Springflow Gauging for Long-term Monitoring of Groundwater Flow into Lake Wingra

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Hydrolic Measurements (CEE 619)

May 12, 2005

Introduction

Lake Wingra is a small lake in central Madison that receives approximately a third of its water from groundwater springs and seeps along its edges. Although the Lake Wingra springs were monitored by several USGS studies in the 1970s, little work has been conducted since then. In addition, Lake Wingra's groundwater basin is the site of an extensive stormwater infiltration project by MG&E that is anticipated to increase nearby spring flows into the lake. Given the lack of current data, there is a need for a more accurate understanding of modern spring flows. Modern data can tell us two things about groundwater discharge into Lake Wingra. First, it allows us to compare the current flow rates with historical discharge to better understand the impacts of urbanization and increased pumping since the 1970s. Second, it will allow us to monitor the effects of MG&E's recharge projects on future base flow rates.

As part of a multi-student project to monitor spring discharge into Lake Wingra our group first visited all the springs to judge for monitoring suitability. We then chose two springs, one at the Nakoma Golf Club and one on a private residential property, for which we built structures to give a stage-discharge relationship. This report begins with a short overview of the historical USGS research of Lake Wingra spring flow. We then describe the design, construction, and calibration of both monitoring structures. Last, we explain in detail how and when to take flow measurements.

For their expertise and advice throughout the project we would like to thank Ken Potter, Steve Glass, David Liebl, and Jean Bahr. We also thank Rick and Patricia Friday and Clark Rowles for their cooperation in allowing us to work on their properties. Last, Jim Robinson from the Nakoma Golf Club workshop deserves special recognition for his help in constructing the golf course's weir.

Physical Description

Lake Wingra is a small (1.37 km^2) eutrophic lake located on the south side of Madison, Wisconsin. Along with Lake Mendota, Lake Monona, and Lake Waubesa, it lies within the drainage valley of the Yahara River. The surficial geology surrounding the lake consists of glacially deposited till (a combination of silt, clay, sand, gravel, cobbles, and boulders) and marsh deposits (muck and peat). The bedrock geology is mainly sandstone (USGS, 1975).

Lake Wingra's surface water and groundwater divides differ significantly (Figure 1). These boundaries are subject to change due to effects of recharge and discharge of the groundwater and topographic alterations such as storm sewer routing (USGS, 1975). Inflows to Lake Wingra consist of direct precipitation, surface runoff within the basin, and groundwater inflow, mainly from springs and seeps. Outflow from the lake consists of evaporation, groundwater recharge, and the Yahara River outlet. The first comprehensive water budget for Lake Wingra was conducted by the USGS in 1972 and showed that 33% (2,305,710 m^3/year) of the lake's inflow came from groundwater, 90% of which was discharged via springs and seeps (USGS, 1975). Figure 2 shows the approximate locations of the springs and seeps that discharge into Lake Wingra. The two springs selected for this project are circled.

