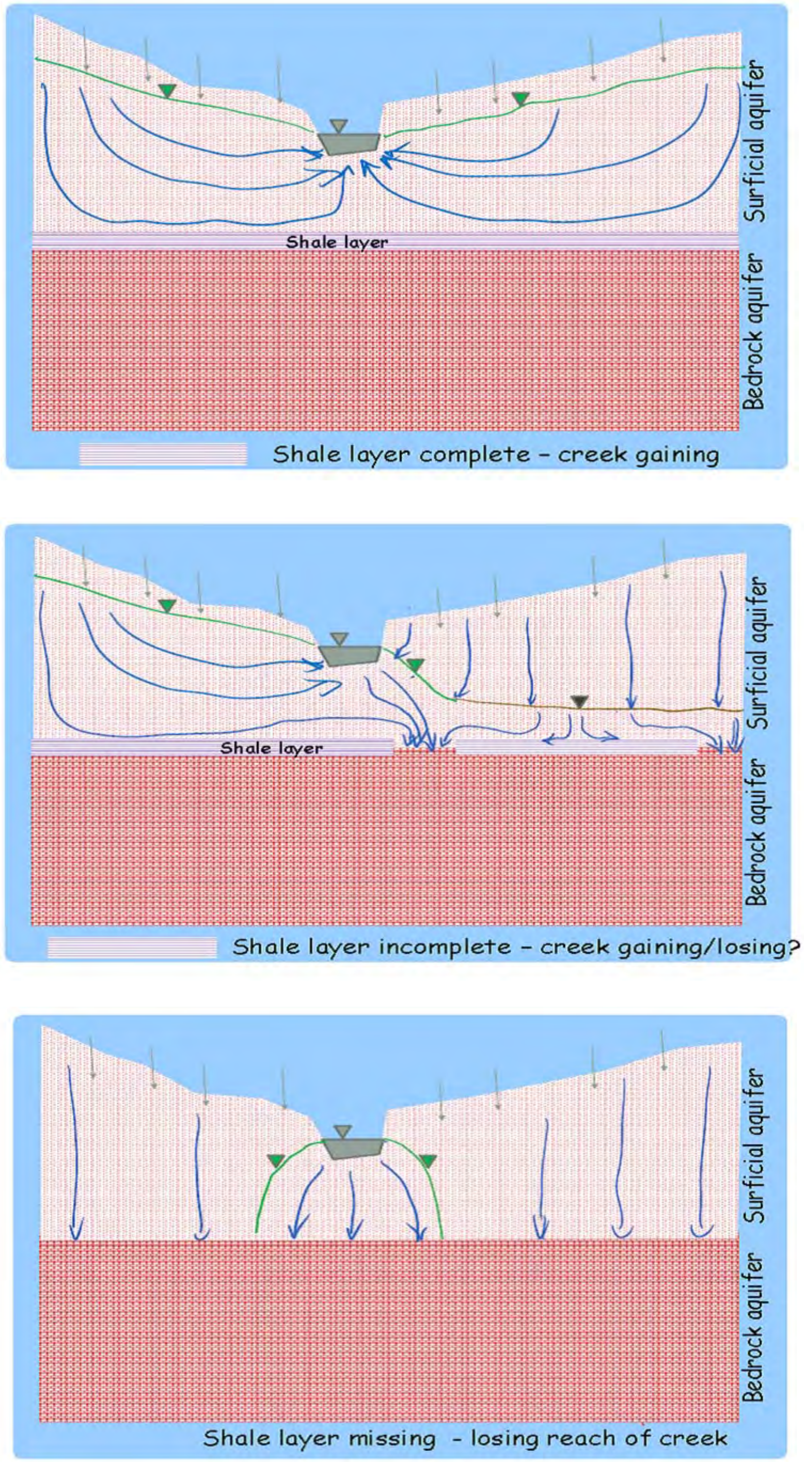


Figure 19. Conceptual illustration of losing and gaining reaches of the stream as influenced by underlying geology. The Platteville-Glenwood-Decorah Shale formation is thought to function as an aquitard, perching the surficial water table and supporting groundwater discharge to Minnehaha Creek (top). This shale layer has been eroded from some areas of the watershed so that the surficial aquifer is in direct contact with underlying bedrock aquifers, namely the Prairie du Chien. Such conditions are thought to permit leakage from the surficial aquifer and losses from the creek (middle). Discontinuous extents of the Platteville-Glenwood-Decorah shale formation lead to surface water losses (bottom).

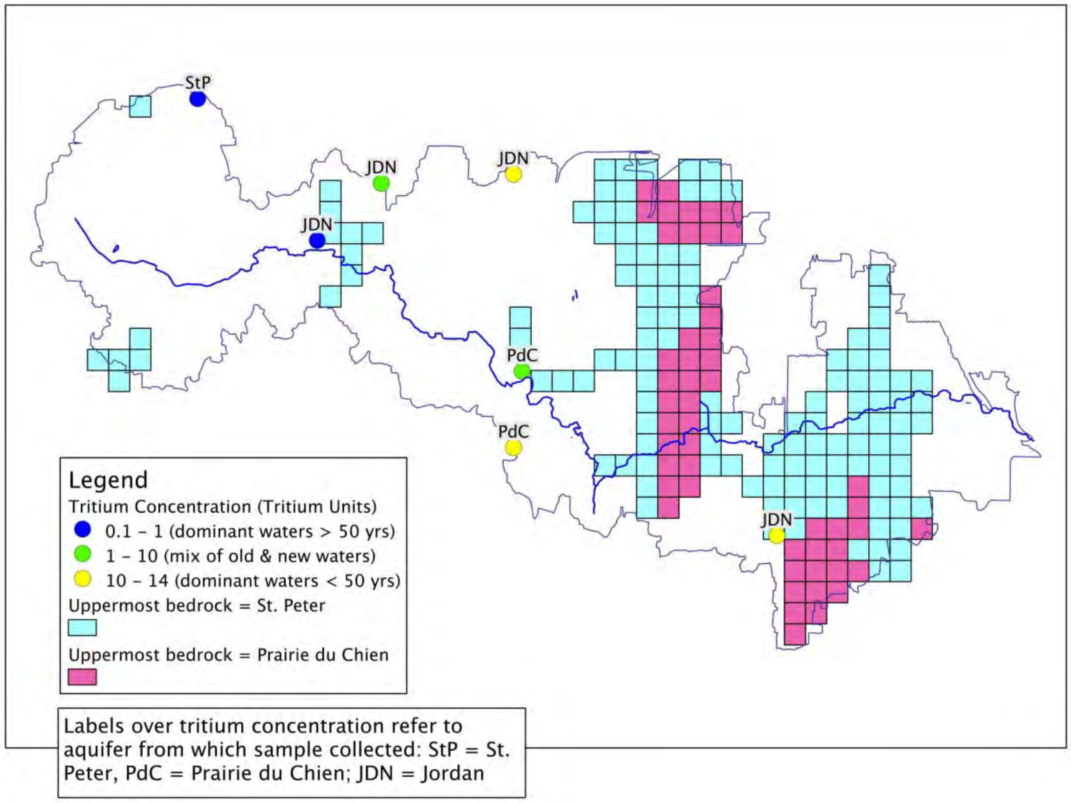


Figure 20. Distribution of tritium in groundwater across the lower Minnehaha Creek Watershed. Tritium concentration is used as an indicator of groundwater age. Concentrations less than 1 Tritium unit indicate water was recharged over 50 years ago. Concentrations greater than 10 indicate water recharged from the surface to aquifer less than 50 years ago. Intermediate values indicate a mix of older and newer waters. Groundwater age tends to decrease with distance downstream along Minnehaha Creek indicating more rapid recharge and, likely, reduced residence time in the surficial aquifer.

As a final line of evidence, we applied a systems model developed by Brutsaert and Nieber (1977) through which physical properties of the aquifer system may be inferred through recession analysis of stream flow data. The details of this analysis are described in Appendix VI. A major outcome of interest to this study was an approximation of the area of the watershed underlain by stream-feeding aquifers in order to support observed baseflow recessions in the Minnehaha Creek stream flow record. The analysis indicated this area was equal to 5% of the watershed area, which can be visualized as equivalent to a 250-ft buffer on either side of the creek. While the influence of Grays Bay was removed from this analysis, other sources of baseflow, such as discharge from wetlands or the Chain of Lakes, were not. If the groundwater fraction of baseflow determined through isotopic analysis during recession periods (0.05 to 0.16) is applied to better represent the groundwater portion of baseflow, then the area of groundwater source contributions may be as little as 2-3% of the total watershed area.

4.2 Other Factors Influencing Groundwater-Surface Water Interactions

Existing geologic controls are believed to exert the dominant influence on observed losses from Minnehaha Creek's shallow groundwater system.

In many ways, geologic factors are beyond control and may have limited sustained baseflows in Minnehaha Creek even in its predevelopment state.

