Karst Hydrogeologic Investigation of Trout Brook, Dakota County, Minnesota

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Above Image: Taken from *Walk-Through of the 2005 Miesville Ravine Park Reserve Master Plan*

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Executive Summary

Trout Brook is a trout stream in Dakota County's Miesville Ravine Park Reserve. An MPCA survey found Trout Brook to have the highest baseflow nitrate concentrations in southeastern Minnesota's karst region. This project investigated the karst hydrogeology and water quality in Trout Brook's water and to gain information on the source and movement of nitrates through the landscape. This investigation located springs, stream sinks, sinkholes, and other karst phenomena in the Trout Brook watershed. We conducted synoptic surveys of the stream and spring flows. Periodic water samples were collected and analyzed to document nitrate and chloride/bromide ratio time trends. Two dye traces were conducted initiating springshed mapping for the springs. Temperature dataloggers were used to obtain 7.5 months of continuous temperature records from two springs. This study combined existing, historic data from 1985 and 1995 with our 2011-2012 results to quantify nitrate time trends for four springs. Data from the 2001, 2002, 2006, and 2010 Dakota SWCD surveys, combined with our 2011-2012 results, permitted documentation of shorter-term time trends for three points in the surface streams. The study period 2011-2012 was a very dry period but significant floods occurred on 6 May 2012 and 14 -15 June 2012.

Our stream and spring flow measurements indicate that 30-40 percent of the water in Trout Brook is from identified discrete springs. As surface runoff contributes to Trout Brook steam flow only during and immediately after major precipitation events, distributed groundwater discharge into the stream channel therefore makes up 60-70 percent of the baseflow.

Nitrate concentrations ranged from about 9 ppm in springs near the downstream end of Trout Brook to over 25 ppm at the upstream springs in the West Branch of Trout Brook. Chloride/ bromide ratios decreased systematically from the upstream springs to the downstream springs. The nitrate concentrations in four of the springs increased at rates ranging from 0.42 to 0.11 ppm/year from 1985 to 2012. The nitrate concentrations at one upstream site, and the downstream surface water sampling points, have increased at similar rates from 2001 to 2012. The nitrate concentration at another upstream surface water sampling point increased from 2001 to 2006 but decreased from 2006 to 2012.

Runoff from a 29 February 2012 winter rain event was sampled on 2 March from two small sub-watersheds along the East Branch of Trout Brook. Runoff from a sub-watershed containing only forest and CRP land contained no detectable nitrate. Runoff from a sub-watershed that was 40 percent row-crop land contained 10.6 ppm nitrate.

Dye tracing documented karst aquifer flow-paths from Weber Sieve to LeDuc and Bridgestone Springs with flow velocities in the range of 15 to 40 meters per day. The temperature logging at Fox and Swede Springs shows small temperature fluctuations apparently due to air temperature cooling and warming immediately near the spring orifices with superimposed larger temperature fluctuations due to surface runoff flooding of the springs.

The results of this study indicate that row-crop agriculture in the surface and subsurface drainage basins of Trout Brook is the primary cause of the water's elevated concentrations of nitrate. This conclusion is supported by the MPCA's correlation between the percentages of row-crop agriculture and the nitrate concentrations in run-off and stream samples.

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List of Acronyms and Abbreviations

ADV	**Acoustic Doppler Velocimeter**
ArcGIS®, ArcMap®	**geographic information system / product, by ESRI**
°C	**degrees Celsius**
cfs	**cubic feet per second**
CST	**Central Standard Time**
DNR	**Department of Natural Resources**
EPA	**Environmental Protection Agency**
HANS	**Hastings Area Nitrate Study**
HTZ	**high transmissivity zone**
GPS	**Global Positioning System**
GIS	**Geographic Information Systems**
LCCMR	**Legislative Citizen Commission on Minnesota Resources**
l/s	**liters per second**
LTC	**Level/Temperature/Conductivity (as part of brand**
MDA	**Minnesota Department of Agriculture**
MPCA	**Minnesota Pollution Control Agency**
MPRB	**Minneapolis Parks and Recreation Board**
N	**nitrogen**
nm	**nanometers**
NPDES	**National Pollution Discharge Elimination System**
ppm	**parts per million**
R^2	**coefficient of determination**
σ or SE	**standard error**
SWCD	**Soil and Water Conservation District**
TMDL	**Total Maximum Daily Load**

1. Abstract

Trout Brook in the Miesville Ravine County Park of Dakota County is the trout stream with the highest nitrate concentration in the karst region of southeastern Minnesota. Water quality data from 1985 and 1995 (Spong, 1995) and from 2001, 2002, 2006 and 2010 by the Dakota County Soil and Water Conservation District (SWCD) (2010) document an increasing level of nitrate in Trout Brook. A karst hydrogeologic investigation was designed to measure nitrate levels at sampling points along the stream and to increase our understanding of the source and movement of nitrates throughout the length of Trout Brook. Eighteen springs and seeps have been located in the Main Branch and tributaries of Trout Brook. A previously unreported flowing section and stream sieve, Weber Sieve, were found above what had been thought to be the head of perennial flow in the East Branch of Trout Brook. Two new sinkholes developed after the 14-15 June 2012 flood in a field northeast of the East Branch of Trout Brook. This investigation included regular monitoring of major anions in the streams and springs, synoptic stream flow measurements, a dye trace of a sinking stream in the Trout Brook drainage, and continuous temperature monitoring at two springs.

The initial assumption was that the majority of the baseflow of Trout Brook was from discrete springs. However, synoptic baseflow and nitrate measurements show that only 30-40 percent of the total flow in Trout Brook is from discrete springs, and the rest appears to be from distributed groundwater discharge directly into the stream. Both the discrete springs and the distributed recharge occur along reaches of Trout Brook that drain the significant high transmissivity zone near the bottom of the regionally important Shakopee aquifer. Dye traces have confirmed flow-paths from Weber Sieve to LeDuc and Bridgestone Springs and have begun to define springsheds for these head water springs. The temperatures of two springs were monitored for 7.5 months. The observed small, seasonal temperature fluctuations at the springs seem to be due to the air temperature while storms that result in flooding and surface runoff cause larger, short-term temperature fluctuations.

Nitrate concentrations and chloride/bromide ratios decreased systematically from the upstream springs to the downstream springs. The nitrate concentrations have been increasing at four springs from 1985 to 2012 and at two surface sampling points from 2001 to 2012. The nitrate concentration of another surface sampling point increased from 2001 to 2006 but decreased from 2006 to 2012. Snowmelt and rainfall runoff was sampled on 2 March 2012 and showed no detectable nitrate in the runoff from a watershed with no row-crop agriculture, but elevated nitrate was detected in an adjacent watershed with row-crop agriculture. All of these trends illustrate the dominance of agricultural sources of nitrate in Trout Brook.

2. Introduction

2.1 Karst: Complex surface and groundwater interactions are dominated by karst processes in southeastern Minnesota. Karst features often include caves, sinkholes, springs, stream sieves, and sinking streams. A stream sieve describes a losing reach of a surface stream where specific water sinking points, stream sinks, are not evident. Karst features result from water containing carbonic acid which dissolves the carbonate in soluble bedrock. Water quality is a concern because karst features allow rapid groundwater velocities and short residence times. Karst springs provide the source water to premier trout streams in southeastern Minnesota. Trout Brook in the Miesville Ravine Park Reserve in southeast Dakota County and south of Miesville, Minnesota is one of these trout streams.

2.2 Nitrate: Reactive nitrogen is an environmental concern. Reactive nitrogen can lead to eutrophication, toxic algae blooms, and hypoxia in the hydrosphere and to acid rain, deposition of nitrogen in forests leading to nitrogen saturation which can alter the soil, and global warming in the atmosphere. Reactive nitrogen can also be harmful to humans due to air pollution and contamination of drinking water. The U.S. Environmental Protection Agency (EPA) reports that greater than 10 ppm of nitrate–nitrogen in drinking water can have adverse health effects (U.S. EPA, 1990). (In the rest of this work, the word “nitrate” is synonymous with “nitrate-nitrogen”.)

The Hastings Area Nitrate Study (HANS, 2003) was carried out in Dakota County, MN near our study area. That study highlights the nitrate contamination problem in groundwater and considers three possible sources: row-crop agriculture, feedlots, and septic systems. The nitrate levels varied among the aquifers. The Shakopee aquifer had the highest concentration of nitrate at 15 ppm, the Quaternary aquifer was next at 8.7 ppm, and the Jordan aquifer had the lowest at 1.85 ppm. This data was collected in 2000 and is already twelve years old.

Modern row-crop agriculture requires fertilizer to meet yield goals, based on the demand for food and energy and modern farming economics. Fertilizer application has been increasing in the last half of the 20th century throughout the United States of America. The report by the Science Advisory Board (U.S. EPA, 2011) explains how some farmers gamble on nitrogen application because there could be only one to two years out of five when weather conditions actually support corn production at these yield goals. The economic incentive of having a good yield on those favorable years is high. Many farmers apply excess nitrogen for this reason (U.S. EPA, 2011). If all of the nitrogen is not utilized by the crops then there is a great possibility that it will be transported into the aquifers.

The Minnesota Department of Agriculture (Bierman et al., 2011) surveyed Minnesota farmers about fertilizer application. This study reports that 59 percent of farmers applied nitrogen during the spring season, 32.5 percent applied nitrogen during the fall, and 9 percent applied nitrogen beside the row after the plants emerged. The longest period between crop uptake and application is in the fall. Application during this season poses the greatest risk of nitrogen loss. The survey also reports that nitrogen application is greater on irrigated corn than the rate applied by all surveyed farmers in Minnesota. The survey states, “An important conclusion from the survey data is that N fertilizer use by Minnesota corn farmers is generally consistent with University of Minnesota Extension N management guidelines (Bierman et al., 2011).”

The main land use type in the Trout Brook watershed is row-crop agriculture, and many farmers irrigate their crops due to the sandy soil. There are livestock feedlots in the watershed, which are also potentially significant sources of nitrate. On a mass loading basis, nitrogen fertilizer and animal waste are the primary causes of elevated nitrate levels at the springs and streams of Trout Brook. The information from the HANS study, the EPA document, and the MDA survey support this conclusion.

2.3 Location, Geology, and Topography: Trout Brook is located in the southeastern part of Douglas Township (T113N, R17W) of Dakota County, south of Miesville, Minnesota in the Miesville Ravine County Park. The area is underlain by a thin cover of flood plain alluvium, colluvium and Illinoian glacial outwash, loess and till (Hobbs et al., 1990). The glacial sediments rest unconformably on the lower Ordovician Shakopee Formation of the Prairie du Chien Group (Mossler, 1990). The Shakopee Formation is a mixture of limestone and dolomite with the New Richmond Sandstone near the bottom of the formation. The Shakopee Formation unconformably overlies the Oneota Dolomite.

The Shakopee and Oneota Dolomite collectively form the Prairie du Chien aquifer, which is one of the most heavily used aquifers in Dakota County. An unconformity between these two formations represents a 10 million year subaerial erosion episode which left a high transmissivity zone (HTZ) of greatly enhanced porosity and permeability in the top of the Oneota. During and after the deposition of the Shakopee, karst solution processes expanded the HTZ up into the lower Shakopee. Runkel et al., (2003) and Tipping et al., (2006) report that this mid-Prairie du Chien HTZ is one of the primary features of the hydrostratigraphy of southeastern Minnesota. The source water for Trout Brook drains directly from this high transmissivity zone along bedding plane fractures, and through solutionally enlarged porosity and permeability and anastomosing karst conduits.

The Trout Brook surface watershed is largely an intensively cultivated gently rolling upland. Very little surface water flows on the upland except during spring snowmelt and after the largest and most intense precipitation events. Most routine precipitation not consumed by evapotranspiration rapidly infiltrates to groundwater. South of Meisville the surface drainage abruptly incises steep-sided valleys to form the West and East Branches of Trout Brook. The East and West Branches join to form the Main Branch of Trout Brook in the Miesville Ravine Reserve Dakota County Park. The lower reaches of both branches of Trout Brook and the Main Branch are widening downstream. All branches of Trout Brook meander across steep-sided flat-bottomed valleys.

2.4 Historical: Ron C. Spong studied Trout Brook, Dakota County, in 1985 and 1995. He analyzed water chemistry at four springs (Beaver, LeDuc, Fox, and Swede Springs) in 1985 and two springs in 1995 (LeDuc and Swede Springs). The two sampling events in 1985 and 1995 were collected during baseflow periods (with no significant stormflow) in years with normal precipitation (Spong, written communication, 2012). He also measured the flows at the springs and streams of Trout Brook in 1985 (Spong, 1995). This data is important because it documents water quality of these springs 27 and 17 years ago. Those data points are critical in defining water quality time trends.

The Dakota County SWCD measured baseflow and obtained grab samples during storm events at Trout Brook during 2001, 2002, 2006, and 2010. Flow measurements were taken to characterize low flow and stormflow. The water samples were analyzed for typical water quality parameters and were reported to the State of Minnesota. Automated stage monitoring was also in place, but the data is suspect due to the flashy nature of this stream (Dakota Co. SWCD, 2010).

Water quality samples are not usually collected at springs due to the inconvenience of remote locations and financial constraints of monitoring programs. Springs provide water to streams and rivers. A springshed is the subsurface and surface areas that provide the discharge to a spring. A karst springshed is often different than the surface watershed. A stream is a collection of water from across an entire surface watershed, and groundwater that discharges into the stream. The source of the groundwater is often quite different from the surface watershed. The water quality of a spring provides useful information on its source water that might not be recognizable in a stream.

2.5 Row-Crop Agriculture versus Nitrate: Figure 1 from Watkins (2011) shows the percent of row-crop agriculture plotted against nitrate plus nitrite in streams at baseflow in the karst region of southeastern Minnesota. Groundwater discharge supports the baseflow of streams and rivers in this karst region and discrete springs typically provide a substantial portion.

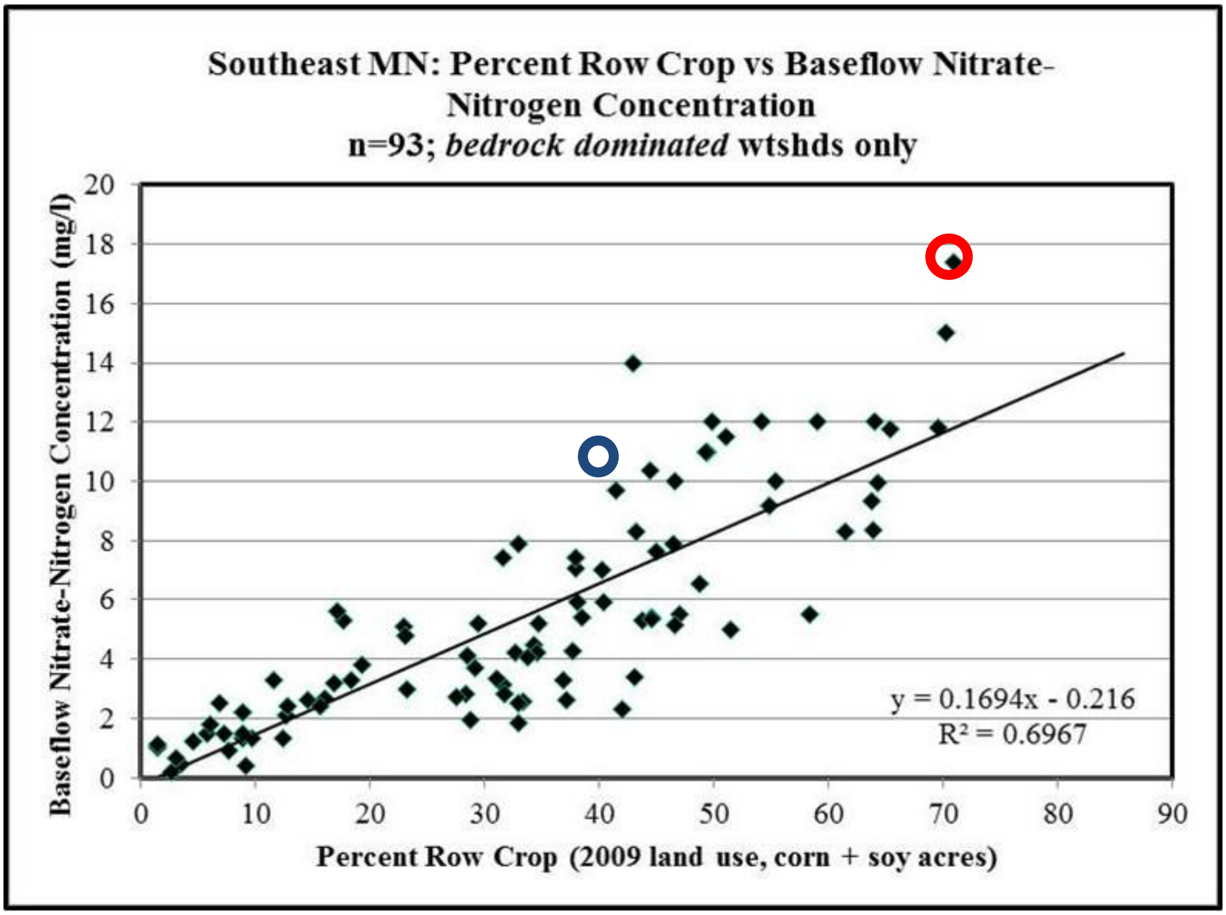


Figure 1: Baseflow nitrate-nitrogen concentration as a function of the percentages of row crop agriculture in the karst region of southeastern Minnesota. The data point from Trout Brook is circled in red. The blue circle illustrates where the 2 March 2012 runoff from the Trout Brook watershed would plot. (With permission from Justin Watkins, MPCA, 2011)

A linear relationship is present with an R² value of 0.70. This indicates a strong relationship between the percentages of row-crop agriculture in watersheds versus the nitrate concentrations in streams at baseflow. The data point from Trout Brook can be seen on **Figure 1** with the red circle around it. Trout Brook was selected for study because it has the highest nitrate concentration at baseflow of monitored streams in southeastern Minnesota.

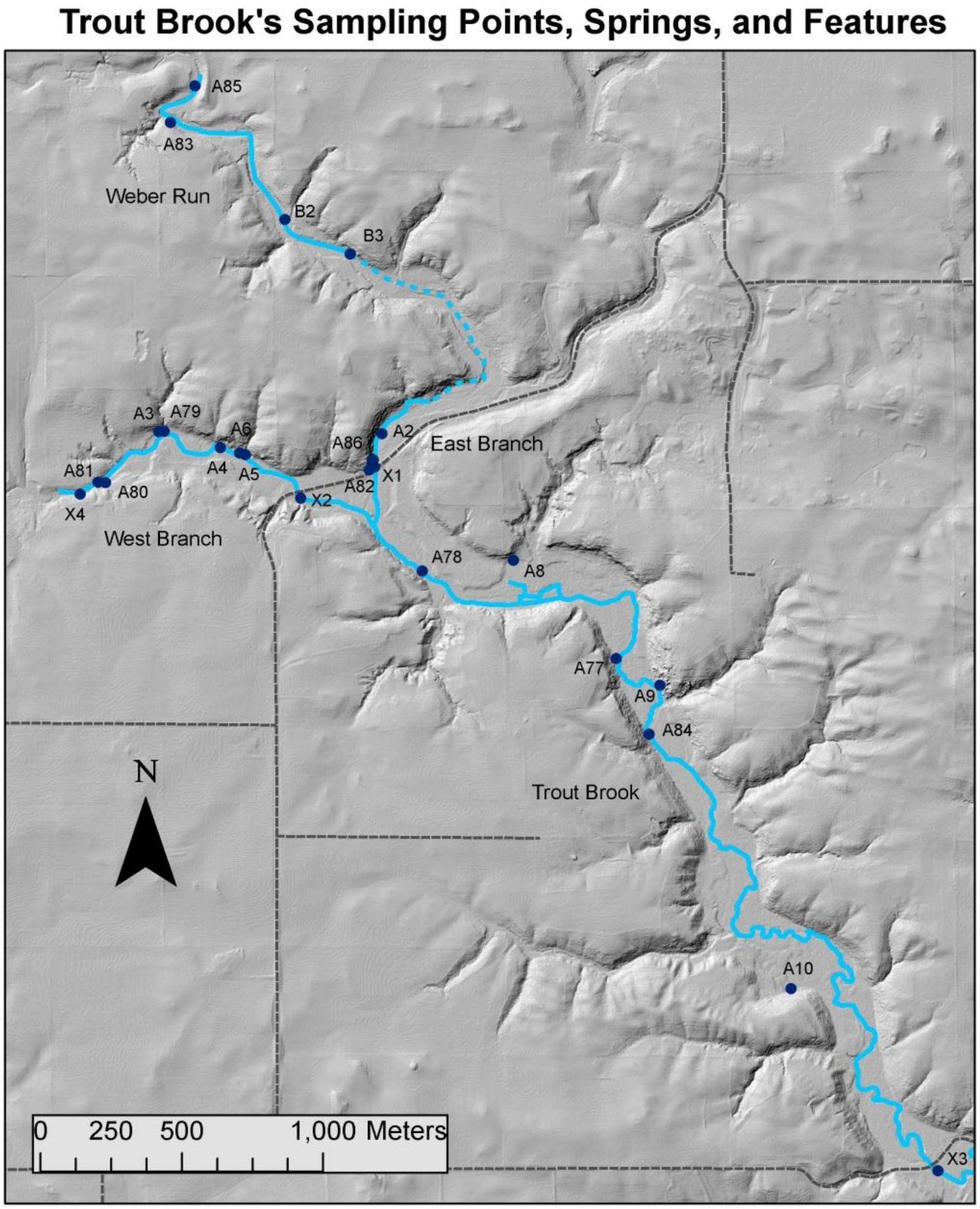


Figure 2: Trout Brook is located in the SE portion of Douglas Township, Dakota County, Minnesota. A 2008 LiDAR shaded relief DEM is the base. Light blue lines denote perennial running water: Weber Run, the East and West Branches of Upper Trout Brook, and the Main Branch of Trout Brook. Light blue dashes denote an ephemeral reach. Dark blue dots show: A#s = springs, B#s = stream sieves, X#s = surface water sampling stations and other features. Dashed gray lines denote roads.

3. Monitoring

3.1 Recent Work: In an initial survey of Trout Brook in February 2011, springs were located, geochemistry samples were gathered, and coordinates were obtained with a global positioning system (GPS). A second round of sampling occurred in July 2011. A systematic water sampling campaign began in October 2011 and ended in October 2012. Certain springs were sampled more often due to cost, accessibility, and interest, providing larger data sets. A map of the sampling points, springs, and other features can be seen on **Figure 2**.

The eighteen discrete springs documented along Trout Brook are shown in Figure 2. The names, identification numbers, location coordinates, and other properties of the springs are listed in **Table 2** (See **Appendix I**). All of the springs emerge where the steep valley walls meet the flat valley floor. All but two of the springs, Beaver and Swede, emerge where Trout Brook has meandered up against the base of the valley walls. Beaver and Swede are buffered from Trout Brook by beaver dam induced wetlands.

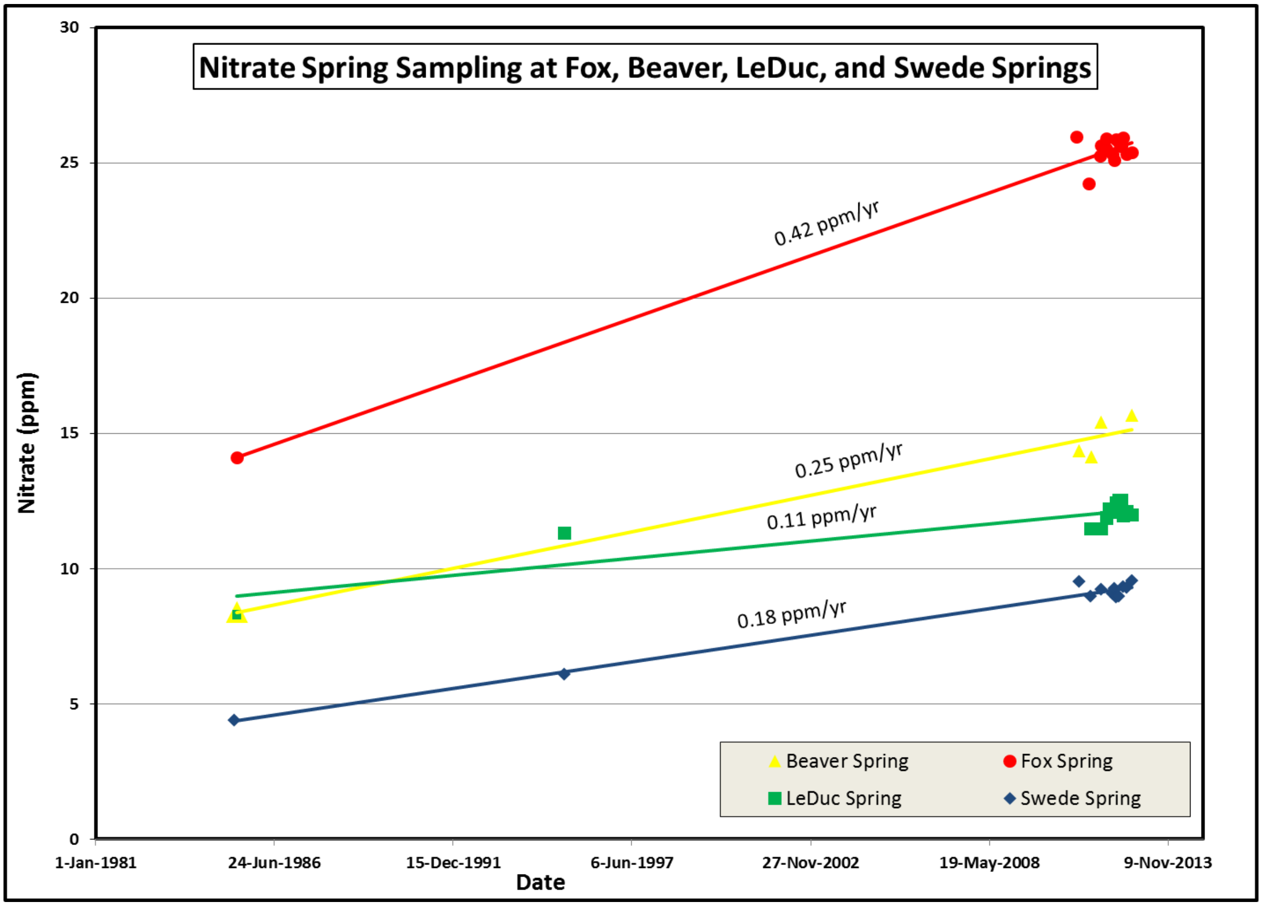


Figure 3: Nitrate concentration is a function of time at four springs: Fox (A3), Swede (A10), Beaver (A8), and LeDuc (A2) Springs (see Figure 2). These four springs were sampled in 1985, 1995, 2011, and 2012 (except that Fox and Beaver Springs were not sampled in 1995). Multiple samples were collected at these four springs between 2011 and 2012. The 1985 and 1995 samples were collected by Spong; the 2011-2012 samples were collected by Groten and Alexander.