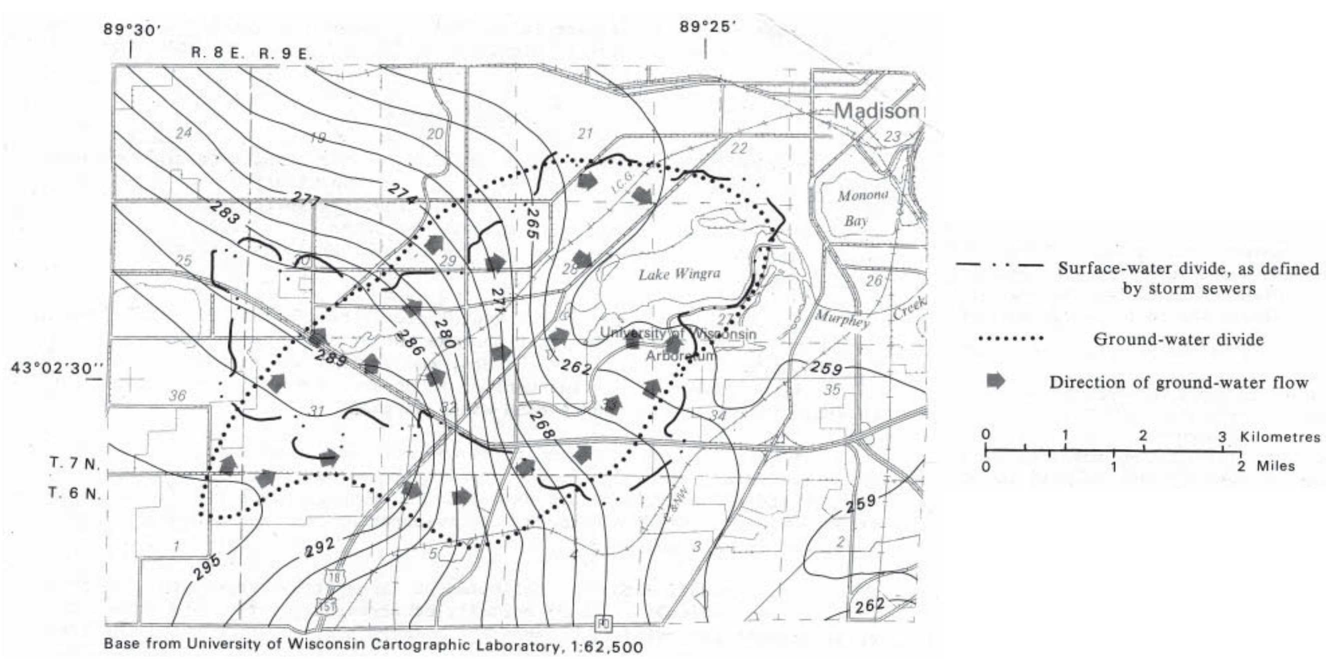

Figure 1. Surface water and groundwater divides of Lake Wingra *(Source: USGS, 1975)*