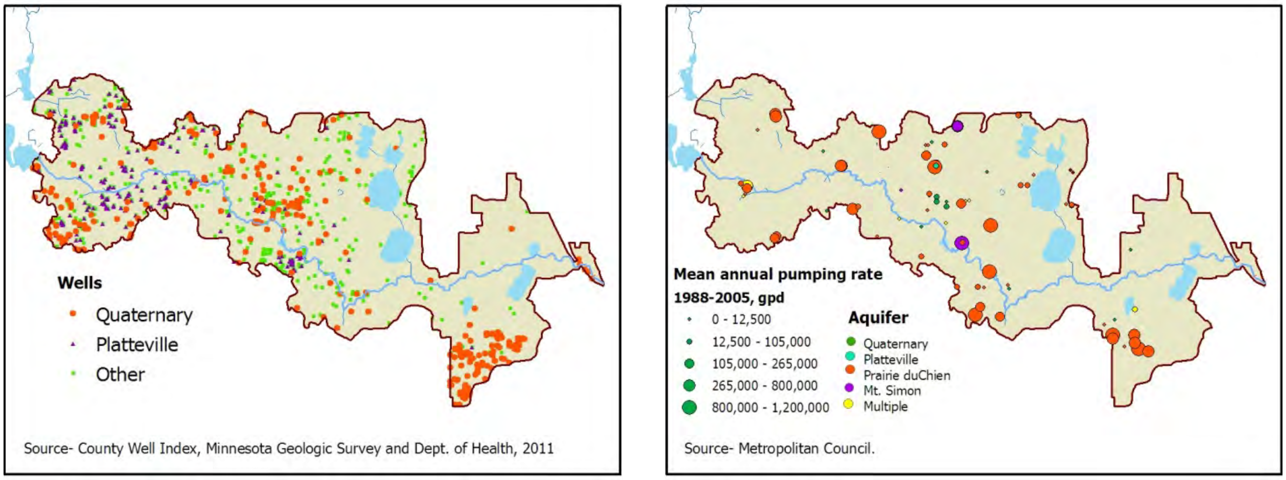


Figure 21. Left: Distribution of active wells in the lower Minnehaha Creek watershed. The color of closed circles indicates the aquifer from which water is drawn (Quaternary/surficial = orange; Platteville = purple; Other aquifers = green). Right: Mean annual pumping rate in high capacity commercial and muncipal wells. Relative marker size denotes pumping rate while color denotes aquifer from which withdraws made. The majority of high capacity wells draw from the Prairie du Chien (orange) aquifer.

However, other anthropogenic factors may be exasperating surficial aquifer losses. Three factors are briefly discussed here, including (1) groundwater pumping, (2) drainage effects of deep stormwater and sanitary sewer infrastructure, and (3) expansion of impervious area.

4.2.1 Groundwater Pumping

The County Well Index, an online database of wells installed in the state maintained by the Minnesota Department of Health, reports a total of 845 active wells (that is, not sealed) throughout the lower Minnehaha Creek watershed (Figure 21, left). Well installation dates range from 1937 to 2008. Of these wells, 317 draw water from the quaternary aquifer. The rest are open to the Platteville (248), St. Peter (44), Prairie du Chien - Jordan (16), or to multiple aquifers (220). The majority of these wells were drilled for domestic purposes and do not have publicly available pumping records. Historic pumping data is available for a number of “high capacity” wells used for industrial and commercial purposes. Annual withdraws from these wells from 1988 to 2005 range from less than 30 gallons per day (gpd) to 1,200,000 gpd (Figure 21, right). Considering just those wells from which pumping rates are known, total annual groundwater pumping may range from 4.1 to 8.5 inches equivalent depth over the watershed (Table 4), with the majority of this volume is drawn from the Prairie du Chien aquifer. Compared to the annual total recharge to the surficial aquifer of 6.7 inches per year, groundwater pumping and subsequent drawdown could accelerate leakage from the surficial aquifer.

Table 4. Range of groundwater pumping volume over lower Minnehaha Creek watershed.

Pumping rate (gpd)	Number of wells	Yield (10^6 ft³/yr/well)		Total Yield (10^6 ft³/yr)	
		Low	High	Low	High
0-12,500	24	0	0.006	0	14.6
12,500-105,000	13	0.006	0.051	7.90	66.4
105,000-256,000	7	0.051	0.129	35.8	90.7
265,000-800,000	9	0.129	0.389	116	350
800,000-1,200,000	8	0.389	0.584	311	467
		TOTAL (million ft³/yr)		**470.7**	**988.7**
		TOTAL (inches/yr)		**4.1**	**8.5**

4.2.2 Drainage along Municipal and Stormwater Sewer Pipes

Drainage along buried municipal pipelines and stormwater pipe are considered to be a possible means through which groundwater may be shunted away from Minnehaha Creek. Preferential flow paths are known to develop along the high conductivity materials comprising backfill around sewer infrastructure. As a result, groundwater may be effectively removed from the system through horizontal drainage along preferential pathways. Preferential flow along most stormwater pipes may not constitute a great concern since the terminus of these pathways is typically Minnehaha Creek. However, preferential flow along sanitary sewer interceptors or deep stormwater tunnels (Figure 1) may serve to exacerbate groundwater losses, particularly below the Chain of Lakes, if groundwater drains horizontally to the Mississippi River. In addition to this French Drain effect, infiltration into sewer systems may serve as another loss mechanism. While leakage into deeper bedrock aquifers likely comprises a greater loss, drainage along and infiltration into sewer infrastructure may be a source of local groundwater losses.

4.2.3 Expansion of Impervious Surfaces

Presently, the average impervious area across Minnehaha Creek is about 30%, most of which is concentrated in the lower 2/3 of the watershed. Impervious surfaces restrict infiltration and, in turn, groundwater recharge. It is likely that expansion of impervious surfaces, particularly near the stream, have decreased groundwater recharge and subsequent discharge as stream baseflow. Regardless, one thing is certain: the annual contribution of stormwater runoff to flow in Minnehaha Creek is much higher than in the watershed’s predevelopment state. We estimated that runoff constitutes about 18% of annual flow in Minnehaha Creek as compared to the 13% provided by baseflow sources other than Lake Minnetonka. The rapid manner with which runoff is conveyed to Minnehaha Creek is contrary to the sustained release delivered by groundwater, wetlands, or other surface reservoirs in the periods between storm events. Capturing stormwater runoff piped to the creek and releasing it in a manner that mimics baseflow sources could potentially double current stream baseflows. Can this be done? This is the focus of the next section of the report, in which key findings and their practical application are highlighted.

5. On the Ground Application of Knowledge Gained from the Minnehaha Creek Baseflow Study

Based on field measurements of groundwater fluxes and supporting evidence from hydrogeologic conditions and stream flow recession analyses, we have developed an understanding of groundwater contributions and loss mechanisms in the Minnehaha Creek watershed. As illustrated in Table 3., groundwater represents about 5% of the total annual stream flow in Minnehaha Creek. From these field measurements, we have developed the following key conclusions and recommendations:

- The current baseline contribution of groundwater to flow in Minnehaha Creek is 0.2-0.3 inches per year. Complete capture of stormwater runoff and redistribution through storage and release from the shallow aquifer would increase this contribution to about 2.3 inches per year, or roughly half of the annual flow in Minnehaha Creek. Spread over the open water season (April through November), this would equate to an additional 10 cfs of flow during non-storm periods.
- We believe that the *greatest opportunity to augment groundwater contributions to stream baseflow through focused stormwater infiltration exist in areas where the Platteville-Glenwood shale formation is relatively continuous and/or where an underlying sandy-clay till layer is present to constrain seepage loss* (Figure 18). This includes relatively impervious areas such as the Knollwood Shopping area and Hopkins Cold Storage site.
- *Baseflow augmentation via stormwater infiltration may be limited below the Chain of Lakes*. Hydrogeologic conditions and measured streambed flux rates between the Chain of Lakes and Minnehaha Falls indicate flow is predominantly in a downward. The predominant wownward flow is likely related to leakage from the surficial aquifer system to the underlying Prairie du Chien bedrock aquifer. This condition does not necessarily preclude baseflow benefits from stormwater management projects. However, the design of systems intended to promote baseflow would likely require placement of an impervious liner to prevent vertical seepage losses.

5.1 Potential Future Steps

5.1.1 Development of a Decision Support Tool

Develop a decision support tool that provides applicable data and useful steps needed to determine the ability for baseflow augmentation or baseflow management at a site for future planning along Minnehaha Creek. Applicable data (i.e. GIS layers, modeling results, field work results, permitting requirements, etc.) would be organized and adequately provided to the user at each specific step. The potential inconsistencies or the margin of error in all provided data would also be adequately outlined. This could involve creation of an interactive tool that includes applicable data links on a map of Minnehaha Creek during each step or just consist of direct links to applicable data within some form of document. Although an interactive tool may not be feasible, some sort of map element would be incorporated into the overall tool in order to allow a user to determine possible data needs for specific locations along the creek. The specific steps within the tool will most likely be formulated during the compilation of all available data for the tool. Each step might include a list of helpful tips or literature to consider after completion of the step and/or links to contacts that may be useful to involve in the decision process. After a basic outline for the tool has been created, a literature review could be completed to locate any currently available support tools. If decision support tools are located, the development, use, and overall formatting of the tools would be heavily considered and used in the formation of the tool for Minnehaha Creek. Following the initial formulation of the tool, the initial outline and literature review would then be assessed to determine the steps needed to move forward. It would also be beneficial at this stage to discuss the initial/revised outline of the tool with MCWD to best integrate their overall goals for the creek. Once a final rendition of the tool has been created, the tool would be tested on an example site along Minnehaha Creek to determine any further edits needed and also to provide an example of correct use of the tool that can be provided to future users at MCWD.

5.1.2 Investigate Where Groundwater is Going (e.g. 'French Drain' Effect of Sanitary Sewer Interceptors and I-35W Storm Sewer Tunnel)

- Modeling Effort: Create a groundwater model or group of models that can be used by MCWD following the completion of the current baseflow project to continue to adequately determine overall groundwater flux into the future. This model would go further than the models and analysis already completed by attempting to include as much relevant information from the watershed as possible. Some parameters might include estimates of evapotranspiration (based on a relevant measurement methodology), bed material or storage changes along the reach and stormwater inputs and/or potential losses. A literature review in conjunction with input from groundwater flow experts would help improve the list of parameters and likely determine the feasibility of including each. The overall goal of the model or group of models would be for staff at MCWD to be able to input up-to-date flow data and precipitation data and new field data to keep groundwater flux estimates current and to build a record of the flux from year to year in conjunction with changes in landuse, climate, and stream morphology.
- Additional GIS comparison of stormsewer locations relative to channel 'losing' areas.
- Mapping of I-35W storm sewer tunnel structure during winter to locate and GPS any potential leaks.

5.1.3 Further Geo-Tech Exploration and Piezometer Installation at Several Sites of Interest (e.g. MPRB BMP Sites)

- Determination of locations for further exploration based on seepage measurements collected this fall.