3.2 Geochemistry

3.2.1 Methods: The field and analytical methods used in this work are described in Alexander and Alexander (2011).

3.2.2 Nitrate Concentration at the Springs of Trout Brook: The nitrate concentrations at Fox, LeDuc, Beaver, and Swede Spring have been increasing with time (See **Figure 3**). These four springs are labeled A3, A2, A8, and A10, respectively, on **Figure 2**. The nitrate concentration of Fox Spring is increasing at the greatest rate of 0.42 ppm/year while the concentrations at Beaver, Swede, and LeDuc Springs are increasing at rates of 0.25, 0.18, and 0.11 ppm/year, respectively. These rates were calculated over a 27 year span. The rate of increase for Fox Spring is almost twice as great as the next highest rate, that of Beaver Spring. These increases are likely due to changes in farming practices over time and the intensity of farming on the contributing springsheds.

Figure 4 shows the concentrations of these four springs compared to the other springs in Trout Brook as color-coded dots. The springs discharging into the West Branch of Upper Trout Brook have the highest nitrate levels. The springs discharging into the East Branch of Upper Trout Brook have low to moderate nitrate levels. The three yellow dots on the Main Branch indicate moderate nitrate levels and the springs further downstream have the lowest nitrate levels.

The nitrate concentrations at springs appear to be controlled by location. This relationship is likely determined by the springshed of each spring. The springs further downstream probably involve longer flowpaths draining deeper parts of the aquifers. The contributing springsheds probably vary substantially by different types and percentages of land use.

3.2.3 Nitrate Concentrations of the Streams of Trout Brook: Figure 5 shows the nitrate concentrations at baseflow in the East, West, and Main Branches of Trout Brook. The West Branch [as represented by the results of sample TB2 (X2)] is increasing at the greatest rate of 0.35 ppm/year. From 2001-2006 the East Branch [represented by the sample TB1 (X1)] was increasing at a rate of 0.11 ppm/year; however, the rate decreased from 2006-2012. The scope of this study did not include further analysis of this phenomenon. The Main Branch [as represented by sample TB3 (X3)] was collected the furthest downstream and had a nitrate increase of 0.09 ppm/year. The TB3 (X3) sample near the end of the Main Branch is a collection of all the water mixing from surface water and groundwater, derived from baseflow and runoff events. At baseflow that water is entirely a variable mixture of discrete spring flow and distributed groundwater discharge. There is no significant surface runoff to Trout Brook during baseflow.

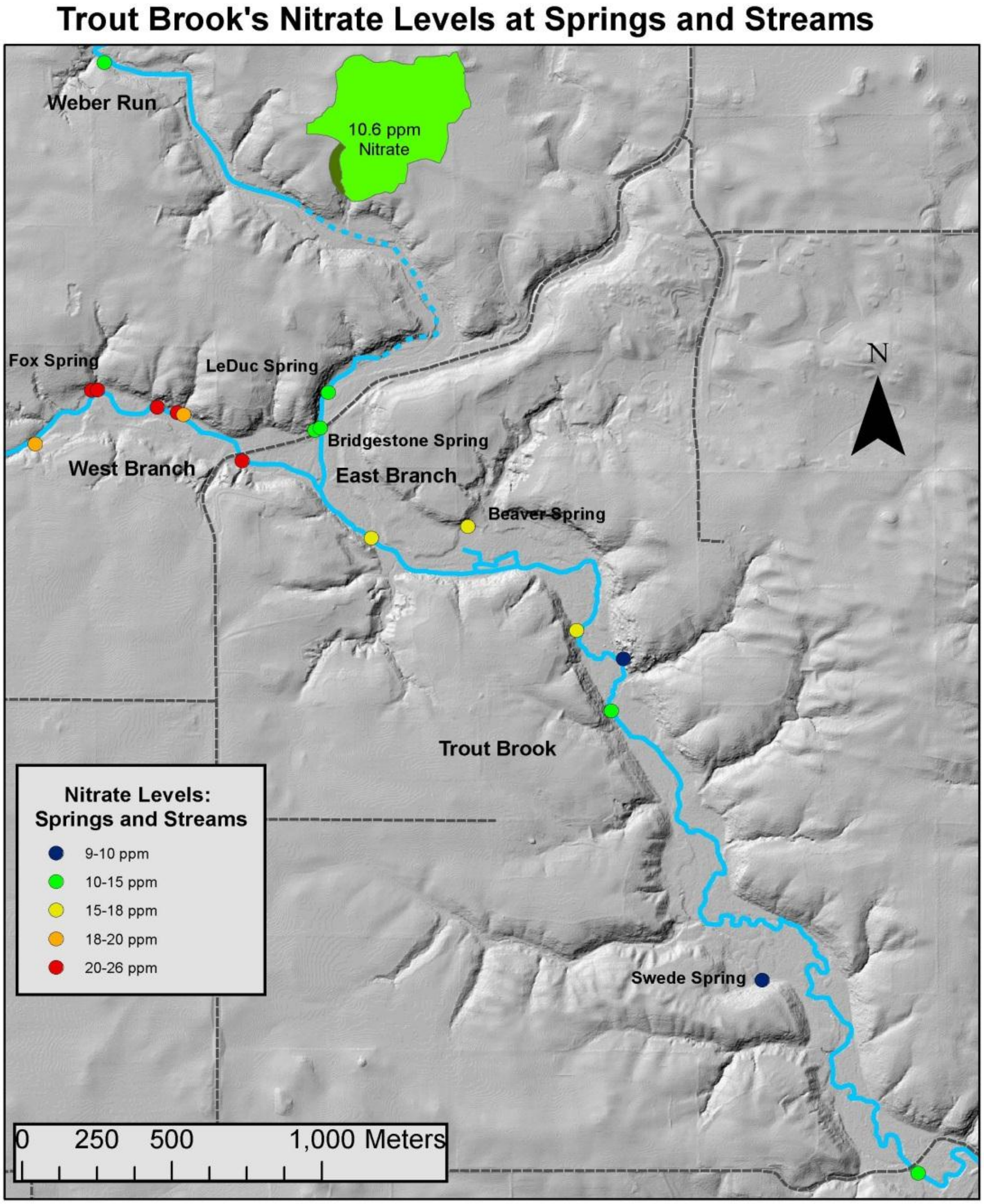


Figure 4: Nitrate levels in the springs and monitoring points of Trout Brook.) The colored dots correspond to a range of nitrate levels at springs and sites along the stream segments. (The base and other features are the same as in Figure 2.) Data are 2011-2012 averages. The lighter green watershed labeled 10.6 ppm shows the nitrate concentration in a 2 March 2012 runoff event and is enlarged in Figure 9.

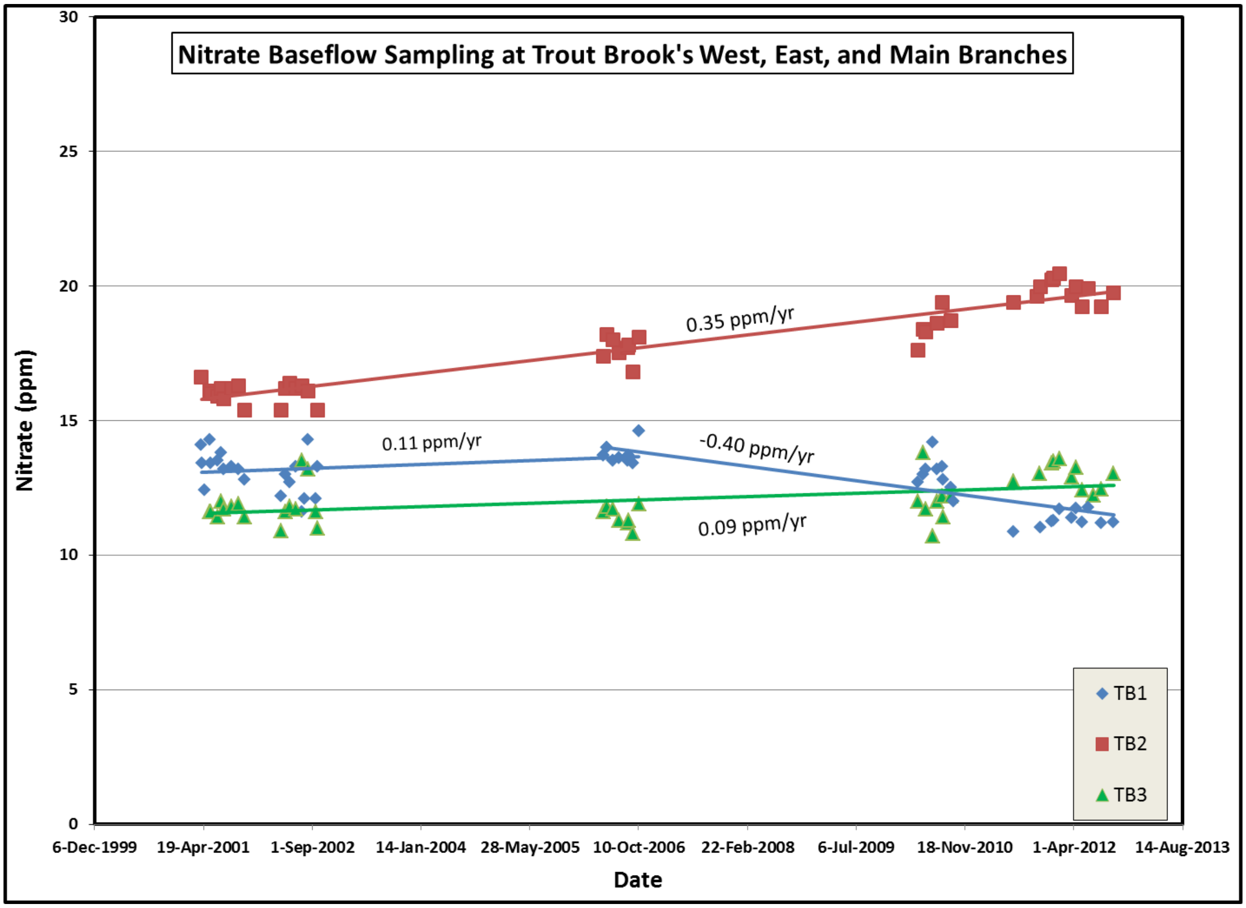


Figure 5: Nitrate baseflow concentration is a function of time at the Main Branch of Trout Brook and its tributaries. Samples were collected at the bridge crossings labeled TB1 (X1), TB2 (X2), and TB3 (X3), shown on Figure 2 and in Tables 1 and 2 (in Appendix I). Samples were collected from 2001-2002, 2006, and 2010 by Dakota County Soil and Water Conservation District and from 2011-2012 in this work.

Figure 6 shows the nitrate concentrations at Trout Brook's East, West, and Main Branches during stormflow and baseflow. Stormflow, dominated by surface runoff, typically contains much less nitrate than does baseflow. Some of the nitrate concentrations are much less than the ones at baseflow because sampling campaigns often target stormflow samples, as they are used to calculate loading for Total Maximum Daily Load (TMDL) studies and regulations.

Rainwater has a low nitrate concentration. Rainfall events dilute the nitrate concentration in the streams because of surface runoff and interception by the stream channel. It is important to sample springs and streams at baseflow to understand the nitrate concentrations from the contributing springsheds and watersheds.

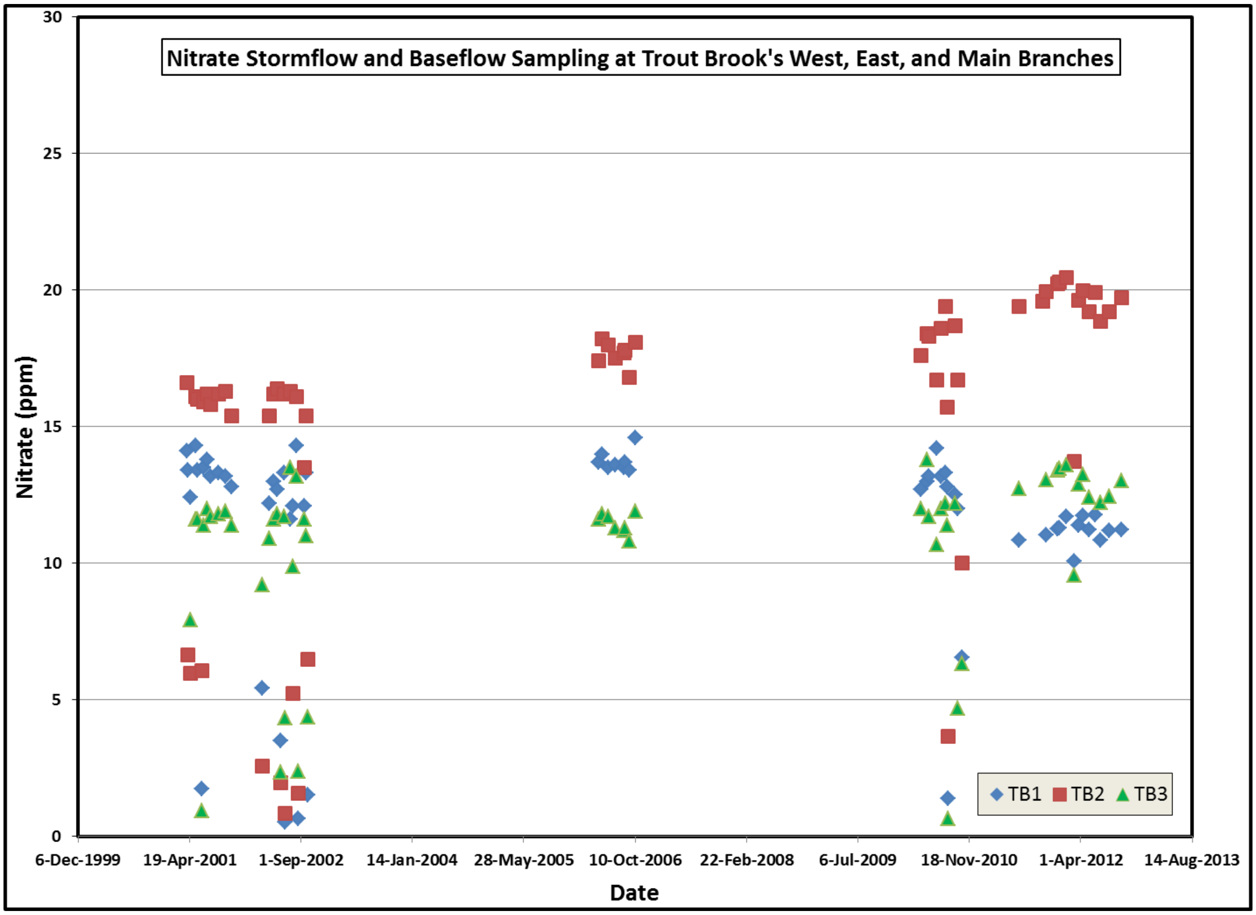


Figure 6: Nitrate baseflow and stormflow concentration are a function of time at the Main Branch of Trout Brook and its tributaries. Samples were collected at the bridge crossings labeled TB1 (X1), TB2 (X2), and TB3 (X3) - as shown on Figure 2. Samples were collected from 2001-2002, 2006, and 2010 by Dakota County Soil and Water Conservation District and from this work.

3.2.4 Chloride/Bromide Ratios: Chloride/bromide ratios are useful in groundwater studies because chloride and bromide are conservative anions that travel with the groundwater and can be used to identify the source water that is recharging the aquifer. Chloride/bromide ratios provide indications of anthropogenic impacts on waters and are explained further by Anger and Alexander (2010).

The chloride/bromide ratios of Trout Brook's springs and streams on **Figure 7** are averaged values from samples collected from 2011 to 2012. The figure also shows the discrete chloride/bromide ratios of the samples collected in the Main Branch of Trout Brook during the 28 October 2011 synoptic stream flow measurement campaign. The West Branch Springs have the highest ratios indicating the greatest anthropogenic impact. The East Branch Springs have the second highest chloride/bromide ratios. The Main Branch Springs have the lowest ratios.

Figure 7 shows that the chloride/bromide ratios are a function of distance downstream. The chloride/bromide ratios at springs seem to be decreasing towards the southeast. This reduction is occurring from the headwater springs of the West Branch towards Swede Spring.

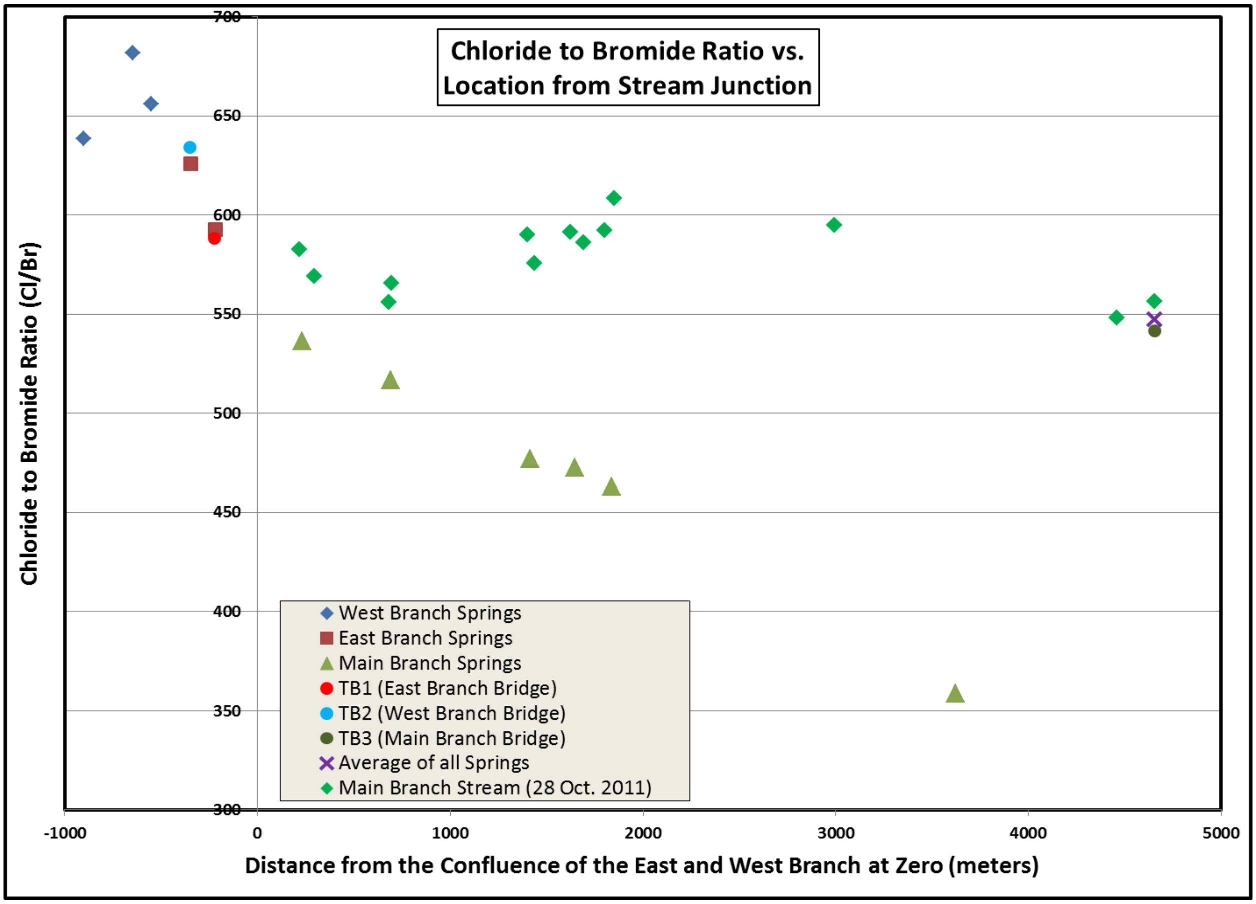


Figure 7: Chloride/bromide ratios are a function of distance from the confluence of the East and West Branches of Upper Trout Brook. Graph shows chloride/bromide averaged ratios for all samples taken from February, 2011 to October, 2012 for the East Branch Springs, West Branch Springs, and Main Branch Springs; and for stream measurements at TB1 (X1), TB2 (X2), and TB3 (X3). Discrete chloride/bromide ratios for the Main Branch, shown by green diamonds are from samples collected on 28 October 2011.

The 28 October 2011 chloride/bromide ratios show that there was not a significant decrease from the upstream to the downstream end of the Main Branch. The total of all the averaged ratios of the springs is shown as the purple “X.” This total averaged value is very similar to the averaged ratios of all samples from TB3 (X3) (denoted by the dark green circle), as well as the discrete chloride/bromide ratio of the sample from TB3 (X3) on 28 October 2011. This is evidence that the majority of flow from disturbed discharge into the stream channel has similar chloride/bromide ratios as the mixed water in the stream channel. The lower chloride/bromide ratios in the Main Branch springs do not significantly lower the chloride/bromide ratios of the mixed water.

Swede Spring has an average chloride/bromide ratio of 348. This is the lowest of the springs and is closest to the ratio of rainwater, which varies from 200-250 in Minnesota. The West Branch Springs have the highest ratios, ranging from 630-680. These ratios are comparable to those found in manure and fertilizer.

The time history of chloride/bromide ratios of both Fox and Swede Springs can be seen on **Figure 8.** Very limited change is evident over the one year sampling interval. The ratios of these two springs seem to be roughly mirroring one another. The fluctuations are more than likely due to seasonal variations caused by snowmelt, rainfall, land cover (plant uptake, bare soil, etc.), and drought.

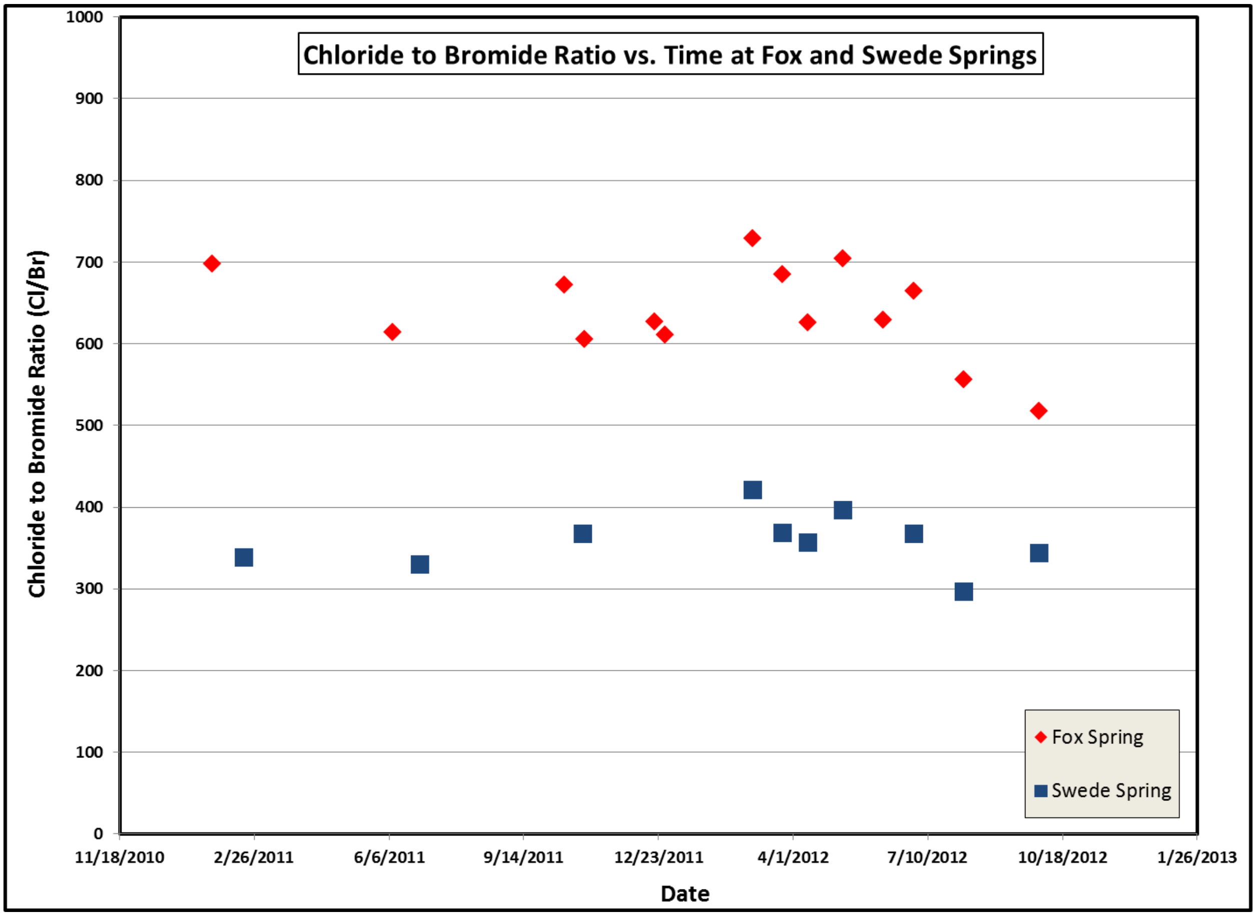


Figure 8: Chloride/bromide ratios are a function of time at Fox and Swede Springs. Samples were collected from February 2011 to October 2012.

3.2.5 Runoff versus Land Use: Surface water runoff was sampled on 2 March 2012 from the recession of 1.67 inches of rain that occurred on 29 February 2012. Two samples were obtained from two different ravines. Each ravine had its own small watershed. The watersheds were delineated using the watershed tool in ArcGIS: ArcMap 10.1. Land use polygons were created using aerial photographs.

In 2011-2012, the smaller watershed (Watershed 2, outlined in fluorescent green on the southwest corner of the larger watershed) did not contain any row-crop agriculture while the larger watershed (Watershed 1, outlined in pink) did have row-crop agriculture (see **Figure 9**). The nitrate concentration was below the detection limit in the samples collected from the watershed with no row-crop agriculture (Watershed 2). The samples from the watershed with row-crop agriculture (Watershed 1) had a nitrate concentration of 10.6 ppm.