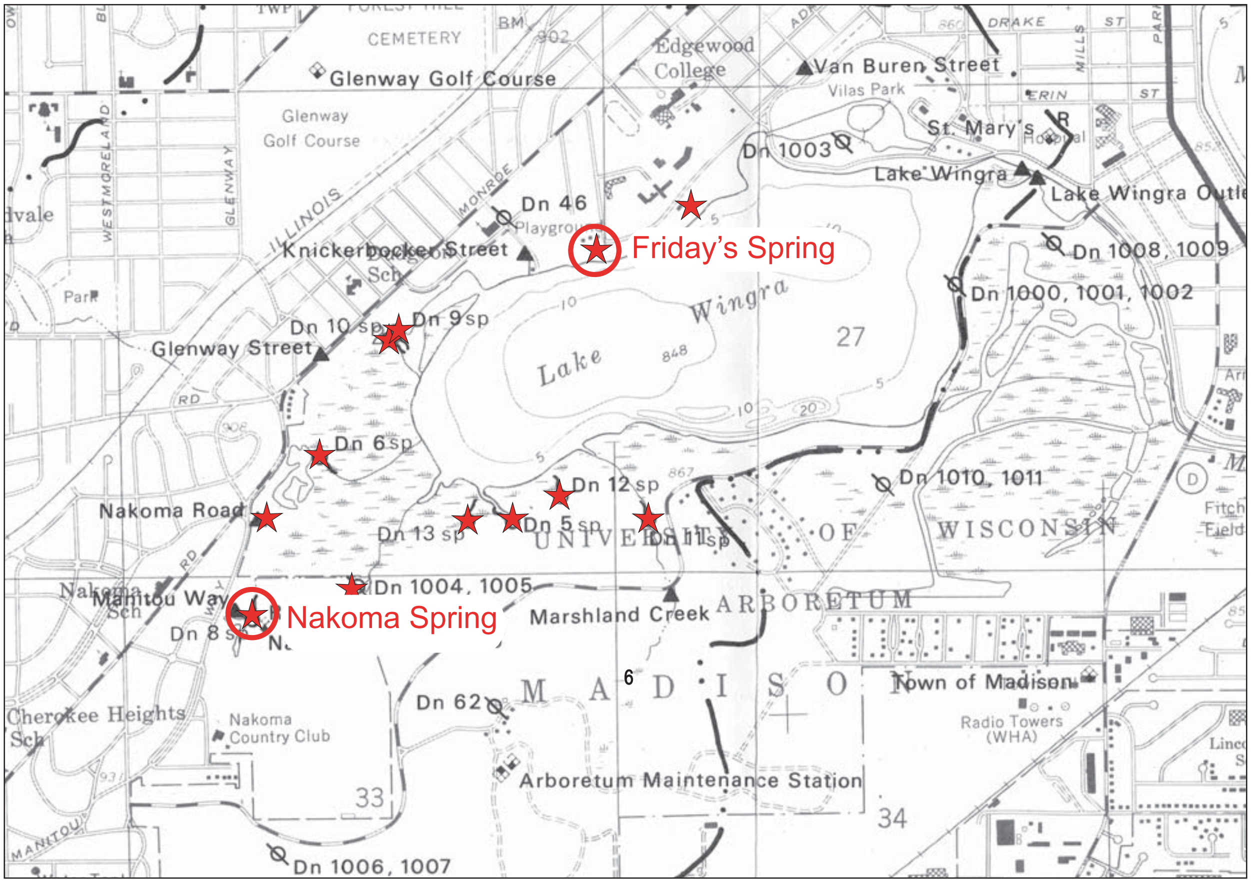

FIGURE 2. Spring and seep locations around Lake Wingra. *(Source: USGS, 1975)*

In 1979, the USGS released another study that showed the results of monitoring spring flow into Lake Wingra. Figure 3 shows the total groundwater inflow to Lake Wingra from 1972 to 1976 based on monitoring wells and piezometers (USGS, 1979). Although the study shows a slight increase in groundwater discharge throughout the 1970s, it is important to note that groundwater pumping has since increased, as has impervious surface area within the watershed, further limiting recharge.

Madison pumps water for its municipal water system from the deep sandstone aquifer underlying the city. A 1978 study by the USGS found that this increased pumping had caused a decrease in the water levels in both shallow and deep regional aquifers (USGS, 1978). The study's model anticipated pumping rates to increase from 42.1 Mgal/d in 1972 to 59.8 Mgal/d in 2000. Although the effects of urbanization were not yet observed in the hydrologic budget analyses conducted in the 1970s, it is assumed that by now the effects of decreased groundwater discharge into Lake Wingra are apparent.

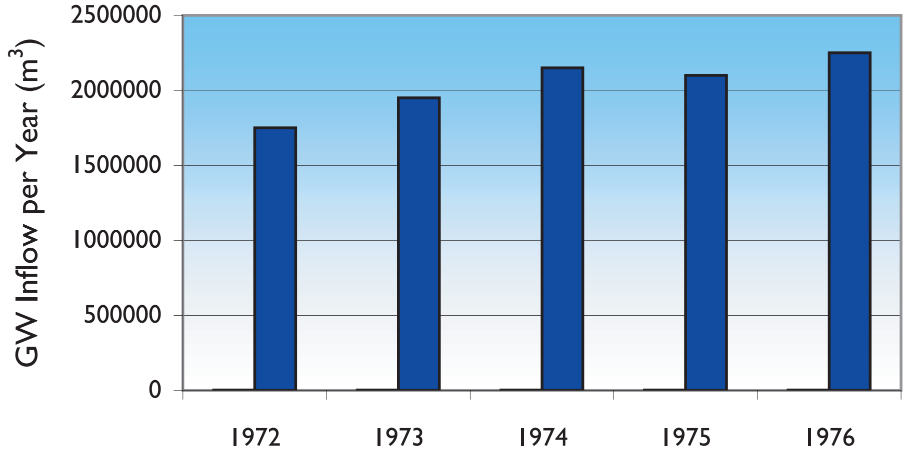

Figure 3. Groundwater inflow into Lake Wingra from 1972 through 1976. *(Source: USGS, 1979)*