- Preclude to pilot studies on sites before future stages of construction of infiltration basin to augment baseflow.
- Further exploration will allow for more adequate constraining of data collected and presented within this report and will help to improve all future steps presented (fieldwork efforts, modeling efforts, and decision support tool).

5.1.4 Addition of Injected Tracer Studies to Several Sites of Interest

- Completion of an injected tracer study will help to answer the following specific questions:
    - *Is shallow groundwater flow near the stream primarily horizontal or vertical?*
    - *Do vertical gradients preclude discharge to stream as horizontal distance from the channel increases?*

5.1.5 Completion of Pilot Studies on Several Sites of Interest to Determine Potential for Artificial Baseflow Augmentation

- Use data from seepage meter measurements at MPRB locations to target sites for pilot studies (i.e. are any of the MPRB sites adequate for baseflow augmentation?)

5.1.6 Completion of Study to Determine Potential Effects of Stream Restoration Efforts on Groundwater Connectivity throughout Minnehaha Creek

- Summarized history and location of restoration efforts on the creek (detailed account of scale and techniques used).
- Potential effects on baseflow within each location based on the specific techniques used.

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Appendices

Appendix I. Flow Error Analysis

Grays Bay Flow Error Analysis

As noted in Section 2.1, a flow error analysis was completed using stage differences and specific D_{calc} (i.e. height of dam opening) values provided by MCWD for the outlet of Grays Bay. Results from the analysis indicated that actual flow levels out of Grays Bay differ considerably from those reported by MCWD, in between periods of dam opening height change. The equation used by MCWD to calculate a D_{calc} value for an input discharge (Q) and stage difference (H) is:

$$\boxed{\begin{array}{l} D = \dfrac{Q}{CNBH} \\ \\ Q = CNBDH \end{array}}$$

Q= discharge (cfs)
H= $\sqrt{LL-TW}$
N= # of gates open
B= width of gate= 10'
D= height of gate opening (notches)
LL= lake elevation
TW= wetland elevation

$$C = \left[\begin{array}{l} \text{1 gate= 6.56} \\ \text{2 gate= 6.40} \\ \text{3 gate= 7.05} \end{array}\right.$$

All values in the above equation were provided by MCWD and all values were held constant during periods of constant dam opening height, with the exception of stage difference, when calculating representative discharge values. Specific periods of constant dam opening height were chosen to calculate error in recorded discharge due to the potential for a fluctuating stage relative to the specifically set dam opening height in between management actions by MCWD. In general, discharge values recorded at the time of dam opening height change were accurate. This was to be expected based on the specific formulation of the equation for the Grays Bay outlet structure. Results of the analysis for years 2008 through 2013 are presented in Figure A.1.

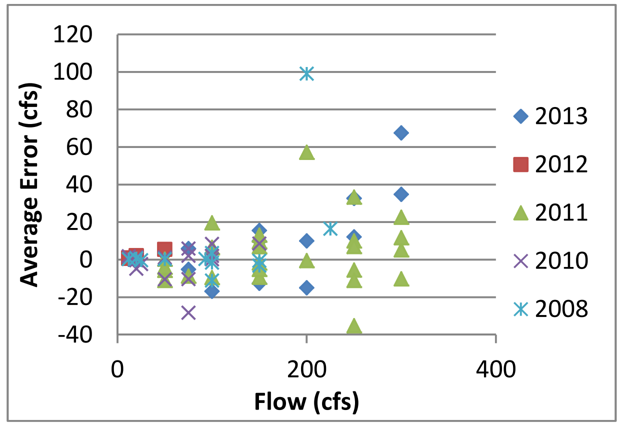


Figure A.1 Grays Bay flow error analysis results. Negative values indicate actual discharge values above those recorded by MCWD. Flow error results for years 2006 and 2007 are not included due to lack of continuous stage difference data. 2009 was also not included due to errors in discharge measurements over the course of the year.

In general, it can be noted that the difference between recorded and actual discharge values increases with increasing flows through the Grays Bay outlet structure. This is to be expected with relatively rapid flow changes during precipitation events and the inability of MCWD staff to constantly change dam opening height relative to all changes. Constant calculation of exact flow levels is likely not of concern to MCWD from a management standpoint, but was very important in determining the flow balance for the Minnehaha Creek Watershed. All results have been tabulated within MS Excel and are available upon request.

Watershed-Scale Flow Error Analysis

In addition to Grays Bay, flow error was also analyzed for several other gauging stations along the length of Minnehaha Creek. Specific gauging stations included (listed from upstream to downstream): CMH 19 at the Interstate 494 crossing, CMH03 at Browndale Dam, and the USGS gauge at Hiawatha Ave. For each gauging station, a nearby direct measurement of discharge using a Flow Tracker was used for comparison and determination of potential error in recorded flows. A direct measurement of discharge near the Grays Bay outlet structure was also included for comparison. All direct measurements of discharge were provided by MCWD (Figure A.2). It is important to note that additional error could be possible at each gauging station and was considered as possible given available information for each specific station. However, in general it was not possible to determine potential errors in measurements at each station due to a lack of active management compared to the Grays Bay outlet structure.

Although many factors could account for the difference between recorded discharges, including small differences in location of measurement, the results in Figure A.2 indicate that discharge can change significantly across the length of Minnehaha Creek, even within a small distance. In general, small differences were noted for both I-494 and Hiawatha Ave compared to Browndale Dam and Grays Bay. The large difference at Browndale Dam was likely due to backwatering effects from the dam and a resulting overall reduction in discharge recorded at the downstream permanent gauge. At Grays Bay, differences could be due to storage effects in the large wetland complex downstream of the outlet structure. At both locations, differences increased during the months of high spring flows. A more in-depth review and synthesis of results will be presented in the final report. During the flow error analysis, tabulated flows were also used to calculate volumes of flow at each permanent gauge during specific time periods of consistent dam opening height at Grays Bay (Figure A.3). With a fixed dam opening height, changes in volume across the length of Minnehaha Creek could be attributed to various storage effects, changes in channel morphology, differences in impervious surface percentages and/or stormwater inputs, and other factors. Preliminary results were used to guide further research into potential factors affecting flow and will be presented more thoroughly in the final report.

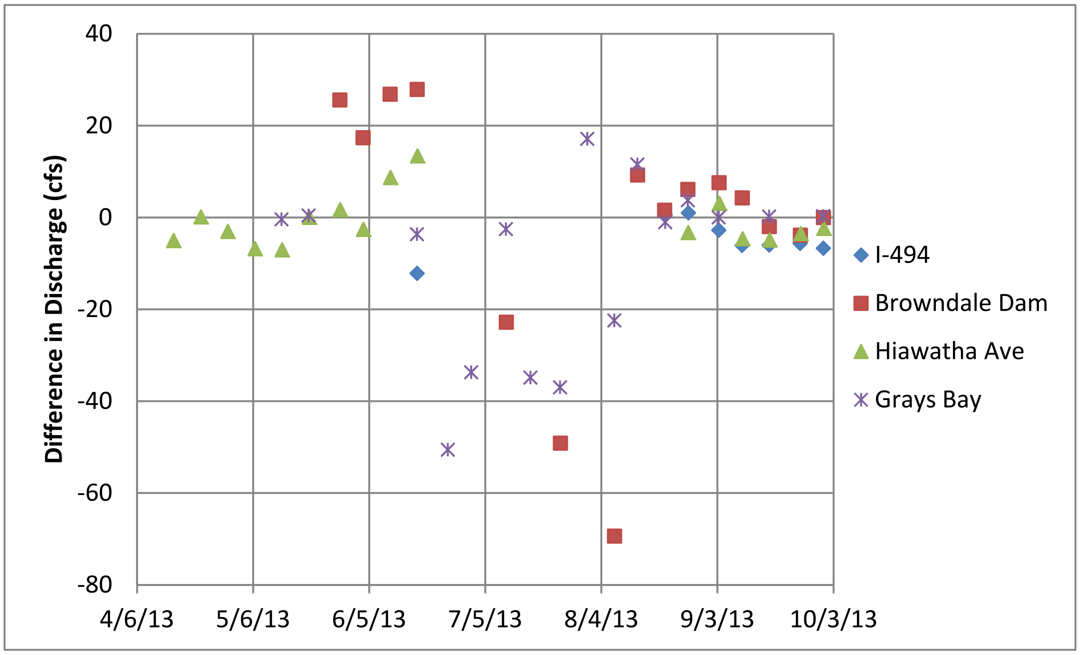
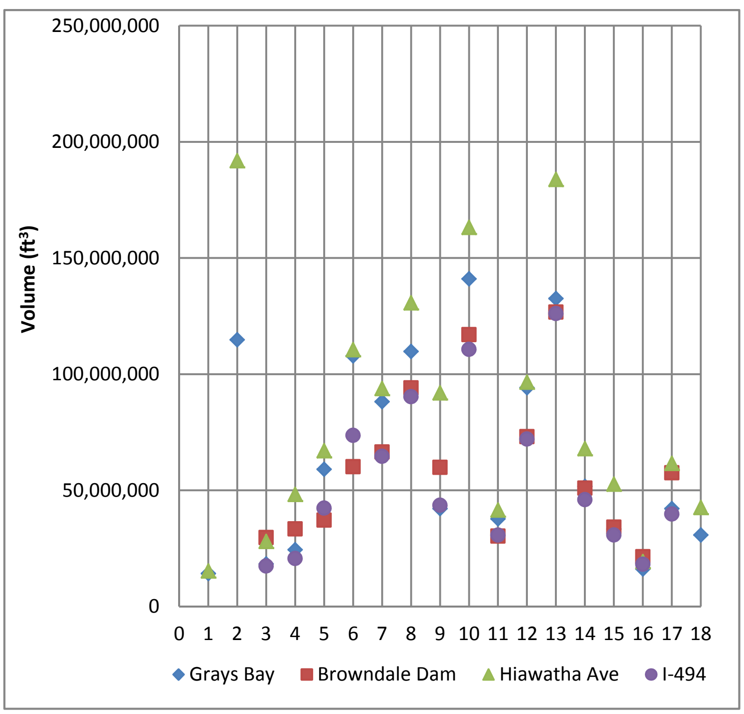


Figure A.2. Difference in recorded discharge between permanent gage locations and Flow Tracker measurements by MCWD staff. Negative values indicate a higher discharge value at the Flow Tracker measurement location.