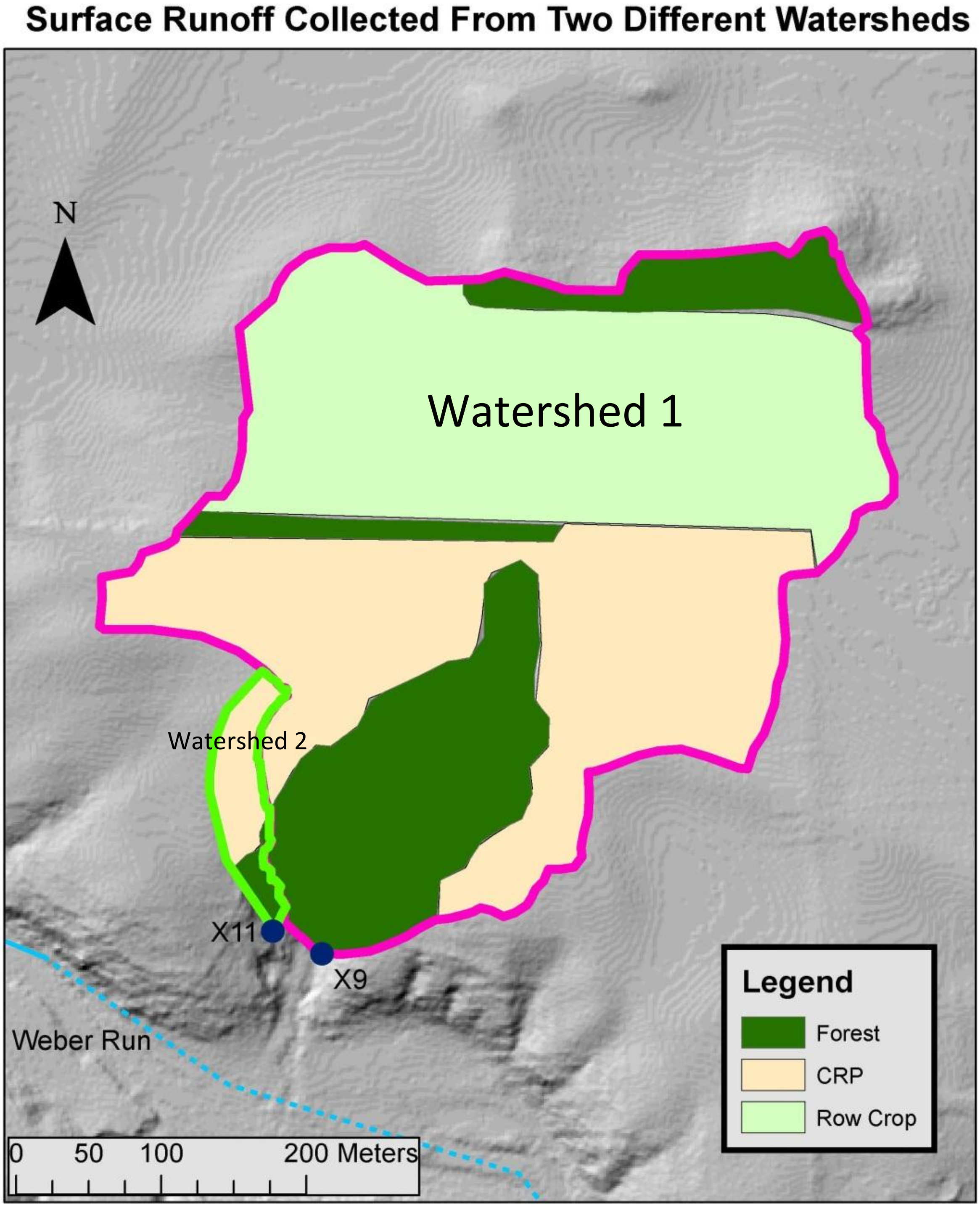
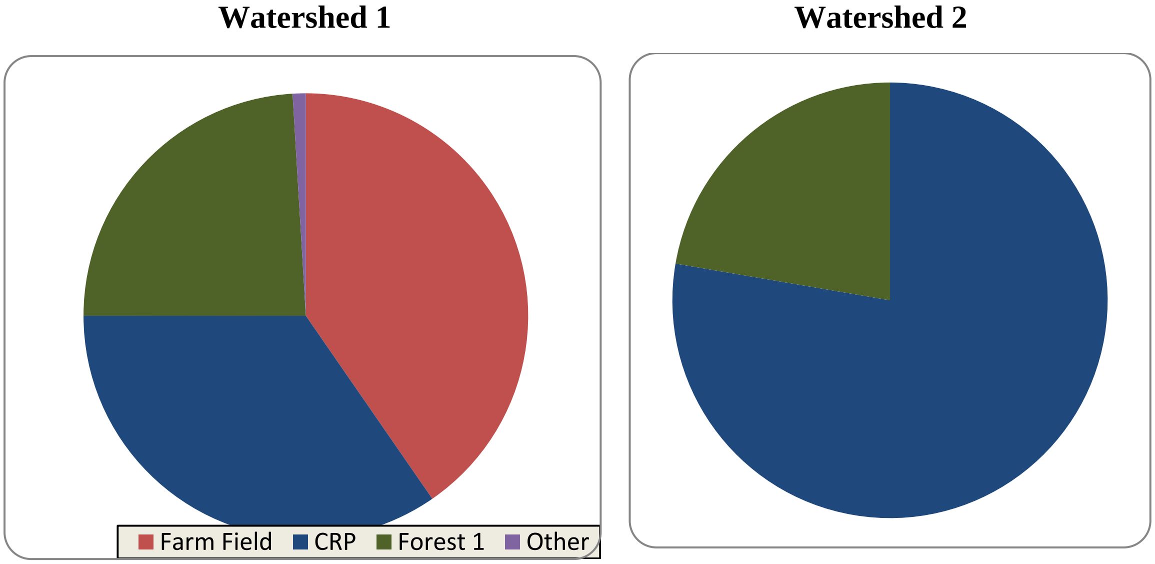


Figure 9: Enlarged portion of the same LiDAR DEM basemap as in Figures 2 and 4. Blue dashes showing the adjacent, ephemeral reach of Weber Run. The dark blue dots (labeled X9 and X11) show surface water sampling stations from two ravines during a 2 March 2012 runoff event. The colors within the two watersheds denote land cover. Watershed 1 has a significant amount of row-crop agriculture. Watershed 2 does not have row-crop agriculture.

Watershed 1 had 40 percent row-crop agriculture contained in it (see **Figure 10**). This 40 percent row-crop agriculture with 10.6 ppm nitrate in its runoff plots on **Figure 1** at the location of the blue circle. The relationship found from the 2 March 2012 surface runoff event is consistent with the results in **Figure 1**. The rapid groundwater velocities and short residence times in karst does not allow enough time for significant nitrate reduction. The nitrate concentrations at springs may be a key indicator of the percent row crop agriculture of their springsheds due to the rapid, direct water flow in karst.


Watershed 1

Watershed 2

Figure 10: Pie Graphs Representing the Percentages of Land Cover. From two distinct watersheds feeding Trout Brook. Watershed 1 covers 1,833,516 square feet while Watershed 2 covers 53,887 square feet. These watersheds are shown in Figure 4 in light green (labeled 10.6 ppm) and dark green. Watersheds are enlarged in Figure 9 (from Figure 2). That map displays the land cover within each sub-watershed.

The above hypothesis needs to be studied in more detail. A potential study could be completed if springsheds were well defined, so the corresponding row-crop agriculture percentages could be calculated with confidence. This would be a great challenge due to the heterogeneous nature of karst flowpaths, and defining springsheds is intensive work with many constraints.

3.3 Synoptic Flow and Nitrate Assessment

3.3.1 Introduction: A synoptic study, 28-29 October, 2011, of the flow and nitrate levels of Trout Brook at baseflow conditions was conducted to understand the interaction between flow and nitrate and to determine if the majority of the flow came from discrete springs or from distributed discharge into the stream channels.

3.3.2 Comparison of Flow Instruments: Three flow instruments were used in this study: two SonTek/YSI FlowTracker Handheld ADV®s (Acoustic Doppler Velocimeters) and a Marsh-McBirney Flo-Mate^{TM} flowmeter. The FlowTracker and Flo-Mate^{TM} were compared at the same location at the TB3 (X3) sampling site (at the downstream portion of a bridge culvert in the Main Branch of Trout Brook: (see **Figure 2**)).

This comparison varied from the study performed with the Flo-Mate^{TM} in Minnehaha Creek (detailed in **Appendix III**) because more measurements were taken at Trout Brook, in an attempt to achieve more robust statistics. Following the standard methods used for flow measurements at Minnehaha Creek, we measured flow at each one-foot interval, to test the precision of the Flo-Mate^{TM} and compare it to the continuous flow monitoring at that NPDES site. According to such standard flow measurement methods, at Trout Brook only thirteen different measurements would need to have been taken because the total width is 13 feet and 10 inches. However, there were twenty-three measurements taken in this cross-section, using the variability of channel depth to define the interval width. Measurements were either taken at a one-foot interval or at a half-foot interval, to improve the precision of the flow calculations

The Flo-Mate^{TM} data from site TB3 (X3) yielded a flow of 12.3 cfs, and the FlowTracker data yielded a flow of 12.8 cfs. These combined data resulted in an average of 12.55 cfs ± 0.35 cfs. The standard deviation corresponds to a ± 3 percent uncertainty.

3.3.3 Methods: Flow measurements were taken in the Main Branch, tributaries, and springs of Trout Brook to estimate the water contribution from the springs to the overall flow of this trout stream. Measurements were taken upstream and downstream of where the identified springs discharge into East, West, and Main Branches of Trout Brook. Flow was measured at 32 locations over a two-day period.

The approximate spring flow was calculated by subtracting the flow of the stream measured upstream of the spring, from the flow measured downstream of the spring. If a spring had formed a channel with enough water, then direct measurements in the spring run were also taken to calculate the flow. All direct flow measurements of the springs were averaged with the flow measurements calculated from the upstream/downstream subtraction. Unfortunately, the flow of some of the springs (with no measureable separate channel) were within the uncertainty of the up and downstream stream flow measurements. In those remaining cases, limits on flow in those spring was visually estimated.

Flow was also measured at certain sites in the stream where a spring was not in close proximity. The objective was to distribute the measurements, in order to interpret reaches that may be gaining or losing flow.

Every location where a flow measurement was taken, a water sample was also obtained. Water samples were retrieved at spring orifices. This was done to understand the mixing concentrations of nitrate and chloride/bromide ratios.

3.3.4 Results: The initial hypothesis that the source of baseflow in the Main Branch of Trout Brook and its tributaries would be primarily from discrete springs is falsified. Data from the two-day synoptic flow measurements show that the majority of the flow is not from discrete springs. Approximately 30-40 percent of the total flow at the sampling point TB3 (X3), close to the outlet of Trout Brook, is from spring water. The remaining flow is apparently from distributed groundwater discharge into the stream channel because no surface runoff was observed during the synoptic measurements. This result is different from the pattern seen in many southeastern Minnesota trout streams.

The water of Trout Brook is from the mid-Prairie du Chien high transmissivity zone (HTZ). The perennial flowing and gaining reach of Trout Brook is entirely in that HTZ stratigraphic interval. Runkel et al. (2003) and Tipping et al. (2006) have shown that water flows in the HTZ through a wide range of solution enlarged conduits, joints, bedding fractures and other interconnected types of porosity. The larger conduits and flow features reach the surface in smaller more distributed discharge features. The channels of Trout Brook were eroded deeper into the bedrock during the Pleistocene, under conditions of glacial low base levels. Those deeper channels were back-filled with glacial sediments at the end of the last glacial cycle, forming the relatively flat bottom of the Trout Brook Valley. Much of the distributed discharge is in reaches where Trout Brook flows across this sediment backfill.

The spring with the greatest contribution of flow to Trout Brook is Beaver Spring. Beaver Spring (X8 on **Figure 2**) discharges into a beaver pond and flows through a swamp before it discharges into the Main Branch at approximately 0.82 cfs. This spring is only 6.5 percent of the total flow of Trout Brook at the site TB3 (X3). The approximated flow from the remaining measured springs can be seen in **Table 1** (in **Appendix I**).

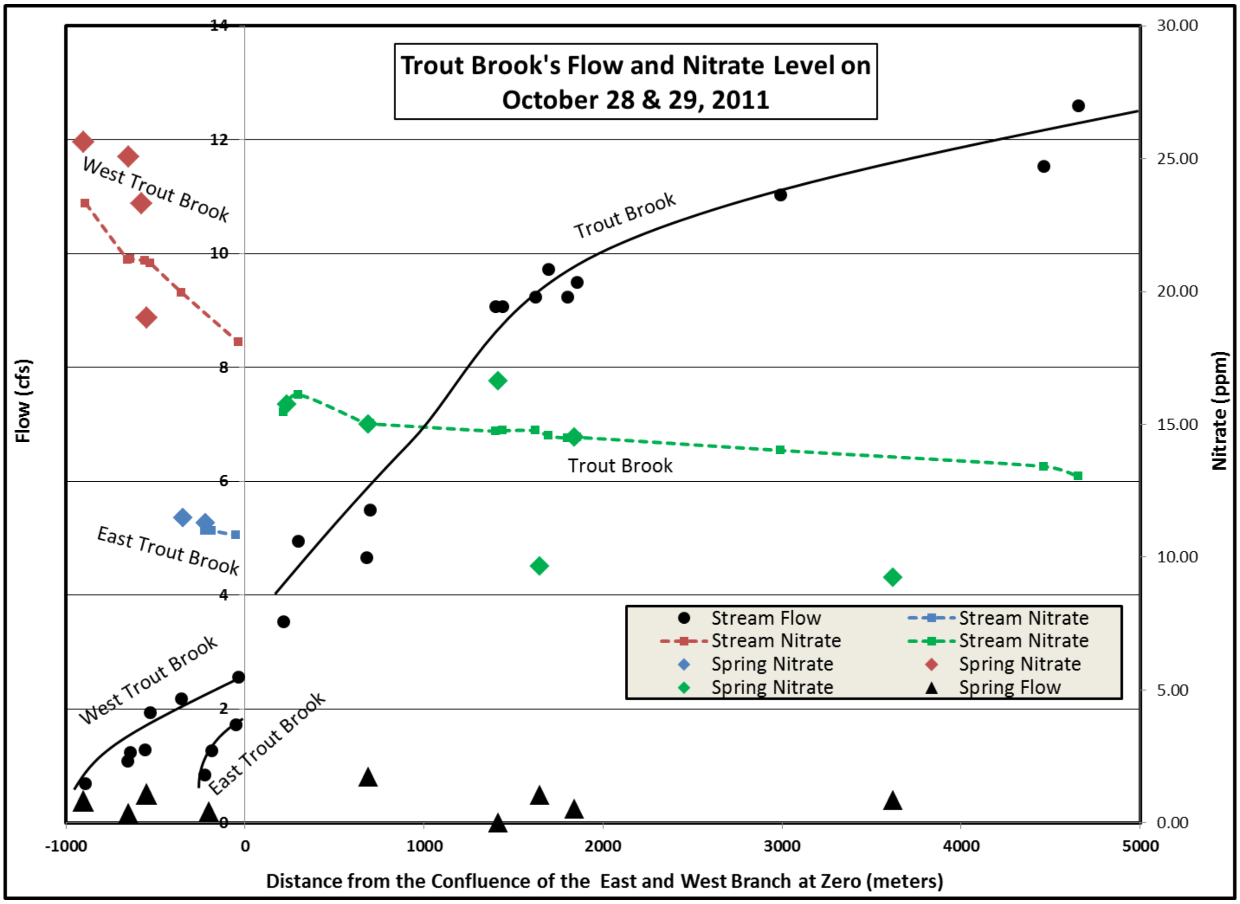


Figure 11: Flow and nitrate concentrations are a function of distance from the confluence of the East and West Branches of Trout Brook. Flows at springs and in the streams are shown in black. Nitrate concentrations at springs and in the streams are shown in red, blue, and green. Samples and flow measurements were collected in cooperation with the Rochester Minnesota Pollution Control Agency (MPCA).

Figure 11 displays nitrate concentration and measured flow versus distance from the confluence of the East and West Branches of Trout Brook. Flow is displayed on the left vertical axis. Nitrate concentration is on the right vertical axis. The horizontal axis displays distance (in meters) along the streams from the confluence of the East and West Branches to form the Main Branch of Trout Brook.

The nitrate concentration decreases only slightly downstream, from ~ 16 ppm below the confluence to ~ 13 ppm at TB3. In contrast, the flows in the Main Branch increase by about a factor of 3 over the same reach, from about 4 cfs to over 12 cfs. This relationship can be seen in **Figure 11.** Distributed groundwater inflow dominates the Main Branch of Trout Brook and the nitrate content of that water is apparently in the 13 to 15 ppm range.

Flow measurements were also taken on 31 March 2012. This was done to see how much flow was gained from the confluence of the East and West Branch to the stream section between Beaver and Hill Springs. The majority of this area was not measured on the 28-29 October 2011 study. It was found that approximately 4.5 cfs of water was gained along this portion of the Main Branch. The only discrete spring in this area is Beaver Spring, which was discharging approximately 0.7 cfs of water into the Main Branch. Approximately 3.8 cfs of water was from distributed discharge into the stream channel.

The flow data gathered in 1985 and 2011 can be seen on **Table 1 (Appendix I)**. More springs were found and measured in the 2011 data which lead to a better estimation of spring flow at 34 percent of the flow at the farthest downstream site, TB3 (X3). This confirms that the majority of flow of Trout Brook is from distributed discharge into the stream channel. However, the flow inputs have changed in Trout Brook. In 1985 the East Branch was contributing more flow to Trout Brook than the West Branch and in 2011 the West Branch was contributing more flow than the East Branch. This illustrates the changes that occur with flow regimes over time. These changes could be from climate, anthropogenic activities such as irrigation, changes in land use, or from changes in the steam channel itself by major floods.

3.4 Weber Run Dye Traces

3.4.1 Introduction: The goal of the Trout Brook dye traces was to identify the spring resurgence(s) in Trout Brook of the surface water that sinks in the Weber Stream Sieve and to estimate the groundwater flow velocity between the sieve and resurgent spring(s). This would begin to define springsheds for those springs.

Tracing is an effective, direct measurement that yields information on the direction of groundwater flow and its travel time. Dye is typically injected in sinkholes, sinking streams, or stream sieves. The dye is transported by the water and is discharged from a spring or springs. Charcoal samplers, commonly referred to as “bugs”, are placed at monitoring sites and act as integrating detectors of any dye that passes the monitoring point. The bugs are replaced on a regular basis, and the retrieved bugs are taken to the lab for processing. In the lab, the adsorbed dye is extracted and analyzed on a scanning spectrofluorophotometer. Detection of the dye from a charcoal detector establishes a connection between the dye input point and the monitoring point. Field records maintained with the dates and times of bug placement and retrieval allow the calculation of an estimate of the travel time, which can be interpreted as the velocity of the groundwater between the injection and detection points (Alexander and Alexander, 2011).

3.4.2 Study Area and Methods: Weber Run is located in the E½ of the SE¼ of sec 22 of Douglas Township on private land on the northwest corner of the County Park. We learned of its existence from the land owner, John Weber on 20 December 2011. Trout Brook and Weber Run are shown on **Figure 2** and in greater detail on **Figure 12**. Weber Run is a short segment of

Results From 28 December 2011 Dye Trace

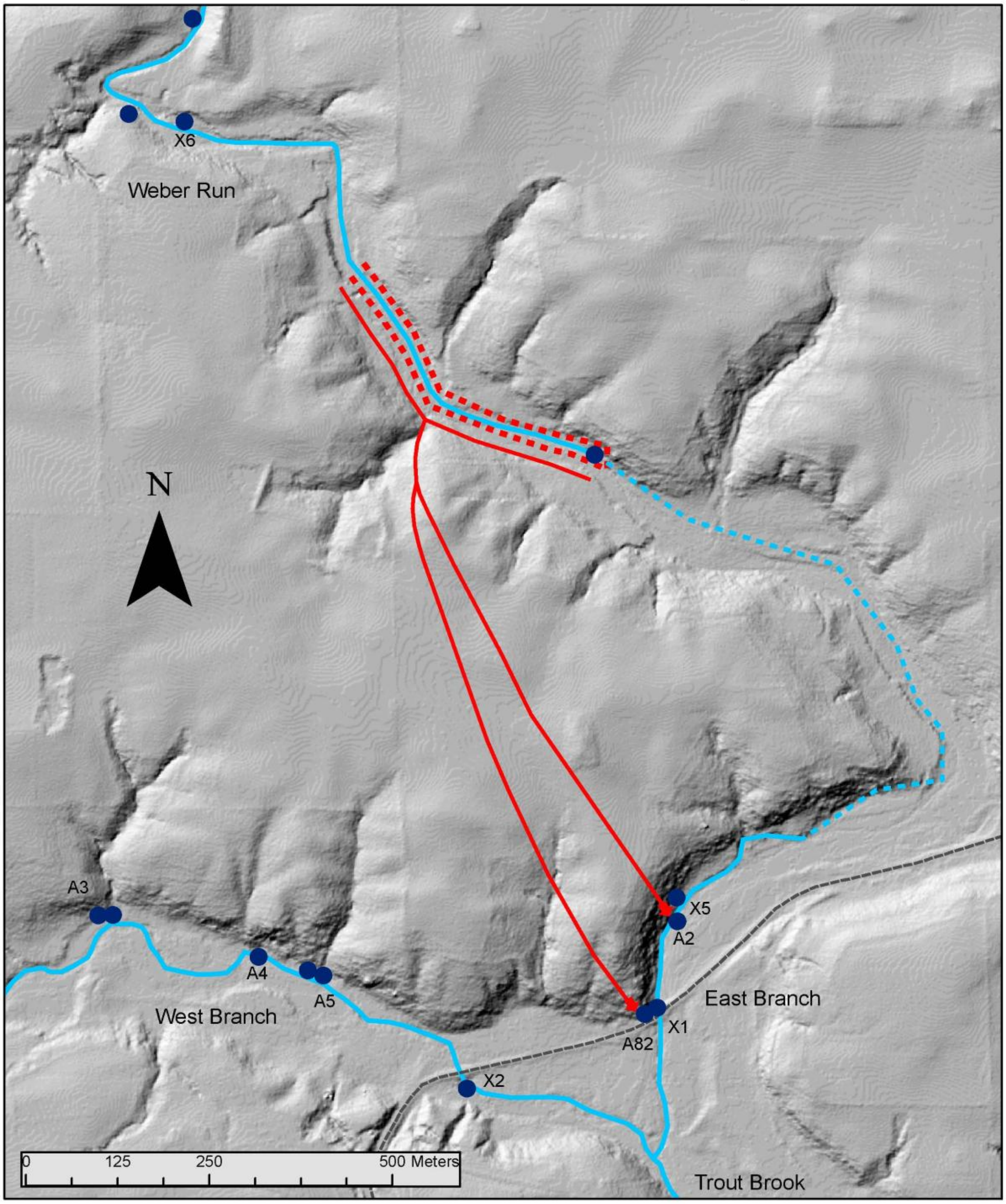


Figure 12: Weber Run and the Upper Trout Brook Basin. This is enlarged portion of the area shown in Figure 2. The dashed red lines highlight the stream sieve reach of Weber Run (B1). The red arrows show, diagrammatically, the underground connection between the stream sieve and LeDuc (A2) and Bridgestone (A82) springs.

surface flow that is fed by several source springs and then, under all but high flow conditions, sinks completely in a stream sieve. The source springs are a series of small springs and seeps on the southwest stream bank. These springs are located on **Figure 2** at A83.

In late December 2011 the upper end of Weber Run was ice covered (~A85 to A83, see Fig. 2), the middle reach (A83 to almost to B2) was an open flowing stream, and the downstream reach was ice covered (B2 to B3). Weber Run's total length (from A85 to B3), including ice covered and open stream flow segments, was 1,150 meters. The approximate distance from A83 to the end of the water and ice flow was 907 meters. The distance, following the dry stream bed, from the end of Weber Run to the start of flow in the East Branch of Trout Brook (B3 to upstream from A2) is 930 meters.

Seven background bugs were installed on 22 December 2011. The Swede Spring bug was added on 12 February 2012. The descriptions and locations of all the sites are included in **List 1** (in **Appendix II**) and **Table 2** (in **Appendix I**). The bugs were initially changed every few days and later, as time passed, the bugs were exchanged every one to two weeks.

On 28 December 2011 Rhodamine WT dye was introduced in Weber Run upstream of the ice and water flow at point X6 (see **Figure 13)**. At 12:20 PM Central Standard Time (CST), 1,050 grams of a 20 weight percent solution of Rhodamine WT dye (Chromatech D 13800, Lot 041807) was introduced into the injection point, X6, downstream of B83. The dye traveled in the stream until it drained into the subsurface.

Figure 13: Rhodamine WT dye injection on 28 December 2011.

3.4.3 Results: Graphs 1-13 (in **Appendix II**) show 13 selected fluorescent spectra. PeakFit^{TM} software was used for spectral analysis. Rhodamine WT exhibits a fluorescent emission peak centered on about ~564 nanometers (nm) wavelength. The amplitude of that peak is proportional to the concentration of dye eluted from the charcoal packet. The detection limit for the dye is set by comparing the amplitude of the peak to the standard error (SE) or σ (shown in the text in **Graphs 1-13**) of the fitted spectra (Alexander, 2005). If the amplitude of a dye peak is greater than 3 σ, the dye has been detected. If the amplitude of a dye peak is greater than 10 σ, the dye is quantifiable.

The results from the spectrofluorometric analyses of the charcoal bugs from Dye Trace #1 are summarized in **Table 3** (in **Appendix II**). Rhodamine WT was detected emerging from LeDuc Spring (A2) and Bridgestone Spring (A82). **Graph 1** is the spectrum from the 9-18 January 2012 LeDuc Spring bug. There is no detectable peak around 564 nm. None of the preceding bugs contained detectable dye. **Graph 2** is the spectrum from the 18-26 January 2012 LeDuc Spring bug. The detectable (3.2 σ) peak at 569 nm is the leading edge of the Rhodamine WT dye pulse. **Graph 3** shows the spectrum from the 26 January to 12 February 2012 LeDuc Spring bug. There is a quantifiable (27.5 σ) peak Rhodamine WT peak at 564 nm. **Graph 4**, the 12 February to 2 March 2012 LeDuc Spring bug also contains a quantifiable (12.5 σ) Rhodamine WT peak. **Graph 5**, the 2-24 March 2012 LeDuc Spring bug, contains the largest (55.9 σ) Rhodamine WT peak observed to date. These four detections of Rhodamine WT dye at LeDuc Spring document a groundwater flowpath between Weber Stream Sieve and LeDuc Spring. That path is shown diagrammatically by the right (eastern) red arrow in **Figure 12.**

Graph 6, the 2-24 March 2012 Bridgestone Spring (A82) bug, contained the first evidence of Rhodamine WT dye, an 11.5 σ quantifiable peak at 565 nm. All of the previous bugs from Bridgestone contained no detectable Rhodamine WT. A diagrammatic flowpath connecting Weber Sieve and Bridgestone Spring is shown by the left (western) red arrow in **Figure 12**.