MG&E'S Groundwater Infiltration Plans

Within the Lake Wingra groundwater divide, infiltration practices are being considered by MG&E as part of a compensatory recharge project related to the new cogeneration power plant being built on the northwest side of the UW-Madison campus. The plant will supply electricity to both the UW campus and to Madison residents and will draw millions of gallons a day from Lake Mendota for cooling purposes. Although this quantity of water will have 'negligible' effects on the level of Lake Mendota, there is concern that during dry spells it may cause low flow in the lower Yahara River, impacting river habitat and downstream wastewater treatment and hydroelectric plants. To mitigate these effects, groundwater will be pumped into the Yahara River during periods of low flow near the Nine Springs wastewater treatment plant. It is estimated that 80 million gallons of groundwater will be drawn from this well per year. To mitigate the effects of pumping, MG&E has selected a compensatory recharge site in the Odana Hills Golf Course where approximately 80 million gallons of storm water runoff will be infiltrated each year. Because this infiltration site is within the groundwater drainage divide for Lake Wingra, it is hypothesized that spring water discharge into the lake will increase.

The Mini-Weir at Fridays' Spring

This section describes the design, construction, and calibration of a small PVC attachment that acts as a 'mini-weir' for a spring discharging on the northwest side of Lake Wingra. The spring is located on the property of Rick and Patricia Friday at 1050 Woodrow St. and they can be contacted at (608) 238-8519.

Site Description

The spring discharges into a geomembrane-lined, artificial pond that was constructed by the Fridays for aesthetic value (Figure 4). The pond drains by means of 4-inch diameter PVC pipe and elbow attachment that extend through a small rock dam built to contain the pond. The Fridays use a plastic extender that fits on the elbow attachment to regulate the height of the pond. When the extender is removed, the four inches of water above the elbow is allowed to drain, removing unwanted algae and debris. The pipe discharges into narrow channel that flows into Lake Wingra.

Figure 4. Photos of the Fridays' spring-fed pond, the channel draining into Lake Wingra, and a close-up of the outlet elbow.

Proposals

With the basic shape of the pond and channel in mind, multiple ideas were proposed for measuring the discharge of the spring. The first idea was to measure the outflow from the drainpipe with a bucket and stopwatch. However, this idea was eliminated because the pipe lay on the bottom of the channel. The next idea was to attach a hose to the drainpipe and run it down the channel to a point where it was possible to do a bucket and stopwatch measurement. However, the lack of sufficient slope between the pipe and the bottom of the channel made this idea infeasible.

Final Design

The final design uses a 4-inch PVC reducer with notches that act as three mini-weirs measuring the water as it falls from the pond into the outflow pipe. Our original idea was to cut triangular weirs, but the spring flow rate was too high, so rectangular weirs were instead carved. To create a tight seal between the weir and the pipe we layered slices of a bicycle tire inner tube around the base of the weir, creating a wide rubber gasket. We also had to plan for the pond debris that would clog the weir openings, artificially damming the pond and giving us inflated spring flow results. For this problem we fastened gutter guard to the outside of a 16-inch foam wreath, which acts to stop debris several inches from the weir openings (Figure 5).