Time Periods	
1	5/6-5/17/2013 - 12 cfs
2	5/22-6/18/2013 - 50 cfs
3	6/18-6/21/13 - 75 cfs
4	6/21-6/23/13 - 150 cfs
5	6/23-6/26/13 - 250 cfs
6	6/26-7/1/13 - 300 cfs
7	7/1-7/5/13 - 250 cfs
8	7/5-7/12/13 - 200 cfs
9	7/12-7/15/13 - 150 cfs
10	7/15-7/22/13 - 300 cfs
11	7/22-7/24/13 - 250 cfs
12	7/24-7/29/13 - 200 cfs
13	7/29-8/9/13 - 150 cfs
14	8/9-8/14/13 - 100 cfs
15	8/14-8/19/13 - 75 cfs
16	8/19-8/23/13 - 50 cfs
17	8/23-9/16/13- 20 cfs
18	9/16-10/16/13- 12 cfs

Figure A.3. Volume of flow change across the length of Minnehaha Creek for specific time periods of constant dam opening height at the Grays Bay outlet structure. In several time periods, volume appears to decrease in the upper portion of the watershed (I-494 & Browndale Dam) before increasing to a final flow volume at Hiawatha Ave. Smaller scale changes between gauges could be a result of factors described in the text above.

Appendix II. Isotope End-Member Mixing Analysis

To quantify relative contributions of multiple sources (e.g., surface waters, precipitation/runoff, and groundwater; also known as end-members) to a mixture (e.g., Minnehaha Creek), an end-member mixing analysis (EMMA) was applied. EMMA entails the use of linear mixing models to partition a composite mixture into contributing end-members. Both 2- and 3-member mixing models were utilized in this study. An example calculation is provided for each.

2-Member Mixing Model: Partitioning Meteoric and Surface Waters in the Jidana Wetland Groundwater

Minnehaha Creek riparian groundwater samples formed two distinct clusters on the basis of their isotopic compositions (Figure 4). Given the position of groundwater samples from the Jidana wetland between surface water samples and all other groundwater samples, it was hypothesized that riparian groundwaters at the Jidana site were comprised of (1) recharged meteoric waters and (2) surface water originating from Lake Minnetonka. To test this hypothesis, a 2-member mixing model was applied with the following system of equations:

$$Q_{gw} = Q_p + Q_M$$
$$Q_{gw}\delta O_{gw} = Q_p \delta O_p + Q_M \delta O_M$$

where Q = fraction of flow, δO = mean ^{18}O isotopic fraction (relative to standard of mean ocean water), and subscripts *gw, p,* and *M* indicate groundwater (mixture), precipitation (end-member #1), and Minnetonka (end-member #2), respectively. The relative fractions of flow contributed by precipitation (Q_p) and Lake Minnetonka (Q_M) are simultaneously solved as:

$$Q_p = Q_{gw} - Q_M$$
$$Q_p = Q_{gw}\frac{\delta O_{gw} - \delta O_M}{\delta O_p - \delta O_M}$$
$$Q_M = Q_{gw} - Q_p$$

Q_p and Q_M were solved in Excel as:

2-member model		
Near stream Jidana wells (Group A): Mixture of Minnetonka and meteoric waters.		
		$\delta^{18}O$
Source 1	Precipitation (mean)	-8.05
Source 2	Minnetonka (mean)	-2.08
Mix, Jidana wells		-6.92
		Fraction of total
Source 1, Precipitation =		**0.8**
Source 2, Minnetonka =		**0.2**

Thus, the isotopic signature of riparian groundwater at the Jidana wetland site indicates the aquifer is composed primarily of meteoric waters (rainfall and snowmelt recharge; about 80% by composition) with additional contributions from Minnehaha Creek waters originating from Lake Minnetonka (about 20%).

3-Member Mixing Model: Partitioning Surface Water, Groundwater, and Runoff in Minnehaha Creek Waters

Minnehaha Creek and source water samples were collected on May 28, 2012 following a 5-day series of rain events during which approximately 4.5 inches fell over the watershed. Subsequent sampling was conducted during the hydrograph recession of this storm series (June 6, 2012) and again on Aug. 22, 2012 following the closure of Grays Bay due to drought. On any of these sampling dates, it was hypothesized that Minnehaha Creek waters were comprised of a mixture of (1) runoff, (2) surface waters, and (3) groundwater. To test this hypothesis, a 3-member mixing model of following system of equations was applied:

$$Q_{RO} + Q_{SW} + Q_{GW} = Q_{MC}$$

$$\delta O_{ro} Q_{ro} + \delta O_{sw} Q_{sw} + \delta O_{gw} Q_{gw} = \delta O_{MC} Q_{MC}$$

$$\delta D_{ro} Q_{ro} + \delta D_{sw} Q_{sw} + \delta D_{gw} Q_{gw} = \delta D_{MC} Q_{tMC}$$

where Q = fraction of flow, δO = mean ^{18}O isotopic fraction (relative to standard of mean ocean water), δD = mean deuterium (^{2}H; relative to standard of mean ocean water), and subscripts *MC*, *ro* (collected from stormwater pond, n=3) *sw* (collected from outlets of Lakes Minnetonka and Harriet, n=6) and *gw* (collected from piezometers at Lahti wetland and Blake sites, n=12) denote Minnehaha Creek (mixture), runoff (end-member #1), surface water (end-member #2), and groundwater (end-member #3), respectively. The relative fractions of flow contributed by runoff (Q_{ro}), surface water (Q_{sw}), and groundwater (Q_{gw}) are simultaneously solved as:

$$Q_1 = \frac{(C_t^1 - C_3^1)(C_2^2 - C_3^2) - (C_2^1 - C_3^1)(C_t^2 - C_3^2)}{(C_1^1 - C_3^1)(C_2^2 - C_3^2) - (C_2^1 - C_3^1)(C_1^2 - C_3^2)} Q_t$$

$$Q_2 = \frac{C_t^1 - C_3^1}{C_2^1 - C_3^1} Q_t - \frac{C_1^1 - C_3^1}{C_2^1 - C_3^1} Q_1$$

$$Q_3 = Q_t - Q_1 - Q_2$$

The relative flow fractions Q_{ro}, Q_{sw}, and Q_{gw} were solved in Excel for Minnehaha Creek samples collected upstream and downstream of Lake Hiawatha for each of hydrologic conditions represented by the sampling date summarized in the set of tables below. Note that the runoff portion (Q_{ro}) of streamflow on the June 6 recession and August 22 drought sampling dates were collected from a stormwater pond that drains to the creek, and thus represent a prolonged release of runoff that has undergone evaporative fractionation.

Storm, hydrograph peak: upstream Lake Harriet. 5/27-5/28 2012 data.

	$\delta^{18}O$	$\delta^{2}H$
Source 1, Runoff (n=2)	-4.93	-26.67
Source 2, surface water (Minnetonka, n=3)	-2.08	-27.84
Source 3, groundwater (n=12)	-9.51	-66.44
Mix, Minnehaha Creek (n=4)	-5.09	-31.36

	Fraction of total
Source 1, Runoff	**0.76**
Source 2, Surface water	**0.13**
Source 3, Groundwater	**0.11**

Storm, hydrograph peak: downstream Lake Harriet. 5/27-5/28 2012 data.

	$\delta^{18}O$	$\delta^{2}H$
Source 1, Runoff (n=2)	-4.93	-26.67
Source 2, surface water (mean, Lakes Minnetonka (n=1) & Harriet (n=1)	-2.73	-30.47
Source 3, Groundwater (n=12)	-9.58	-65.53
Mix, Minnehaha Creek (n=3)	-4.49	-30.47

	Fraction of total
Source 1, Runoff	**0.6**
Source 2, Surface water	**0.34**
Source 3, Groundwater	**0.06**

Conclusions, stormflow peak (May 27-28, 2012). Isotopic composition of creek indicates flow dominated by runoff, as would be expected following the series of storms that took place before sampling. Runoff contributions based on the isotopic composition of creek samples downstream of Lake Harriet (60%) agrees will with the runoff estimate from a baseflow filter applied to flow data collected at Hiawatha Avenue (65%). Groundwater is estimated to contribute 6 to 11% of flow in the stream.

Post-storm, hydrograph recession: upstream Lake Harriet. 6/6/2012, 9 days since last rain event		
	$\delta^{18}O$	$\delta^{2}H$
Source 1, runoff (pond, n=1)	-3.68	-22.75
Source 2, surface water (Minnetonka, n=1)	-2.08	-27.84
Source 3, Groundwater (n=12)	-9.58	-65.53
Mix, Minnehaha Creek, upstream Harriet	-3.77	-33.89
Source 1, runoff (pond)	0.20	
Source 2, surface water (Minnetonka)	0.61	
Source 3, Groundwater	0.18	
Source 3, Groundwater	0.18	

Post-storm, hydrograph recession: downstream Lake Harriet; 6/6/2012, 9 days since last rain event		
	$\delta^{18}O$	$\delta^{2}H$
Source 1, surface water (Minnetonka, n=1)	-2.08	-27.84
Source 2, surface water (Harriet, n=1)	-3.52	-33.46
Source 3, Groundwater (n=12)	-9.58	-65.53
Mix, Minnehaha Creek, downstream Harriet	-3.94	-33.89
Source 1, Minnetonka	0.11	
Source 2, Harriet	0.78	
Source 3, Groundwater	0.11	
Source 3, Groundwater	0.11	

Conclusions, hydrograph recession (June 6, 2012). Despite collection 9 days following last rainfall, creek waters still seem to retain some stormwater runoff signature. This could be water released from other surface storages (e.g., headwater wetlands). Above Lake Harriet, Minnetonka's flow contribution is similar among different end-member combinations, ranging from 60-66%. Groundwater estimates range from 10-20%. Downstream of Lake Harriet, Harriet waters are consistently a greater contributor than Minnetonka, in agreement with flow.