If we take 26 January as the arrival of dye at LeDuc Spring, the travel time of the leading edge of the dye from Weber Sieve to LeDuc Spring was 29 days. The straight-line distance from the middle of the portion of the Weber Run Sieve to LeDuc Spring is 786 meters. Dividing the distance by the travel time produces a groundwater flow velocity of 27 meters/day in the south-southeastern direction. Given the uncertainty in where the dye actually sank underground and the unknown geometry of the underground flowpath (typically assumed to be about 1.5 times the straight line distance) the groundwater speed is probably about 41 meters/day at an average point along the underground flow-paths, for the leading edge of the dye pulse. The rest of the dye, which was still coming out of LeDuc Spring (through the end of sampling in October 2012) traveled slower. We note that this trace took place under low flow conditions, during 2012 which was a year of progressively more severe drought conditions.

Although the straight-line distance from the middle of the Weber Sieve to Bridgestone Spring (~ 885 meters) is only roughly 100 meters longer than that to LeDuc Spring, the leading edge of the dye took 65 to 87 days. That range and the assumptions of the previous paragraph corresponds to the leading edge flow velocity of approximately 15-20 meters/day from Weber Sieve to Bridgestone Spring

Under normal flow conditions, surface water does not flow from the end of Weber Run to the start of flow in the East Branch of Trout Brook a few hundred feet upstream of LeDuc Spring, and the surface valley stream bed is dry. However, 1.67 inches of rain fell on 29 February 2012, and a stormflow event in the basin caused surface water to flood the entire length of the East Branch of Trout Brook between the normal end of Weber Run and LeDuc Spring. The flood event was still connecting these two sites when the area was visited on 2 March 2012. That surface connection raises the possibility that some of the detected dye (as shown in **Graph 4**) could have been transported on the surface.

However, **Graph 7** shows the fluorescent spectrum from the 26 January to 12 February bug at the monitoring station (X5) in the East Branch of Trout Brook about 35 meters upstream from LeDuc Spring. **Graph 8** shows the fluorescent spectrum from the 12 February to 2 March 2012

X5 bug. There is no hint of a Rhodamine WT in either of these two bugs. Thus, we conclude that the Rhodamine WT peak in LeDuc Spring in the 12 February to 2 March 2012 bug was not due to surface flow.

Finally, the bug at TB1 (X1) is not far downstream from LeDuc Spring. Dye emerging at LeDuc Spring should be detected at TB1. **Graphs 9** and **10** show the spectra from the TB1 (X1) bugs from 26 Jan to 12 Feb and 12 Feb to 2 Mar 2012, respectively. Both bugs contain small but detectable Rhodamine WT peaks. Rhodamine WT peaks are absent in the preceding bugs.

3.4.3.1 Dye Trace #2: A second dye trace of Weber Run using a different dye was initiated. On 12 April 2012, 2.137 kg of a 33 weight percent solution of eosine dye was introduced at the same point as where the Rhodamine WT dye was injected. The objectives of the second trace were: 1) to replicate the first trace, 2) to obtain a breakthrough curve from Weber Sieve to LeDuc Spring using ISCO automated samplers, in order to produce time-based sampling, and 3) to use timed sampling in order to obtain a better measurement of the groundwater flow velocity between those points. Two floods disabled the ISCO automated samplers, and they did not obtain samples which defined a breakthrough curve. However, the bugs survived the floods and detected the emergence of the eosine dye at LeDuc Spring.

This dye trace did confirm the flowpath from Weber Run to LeDuc Spring. The results from the spectrofluorometric analyses of the charcoal bugs are summarized in **Table 4 (Appendix II).** Eosine was detected emerging from LeDuc Spring (A2). The LeDuc Spring bug, 30 June -13 July, had a quantifiable (21.8 σ) eosine peak at 540 nm (**Graph 11**). This is part of the leading edge of the eosine dye pulse. Eosine was observed at LeDuc Spring two more times. The LeDuc Spring bug, 13 July – 6 August, had a detectable (7.3 σ) eosine peak (**Graph 12**). The LeDuc Spring bug, 6 August – 01 October, had a quantifiable (19.6 σ) eosine peak (**Graph 13**).

If 30 June is taken as the arrival date of the eosine, the travel time of the leading edge of the dye of the second trace from Weber Sieve to LeDuc Spring was 79 days. This is considerably slower than the dye trace on 28 December 2011 which resulted in a travel time of 29 days from Weber Sieve to LeDuc Spring. This reduction is most likely due to the low flow conditions that resulted from the progressively more severe drought throughout the year.

3.4.4 Conclusion: The four positive detections of Rhodamine WT and three positive detections of eosine at LeDuc Spring confirm that at least a portion of the water of LeDuc Spring is derived from the Weber Sieve area of Weber Run. The 29-day travel time between Weber Sieve and LeDuc Spring corresponds to a groundwater flow velocity of ~27 meters/day in the south-southeast direction. The actual groundwater flow speed at an average point along the flowpath was likely at least ~41 meters/day during the period of the first dye trace. The 79-day travel time between Weber Sieve and LeDuc Spring corresponds to a ~10 meters/day groundwater velocity, and the actual speed at an average point on the flowpath was probably only ~15 meters/day during the second trace

The first positive detection of Rhodamine WT at Bridgestone Spring was detected in the 2-24 March 2012 bug. This detection demonstrates a groundwater flow connection between Weber Sieve and Bridgestone Spring with a flow velocity of 15-20 meters/day during the first dye trace. The slower flowpath emphasizes the heterogeneous nature of these karst groundwater flowpaths. As the 28 December 2011 and 12 April 2012 traces took place under low flow conditions in an exceptionally dry winter, spring, summer, and fall, the flow velocities under normal, higher flow conditions may be faster.

3.5 Temperature

3.5.1 Temperature Correction: Two Solinst LTC Leveloggers® were used to monitor temperature variation in Fox Spring (A3) and Swede Spring (A10) between 9 February and 5 October 2012.

Before the loggers were installed and after they were recovered, temperature correction curves were measured for each. The dataloggers were placed in a FLUKE® Hart Scientific 7102 MICRO-BATH. It is a high precision temperature bath that controls and reads temperature to a hundredth of a degree Celsius (°C). The temperature bath has a temperature range from -5°C to 125°C, accuracy of ±0.25°C, and a resolution of ±0.01°C. This temperature bath was calibrated on 14 April 2011. A precision glass thermometer was placed in the temperature bath for quality control/quality assurance.

The dataloggers were programmed to take and record a measurement every five seconds. The temperature bath was sequentially adjusted to 5.00, 6.00, 7.00, 8.00, 9.00, 10.00, and

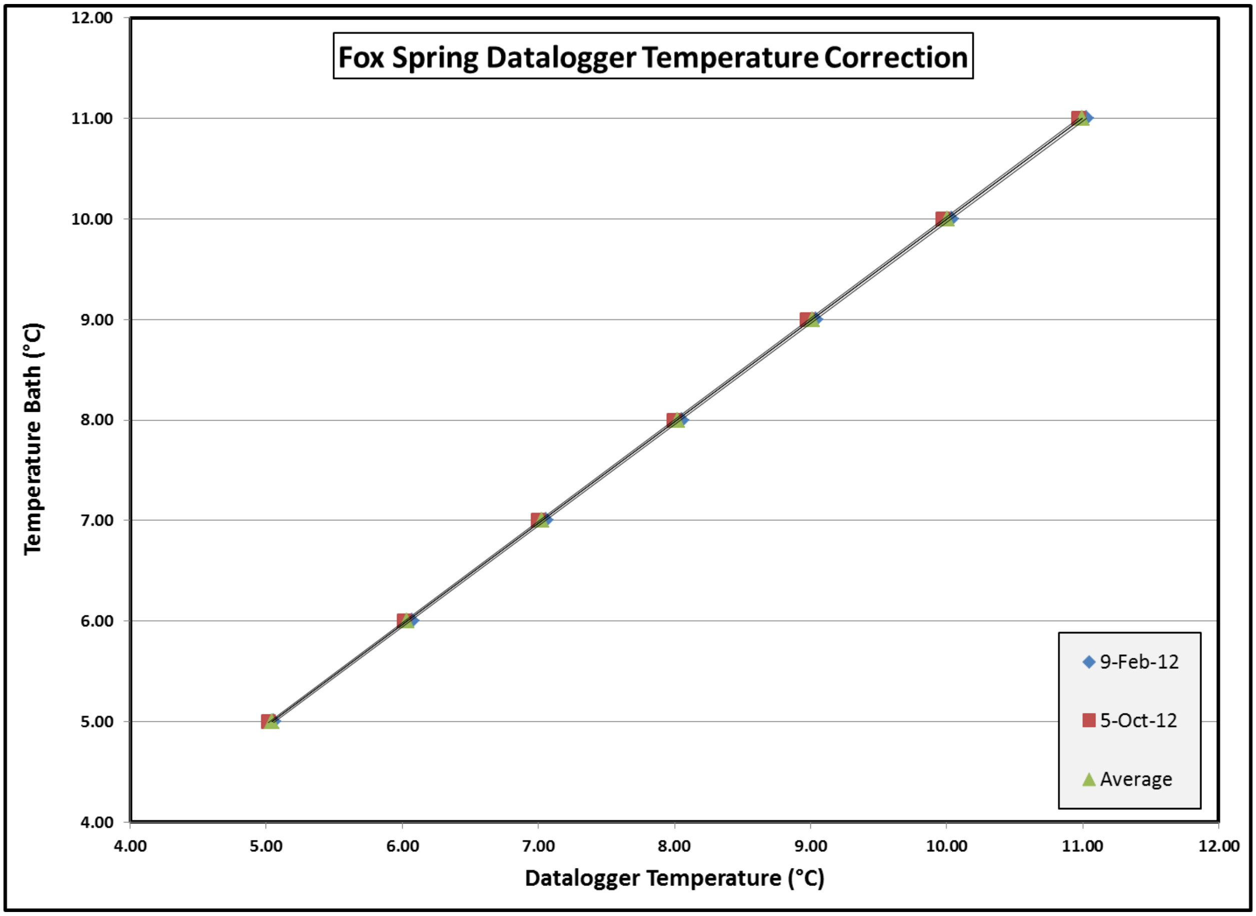


Figure 14: Fox Spring datalogger temperature plotted against readings for the temperature bath. The datalogger corrections were checked against the temperature bath before (on 9 February 2012) deployment and after temperature monitoring ceased (on 5 October 2012).

11.00°C. The temperature remained on each of these temperatures for approximately 15 minutes before being increased to the next temperature.

After the dataloggers were downloaded, approximately five minutes of temperature data was averaged from the middle of the 15 minute temperature ranges at 5.00, 6.00, 7.00, 8.00, 9.00, 10.00, and 11.00°C. These averaged temperature values were plotted against the readings of the temperature bath (See **Figures 14 and 15**).

The temperatures recorded by the Solinst LTC dataloggers were measurably different from those in the calibrated temperature bath. The two loggers' offsets were different from each other and the offsets of each changed slightly while the loggers were in the field. The temperature shifts from 9 February 2012 (blue diamonds) to 5 October 2012 (red squares) correction lines and the average of the two (green triangles) are shown in **Figure 14** for the Fox Spring logger and **Figure 15** for the Swede Spring logger.

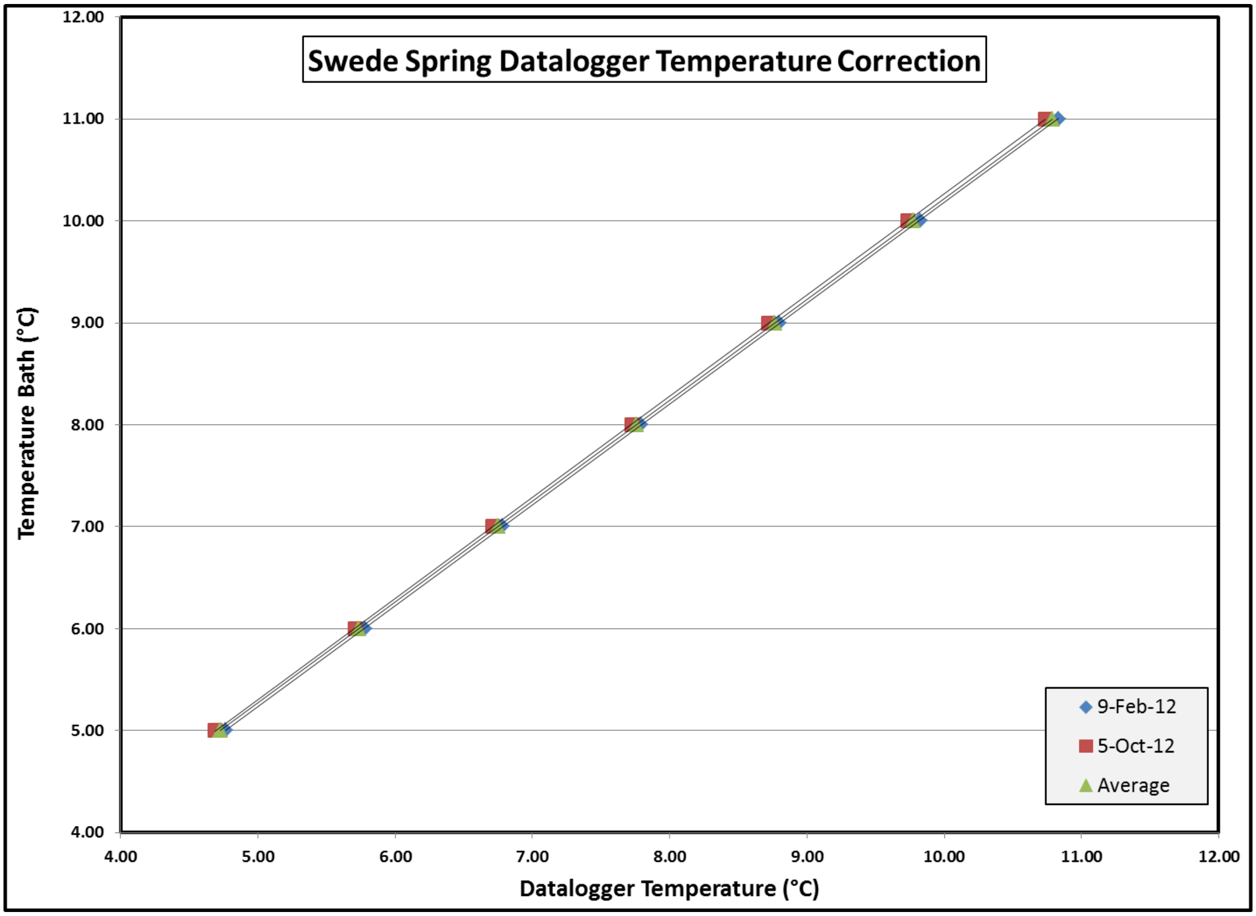


Figure 15: Swede Spring datalogger temperature plotted against readings for the temperature bath. The datalogger corrections were checked against the temperature bath before (on 9 February 2012) deployment and after temperature monitoring ceased (on 5 October 2012).

Average temperature correction lines were calculated for each datalogger by adding trend lines and the corresponding linear line equations to all four data sets, 9 February 2012 and 5 October 2012 for each datalogger. The new lines pass through the green triangles in **Figures 14**

and 15. This process was done for both dataloggers, so two equations were created. The equation for each average correction line was applied to the temperature data recorded at Fox and Swede Springs and can be seen on **Figures 15**. The gray data are the original data. The red (Fox Spring) and blue (Swede Spring) data are the corrected data.

3.5.2 Temperature Monitoring at Springs: The water temperatures at springs can provide insights about the contributing aquifers to the springs (Luhmann et al., 2011). It is important to have high resolution and correct temperature data because temperature changes can be small in aquifers. The orange vertical lines in **Figure 16** indicate when the dataloggers were removed to be downloaded, reset, and placed back into the springs. There was a drop in the temperature readings after the dataloggers were downloaded for the first time in early March. The air temperature was colder than the water temperature of the springs. When they were removed, the dataloggers probably cooled due to the colder air temperature and then began recording colder temperatures when they were placed back in the springs.

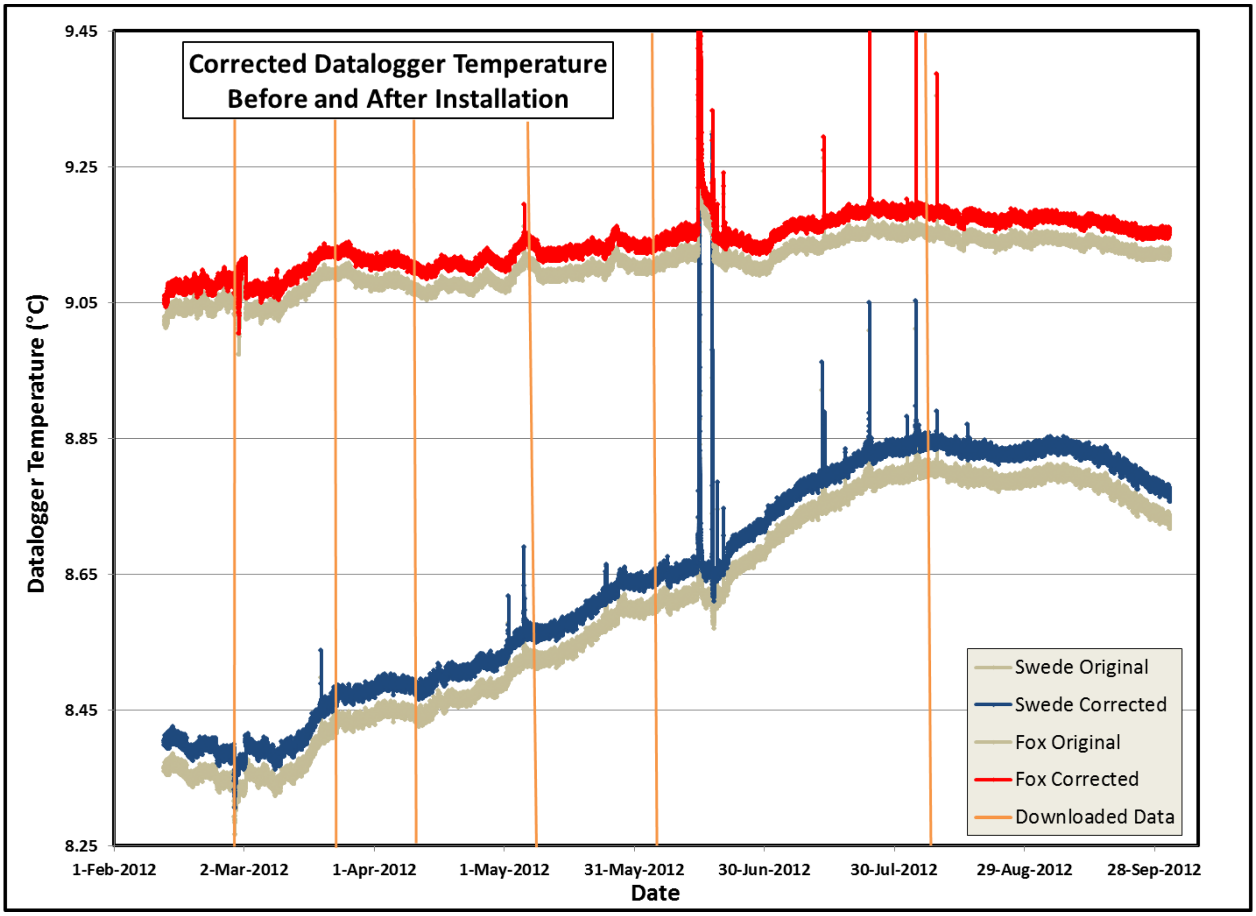


Figure 16: Water temperature versus time at Fox and Swede Springs. The uncorrected datalogger records are shown in gray. The corrected temperatures at Fox and Swede Springs are shown as red and blue lines. This 15-minute temperature data was collected between 12 February 2012 and1 October 2012. The orange vertical lines indicate when the dataloggers were removed, downloaded, and then reinstalled. The full extent of the 14-15 June 2012 storm event is shown in Figure 19.

The installation geometry of the dataloggers in the springs was dictated by the geometry of the springs and was near the water surface at both but configured differently at the two springs. The datalogger at Swede was placed in one to three inches of water that emerged from the ground and flowed slowly past the datalogger. That logger was then covered with a piece of a log to protect it from disturbance. The datalogger at Fox Spring was suspended about a foot down inside a vertical conduit with water roiling vigorously upward past the datalogger.

Figure 17 shows water temperatures at Fox and Swede Springs and the daily average air temperature at Cannon Falls, MN. (Daily air temperatures are the average of the daily maximum and minimum data from the Cannon Falls, Minnesota National Weather Service Cooperative Station on the Little Cannon River. The data was retrieved from the MDNR-Waters State Climatology Office website.) The temperature data from both springs show small, reasonably smooth, apparently seasonal temperature fluctuations. The smooth fluctuation of Fox Spring is about ±0.15 °C while the smooth fluctuation of Swede Spring is greater than ±0.4 °C. Both patterns were near minima when the datalogging began in February, rose to maxima in early August, and then declined through the end of sampling in October.

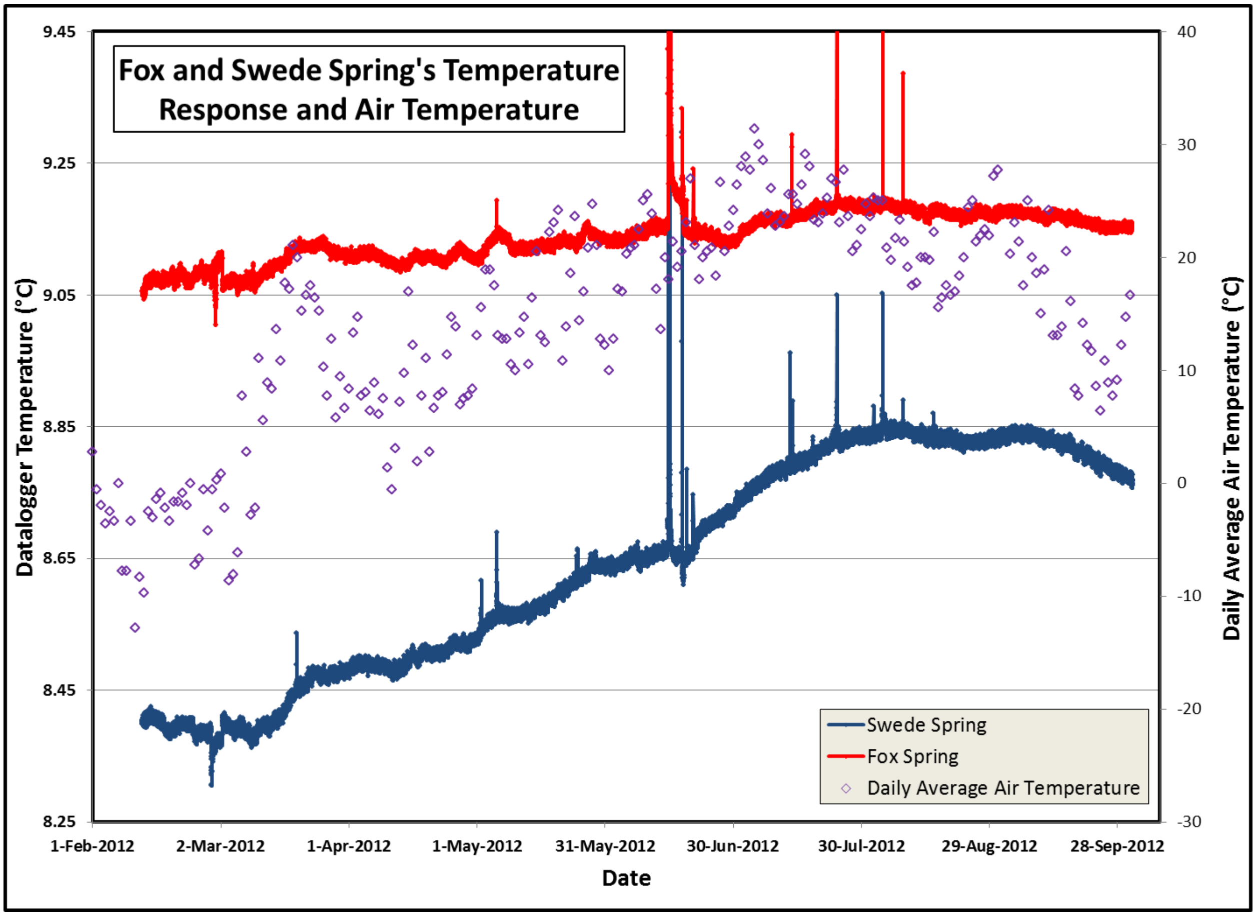


Figure 17: Corrected water temperature as function of time at Fox and Swede Springs. For comparison, average daily air temperatures at Cannon Falls, Minnesota are shown as purple diamond shapes. The Little Cannon River weather station is 11.5 miles southwest of Swede and Fox Springs.