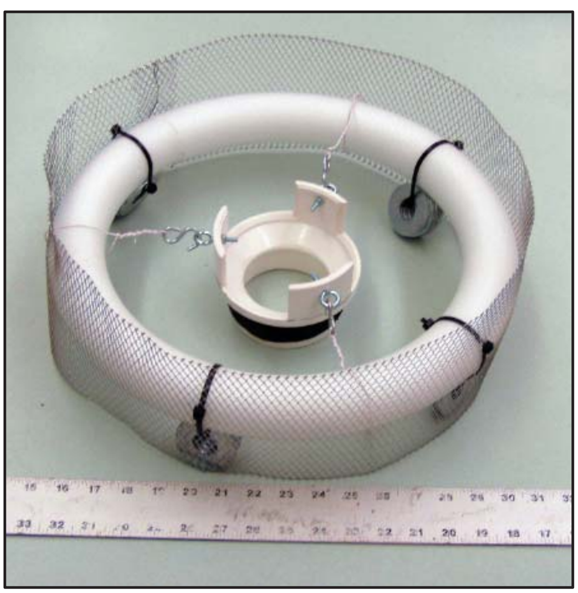

Figure 5. The 'mini-weir' is constructed out of a PVC reducer that is designed to attach to the elbow of the outflow pipe from the pond. Three rectangular notches (small weirs) were cut to measure the spring discharge as water exits the pond. The foam wreath and gutter guard prevent debris from clogging the weir entrances. Washers were fastened to the wreath to ensure that it stay floating and not blow away.

CALIBRATION

FIGURE 6. Calibration with the hose and bucket set-up and the mini-weir in place.

To calibrate the mini-weir we needed a variable flow source to develop a rating curve as well as a method to accurately measure the discharge. Our technique involved a shallow wash basin with a hole cut in the bottom for drainage (Figure 6). The mini-weir was attached around the hole with plumber's putty. To calibrate the lower end of the rating curve up to 0.015 cfs we used a garden hose as the water source. To still the water surface, a baffle was created out of a piece of plexiglass placed between the inflow and the weir. Finally, a caliper was used to measure the height from the top of the weir down to the water surface. This value was then subtracted from the total opening height of 1.5 inches to determine the height of the water over the nappe. To measure the discharge, a 5-gallon bucket was placed under the weir and timed to see how long it took for the bucket to fill. When higher flow rates were needed, we set up a similar structure in the Environmental Fluid Mechanics Lab in the basement of Engineering Hall and weighed the 5-gallon bucket to determine the exact volume. To convert the 5-gallon fill times and weights to a discharge in cubic feet per second, Q(cfs), the following equations were used:

$$q(cfs) = \frac{5(gallons)}{7.481\frac{(gallons)}{(cubicfoot)} \times Time(\sec)} \qquad q(cfs) = \frac{weight(lbs)}{62.4\,{}^{(lbs)}\!/\!_{(cubicfoot)}} \times \frac{1}{time(\sec)}$$

Using these two calibration setups, we generated about ten unique values for stage versus discharge (Figures 7 and 8). By plotting the data and fitting a power-regression line we produced the following discharge equation with H being the height of the water over the nappe.

$$Q = 0.0673 \times H^{1.5213}$$

This is close to the theoretical rectangular weir equation of $Q = cd \times H^{1.5}$. The slight difference in our equation may come from measurement errors or because the weirs are slightly curved.

Dist From Weir Top (in)	Height From Nappe (in)	Time To Fill (sec)	Weight (lbs)	Actual Discharge (cfs)	Calculated Discharge (cfs)
0.773	0.727	16.16	40.45	0.0401	0.04140
0.836	0.664	17.60	38.95	0.0355	0.03610
0.844	0.656	19.84	42.95	0.0347	0.03546
0.984	0.516	25.44	39.60	0.0249	0.02457
1.117	0.383	43.17	-	0.0155	0.01562
1.125	0.375	44.17	-	0.0151	0.01514
1.133	0.367	40.77	-	0.0164	0.01466
1.227	0.273	69.50	-	0.0096	0.00936
1.289	0.211	108.00	-	0.0062	0.00631
1.313	0.188	134.00	-	0.0050	0.00527

FIGURE 7. Table of the measured weir heights and discharges used to create a rating curve.