Drought flow, hydrograph recession: upstream Lake Harriet, 8/22/12, 7 days since last rain event (0.75 in)		
	$\delta^{18}O$	$\delta^{2}H$
Source 1, surface water (Minnetonka)	-2.10	-26.61
Source 2, runoff (pond)	-5.76	-26.67
Source 3, Groundwater	-9.33	-64.94
Mix, Minnehaha Creek, US Harriet	-2.08	-28.68
	Fraction of total	
Source 1, surface water (Minnetonka)	1.13	
Source 2, runoff (pond)	-0.16*	
Source 3, Groundwater	0.02	

Drought flow, hydrograph recession: downstream Lake Harriet, 8/22/12, 7 days since last rain event (0.75 in)		
	$\delta^{18}O$	$\delta^{2}H$
Source 1, surface water (mean, Minnetonka & Harriet)	-2.65	-29.85
Source 2, runoff (pond)	-5.76	-39.04
Source 3, Groundwater	-9.33	-64.94
Mix, Minnehaha Creek, DS Harriet	-3.32	-32.45
	Fraction of total	
Source 1, surface water (mean, Minnetonka & Harriet)	0.83	
Source 2, runoff (pond)	0.13	
Source 3, Groundwater	0.04	

*the negative value calculated for the runoff component indicates that the 3-member model is not the best fit given the data points collected. Various combinations of end-members were tried without success. Therefore, a 2-member model was applied to explain source components in creek water upstream of Lake Harriet:

2-member model, upstream Lake Harriet, 8/22/12.		$\delta^{18}O$
Source 1	Minnetonka	-2.08
Source 2	Runoff (pond)	-5.76
Source 2	Groundwater	-9.38
Mix, Minnehaha Creek, US Harriet		-2.08
		Fraction of total flow
Source 1, Minnetonka		1.00
Source 2, Groundwater		0.00
Source 1, Minnetonka		1.00
Source 2, Runoff		0.00

Conclusions, 8/22/12 drought period: Insignificant groundwater at drought-flow upstream of Lake Harriet. Although Grays Bay dam was closed two days prior, it appears that nearly all water in the channel originated from Lake Minnetonka. **Groundwater estimated to contribute < 5% of flow downstream of Lake Harriet**. Lakes Harriet and Minnetonka supply majority of baseflow.

Appendix III. Temperature-Based Approximation of Groundwater Fluxes

Groundwater flux rates were approximated based upon streambed temperature profiles using both steady state and transient models. Stallman (1965) described heat and fluid flow through a fully saturated, porous medium with the following general differential equation:

Equation 1

$$\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}+\frac{\partial^2 T}{\partial z^2}-\frac{c_w p_w}{k}\left[\frac{\partial(v_x T)}{\partial x}+\frac{\partial(v_y T)}{\partial y}+\frac{\partial(v_z T)}{\partial z}\right]=\frac{cp}{k}\frac{\partial T}{\partial t}$$

With application to groundwater flux through porous streambed material, T is the temperature at any point in time t; c is the specific heat of the sediment-water matrix; p is the density of water; k is the thermal conductivity of saturated streambed materials; v_x, v_y, and v_z are components of groundwater velocity in the x, y, and z directions; c_w is the specific heat of groundwater; p_w is the density of groundwater; and x, y, and z are Cartesian coordinates. Assuming groundwater and heat fluxes are predominantly in the vertical direction, the differential equation above may be simplified to:

Equation 2

$$\frac{\partial^2 T}{\partial z^2}-\frac{c_w p_w v_z}{k}\left[\frac{\partial T}{\partial z}\right]=\frac{cp}{k}\frac{\partial T}{\partial t}$$

Following this assumption, groundwater velocity v_z may be determined by measuring the temperature T at any depth z within the streambed and assigning typical values for parameters c_w (4.18 J $g^{-1}C^{-1}$), p_w (1x10^6 g m^{-3}), k (0.85 to 1.68 J $m^{-1}s^{-1}C^{-1}$ for saturated fine- to coarse-grained sediments, respectively), c (0.6 to 0.85 Cal $cm^{-3}C^{-1}$ for coarse to fine-grained sediments), and p (1.4x10^6 to 2.3x10^6 g m^3 for fine- to coarse-grained sediments) and applying either the steady-state or transient solutions for the differential equation. In this study, both solutions were applied; a description and example calculation for each follow.

Steady-State Solution Applied to Streambed Flux Calculations

Assuming steady-state conditions, that is, that temperature is constant with time, simplifies the solution to Equation 2 considerably as the left-hand side of the equation reduces to zero. Following the boundary conditions illustrated in Figure A2.1, Equation 2 may be solved as:

Equation 3

$$\frac{\partial^2 T}{\partial z^2}-\frac{c_w p_w v_z}{k}\left[\frac{\partial T}{\partial z}\right]=0$$

$$\frac{T_Z-T_o}{T_L-T_o}-\frac{e^{\beta(z/L)}-1}{e^{\beta}-1}=0 \quad where\ \beta=\frac{c_w p_w v_z L}{k}$$

The value of β was approximated using the numerical iterative algorithms built into Microsoft Excel Solver as demonstrated by Arriaga and Leap (2006). Groundwater velocity v_z, defined positive in the downward z direction, was determined assuming typical values of c_w, p_w, and k given the total vertical distance L over which temperature T was measured.

Steady-state solution, applied at Blake Road site in Hopkins, MN, August 15, 2013. (Vertical depth z defined positive in the downward direction.)

z (m)	T_z (C)	z/L (m/m)	β	$\frac{T_z - T_o}{T_L - T_o} = \frac{e^{\beta(z/L)} - 1}{e^{\beta} - 1}$
0	22.1	0.00		
0.25	17.2	0.38	-1.526	0
0.3	16.3	0.45	-1.684	0
0.66	13.4	1.00		

Constants	Value	Units
c_w (specific heat of groundwater)	4.18	J/g-C
p_w (density of groundwater)	1E+06	g/m3
k (streambed thermal conductivity)	0.85 to 1.62	J/m-s-C
	V_z low (k=0.85)	V_z high (k=1.62)
$V_z = \beta k/(c_w p_w L)$ where L = 0.66 m	**-4.3 cm/d**	**-8.1 cm/d**

The steady-state solution for the profile taken at this location within the Blake site indicates upward discharging groundwater on the order of -4.3 to -8.1 cm/d. This range represents upper and lower bounds for velocity based upon the expected range in thermal conductivity of streambed materials reported in the literature (Constantz et al., 2008; Stonestrom and Blasch, 2003; Stonestrom and Constantz, 2003). Though thermal conductivity of streambed sediments was not measured in this study, literature values for the sand/gravel textured sediments encountered at this site range up to 1.62 J/m-s-C, suggesting groundwater discharge rates at this site may be on the upper end of the calculated range.

Transient Solution Applied to Groundwater Flux Calculations

Steady-state solutions for all sites represent temperature profile measurements taken at a discrete point in time. At the Blake site, groundwater flux calculations based on discrete measurements were compared with temperature data recorded every 15 minutes by a data logger installed at 2 depths within the streambed (0.15 and 0.2 meters). Temperature

was also recorded just above the sediment-water interface. A transient solution to the 1-dimensional heat flux equation (Eqn. 2) was solved using these continuous temperature data to compare to steady-state approximations of groundwater flux.

Equation 2 was solved numerically following the explicit finite-difference scheme for combined convection and diffusion outlined by Gulliver (2007) and Lapham (1989):

Equation 4

$$T_i^{n+1} = \frac{k\Delta t}{pc\Delta z^2}\left(1 + \frac{p_w c_w v_z \Delta z}{2k}\right)T_{i-1}^n + \frac{k\Delta t}{pc\Delta z^2}\left(1 - \frac{p_w c_w v_z \Delta z}{2k}\right)T_{i+1}^n + \left(1 - \frac{2k\Delta t}{pc\Delta z^2}\right)T_i^n$$

where T_i^{n+1} is the temperature at node *I* at time step *n+1*, T^n_{i-1} is the temperature at node *i-1* at time step *n*, T^n_{i+1} is the temperature at node *i+1* at time step *n*, Δt is the time increment between time steps, and Δz is the spacing between nodes.

Variables p_w, c_w, k, c, and p are as defined previously. The numerical stability of the solution requires that the unitless parameter $k\Delta t/c\Delta z^2$ is less than 0.5; to fulfill this requirement, the values of Δt and Δz were set to 60 minutes and 7.5 cm, respectively.