The smooth temperature patterns are analogous to Luhmann et al.'s (2011) Type 2, which they defined as a "seasonal in phase with surface temperature pattern". However, Luhmann et al. (2011) interpreted their Type 2 pattern as driven by a major component of perennially sinking surface water. No such source of perennially sinking surface water is known in the Trout Brook watershed. The dye tracing found no evidence that the (volumetrically minor) Weber Run Stream Sieve contributes flow to either Fox or Swede Springs. The basis for the two smooth, seasonal temperature changes is consistent with: 1) heating and cooling of the water of the springs near the dataloggers, and 2) placements of the loggers in and near the orifices of the springs. We conclude that, is this case, the small "in phase" seasonal temperature fluctuations were caused by heating and cooling of the spring water at the spring. The Fox Spring datalogger, with the relatively more muted smooth temperature fluctuation was in deeper water

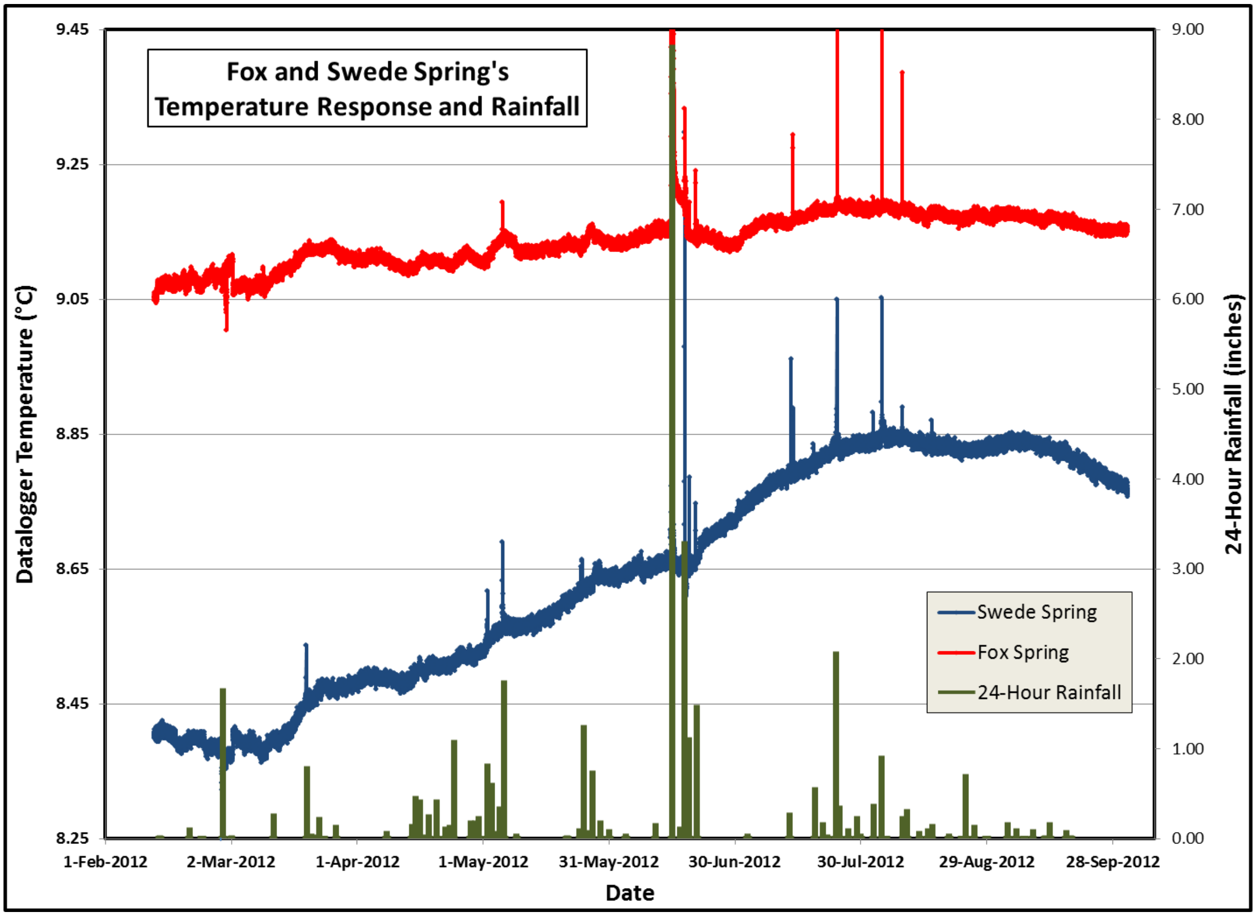


Figure 18: Water temperatures and rainfall are a function of time at Fox and Swede Springs. The red and blue lines denote the temperature readings at the springs. This 15-minute temperature data was collected from 12 February 2012 to 1 October 2012. The green bars are 24-hour rainfall. Rainfall data was retrieved from the State Climatology Office MnDNR Waters website which was collected at the Cannon Falls Minnesota National Weather Service Cooperative station on the Little Cannon River. The weather station is 11.5 miles from Swede and Fox Springs.

and in a significantly stronger flow of spring water. The Swede Spring datalogger with the relatively stronger temperature fluctuations was closer to the air surface and in a significantly less flow.

While this interpretation of the smooth temperature changes of the springs is consistent with the data and field relationships, other interpretations are possible. One alternative is that the patterns could be explained by temperature changes which occur in the aquifer, or by the mixing of different waters with different temperatures. The water at Fox Spring could be from deeper in the aquifer than Swede Spring. This would explain why the temperature of Fox Spring has a lesser rate of change. Another alternative is that both springs are discharging a significant component of hyporheic flow from Trout Brook. Swede Spring is downstream and adjacent to a much larger flow of surface water than is Fox Spring.

Superimposed on the smooth temperature fluctuations of both springs are short temperature excursions. These short excursions are analogous to the Type 1, “recharge event scale” temperature patterns discussed by Luhmann et al. (2011). **Figure 18** shows the temperatures at Fox and Swede Springs and the daily rainfall totals. The spikes in temperature closely correspond with storm events through time. The temperature spikes are clearly correlated with the interception of rainfall or with increased flow or flooding at the spring orifice. The spikes that occur in the upward direction are warm rain events in the spring and summer months, while the spike in the downward direction occurred in late winter after a cold rain on frozen ground.

3.6 (14-15) June 2012 Flood Event

3.6.1 (14-15) June 2012 Rain and Response: The Minnesota Climatology Working Group (2012) reported that “Torrential rains fell during the afternoon and evening of June 14 in Goodhue, Rice and Dakota Counties.” They also stated that, “The 8.83 inches measured at Cannon Falls is the largest 24-hour total June rainfall measured at a Minnesota National Weather Service Volunteer Cooperative station in the history of the program.” They explained that, “The focus for the heavy rain was a stalled warm front that was draped across southern Minnesota.” From the data, we estimate the springsheds feeding Trout Brook received roughly between 6 to 9 inches of rainfall.

The temperature responses due to the flood at Fox and Swede Springs can be seen on **Figure 19**. The rainfall data was collected at a Department of Natural Resources (DNR) stream gage (DNR/MPCA Cooperative Stream Gauging, 2012), and the location of the gage can be seen on **Figure 20**. The measured rainfall at this gage was 7.22 inches from 10:15-23:15 on 14 June 2012. The temperatures rose rapidly at both springs because the temperature of rainfall in June is much higher than the seasonal water temperatures of the springs. This data hints at the magnitude of flooding which reached the orifices of Fox and Swede Springs. Given the temperature change, this may be an unusually dramatic illustration that rain events directly affect the water temperatures at Fox and Swede Springs either from flooding and/or the interception of rainfall at the orifices.

3.6.2 Post 14-15 June 2012 Flood: The 14-15 June 2012 flooding caused significant geomorphologic changes in the watershed of Trout Brook and its streams. Sinkholes are common but often ephemeral features in karst regions. When new sinkholes develop, they are often rapidly backfilled in an attempt to restore the altered landscape. The locations of many

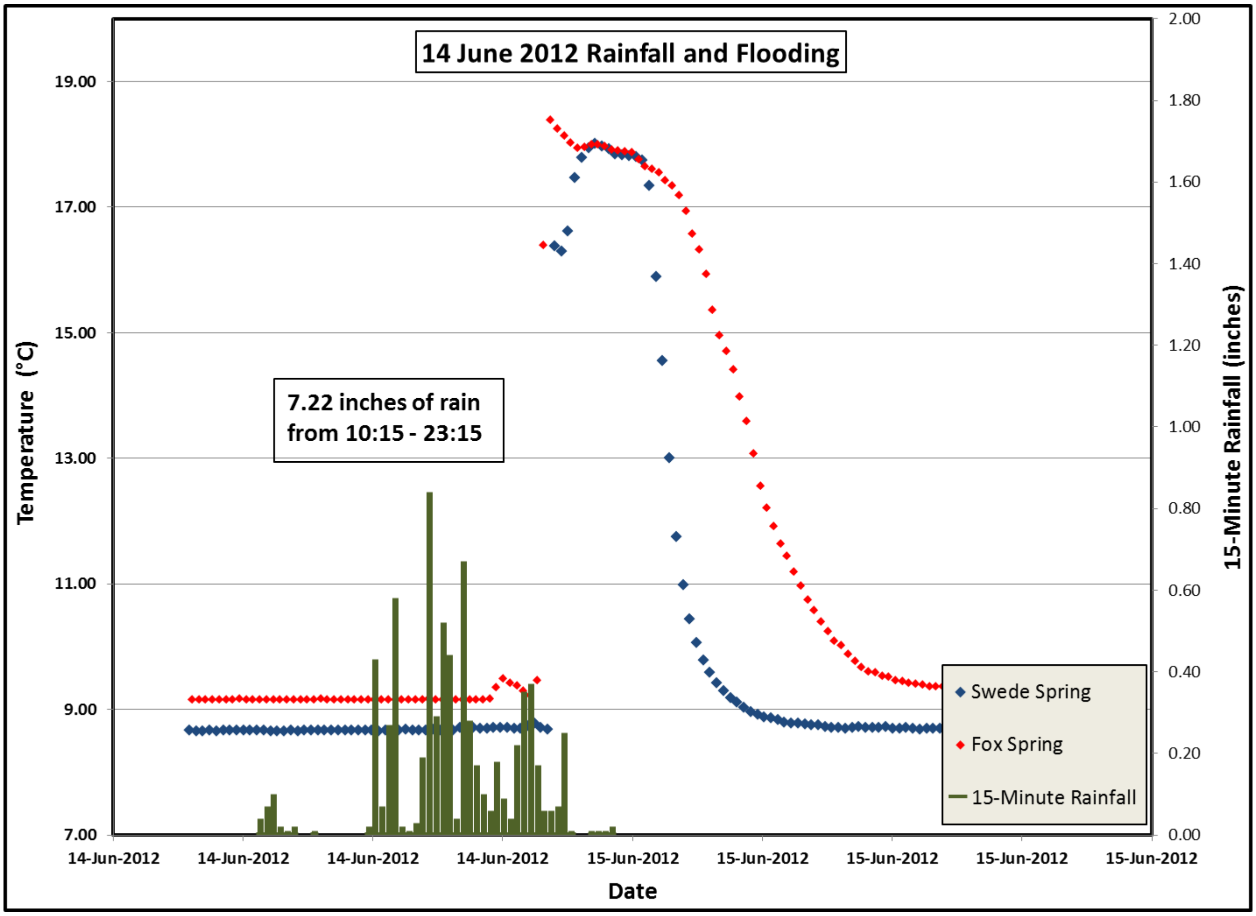


Figure 19: Water temperature and rainfall are a function of time at Fox and Swede Springs. The red and blue diamond shapes denote the temperature readings at the springs. This 15-minute temperature data is a small portion of the data which was collected from 12 February 2012 – 1 October 2012. The green bars are 15-minute rainfall. Rainfall data was retrieved from the DNR/MPCA Cooperative Stream Gauging website.

filled sinkholes are not recorded and then forgotten. It is useful to know the whereabouts of sinkholes because they can be used for dye tracing. They are potentially an environmental concern because of their ability to transport contaminants. At least two new sinkholes developed as a result of the 14-15 June 2012 flood. Their locations are shown on **Figure 21**. **Figures 22 and 23** are pictures of these two new sinkholes.

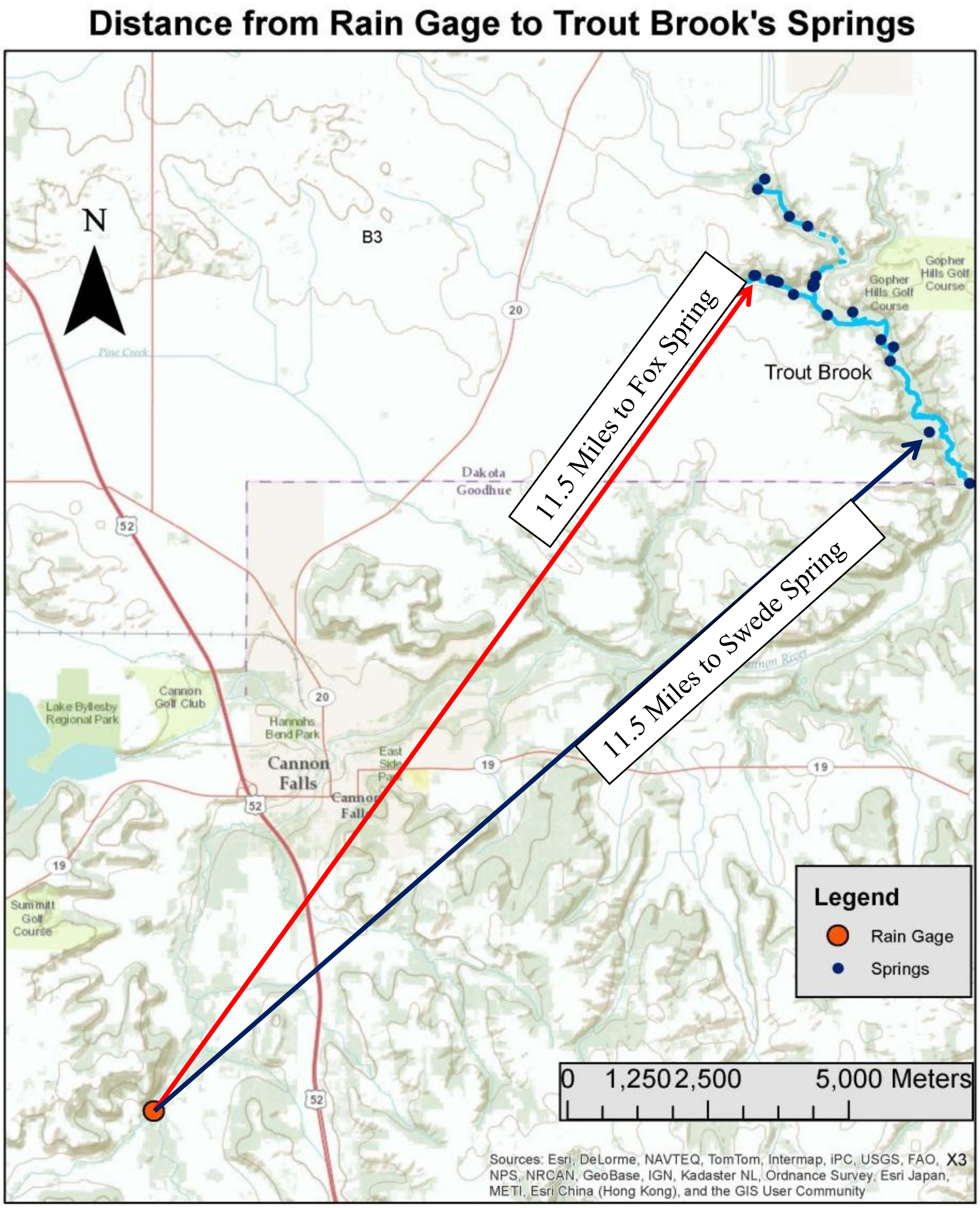


Figure 20: Trout Brook and Cannon Falls, Minnesota displayed on a topographic ArcGIS 10.1 basemap. Light blue lines denote perennial running water in Weber Run, the East and West Branches of upper Trout Brook, and the Main Stream of Trout Brook. Light blue dashes denote an ephemeral reach. Dark blue dots show springs, stream sieves, surface water sampling stations, and other features. The dark orange dot shows a DNR stream gage located on the Little Cannon River southeast of Cannon Falls, MN. 15-Minute Rainfall data was collected from this gage. The red and blue lines show the distance from the rain gage to Fox and Swede Springs.

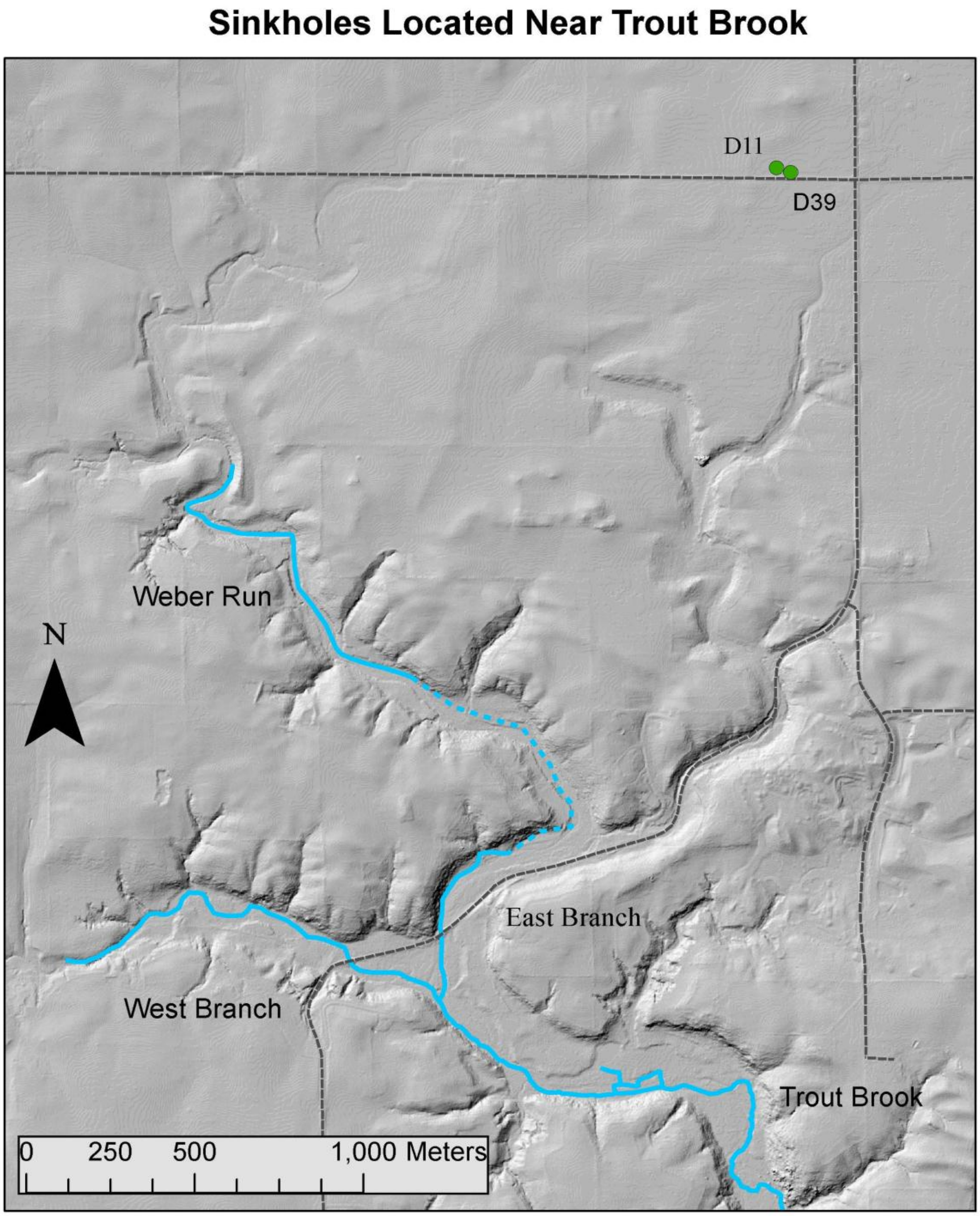


Figure 21: Trout Brook in the SE portion of Douglas Township, Dakota County, Minnesota. Enlarged portion of the 2008 LiDAR shaded relief DEM basemap. Light blue lines denote perennial running water in Weber Run, the East and West Branches of upper Trout Brook, and the Main Stream of Trout Brook. Light blue dashes denote an ephemeral reach. Dashed gray lines denote roads. The two green dots represent sinkholes that were discovered after the 14-15 June 2012 flood event. See Figures 22 and23.

Figure 22: Picture of Sinkhole D39. (Location of Sinkhole D39 is shown on Figure 21.) This sinkhole formed due to the 14-15 June 2012 flood and was discovered afterwards. Picture is looking east.

Figure 23: Picture of Sinkhole D11. (Location of Sinkhole D11 is shown on Figure 21.) This sinkhole formed due to the 14-15 June 2012 flood and was discovered afterwards. Picture is looking east.

The stream geomorphology changed significantly in the Main Branch of Trout Brook and its tributaries as a result of the flood. One example can be seen on **Figure 24.** This bridge is at the site TB1 (X1) on the East Branch of Trout Brook. The picture shows that the road was washed out on both sides of the bridge. This and other major washouts closed the road through the Miesville Ravine Park Reserve and that road remains impassable.

Figure 24: Picture of Bridge on the East Branch of Trout Brook: X1. (Location of X1 is shown on Figure 2.) This wash out damage occurred from the 14-15 June 2012 flood.

4. Recommendations

- We recommend that the waters of Trout Brook be monitored for nitrates at least annually for the foreseeable future. The springs with the longest data sets: Fox, Swede, LeDuc, and Beaver Springs are the highest priority. These are the largest of the springs, which feed the East and West Branches and the Upper and Lower reaches of the Main Branch of Trout Brook. As the most nitrate contaminated trout stream in southeastern Minnesota, Trout Brook is an important sentinel for the future. Comprehensive biological monitoring of the water would add a significant new dimension to the information.
- Dye tracing should be expanded and other hydrogeologic tools should be used to more clearly define the springsheds of Trout Brook. The two new sinkholes are potential candidates for dye input points. The use of one or more center pivot spray irrigation

systems in the basin as dye input devices could yield significant new evidence on the interactions between groundwater and irrigation. Better defined springsheds will allow for a more precise evaluation of the relationship between row-crop agriculture and nitrate concentrations in the springs and streams. Such knowledge may also provide better estimates of the travel times of groundwater flow, as well as transport of nitrates and other contaminants.

- A detailed GIS-based, historic, current, and future record of farming and other human activities in the Trout Brook watershed needs to be developed and maintained. Information on the historic and current application rates of fertilizer/manure, the timing of fertilizer application, and the pumping rates of irrigation would be beneficial in designing watershed/springshed specific management plans for farmers. Such plans could help reduce the nitrate concentrations in the waters of Trout Brook. Annual updating of such plans with the results of sampling could help to analyze the effects of changes in nutrient management efforts. The nitrate levels in Trout Brook can only be reduced on the watershed/springshed level.

5. Acknowledgments

Funding for this project was provided by the Minnesota Environment and Natural Resources Trust Fund as recommended by the Legislative Citizen Commission on Minnesota Resources (LCCMR). A special thanks to the Karst Waters Institute for awarding the William L. Wilson Scholarship to help support this work.

We acknowledge and thank Dakota County’s Miesville Ravine Park for permission to study Trout Brook, Mr. John Weber for access to his property adjacent to the Park and information about the history of the area, and other local residents for access permission to their property. Justin Watkins of the Minnesota Pollution Control Agency (MPCA) introduced us to Trout Brook and its high nitrate problem. He and his MPCA colleagues have been very helpful with several parts of this work. Mr. Johnny Forrest, the Miesville Ravine Park Naturalist, has provided important historical documents and information on the history of the site. Travis Bistodeau, formerly of the Dakota County SWCD, has facilitated several parts of this work and collected the nitrate data in 2006 and 2010 from Trout Brook. Travis provided the photo shown in **Figure 13**. Jeff Green of the DNR loaned two Solinst LTC Leveloggers that were used to measure temperature at Fox and Swede Springs. We acknowledge the Minneapolis Parks and Recreation Board for loaning us their FLO-MATE flowmeter to measure flow in Trout Brook. Eric Vogel helped sample Trout Brook. This work builds on the work of Bomberg et al. (2011) and other students and summer interns at the University of Minnesota.

Last, but far from least, we acknowledge the pioneering work that Ron C. Spong conducted on Trout Brook in 1985 and 1995. His work provides enormously important data on the water quality and flows from 1985 and 1995, as well as locations and maps of several of the critical springs. It is difficult to overstate the importance of his work.

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Appendix I

Site	Flow (l/s)	Flow (cfs)	Flow (cfs)	% of Total Flow	% of Total Flow
	1985	1985	2011	1985	2011
LeDuc	61	2.2	0.84	11.51	6.67
Bridgestone Spring			0.43		3.41
Trout Brook Main: TB3	530	18.7	12.6	100.00	100.00
Fox Spring	5	0.18	0.38	0.94	3.02
Root Spring			0.15		1.19
Ravine Spring			0.51		4.05
West Trout Brook: TB2	66	2.3	2.56	12.45	20.32
Swede Spring	11	0.39	0.4	2.08	3.17
Beaver Spring	19	0.67	0.82	3.58	6.51
Hillspring			0.005		0.04
Cedar Spring			0.489		3.88
Britco Spring			0.255		2.02
East Trout Brook: TB1	71	2.5	1.72	13.40	13.65
Unaccounted	393	13.9	8.32	74.15	66.03

Table 1: Flow Measured at Streams and Springs of Trout Brook in 1985 and 2011. LeDuc includes all of the flow upstream of Bridgestone Spring. This flow includes upstream of LeDuc, LeDuc Spring, and any flow gained downstream of LeDuc Spring but upstream of Bridgestone Spring. The 1985 flow data was collected by Spong.

Area	Feature	Location		KFDB	Short	Spong
		UTM E	UTM N	#	#	#
Weber Run	Weber Run Headwater Spring (20 Dec 2011)	512991	4936112	MN19:A0085	A85	
	Start of Webber Run Stream Sieve & Webber Springs	512903	4935981	MN19:A0083 MN19:B0001	A83 B1	
	End of Weber Run Stream Sieve (20 Dec 2011)	513537	4935508	MN19:B0002	B2	
	End of Weber Run Stream Sieve (14 Mar 2012)	513307	4935632	MN19:B0003	B3	
	Dye Input Point, 28 Dec 2011 & 12 Apr 2012 Trout Brook Dye Traces	512979	4935970	MN19:X0006	X6	
East Branch of Trout Brook	Upstream of LeDuc Spring	513646	4934896	MN19:X0005	X5	
	LeDuc Spring	513647	4934863	MN19:A0002	A2	DKD 202
	Emergent Spring	513614	4934770	MN19:A0086	A86	
	Bridgestone Spring	513602	4934735	MN19:A0082	A82	DKD 203
	TB1 NE Stream Bridge	513619	4934744	MN19:X0001	X1	
West Branch of Trout Brook	Ledge (dry waterfall)	512579	4934651	MN19:X0004	X4	
	Falls Seep	512642	4934694	MN19:A0081	A81	
	Sand Boil Seep	512669	4934693	MN19:A0080	A80	
	Fox Spring	512857	4934874	MN19:A0003	A3	DKD 206
	Fox Seep	512877	4934875	MN19:A0079	A79	
	Root Spring	513076	4934816	MN19:A0004	A4	DKD 207
	TB2 Seep	513143	4934797	MN19:A0006	A6	DKD 205
	Ravine Spring	513164	4934790	MN19:A0005	A5	DKD 204
	TB2 NW Stream Bridge	513359	4934633	MN19:X0002	X2	
Main Branch of Trout Brook	Boiling Sand Spring	513788	4934371	MN19:A0078	A78	DKD 210
	Beaver Spring	514110	4934408	MN19:A0008	A8	DKD 201
	Hill Spring	514472	4934055	MN19:A0077	A77	
	Cedar Spring	514627	4933959	MN19:A0009	A9	DKD208
	Britco Spring	514587	4933784	MN19:A0084	A84	
	Swede Spring	515086	4932871	MN19:A0010	A10	DKD209
	TB3 Stream Bridge S	515603	4932217	MN19:X0003	X3	
Sinkholes	Sinkhole 1	514666	4937024	MN19:D0039	D39	
	Sinkhole 2	514625	4937037	MN19:D0011	D11	
CRP vs Ag. Watersheds	CRP Field	513679	4935579	MN19:X008	X8	
	Ag. Dominated Watershed Ravine	513730	4935509	MN19:X009	X9	
	AG Field	513902	4935810	MN19:X010	X10	
	CRP Dominated Watershed Ravine	513883	4935740	MN19:X011	X11	
	Start of Ravine	513893	4935797	MN19:X012	X12	

Table 2: Coordinates and Identifiers for Sampling Points, Springs and Features. The location coordinates are UTM northing and easting values, Zone 15, NAD83. The KFDB #s are the formal numbers of the features (19 denotes Dakota Co., A = springs, B = stream sinks/sieves, X = other locations. The short #s are used in the Figures and the text. The Spong #s are an unpublished system he uses and are included for reference purposes.