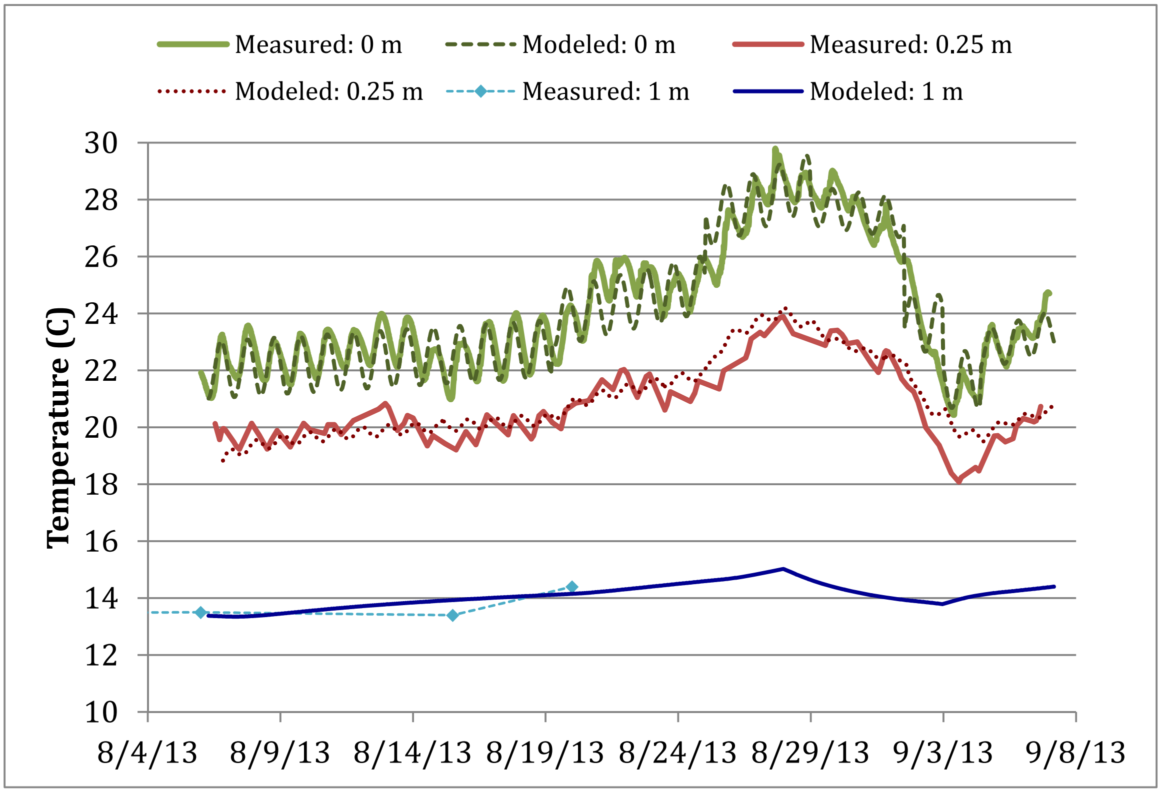


Figure A.4. Measured and modeled surface water and streambed temperatures at the Blake Cold Storage site, as approximated by solving numerically the explicit finite-difference scheme for combined convection and diffusion. Modeled curves were fit as close as possible to measured temperatures by adjusting the groundwater velocity term v_z in Equation 4 over the range of expected streambed thermal conductivities k (0.003 to 0.006 Cal $cm^{-3}C^{-1}$) . Streambed flux ranged from **1.8 to 6.1 cm day^{-1} in the upward direction** to produce the fit seen above.

Computations were carried out in Microsoft Excel. Model boundaries included the stream surface temperature, which was modeled as a sinusoidal curve fit to 15-min surface temperature measurements, and groundwater temperature at depth L (0.7 m), which was allowed to vary linearly to match weekly temperature measurements of adjacent riparian wells at the Blake site. Groundwater velocity was then approximated across the range of expected streambed thermal conductivities by adjusting the velocity term to fit the observed temperature profile. Measured and modeled temperatures are displayed in Figure A.4.

Summary: Temperature-Based Approximations of Groundwater Flux by Site and Reach

As approximated using steady-state and transient methods for solution of the differential equation describing heat flux through saturated porous media, groundwater discharge on the order of 2 to 6 cm/d (transient) or 4 to 8 cm/d (steady-state) was calculated for this site. Included in the uncertainty in the magnitude of groundwater flux is thermal conductivity of streambed sediments, which was not measured but assigned a range of expected values from the literature. Despite differences in the approaches, flux estimates overlap in range, indicating that the steady-state solution to discrete temperature probe measurements may be an adequate surrogate for more expensive continuous data required for application of transient models. In a similar comparison of methods, Arriaga and Leap (2006) found that the steady-state assumption compared favorably to fluxes obtained through transient models during a period in mid- to late summer when differences between surface and groundwater temperatures were greatest. Though continuous subsurface temperature data were not collected from any of the other sites, we believe that the direction (upward or downward) if not the magnitude of groundwater fluxes calculated by the steady state solution to numerous temperature profiles measured along the length of the creek are valid. The results of these measurements are summarized in Figure 11.

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Appendix IV. Piezometer Installation Details

Shallow monitoring wells were installed at 4 sites along the creek as described in Section 3.3. At each site, three to four 2-in diameter, PVC wells were installed in the riparian zone approximately perpendicular to flow in the creek. A plan view of piezometer locations is provided in Figure 12. The following sections provide greater detail as to piezometer installations and observed stratigraphy for each of the sites.

Jidana Wetland

All wells at the Jidana wetland site were hand-augered to a depth ranging from 3 to 5.5 ft below the surface. Vegetation at the site transitioned from cattails (edge of the channel to piezometer 2 as labled in Figure A.5.), to *Phragmites* (piezometer 1), to trees (piezometer A). All piezometers were screened in the sandy aquifer underlying up to 4 feet of organic material at the site. Piezometers were screened across the bottom-most 10-inches of the PVC pipe. The aquifer was comprised predominantly of coarse sand interspersed with gravel and small rocks (up to 3-inches in diameter). With the exception of piezometer 1, which was dry from August 2012 to March 2013, the water table remained above screened sections.

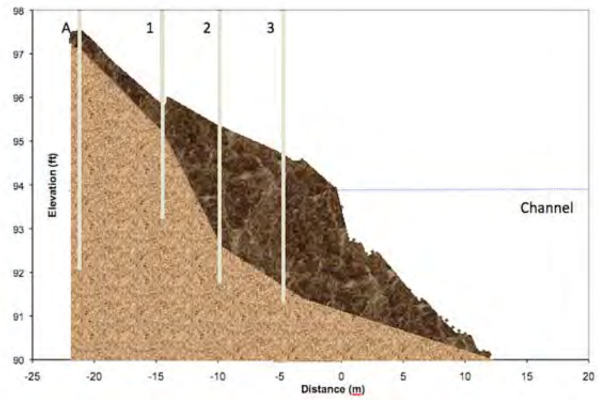

Figure A.5. Cross-section of wells installed at the Jidana wetland. The cross section is comprised of a layer of organic material (dark brown shading) up to 4-ft thick near the stream underlain by a layer of coarse sand and gravel/cobble (light brown shading) to which the 10-in screened interval at the bottom of all wells is open.

Lahti Wetland

Two sets of piezometers were installed at the Lahti wetland (Figure 12). Piezometers at the upstream end of the site were installed during the spring of 2013. Piezometers 1 and 3 were installed by hand while a drill rig was used to install piezometers 2s and 2d. Cattails were the dominant vegetation type from the channel to piezometer 1. A layer of organic material with a relatively uniform thickness of 4 to 5 ft was encountered at this site. Although at different depths (Figure A.6.), all piezometers were open to the same sand and gravel aquifer underlying the layer of organic material. An additional bore hole was augered near the location of piezometers 2s and 2d to discern the presence of any low permeability layers within the aquifer. Such a layer, consisting of silty-clay till, was encountered at a depth of 45 ft. The water table remained perched above the ground surface at all piezometers from June to early August, 2013.

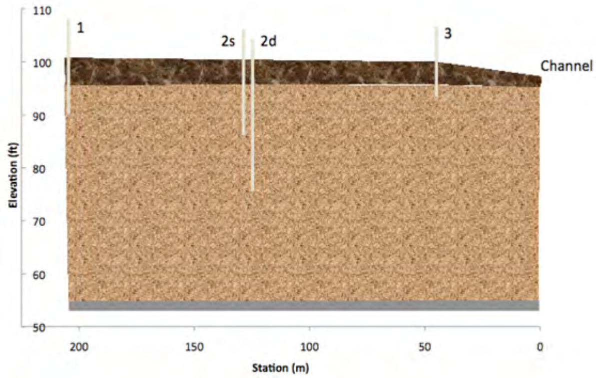

Figure A.6. Cross-section of wells installed on the upstream end of the Lahti wetland site. A relatively uniform, 4-ft thick organic layer (brown shading), overlays the sandy aquifer (light brown shading). The 10-in screened interval of all piezometers is open to the sandy aquifer. A confining sandy clay layer (dark gray shading) was encountered at a depth of about 45 ft in a boring conducted near piezometers 2s and 2d. Note that the extension of this layer across the rest of the site is assumed.

The second set of piezometers was installed approximately 1000 ft downstream (Figure A.7.) Grasses, namely *Phragmites,* were the dominant vegetation type across this site. A relatively thick (about 6 ft) organic layer was encountered immediately below the ground surface. A 10-inch screened section at the bottom of all piezometers was open to the sand and gravel aquifer underlying this organic layer. A thin clay layer was encountered between the organic and sandy aquifer at piezometers 1 and 2.

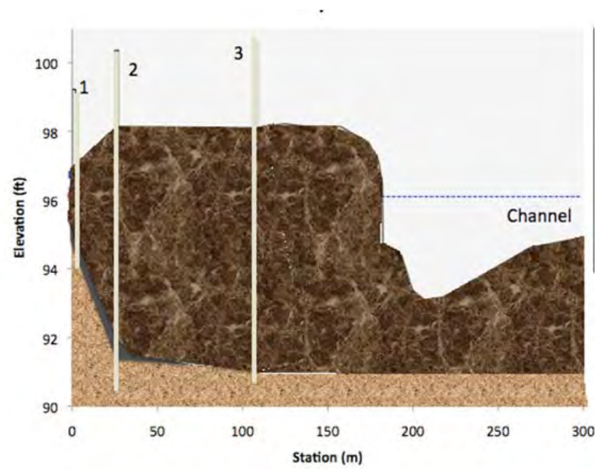

Figure A.7. Cross-section of wells installed on the downstream end of the Lahti wetland site. A thick layer (up to 6 ft) of organic soil (brown shading) overlays a layer of gleyed, silty sand (light brown shading) to which the 10-in screened interval of all piezometers is open. A thin clay layer (solid gray shading) capping the sand layer was observed at Piezometers 1 and 2. The piezometric head in piezometer 3 was greater than the ground surface throughout monitoring in 2013.

Blake Cold Storage Site

Soil characteristics within the riparian area immediately adjacent to the site were examined with a hand auger (Figure A.8.). Piezometer installation was also completed with a hand auger in July 2012. A silt layer ranging in thickness from 1 to 3 feet overlays a relatively compacted till layer (Figure A.9.) Compared to the other sites, this gravely sand layer was more difficult to penetrate with the hand auger. Additional soil explorations of the lawn area between the wooded riparian area and parking lot of the Cold Storage plant were conducted by a drill rig (Figure A.8.). Borings in the lawn area indicated the presence of a 7 to 12 ft layer of silty- to clayey- sand fill material overlying a silty-sand aquifer.

Figure A.8. Approximate locations of piezometer installations (solid red circles) within wooded riparian area of creek and soil borings completed with a drill rig (black and white circles) in the upslope lawn area.

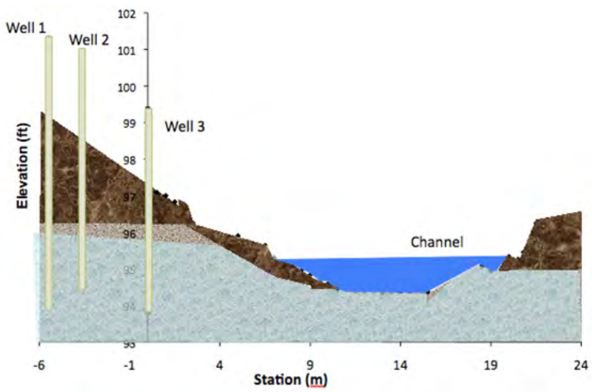

Figure A.9. Cross-section of wells installed at the Cold Storage site on Blake Road. Underlying a 1-2 foot layer of silt (dark brown shading) is a thick layer of compacted loamy sand till with large gravel and stones embedded throughout. The 10-in screened interval of all wells is open to this layer.

Utley Park

Soil stratigraphy was initially explored by hand auger during 2012 in the lawn area immediately adjacent the stream. In general, the site is overlain by about 0.5 ft of top soil, underlain by about 2 ft of compacted clay. A graveley sand layer was encountered below the clay layer; however, the diameter of gravel in this layer was too large to permit penetration with the hand auger. Due to interest in this site as a location in which groundwater may be perched, subsequent borings and piezometer installations were conducted during the spring of 2013. Figure A.10. illustrates the location and depth of piezometers relative to the stream channel. A relatively low conductivity till layer was encountered at a depth of 50 ft.

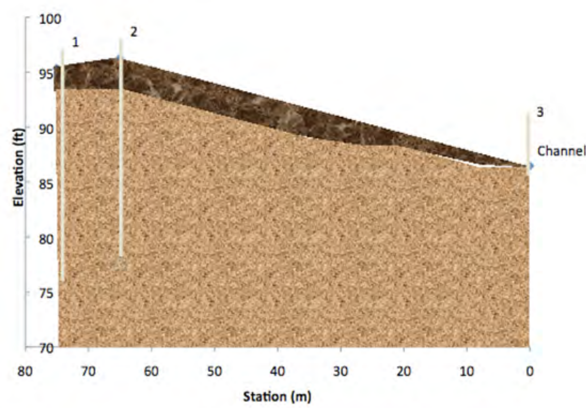

Figure A.10. Cross-section of wells installed at the Utley Park site in Edina. Underlying a 1-2 foot layer of silty-clay fill material (dark brown shading) is a thick layer of compacted loamy sand till with large gravel and stones embedded throughout. The 10-in screened interval of all wells is open to this layer.

Appendix V. Channel Width Analysis

As indicated in Section 3.4, a channel width analysis for length of Minnehaha Creek was initially completed to confirm a historic reduction in channel width due to straightening and channelization. A reduction in channel width would indicate an overall decrease in channel storage and a resulting lower baseflow. However, overall results did not indicate a large or conclusive historic decrease in channel width from 1892 and 1912 survey maps to current conditions. Results did indicate a large reduction in sinuosity due to straightening and channelization and a resulting much lower overall channel length. This finding supports an overall decrease in channel storage, but a historic decrease in channel sinuosity is the main factor, not a decreased channel width. Because of inconclusive results and inability to confirm whether channel conditions were drawn anatomically correct on survey maps, on-the-ground analysis of areas where historic channel conditions may be preserved should be conducted where possible. This would help to confirm results and/or provide representative, historic conditions for future comparisons. Specific areas where channel conditions could be preserved may include relict floodplain areas where the channel used to be present as indicated by 1892 and 1912 survey maps. Results of this analysis are presented in Table A.1.; specific locations for on-the-ground confirmation of channel width could be located through future analyses.

Table A.1. Channel width analysis results for Reaches 1-12 of Minnehaha Creek. The largest calculated channel width for each reach is indicated by the red text. The total at the bottom of the table indicates an average channel width across Reaches 1-12 for each year.

Reach	*1892-Width (ft)*	*1912-Width (ft)*	*2012-Width (ft)*
1	**37**	-	35
2	29	**43**	34
3	38	49	**80**
4	**43**	-	39
6	34	-	34
7	33	31	**34**
8	**34**	29	33
9	33	31	33
10	**38**	32	32
11	15	26	**36**
12	29	-	**33**
Total (average)	31	31	**38**

As indicated in Table A.1., historic channel width could only be confirmed for Reaches 1 through 12 due to historic survey map limitations. Current channel widths (and channel area) were calculated for all reaches for use in reach-representative groundwater fluxes.

Appendix VI. Evidence of a "Leaky" Aquifer: Darcy Flux Calculations

Annual estimates of groundwater discharge to Minnehaha Creek (0.2 to 0.3 inches per year as determined through corroboration of seepage meter measurements, temperature-based approximations, and isotope-based groundwater partitioning) is much less than annual groundwater recharge estimates of 6.7 inches per year over the watershed (Barr, 2008). We hypothesized that the difference between annual groundwater recharge and groundwater discharge to Minnehaha Creek could be attributed to leakage to the underlying bedrock aquifer system. The surficial aquifer system of the lower Minnehaha Creek watershed is underlain by a series of bedrock formations, the uppermost of which are (in order of descent) the Platteville-Glenwood-Decorah shale association, the St. Peter sandstone, and the Prairie du Chien dolomite. Low vertical conductivity units within the Platteville and St. Peter formations are believed to restrict vertical leakage from the overlying surficial aquifer (Runkel et al., 2003; Runkel et al., 2011). Therefore, to test our hypothesis we calculated leakage rates between the surficial and Prairie du Chien under the assumption that significant leakage only occurred through direct contact between these two aquifer systems. Such areas of contact underlie approximately 9% of the watershed based on Minnesota Geologic Survey mappings.

Leakage rates were calculated using the Darcy Flux approach, illustrated in Figure A.11:

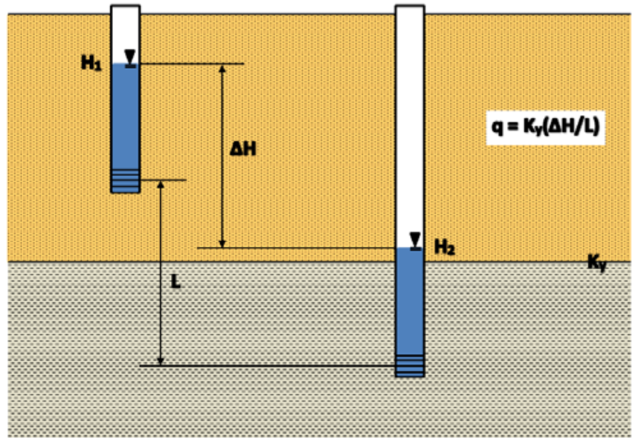

Figure A.11. Darcy flux approach used to calculate value effective k_v to supply 6.5 inches/yr leakage between the surficial and underlying Prairie du Chien aquifers in regions of the watershed where these aquifers are in direct contact.

where q = flux (in feet per day), k_z is the effective vertical hydraulic conductivity (in feet per day), h_1 and h_2 are the hydraulic head (in feet) of the surficial and Prairie du Chien aquifers, respectively, and L is the distance (in feet). Values for h_1, h_2, and L were obtained from a gridded dataset (250 x 250 m^2) developed by Tipping (2011). Using Tipping's data, the hydraulic gradient $(h_1 - h_2)/L$ was calculated for each 250 x 250 m^2 grid cell in which the surficial and Prairie du Chien aquifers are in direct contact (Figure A.12.). The effective vertical conductivity required to support a leakage rate of 6.5 in/year (0.54 ft/year) over the entire watershed (equal to 70.2 in/year over just the 9% in which the surficial and Prairie du Chien are in direct contact and assumed to permit leakage) was calculated by solving for k_v such that the sum of leakage through each grid cell highlighted in Figure A.12 summed to 70.2 in/year (5.85 ft/yr; Table A.2.). An effective k_v of 0.076 ft/d was required to meet the hypothesized leakage loss of 6.5 in/year. This value falls within the range of k_v expected for the Prairie du Chien. Thus, losses of 6.5 in/year to underlying bedrock aquifers is a plausible explanation for the lack of groundwater discharge to Minnehaha Creek.

Appendix VII. Recession analysis.

Groundwater discharge to surface waters such as Minnehaha Creek is directly related to the physical connection between the stream channel and the adjacent riparian zone and underlying shallow aquifers. Typically, the magnitude of groundwater discharge can be described in terms of the hydraulic properties of connected shallow aquifers, namely the thickness, length, and hydraulic conductivity of the saturated zone as well as the drainable porosity (or the pore volume of water removed when the aquifer is drained) of the aquifer materials. Based on the relationship between groundwater discharge (quantification of which is often simplified by setting equal to stream flow at low flow periods) and aquifer properties (generally difficult to measure), storage and transmissivity properties of the shallow aquifer can be derived based on streamflow records.