Appendix II

List 1: Charcoal Bug Locations, Instructions, and Dye Input Details.

Bug Locations and Site Descriptions

X1 – (MN19:X00101) –TB1 East Branch Trout Brook Bridge: (4,934,744 N; 513,619E)
Follow County Road 91 south of Miesville, MN. County Road 91 curves SW and continue to the first bridge. Bug is located under the NE portion of the bridge and is attached to a rock in the stream.

X2 – (MN19:X0002) –TB2 West Branch Trout Brook Bridge: (4,934,633 N; 513,359 E)
Continue following County Road 91 SW of TB1 to a second bridge. Bug is located on the NE side of the bridge. String is attached to a metal rod at the end of a culvert before there is a several foot drop off which creates a small man made waterfall. A rock is attached to the string and a bug is attached to the rock which is at the lower elevation of the water fall.

X3 – (MN19:X0003) – TB3, Trout Brook downstream bridge: (4,932,217 N; 515,603 E)
Continue following County Road 91 south. Go east on 280th at the 'T' intersection to the first bridge on 280th. Bug is located downstream of the bridge. A string is attached to a staff gage and the rock and bug are attached to the string.

A3 – (MN19:A0003) – Fox Spring: (4,934,874 N; 512,857 E)
Follow the West Branch of Trout Brook upstream from the TB2 bridge crossing. Bug is located 5 meters from a bedrock outcrop and bug is located in an upwelling of water.

A82 – (MN19:A0082) – Bridgestone Spring: (4,934,735 N; 513,602 E)
It is located on the southwest corner of the TB1 bridge crossing. Bug is attached to a rock and string underneath the foundation of the bridge.

A2 – (MN19:A0002) – LeDuc Spring: (4,934,863 N; 513,647 E)
Follow the East Branch of Trout Brook upstream from the TB1 bridge crossing. Spring and bug are located on the south bank. Spring is discharging from a gap in the bedrock, and the bug is attached to a rock in the spring.

X5 – (MN19:X0005) – Upstream of LeDuc Spring: (4,934,896 N; 513,646 E)
Is located upstream of LeDuc Spring approximately 20 meters. A dead tree is overhanging and extending the channel of the East Branch of Trout Brook. A string is attached to this dead tree with a rock and bug connected.

A10 – (MN19:A0010) – Swede Spring: (4,932,871 N; 515,086 E)
Is located upstream of TB3 bridge crossing along the Main Branch of Trout Brook. There is a defined trail to this spring with a boardwalk leading directly to the spring. Bug is located at a rock outcrop at the upmost reach of the spring run.

A4 – (MN19:A0004) – Root Spring (4,934,816 N; 513,076 E)
Follow the West Branch of Trout Brook upstream from the TB2 bridge crossing. Bug is located underneath overhanging roots from a tree. Bug is tied to a root. Root Spring is located between Fox and Ravine Springs.

A5 – (MN19:A0005) – Ravine Spring (4,934,790 N; 513,164 E)
Follow the West Branch of Trout Brook upstream from the TB2 bridge crossing. Bug is located downstream of a ravine. Bug is in a formed spring channel and is attached to a dead limb. Ravine Spring is the first spring on the West Branch traveling upstream.

Dye Input Information

X5 - (MN19:X0005) – (512,979 E; 4,935,970 N – UTM, Zone 15, NAD 83)

Dye Trace #1

Dye Injected: 1,050 grams of 20% weight solution of Rhodamine WT Dye, Chromatech D 13800 (Lot 041807).

Date and Time: 28 December 2011 at 12:20 PM CDT

Dye Trace #2

Dye Injected: 2.137 kg of 33 wt. % Eosine Solution

Date: 12 April 2012

Land Owner: John Weber
12732 260th St. NE
Cannon Falls, MN 55009
(507) 263-2737

Table 3: Results from Spectrofluorophotometric Analysis of Dye Trace # 1

Trout Brook Dye Trace (2011-2012) #1			TB1		TB2	TB3	TB4	TB5	TB6	TB7	TB8	TB9
KFDB #	Short #	Site	Dec. 22-28, 2011	28 Dec. 2011 Dye Poured	Dec. 28-31, 2011	Dec. 31, 2011-Jan. 9, 2012	Jan. 9-18, 2012	Jan. 18-26, 2012	Jan. 26-Feb. 12, 2012	Feb. 12-Mar. 2, 2012	Mar. 2-Mar. 24, 2012	Mar.24-Apr. 12, 2012
MN19:A0003	A3	Fox Spring	nd		nd	nd	nd	nd	nd	nd	nd	nd
MN19:A0004	A4	Root Spring	🟨		🟨	🟨	🟨	🟨	🟨	🟨	🟨	nd
MN19:A0005	A5	Ravine Spring	🟨		🟨	🟨	🟨	🟨	🟨	🟨	🟨	nd
MN19:A0082	A82	Bridgestone Spring	nd		nd	nd	nd	nd	nd	nd	RhWT (11.5 σ)	RhWT (37.1 σ)
MN19:A0002	A2	LeDuc Spring	nd		nd	nd	nd	nd	RhWT (27.5 σ)	RhWT (12.5 σ)	RhWT (56 σ)	RhWT (53.2σ)
MN19:X0005	X5	Upstream of LeDuc Spring	nd		nd	nd	nd	nd	nd	nd	nd	nd
MN19:X0001	X1	TB1 NE Stream Bridge	nd		nd	nd	nd	nd	nd	RhWT (3.8 σ)	nd	nd
MN19:A0002	X2	TB2 NW Stream Bridge	nd		nd	nd	nd	nd	nd	🟨	nd	nd
MN19:X0003	X3	TB3 South Stream Bridge	nd		nd	nd	nd	nd	nd	nd	nd	nd
MN19:A0010	A10	Swede Spring	🟨		🟨	🟨	🟨	🟨	🟨	nd	nd	nd

nd = no dye detected

empty = no charcoal in bug

yellow highlighted cell = no bug was received

RhWT = Rhodamine WT dye present in quantifiable levels (>10 σ)

RhWT = Rhodamine WT dye detected at less than quantifiable levels (3 < σ < 10)

Rhodamine WT was poured on 28 December 2011 into Weber Run.

Table 4: Results from Spectrofluorophotometric Analysis of Dye Trace # 2

Trout Brook Dye Trace (2011-2012) #2				TB1	TB2	TB3	TB4	TB5	TB6	TB7	TB8	TB9	TB10	TB11	TB12	TB13
KFDB #	Short #	Site	12 Apr. 2012 dye poured	Apr. 12-26, 2012	Apr. 26-May 2, 2012	May 2 - May 8, 2012	May 8 - May 16, 2012	May 16 - May 31, 2012	May 31 - June 7, 2012	June 7 - June 21, 2012	Jun 13 - Jun 21, 2012	Jun 21 - Jun 30, 2012	Jun 21 - July 13, 2012	Jun 30 - Jul 13, 2012	July 13 - Aug. 6, 2012	Aug. 6 - Oct. 01, 2012
MN19:A0003	A3	Fox Spring		nd	🟨	🟨	nd	nd	nd	nd		nd	🟨	nd		nd
MN19:A0004	A4	Root Spring		nd	🟨	🟨	nd	nd	nd	nd			🟨	nd		
MN19:A0005	A5	Ravine Spring		nd	🟨	🟨	nd	nd	nd	🟨	🟨	🟨	🟨	nd		
MN19:A0082	A82	Bridgestone Spring		RhWT (61.9σ)	RhWT (10.8σ)	🟨	RhWT (39.5σ)	RhWT (30.3σ)	RhWT (52.1σ)	🟨	RhWT (7.2σ)		RhWT (4.5σ)		nd	RhWT (5.6σ)
MN19:A0002	A2	LeDuc Spring		RhWT (41.9σ)	RhWT (15.3σ)	RhWT (14.5σ)	RhWT (13.2σ)	RhWT (13.5σ)	RhWT (33.3σ)	🟨	nd	nd	🟨	EOS (21.8σ) RhWT (51.1σ)	EOS (7.3σ) RhWT (11.9σ)	EOS (19.6σ) RhWT (12.9σ)
MN19:X0005	X5	Upstream of LeDuc Spring		nd	nd	🟨	nd	nd	nd	🟨	nd	nd	🟨	nd	nd	nd
MN19:X0001	X1	TB1 NE Stream Bridge		RhWT (3.3 σ)	🟨	🟨	RhWT (12.4σ)		nd	🟨	🟨	🟨	🟨	nd	nd	nd
MN19:A0002	X2	TB2 NW Stream Bridge		nd	🟨	🟨	🟨	🟨	nd	nd	🟨	nd	🟨	nd		nd
MN19:X0003	X3	TB3 South Stream Bridge		nd	🟨	🟨	RhWT (5.9 σ)			🟨	🟨	🟨	🟨	nd		nd
MN19:A0010	A10	Swede Spring		nd	🟨	🟨	nd			nd	🟨	nd	🟨	nd		nd

nd = no dye detected

empty = no charcoal in bug

yellow highlighted cell = no bug was received

RhWT = Rhodamine WT dye present in quantifiable levels (>10 σ)

RhWT = Rhodamine WT dye detected at less than quantifiable levels (3 > σ < 10)

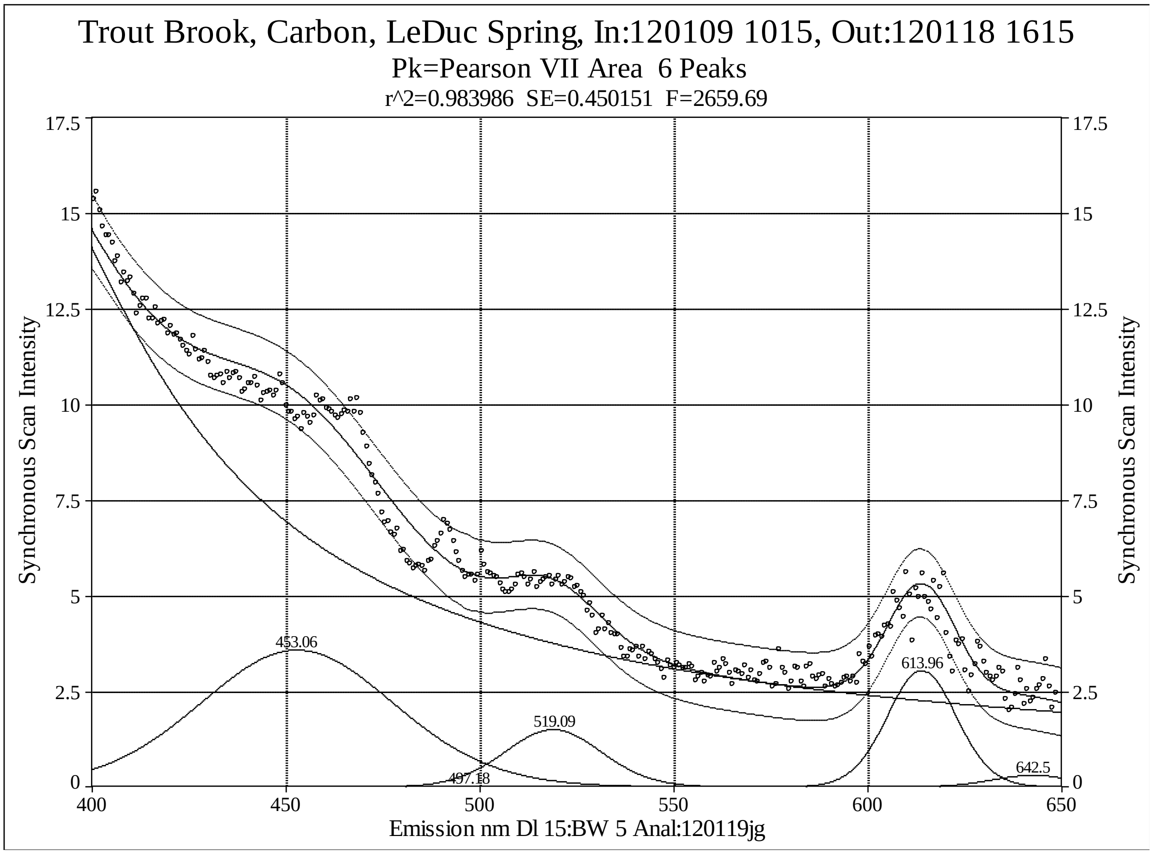
EOS = eosine dye present in quantifiable levels (>10 σ)

EOS = eosine dye present at less than quantifiable levels (3 > σ > 10)

Rhodamine WT was poured on 28 December 2011 into Weber Run.

Eosine was poured on 12 April 2012 into Weber Run.

Graph 1: Fluorescent Spectrum, LeDuc Spring Bug, 9 Jan to 18 Jan 2012



Description: Trout Brook, Carbon, LeDuc Spring, In:120109 1015, Out:120118 1615
X Variable: Emission nm Δλ 15:BW 5 Anal:120119jg
Y Variable: Synchronous Scan Intensity
File Source: c:\karst stuff\joel\troutbrook\january 2012\tbld011

Fitted Parameters

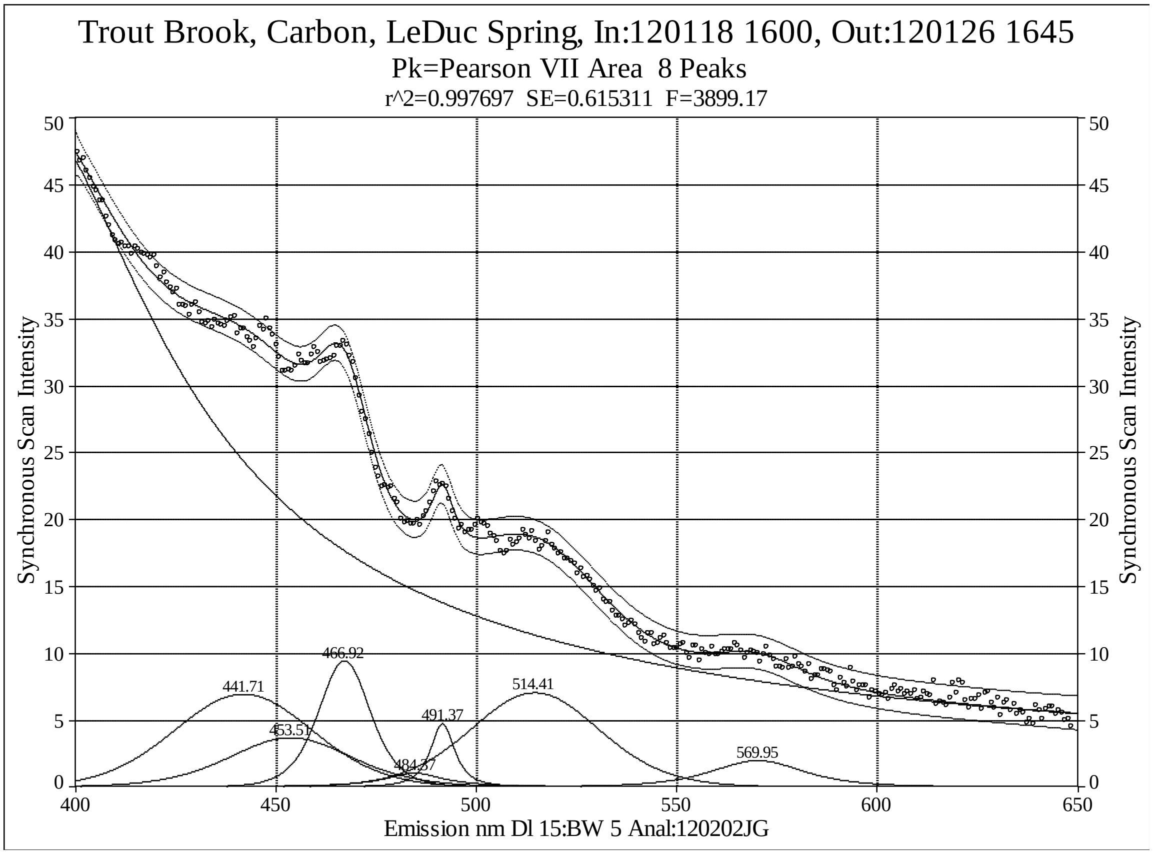
r^2 Coef Det	DF Adj r^2	Fit Std Err	F-value
0.98398588	0.98356167	0.45015103	2659.68690

Peak	Type	a_0	a_1	a_2	a_3
1	Pearson VII Area	55716.3274	377.888018	111.891592	0.51024918
2	Pearson VII Area	231.975070	453.056517	59.4002307	10.0000000
3	Pearson VII Area	6.59124227	497.181191	14.8541831	0.51000000
4	Pearson VII Area	48.7630773	519.088812	29.6846955	10.0000000
5	Pearson VII Area	68.8525174	613.956171	20.7612457	10.0000000
6	Pearson VII Area	8.65125088	642.502884	25.3748558	10.0000000

Measured Values

Peak	Type	Amplitude	Center	FWHM	Asym50	FW Base	Asym10
1	Pearson VII Area	17.1106904	377.912341	111.891634	0.99913084	0.00000000	0.00000000
2	Pearson VII Area	3.59120521	453.056517	59.4002307	1.00000000	124.072338	1.00000000
3	Pearson VII Area	0.01488856	497.181191	14.8541831	1.00000001	92.8775570	1.00000000
4	Pearson VII Area	1.51058632	519.088812	29.6846955	1.00000000	62.0039606	1.00000000
5	Pearson VII Area	3.04967427	613.956171	20.7612457	1.00000000	43.3650890	1.00000000
6	Pearson VII Area	0.31351792	642.502884	25.3748558	1.00000000	53.0017754	1.00000000

Graph 2: Fluorescent Spectrum, LeDuc Spring Bug, 18 Jan to 26 Jan 2012



Description: Trout Brook, Carbon, LeDuc Spring, In:120118 1600, Out:120126 1645
X Variable: Emission nm Δλ 15:BW 5 Anal:120202JG
Y Variable: Synchronous Scan Intensity
File Source: c:\karst stuff\joel\troutbrook\january 2012\1-26-2012\tbls01

Fitted Parameters

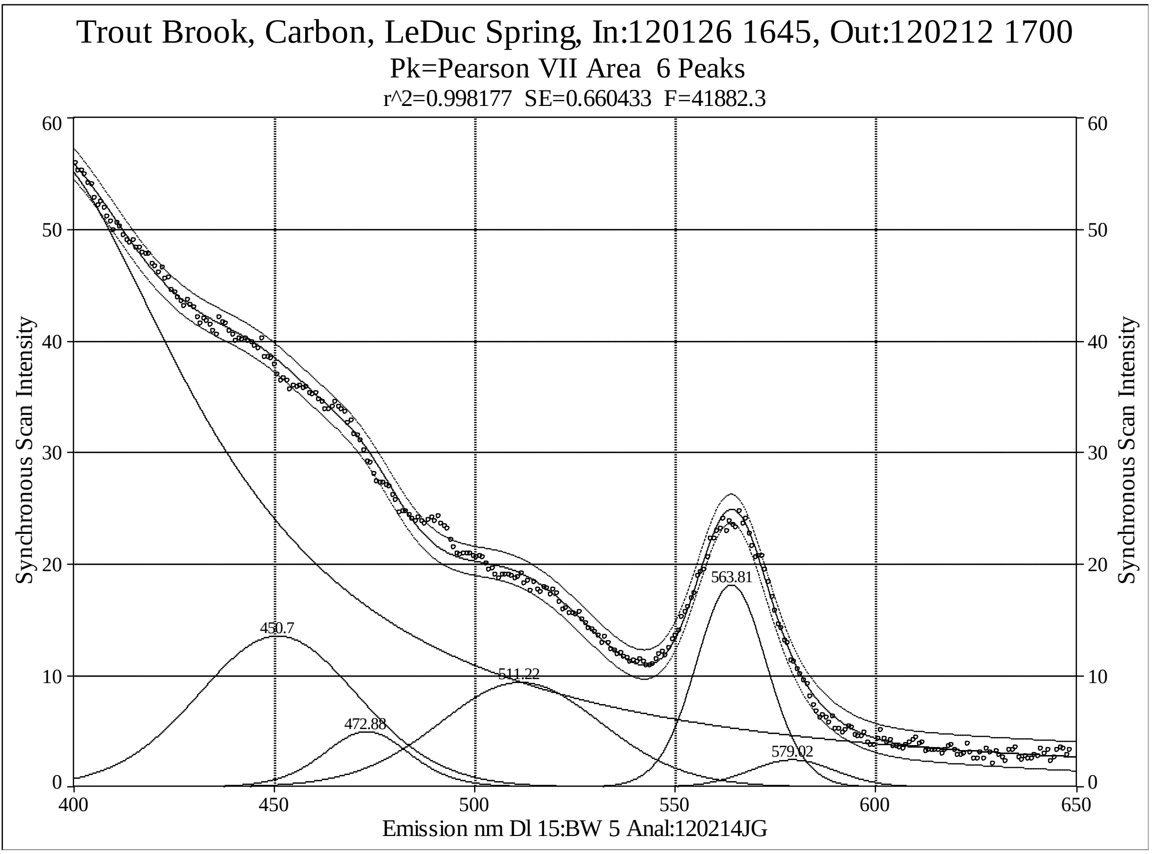
r^2 Coef Det	DF Adj r^2	Fit Std Err	F-value
0.99769713	0.99743205	0.61531104	3899.16719

Peak	Type	a0	a1	a2	a3
1	Pearson VII Area	1.0795e+05	387.542384	103.251756	0.51465040
2	Pearson VII Area	309.574245	441.713379	40.9448418	11.0654557
3	Pearson VII Area	153.082057	453.514384	36.4031555	3.78759061
4	Pearson VII Area	167.803158	466.923250	15.2815453	2.91573461
5	Pearson VII Area	34.1673764	484.374555	18.3766103	0.88123087
6	Pearson VII Area	46.9813166	491.372370	7.19117858	1.28550032
7	Pearson VII Area	298.467014	514.405364	38.2997436	6.33880776
8	Pearson VII Area	69.6517794	569.945652	27.6225427	1.70694076

Measured Values

Peak	Type	Amplitude	Center	FWHM	Asym50	FW Base	Asym10
1	Pearson VII Area	50.5390770	389.543726	103.549656	0.92556770	0.00000000	0.00000000
2	Pearson VII Area	6.96776142	441.713379	40.9448418	1.00000000	85.1664657	1.00000000
3	Pearson VII Area	3.71220698	453.514384	36.4031555	1.00000001	81.8843084	1.00000000
4	Pearson VII Area	9.47663323	466.923250	15.2815453	0.99999999	35.6882249	0.99999999
5	Pearson VII Area	1.06739192	484.374555	18.3766103	1.00000000	66.4613489	1.00000000
6	Pearson VII Area	4.74832780	491.372369	7.19117858	1.00000038	21.0810199	1.00000014
7	Pearson VII Area	7.07002454	514.405362	38.2997436	1.00000020	82.0637601	1.00000010
8	Pearson VII Area	1.99972304	569.945652	27.6225427	1.00000000	72.9366522	1.00000000

Graph 3: Fluorescent Spectrum, LeDuc Spring Bug, 26 Jan to 12 Feb 2012



Description: Trout Brook, Carbon, LeDuc Spring, In:120126 1645, Out:120212 1700
X Variable: Emission nm Δλ 15:BW 5 Anal:120214JG
Y Variable: Synchronous Scan Intensity
File Source: c:\karst stuff\joel\troutbrook\February 2012\2-12-2012\tbls02

Fitted Parameters

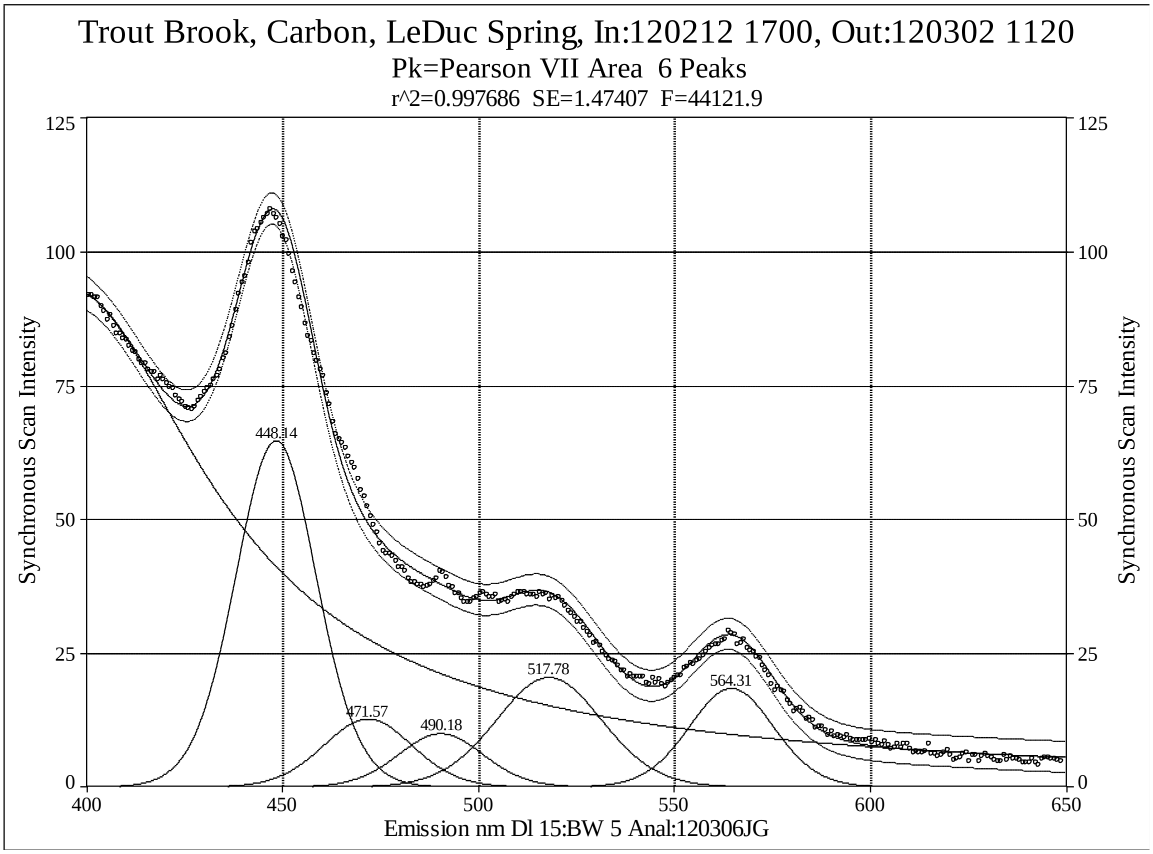
r^2 Coef Det	DF Adj r^2	Fit Std Err	F-value
0.99817678	0.99814690	0.66043314	41882.3439