To characterize aquifer properties pertaining to groundwater discharge, we adopted the method proposed by Brutsaert and Nieber (1977) in which physical properties of the shallow aquifer system (including hydraulic conductivity, porosity, and the fraction of the watershed underlain by stream-feeding aquifers) are inferred from streamflow during drought periods. Brutsaert and Nieber's approach was derived from the nonlinear solution of the *Boussinesq* equation, and is executed by plotting the change in daily discharge against the average daily discharge for the corresponding period during flow recession:

$$(Q_i - Q_{i-1})/\Delta t = f((Q_i - Q_{i-1})/2)$$

where Q is daily streamflow ($m^3\ s^{-1}$), the subscript i refers to any time t, and $i-1$ to the time $t - \Delta t$ where Δt is equal to one day. To isolate recession flows originating from unquantified surface and groundwater sources, streamflow data were screened to remove daily flows that occurred (1) during periods in which flow was being released from Grays Bay dam, (2) within five days of rainfall (Brutsaert and Nieber, 1977), or (3) during the months in which ice formation is likely to introduce additional error to flow measurements. The resulting plot is presented in Figure A.13. A power function regression model describing storage in a non-linear aquifer was fit to the lower envelop of plotted flow data as

$$-dQ/dt = aQ^b$$

For a regression slope of b = 1.5, which has been found to adequately describe the lower envelope of the recession plot in a variety of stream settings (Brutsaert and Nieber, 1977), the regression coefficient a may be related to aquifer parameters though solution of Boussinesq's non-linear equation as

$$a = 4.8038k^2L/f(\alpha A)^{3/2}$$

where k is the aquifer hydraulic conductivity ($m\ s^{-1}$), L is the total stream and tributary length (m), f is the drainable porosity, α is the fraction of the watershed underlain by stream-feeding aquifers, and A is the watershed area (m^2).
The regression model of the power function describing storage in a non-linear aquifer that was fit to the lower envelop of plotted flow data is displayed in Figure A.13. This lower envelope is taken taken to be representative of groundwater-fed base flow. Based on known values of the watershed area ($130x10^6\ m^2$) and stream length (50,000 m), and the expected range of values of

hydraulic conductivity *k* ($1.7x10^{-4}$ m s^{-1}) and porosity (0.05 to 0.1) from existing surficial mappings, the contributing aquifer must represent a small fraction of the total watershed area (about 5%) to satisfy resulting regression coefficients. For perspective, this area amounts to an approximately 250-ft wide buffer on either side of the creek. That the contributing aquifer system is likely small is in accordance with the rapid vertical travel through the quaternary aquifer system calculated by Tipping (2011).

The aquifer parameters obtained through the Brutsaert and Nieber approach can be used to estimate transmissivity and storage characteristics of the aquifer. Following Brutsaert (2005), the effective hydraulic transmissivity of the creek's aquifer system can be estimated as $T_e=kpD$ where *k* (saturated hydraulic conductivity) and *pD* (saturated thickness of the aquifer multiplied by the constant *p*) were determined through the Brutsaert and Nieber analysis (50 ft d^{-1} and 21 ft for *k* and *pD*, respectively). These values yield an effective aquifer transmissivity of 1050 ft^2 day^{-1}. This value falls between transmissivity test values of 242 and 3108 ft^2 d^{-1} obtained from 2 wells located adjacent to the creek near the Schloff Chemical site in St. Louis Park (Section IV.F.) compiled by Tipping (2011).

Aquifer storage, or the volume of water per unit area stored in the aquifer, can be estimated through this method.

References

Brutsaert, W., 2008. Hydrology, An Introduction, Cambridge University Press,

Brutsaert, W., Nieber, J.L. 1977. Regionalized drought flow hydrographs from a mature glaciated plateau. *Water Resour Res* 13(3): 627-642.

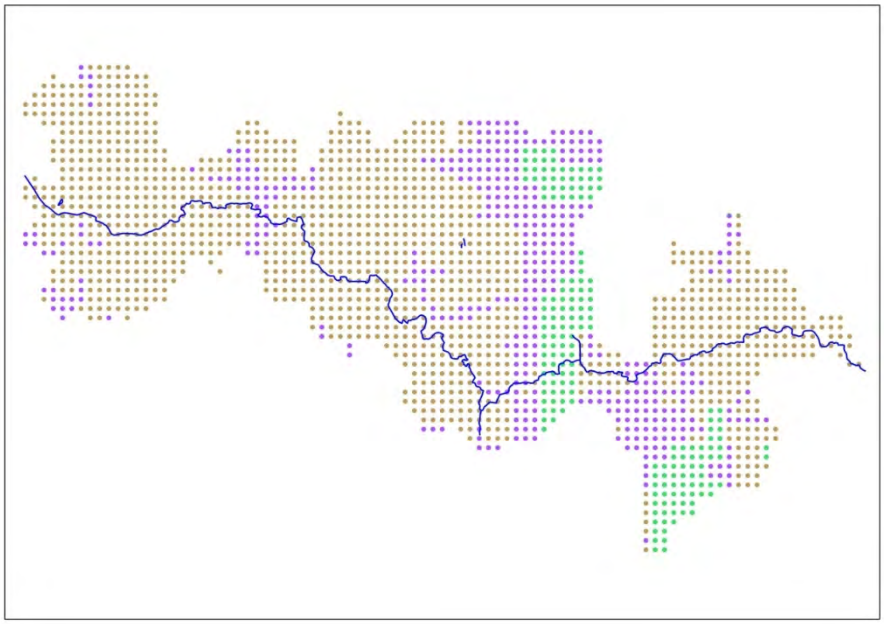

Figure A12. Map depicting gridded data points developed by Tipping (2011) from which hydraulic gradient $(h_1 - h_2)/L$ was calculated. Green points denote grid cells for with the surficial and Prairie du Chien aquifers are in direct contact. Vertical leakage through points where the surficial aquifer is in direct contact with the St. Peter (purple) or Platteville-Glenwood-Decorah shale formations (brown) are assumed to be minimal.

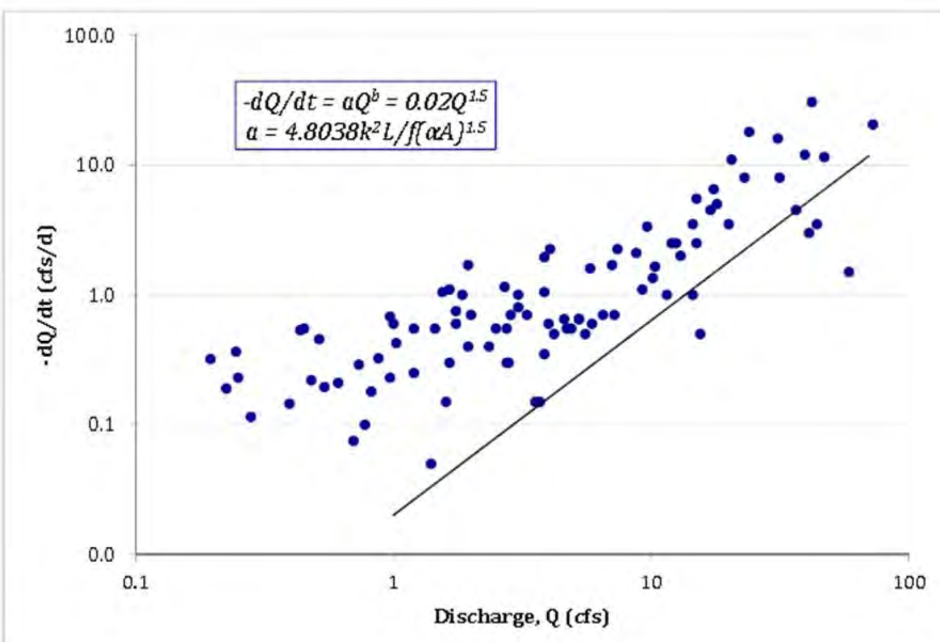

Figure A.13**.** Change in daily discharge (*-dQ/dt*) versus discharge for drought flows at Hiawatha Avenue. The coeffients *a* and *b* are determined from the line fitted to the lower envelop of flows, assumed representative of groundwater-fed base flow. Based on watershed area *A*, streamlength *L*, and value of regression coefficient *a*, aquifer properties for hydraulic conductivity *k*, drainable porosity *f*, and fraction of stream-feeding aquifer *α* may be approximated.

Table A.2. Example data set used to calculate required effective k_v based on hydraulic gradient as calculated for 180, 250 x 250 m^2 grid cells (representing the 9.2% of the lower watershed in which the surficial and Prairie du Chien aquifers are in direct contact) from hydraulic head and distance values provided by Tipping (2011)

Cell	h_1 (ft)	h_2 (ft)	L (ft)	dH/L (ft/ft)	Kv_interface (ft/d)	Darcy flux, q ft/d	in/yr	Volume ft3/yr
1	811.1	746.7	153	0.421	0.076	0.032	140.2	7856984
2	810.0	745.3	199	0.325	0.076	0.025	108.3	6073426
3	811.0	749.3	143	0.431	0.076	0.033	143.6	8048920
4	810.0	748.0	174	0.356	0.076	0.027	118.5	6643759
5	810.9	751.0	142	0.421	0.076	0.032	140.3	7865209
6	809.4	750.2	168	0.353	0.076	0.027	117.4	6579725
7	811.6	752.7	151	0.390	0.076	0.030	129.9	7279712
8	811.4	751.9	177	0.336	0.076	0.026	112.0	6277093
9	812.1	751.1	216	0.282	0.076	0.021	94.0	5270860
	□	□	□	□	□	□	□	□
	□	□	□	□	□	□	□	□
	□	□	□	□	□	□	□	□
180	812.1	751.1	216	0.282	0.076	0.021	94.0	5270860
SUM (ft^3/yr), between PdC and surficial aquifer (9.2% watershed)								708231504.7
SUM (in/yr), between PdC and surficial aquifer (9.2% watershed)								70.2
SUM (in/yr), net leakage over entire watershed (100%)								**6.5**