Peak	Type	a_0	a_1	a_2	a_3
1	Pearson VII Area	10340.2530	388.762386	102.382820	0.87995432
2	Pearson VII Area	698.184310	450.697080	47.2895030	10.0000000
3	Pearson VII Area	141.998940	472.877060	25.3748560	4.73376368
4	Pearson VII Area	493.160960	511.216730	48.1622300	10.0000000
5	Pearson VII Area	413.331670	563.814960	20.9125480	10.0000000
6	Pearson VII Area	67.9782150	579.024080	25.3748560	10.0000000

Measured Values

Peak	Type	Amplitude	Center	FWHM	Asym50	FW Base	Asym10
1	Pearson VII Area	57.8962441	389.131812	102.388681	0.98567107	0.00000000	0.00000000
2	Pearson VII Area	13.5766423	450.697080	47.2895030	1.00000000	98.7760338	1.00000000
3	Pearson VII Area	5.00966035	472.877060	25.3748560	1.00000007	55.7011139	1.00000003
4	Pearson VII Area	9.41605836	511.216730	48.1622300	1.00000000	100.598944	1.00000000
5	Pearson VII Area	18.1751821	563.814961	20.9125480	0.99999976	43.6811220	0.99999987
6	Pearson VII Area	2.46350365	579.024081	25.3748560	0.99999982	53.0017758	0.99999991

Graph 4: Fluorescent Spectrum, LeDuc Spring Bug, 12 Feb to 2 Mar 2012



Description: Trout Brook, Carbon, LeDuc Spring, In:120212 1700, Out:120302 1120
X Variable: Emission nm Δλ 15:BW 5 Anal:120306JG
Y Variable: Synchronous Scan Intensity
File Source: c:\karst stuff\joel\troutbrook\march 2012\3-02-12\tbls03

Fitted Parameters

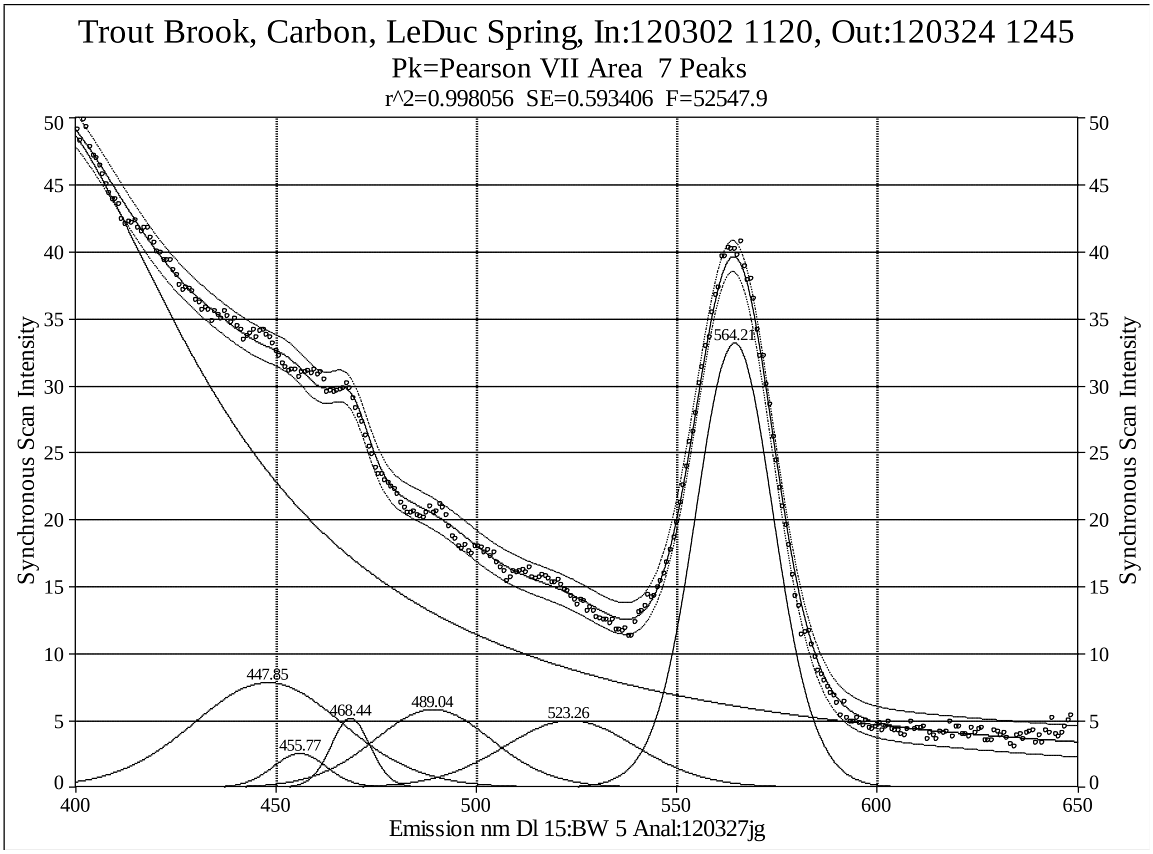
r^2 Coef Det	DF Adj r^2	Fit Std Err	F-value
0.99768603	0.99765578	1.47407318	44121.8613

Peak	Type	a_0	a_1	a_2	a_3
1	Pearson VII Area	19704.3911	395.509682	92.4094074	0.71868368
2	Pearson VII Area	1718.21260	448.138639	24.3902439	10.0000000
3	Pearson VII Area	374.465900	471.566110	26.9576380	10.0000000
4	Pearson VII Area	280.212580	490.179720	25.6739410	10.0000000
5	Pearson VII Area	716.452620	517.779200	32.0924260	10.0000000
6	Pearson VII Area	515.845890	564.313220	25.6739410	10.0000000

Measured Values

Peak	Type	Amplitude	Center	FWHM	Asym50	FW Base	Asym10
1	Pearson VII Area	93.1671403	395.509682	92.4094074	1.00000000	0.00000000	0.00000000
2	Pearson VII Area	64.7810219	448.138639	24.3902439	1.00000000	50.9451655	1.00000000
3	Pearson VII Area	12.7737225	471.566110	26.9576380	0.99999994	56.3078145	0.99999997
4	Pearson VII Area	10.0364963	490.179718	25.6739410	1.00000038	53.6264901	1.00000020
5	Pearson VII Area	20.5291972	517.779199	32.0924260	1.00000013	67.0331121	1.00000007
6	Pearson VII Area	18.4762775	564.313222	25.6739410	0.99999968	53.6264901	0.99999983

Graph 5: Fluorescent Spectrum, LeDuc Spring Bug, 2 to 24 Mar 2012



Description: Trout Brook, Carbon, LeDuc Spring, In:120302 1120, Out:120324 1245

X Variable: Emission nm Δλ 15:BW 5 Anal:120327jg

Y Variable: Synchronous Scan Intensity

File Source: c:\karst stuff\joel\troutbrook\march 2012\3-24-12\tbls03

Fitted Parameters

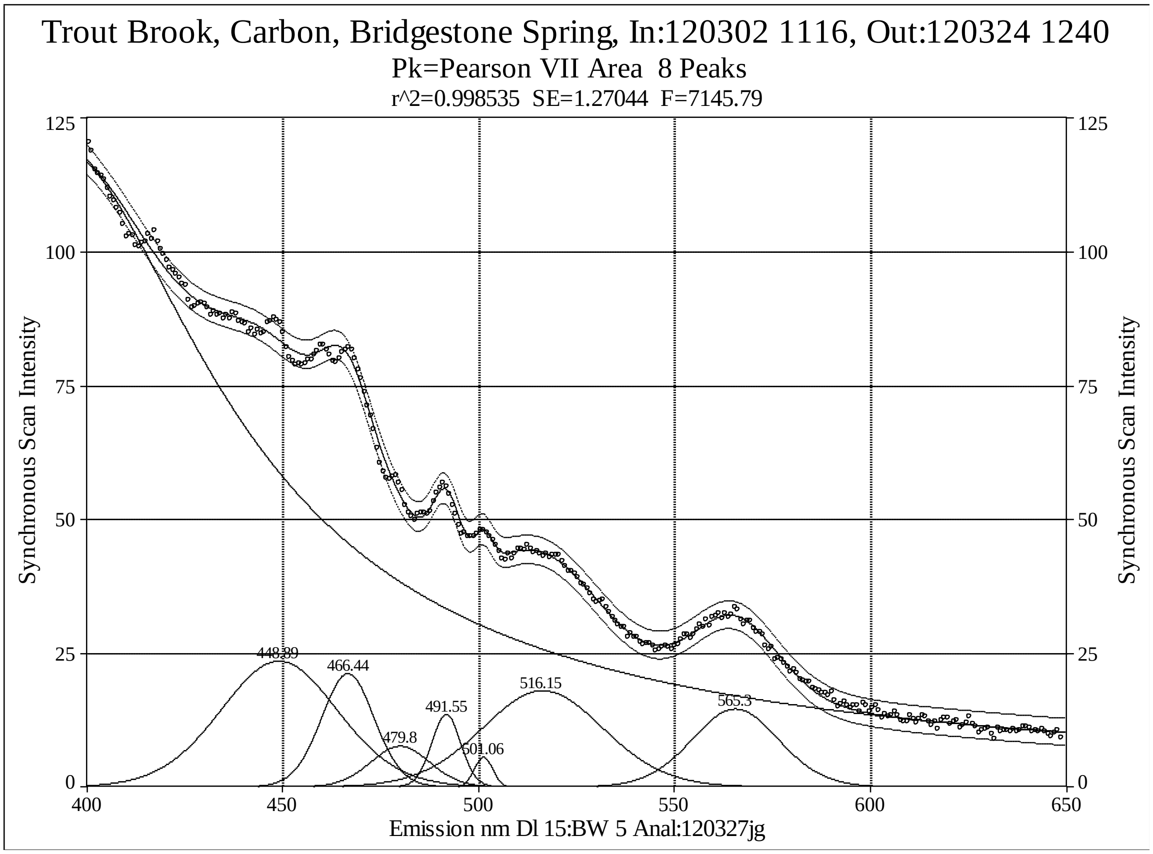
r^2 Coef Det	DF Adj r^2	Fit Std Err	F-value
0.99805636	0.99803095	0.59340567	52547.8955

Peak	Type	a_0	a_1	a_2	a_3
1	Pearson VII Area	11671.4533	386.882412	110.691775	0.77136661
2	Pearson VII Area	378.522670	447.845370	44.3599490	10.0000000
3	Pearson VII Area	44.0142640	455.766790	15.8428390	10.0000000
4	Pearson VII Area	64.5123360	468.441060	11.4068440	10.0000000
5	Pearson VII Area	221.328870	489.036760	34.8542460	10.0000000
6	Pearson VII Area	214.412340	523.257290	39.2902410	10.0000000
7	Pearson VII Area	839.510470	564.214200	23.2446130	10.0000000

Measured Values

Peak	Type	Amplitude	Center	FWHM	Asym50	FW Base	Asym10
1	Pearson VII Area	51.4587029	390.683871	111.331242	0.87214913	0.00000000	0.00000000
2	Pearson VII Area	7.84671531	447.845369	44.3599490	1.00000005	92.6569227	1.00000003
3	Pearson VII Area	2.55474451	455.766789	15.8428390	1.00000029	33.0917582	1.00000015
4	Pearson VII Area	5.20072997	468.441060	11.4068440	1.00000002	23.8260658	1.00000001
5	Pearson VII Area	5.83941598	489.036760	34.8542460	0.99999997	72.8018686	0.99999998
6	Pearson VII Area	5.01824804	523.257288	39.2902410	1.00000023	82.0675610	1.00000012
7	Pearson VII Area	33.2116794	564.214201	23.2446130	0.99999986	48.5522269	0.99999993

Graph 6: Fluorescent Spectrum, Bridgestone Spring Bug, 2 to 24 Mar 2012



Description: Trout Brook, Carbon, Bridgestone Spring, In:120302 1116, Out:120324 1240
X Variable: Emission nm Δλ 15:BW 5 Anal:120327jg
Y Variable: Synchronous Scan Intensity
File Source: c:\karst stuff\joel\troutbrook\march 2012\3-24-12\tbbs03

Fitted Parameters

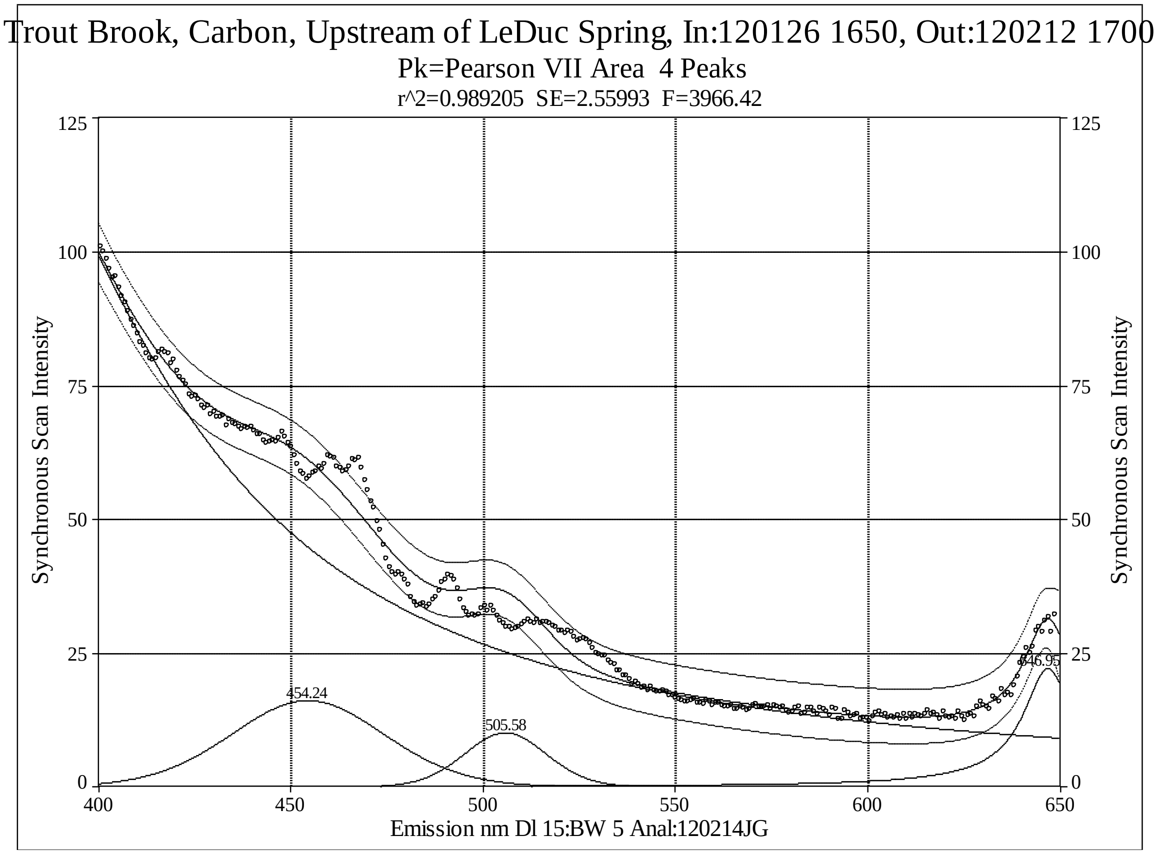
r^2 Coef Det	DF Adj r^2	Fit Std Err	F-value
0.99853534	0.99838992	1.27044414	7145.79266

Peak	Type	a_0	a_1	a_2	a_3
1	Pearson VII Area	35941.2403	391.202230	112.606355	0.67070398
2	Pearson VII Area	908.756690	448.893070	35.4430380	10.0000000
3	Pearson VII Area	368.774671	466.441347	15.9630207	10.0000000
4	Pearson VII Area	150.124033	479.798250	17.9199752	10.0000000
5	Pearson VII Area	129.934614	491.551960	8.74472072	10.0000000
6	Pearson VII Area	32.9420987	501.056126	5.52741292	167.867755
7	Pearson VII Area	721.892448	516.150855	36.7624881	10.0000000
8	Pearson VII Area	418.539271	565.303574	26.2782711	10.0000000

Measured Values

Peak	Type	Amplitude	Center	FWHM	Asym50	FW Base	Asym10
1	Pearson VII Area	120.275941	391.202230	112.606355	1.00000000	0.00000000	0.00000000
2	Pearson VII Area	23.5778239	448.893069	35.4430380	1.00000006	74.0317089	1.00000003
3	Pearson VII Area	21.2438413	466.441347	15.9630207	1.00000000	33.3427879	1.00000000
4	Pearson VII Area	7.70370882	479.798250	17.9199752	1.00000000	37.4303801	1.00000000
5	Pearson VII Area	13.6636257	491.551960	8.74472072	1.00000000	18.2655510	1.00000000
6	Pearson VII Area	5.59208175	501.056124	5.52741292	1.00000139	11.0917422	1.00000076
7	Pearson VII Area	18.0573760	516.150855	36.7624881	1.00000000	76.7877127	1.00000000
8	Pearson VII Area	14.6462507	565.303574	26.2782711	1.00000000	54.8887858	1.00000000

Graph 7: Fluorescent Spectrum, Upstream of LeDuc Bug, 26 Jan to 12 Feb 2012



Description: Trout Brook, Carbon, Upstream of LeDuc Spring, In:120126 1650, Out:120212 1700
X Variable: Emission nm Δλ 15:BW 5 Anal:120214JG
Y Variable: Synchronous Scan Intensity
File Source: c:\karst stuff\joel\troutbrook\febuary 2012\2-12-2012\tbup02

Fitted Parameters

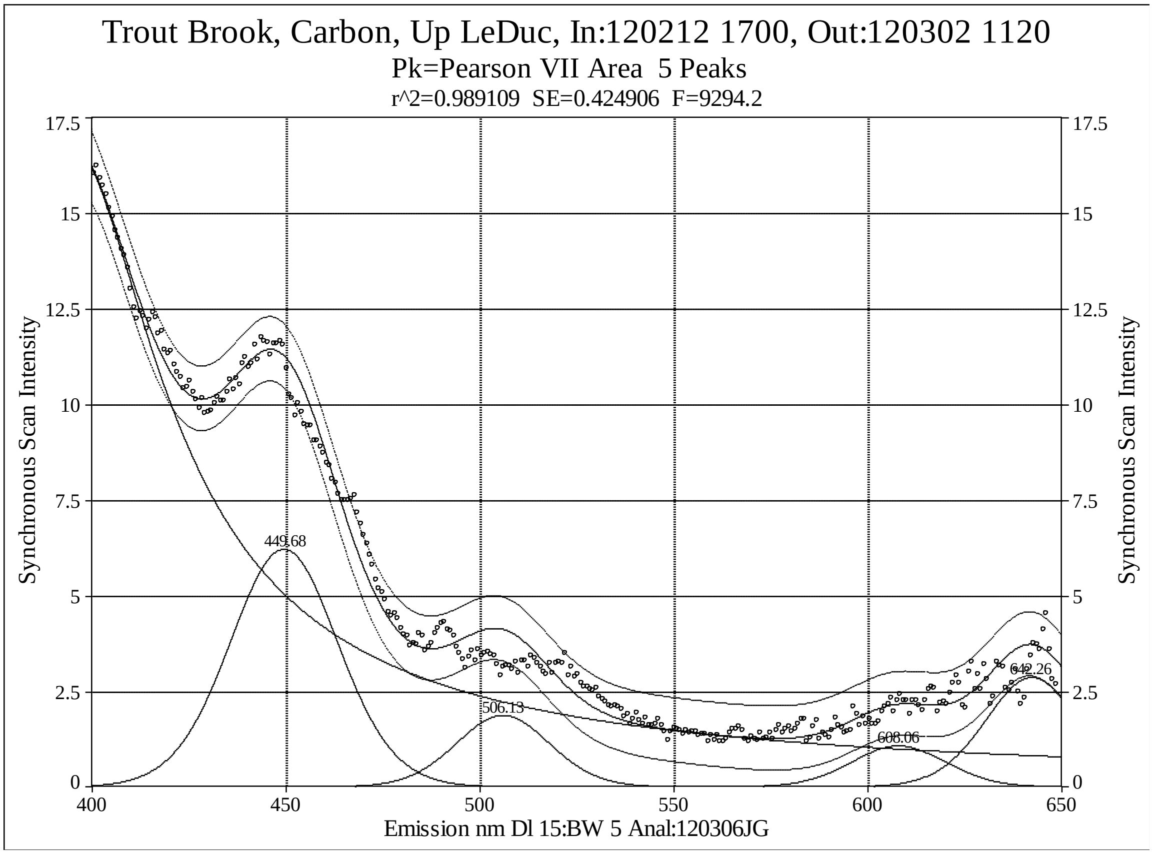
r^2 Coef Det	DF Adj r^2	Fit Std Err	F-value
0.98920477	0.98891880	2.55993093	3966.42075

Peak	Type	a_0	a_1	a_2	a_3
1	Pearson VII Area	34547.4097	361.406857	121.063265	0.77814540
2	Pearson VII Area	833.316763	454.236200	47.2895031	10.0000000
3	Pearson VII Area	280.976623	505.584082	25.3748560	10.0000000
4	Pearson VII Area	760.344721	646.953459	16.6884328	0.76702847

Measured Values

Peak	Type	Amplitude	Center	FWHM	Asym50	FW Base	Asym10
1	Pearson VII Area	131.813418	377.214377	130.736847	0.61053682	0.00000000	0.00000000
2	Pearson VII Area	16.2043796	454.236200	47.2895031	1.00000000	98.7760339	1.00000000
3	Pearson VII Area	10.1824818	505.584082	25.3748560	1.00000000	53.0017759	1.00000000
4	Pearson VII Area	22.1700717	646.953460	16.6884328	0.99999960	67.0888630	0.99999989

Graph 8: Fluorescent Spectrum, Upstream of LeDuc Bug, 12 Feb to 2 March 2012



Description: Trout Brook, Carbon, Up LeDuc, In:120212 1700, Out:120302 1120
X Variable: Emission nm Δλ 15:BW 5 Anal:120306JG
Y Variable: Synchronous Scan Intensity
File Source: c:\karst stuff\joel\troutbrook\march 2012\3-02-12\tbup03

Fitted Parameters

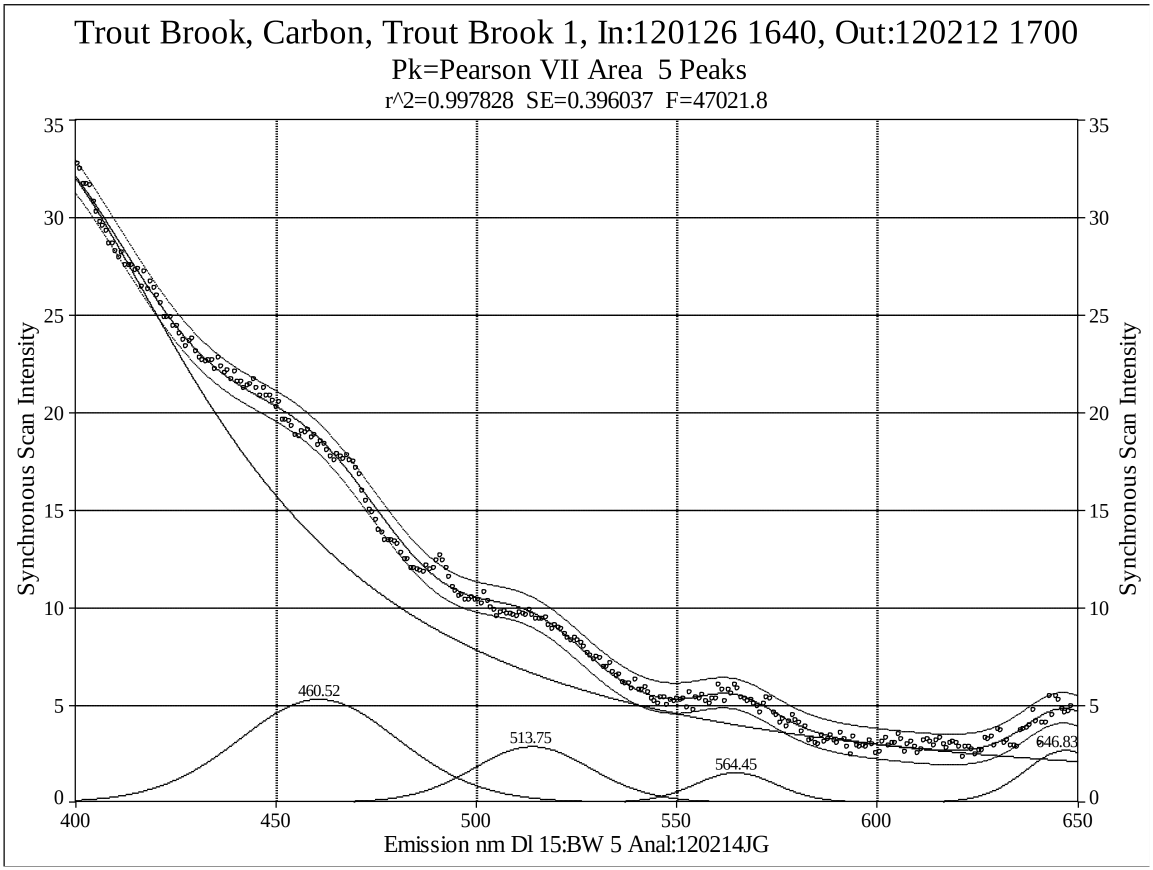
r^2 Coef Det	DF Adj r^2	Fit Std Err	F-value
0.98910946	0.98896710	0.42490579	9294.19760

Peak	Type	a_0	a_1	a_2	a_3
1	Pearson VII Area	3410.02190	394.394287	65.6477945	0.63539330
2	Pearson VII Area	222.814550	449.677420	32.9032260	10.0000000
3	Pearson VII Area	58.4289360	506.129030	28.5171100	10.0000000
4	Pearson VII Area	33.6709120	608.064520	28.5171100	10.0000000
5	Pearson VII Area	89.1288850	642.258060	28.5171100	10.0000000

Measured Values

Peak	Type	Amplitude	Center	FWHM	Asym50	FW Base	Asym10
1	Pearson VII Area	16.8113517	394.394289	65.6477945	0.99999990	0.00000000	0.00000000
2	Pearson VII Area	6.22718985	449.677419	32.9032260	1.00000008	68.7266721	1.00000004
3	Pearson VII Area	1.88412411	506.129032	28.5171100	0.99999968	59.5651644	0.99999983
4	Pearson VII Area	1.08576643	608.064516	28.5171100	1.00000054	59.5651644	1.00000029
5	Pearson VII Area	2.87408761	642.258058	28.5171100	1.00000027	59.5651644	1.00000014

Graph 9: Fluorescent Spectrum, TB1 Bug, 26 Jan to 12 Feb 2012



Description: Trout Brook, Carbon, Trout Brook 1, In:120126 1640, Out:120212 1700
X Variable: Emission nm Δλ 15:BW 5 Anal:120214JG
Y Variable: Synchronous Scan Intensity
File Source: c:\karst stuff\joel\troutbrook\febuary 2012\2-12-2012\tbt102

Fitted Parameters

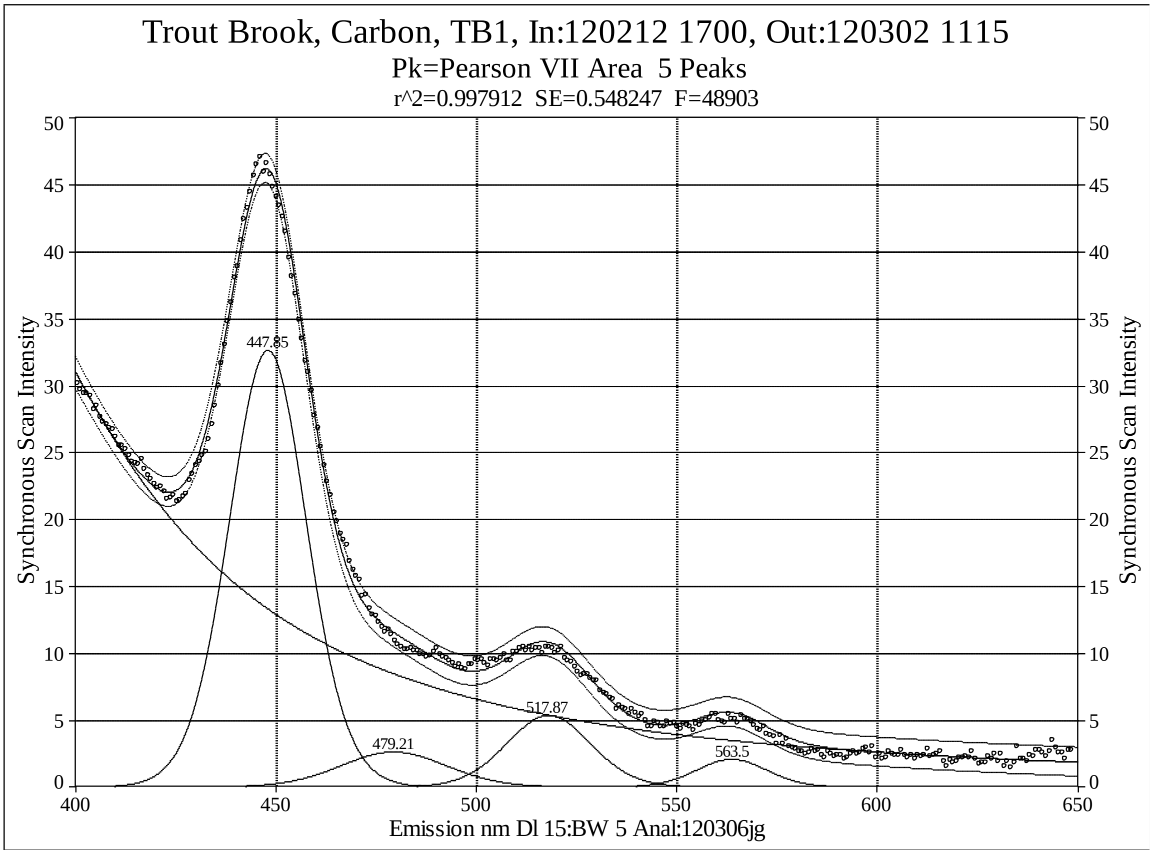
r^2 Coef Det	DF Adj r^2	Fit Std Err	F-value
0.99782843	0.99780004	0.39603746	47021.7740

Peak	Type	a_0	a_1	a_2	a_3
1	Pearson VII Area	7360.91066	382.744156	121.959435	0.88205872
2	Pearson VII Area	272.610940	460.519650	47.2895030	10.0000000
3	Pearson VII Area	108.935300	513.751580	34.8542460	10.0000000
4	Pearson VII Area	40.1410090	564.448670	24.0811150	10.0000000
5	Pearson VII Area	70.2467660	646.831430	24.0811150	10.0000000

Measured Values

Peak	Type	Amplitude	Center	FWHM	Asym50	FW Base	Asym10
1	Pearson VII Area	34.6805540	382.744156	121.959435	1.00000000	0.00000000	0.00000000
2	Pearson VII Area	5.30109479	460.519650	47.2895030	1.00000000	98.7760338	1.00000000
3	Pearson VII Area	2.87408747	513.751579	34.8542460	1.00000010	72.8018686	1.00000005
4	Pearson VII Area	1.53284673	564.448669	24.0811150	1.00000013	50.2994720	1.00000007
5	Pearson VII Area	2.68248179	646.831432	24.0811150	0.99999964	50.2994720	0.99999981

Graph 10: Fluorescent Spectrum, TB1 Bug, 12 Feb to 2 Mar 2012



Description: Trout Brook, Carbon, TB1, In:120212 1700, Out:120302 1115
X Variable: Emission nm Δλ 15:BW 5 Anal:120306jg
Y Variable: Synchronous Scan Intensity
File Source: c:\karst stuff\joel\troutbrook\march 2012\3-02-12\tbt103

Fitted Parameters

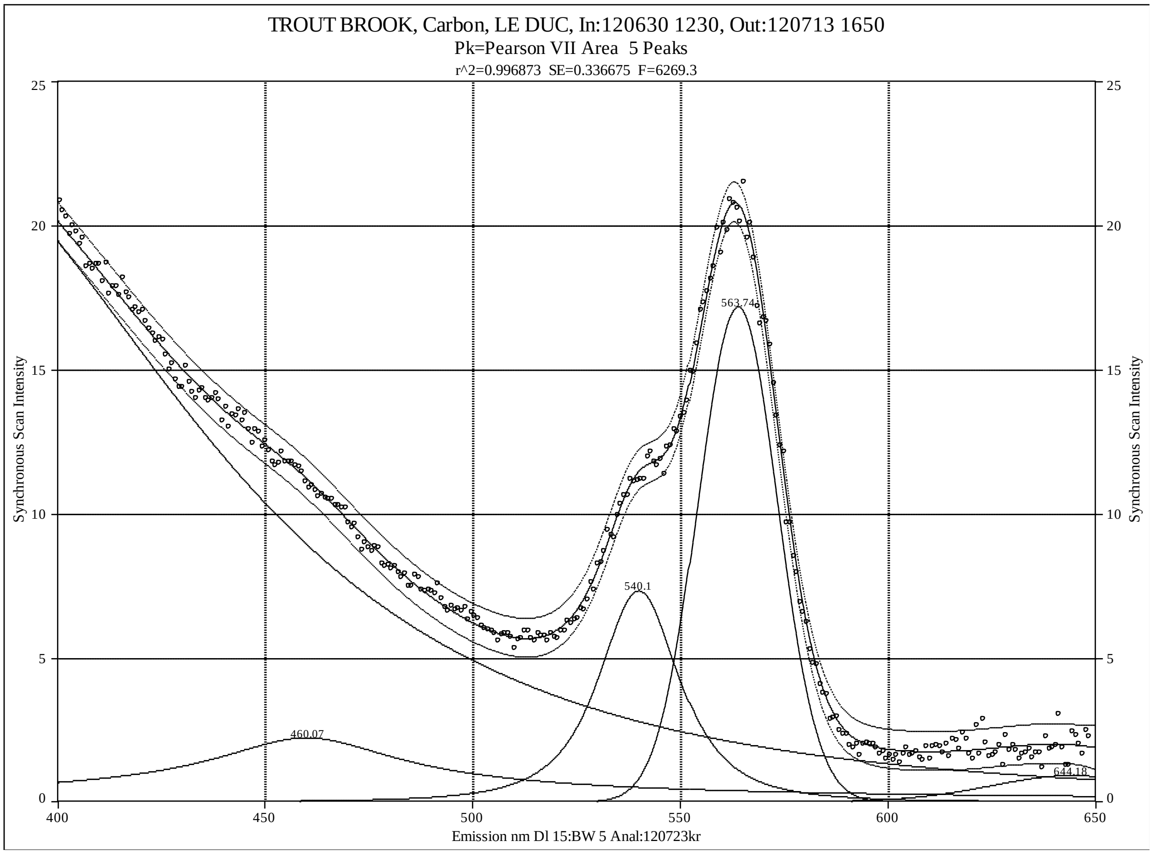
r^2 Coef Det	DF Adj r^2	Fit Std Err	F-value
0.99791179	0.99788450	0.54824741	48903.0269

Peak	Type	a_0	a_1	a_2	a_3
1	Pearson VII Area	8685.80583	360.140252	105.378402	0.91380380
2	Pearson VII Area	810.365480	447.845370	22.8136880	10.0000000
3	Pearson VII Area	89.9785680	479.214200	31.2707770	10.0000000
4	Pearson VII Area	144.681170	517.870720	24.7148290	10.0000000
5	Pearson VII Area	47.7240380	563.498100	20.9125480	10.0000000

Measured Values

Peak	Type	Amplitude	Center	FWHM	Asym50	FW Base	Asym10
1	Pearson VII Area	47.6751015	368.504436	108.176245	0.73214170	0.00000000	0.00000000
2	Pearson VII Area	32.6642337	447.845369	22.8136880	1.00000010	47.6521315	1.00000005
3	Pearson VII Area	2.64598540	479.214202	31.2707770	0.99999973	65.3168913	0.99999986
4	Pearson VII Area	5.38321148	517.870722	24.7148290	0.99999961	51.6231432	0.99999979
5	Pearson VII Area	2.09854010	563.498099	20.9125480	1.00000022	43.6811220	1.00000011

Graph 11: Fluorescent Spectrum, LeDuc Spring Bug, 30 June to 13 July 2012



Description: TROUT BROOK, Carbon, LE DUC, In:120630 1230, Out:120713 1650
X Variable: Emission nm Δλ 15:BW 5 Anal:120723kr
Y Variable: Synchronous Scan Intensity
File Source: c:\documents and settings\peakfit\desktop\reu rawdata\rawdata0713\lduc07

Fitted Parameters

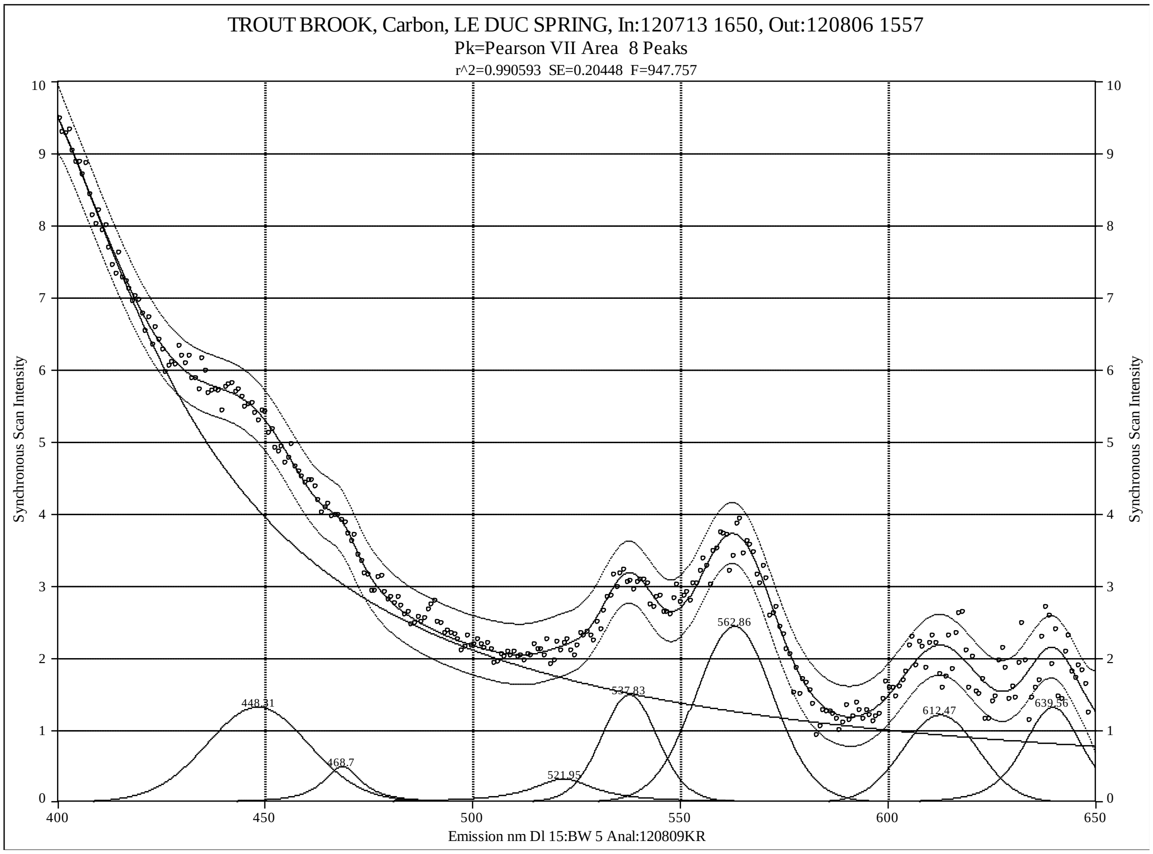
r^2 Coef Det	DF Adj r^2	Fit Std Err	F-value
0.99687283	0.99670264	0.33667521	6269.29807

Peak	Type	a_0	a_1	a_2	a_3
1	Pearson VII Area	4669.03223	363.561470	157.794677	1.63337039
2	Pearson VII Area	1176.87694	460.066962	69.2779930	0.54347991
3	Pearson VII Area	219.332332	540.102467	22.8864374	1.49770095
4	Pearson VII Area	412.013105	563.742142	22.4760237	167.918401
5	Pearson VII Area	47.6251304	644.175246	47.0980125	9.16565455

Measured Values

Peak	Type	Amplitude	Center	FWHM	Asym50	FW Base	Asym10
1	Pearson VII Area	23.2142857	363.561470	157.794677	1.00000000	0.00000000	0.00000000
2	Pearson VII Area	2.24059946	460.066962	69.2779930	1.00000000	398.157409	1.00000000
3	Pearson VII Area	7.34165972	540.102467	22.8864374	0.99999986	63.1356059	0.99999994
4	Pearson VII Area	17.2002937	563.742142	22.4760237	1.00000003	45.1021261	1.00000002
5	Pearson VII Area	0.92794398	644.175246	47.0980125	1.00000000	98.7676939	1.00000000

Graph 12: Fluorescent Spectrum, LeDuc Spring Bug, 13 July to 6 Aug 2012



Description: TROUT BROOK, Carbon, LE DUC SPRING, In:120713 1650, Out:120806 1557
X Variable: Emission nm Δλ 15:BW 5 Anal:120809KR
Y Variable: Synchronous Scan Intensity
File Source: c:\karst stuff\2012\lccmr\2012_kelsi\trout brook\lduc08

Fitted Parameters

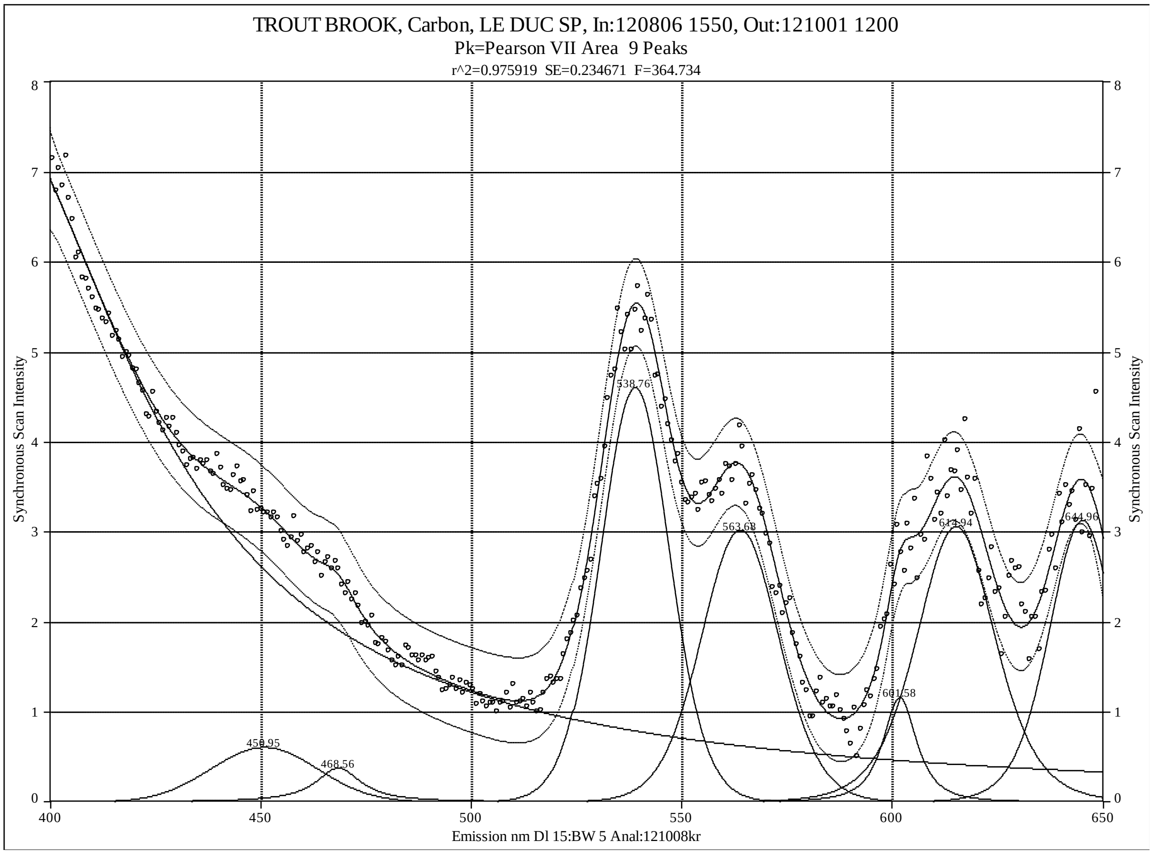
r^2 Coef Det	DF Adj r^2	Fit Std Err	F-value
0.99059322	0.98951042	0.20447986	947.756703

Peak	Type	a_0	a_1	a_2	a_3
1	Pearson VII Area	3329.92912	387.427460	92.7116384	0.61555518
2	Pearson VII Area	41.7701067	448.314036	29.1770664	12.6807161
3	Pearson VII Area	7.89935511	468.703101	11.1110266	1.16887517
4	Pearson VII Area	9.79376481	521.947536	18.7194793	0.96047757
5	Pearson VII Area	26.0650196	537.832700	15.9575637	7.94265530
6	Pearson VII Area	58.3622449	562.862059	22.0512664	12.1382879
7	Pearson VII Area	27.5801774	612.469234	21.3562197	167.918151
8	Pearson VII Area	25.7985027	639.563841	16.5685102	2.47674583

Measured Values

Peak	Type	Amplitude	Center	FWHM	Asym50	FW Base	Asym10
1	Pearson VII Area	10.4019874	387.440482	92.7116496	0.99943834	0.00000000	0.00000000
2	Pearson VII Area	1.32270370	448.314036	29.1770664	0.99999999	60.3877333	1.00000000
3	Pearson VII Area	0.49554400	468.703101	11.1110266	0.99999998	34.0375540	0.99999999
4	Pearson VII Area	0.32342364	521.947535	18.7194793	1.00000008	63.9540526	1.00000003
5	Pearson VII Area	1.49312377	537.832700	15.9575637	1.00000000	33.7118040	1.00000000
6	Pearson VII Area	2.44342221	562.862059	22.0512664	1.00000000	45.7089653	1.00000000
7	Pearson VII Area	1.21176105	612.469234	21.3562197	1.00000000	42.8550410	1.00000000
8	Pearson VII Area	1.31861589	639.563841	16.5685102	1.00000006	39.8603397	1.00000003

Graph 13: Fluorescent Spectrum, LeDuc Spring Bug, 6 Aug to 01 Oct 2012



Description: TROUT BROOK, Carbon, LE DUC SP, In:120806 1550, Out:121001 1200
X Variable: Emission nm Δλ 15:BW 5 Anal:121008kr
Y Variable: Synchronous Scan Intensity
File Source: c:\karst stuff\2012\lccmr\2012\trout brook\raw\lduc1

Fitted Parameters

r^2 Coef Det	DF Adj r^2	Fit Std Err	F-value
0.97591873	0.97314678	0.23467056	364.734435

Peak	Type	a0	a1	a2	a3
1	Pearson VII Area	1349.16463	383.231164	91.5258036	0.82812277
2	Pearson VII Area	19.4287807	450.947217	29.9005476	167.345199
3	Pearson VII Area	7.95159360	468.557509	13.0200202	0.97081084
4	Pearson VII Area	96.7343556	538.758363	19.2994830	9.78344107
5	Pearson VII Area	72.3086535	563.681321	21.7972566	7.39448678
6	Pearson VII Area	14.7006436	601.582819	9.44233651	1.38911623
7	Pearson VII Area	76.8268891	614.938089	21.9482975	3.40972982
8	Pearson VII Area	65.7468700	644.964457	18.7410127	4.51726910

Measured Values

Peak	Type	Amplitude	Center	FWHM	Asym50	FW Base	Asym10
1	Pearson VII Area	7.92475621	383.770287	91.5404705	0.97671644	0.00000000	0.00000000
2	Pearson VII Area	0.60968979	450.947217	29.9005476	1.00000002	60.0012597	1.00000001
3	Pearson VII Area	0.38060260	468.557508	13.0200202	1.00000005	44.1870397	1.00000002
4	Pearson VII Area	4.60685344	538.758365	19.2994830	0.99999978	40.3507337	0.99999988
5	Pearson VII Area	3.02582011	563.681321	21.7972566	1.00000000	46.2388733	1.00000000
6	Pearson VII Area	1.16440606	601.582819	9.44233651	1.00000000	26.8017879	1.00000000
7	Pearson VII Area	3.06495102	614.938089	21.9482975	1.00000000	50.0542817	1.00000000
8	Pearson VII Area	3.13235625	644.964459	18.7410127	0.99999950	41.3303404	0.99999975

Appendix III

Flow Measurement Repeatability Test with a Marsh-McBirney FLO-MATE Flowmeter

1. Study Site

The study site is in Minnehaha Creek along the border of Minneapolis and Edina, Minnesota. Flow measurements were taken, upstream from Xerxes Avenue South Bridge, at two segments of the stream. The coordinates that were collected, with a handheld Garmin GPSMAP 76Cx, are: 4,972,486 Northing; 474,795 Easting ± 1.4 meters (UTM, NAD 83, Zone 15). The image below shows the two segments of the creek where flow measurements were taken. Notice the measurements are west of Xerxes Avenue South Bridge.

This site is a National Pollution Discharge Elimination System (NPDES) monitoring station for the City of Minneapolis. The site is maintained and operated by the Minneapolis Parks and Recreation Board (MPRB). The MPRB loaned us a Marsh-McBirney FLO-MATE portable flowmeter, a wading rod, a tape measure, and two stakes so this precision test could be performed on October 21, 2011.

2. Methods

The upstream segment of Minnehaha Creek was measured first. Two stakes were placed on the banks of the stream at the sediment-water interface. One was placed on the north bank, the cut bank, and the other was placed on the south bank, the depositing bank. A tape measure was positioned across the river and fastened to the stakes. The total length was recorded. A sliding wading rod was attached to the Marsh-McBirney FLO-MATE, to accurately adjust the measuring position to the 60% of depth level.

A depth and a flow measurement were recorded at each one foot interval. Since all depths were less than two feet, only one measurement was taken at 60 percent of the total depth, as proscribed in the standard procedures. This process was repeated at every foot along the entire width of the stream. The entire sequence of measurements was then repeated along the same segment using the same methods.

The second position was downstream approximately 5-10 meters from the first position. The same methods were used at the downstream segment as at the upstream segment. The two positions were chosen because they were close together and had similar cross-sections. Stream flow was assumed to be the same at the two positions.

3. Calculations

The flow was calculated by using the flow and depth at each one foot interval. First the area of a trapezoid was calculated for each one foot interval. The area of a trapezoid was calculated with the following formula [(d1+d2) ÷ 2] x W (d1=depth 1, d2=depth 2, W=segment width). This area was then multiplied by the corresponding flow measurement. The resulting values were in cubic feet per second (cfs) and were summed to get a total flow.

The first measurement of the upstream segment yielded a flow of 1.93 cfs and the second measurement yielded 2.04 cfs. This yields an average of 1.99 ± 0.08 cfs (1 σ) or an uncertainty of 4 percent. The first downstream measurement yielded a flow of 1.67 cfs, and 1.69 cfs was calculated for the second measurement. This yields an average of 1.68 ± 0.02 cfs (1 σ) or an uncertainty of 1.2 percent. All four flow measurements were averaged and yielded a total flow of 1.83 cfs ± 0.19 cfs (1 σ) with an uncertainty of 10.4 percent.

4. Recalculations

The previous calculations did not take into account the full geometry of the river channel on the edges. The spreadsheet calculations assumed that the depth was zero at d1 on the first trapezoid and d2 at the last trapezoid along the stream profile. Streams are constantly evolving and there is often a cut bank and a depositing bank. A cut bank can have a significant depth along the soil and water interface. A zero depth on the trapezoid representing the cut bank only accounts for the area of a triangle. The zero was replaced with the depth measurement of the other side of the cut bank trapezoid and was recalculated for the upstream and downstream sections.

The previous calculations used the flow measurement that was accounted for at the second depth (d2) of the trapezoid. There can be significant variation from d1 and d2. To get a more representative flow for each trapezoid, d1 and d2 were averaged and multiplied by the corresponding area to produce each interval flow value. Then, all the interval values were summed to get the total flow in cfs.

The recalculation of the first measurement of the upstream segment yielded a flow of 1.97 cfs and the recalculation for the second measurement yielded 2.10 cfs. This yields an average of 2.04 ± 0.09 cfs (1 σ) or an uncertainty of 4.4 %. The recalculation of the first measurement of the downstream segment yielded a flow of 1.58 cfs and the recalculation for the second measurement yielded 1.63 cfs. This yields an average of 1.61 cfs ± 0.04 cfs (1 σ) or an uncertainty of 2.5%. All four recalculated flow measurements were averaged and yielded a total flow of 1.82 cfs ± 0.25 cfs (1 σ) with an uncertainty of 13.7 percent.

Conclusion

The work done to assess the precision of the Marsh-McBirney FLO-MATE flowmeter results in four different flow measurements, including two flow measurements from an upstream site and two flow measurements from a downstream site. The flow was assumed to be the same at these two sites because of their proximity. The results indicate that our flow measurements with this equipment are reproducible to about 10-15 percent for these low flows.