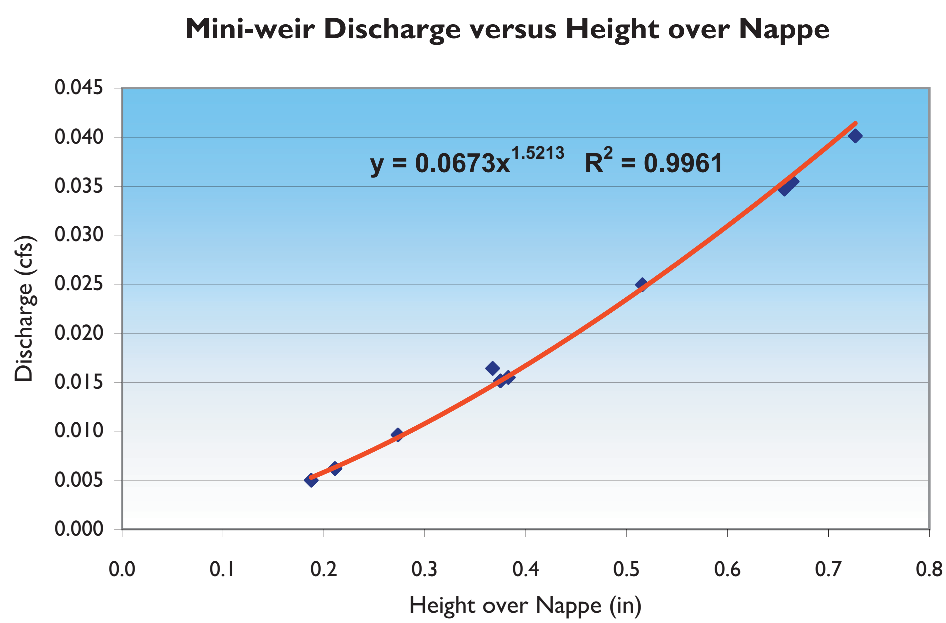

FIGURE 8. Graph of the measured weir heights and discharges and the discharge versus stage equation.

Mini-Weir Field Measurement Instruction

1. Attach the mini-weir to the elbow at least 8 hours before measuring to allow the spring discharge to equilibrate with the level of the pond.
2. Make sure the top of the weir is completely level and adjust if necessary.
3. Using a caliper, measure the height of the water at three places around the weir.
4. Calculate the height of the water by subtracting the caliper measurement from 1.5 inches.
5. Calculate the spring discharge in cfs using the following equation with 'H' in inches:

$$Q = 0.0673 \times H^{1.5213}$$

6. Measurements should be taken monthly and effort should be taken to avoid storm events.

The Cipolleti Weir at Nakoma Golf Club

After exploring the remainder springs around Lake Wingra, we decided that the Nakoma Golf Club course ponds offered the best option for flow monitoring with a traditional weir. The site is located just off of Manitou Way on the west side of Madison. Clark Rowles, the course superintendent, was very helpful and can be contacted at clark@nakoma.org or (608) 238-2033.

Figure 9. Photo of the Nakoma Golf Club ponds.

Site Description

The ponds are spring fed, with the upper pond draining into the lower pond by a waterfall. The lower pond drains over an existing concrete structure and into a rock-lined channel (golf course channel) which then empties into a storm water channel that discharges into Lake Wingra (Figure 9). A rough measurement of the outflow from the ponds was around 0.5 cfs (225 gallons per minute) which served as the design flow rate for the weir.

Proposals and Final Design

Our initial weir designs were centered on a triangular, sharp-crested weir which allows for the most sensitivity to changes in the flow rate brought on by increased spring flow. With a triangular weir and the measured flow rate, our calculations showed a minimum ponding depth (head) of 0.5 ft behind the weir. The golf course channel was selected over using the storm water channel because the high flow during storm events could compromise the weir.

However, after an investigatory survey it was determined that the channel did not have sufficient gradient to allow for the required head loss. After a discussion with Clark Rowles, we decided that the lower pond could in fact be raised six inches with little ill effect. At this location, a triangular notch weir was deemed unacceptable because if the spring discharge increased it would raise the level of the pond by too much.

Figure 10. The Cipoletti weir at the Nakoma Golf Club with a close-up of the bracket system. (The algae in the photos is not typical!)

A Cipoletti (trapezoidal) sharp-crested weir was determined to be the next best option (Figure 10). A Cipoletti weir allows for a smaller head increase at baseflow (4 inches), but still provides sufficient sensitivity for flow monitoring. Another benefit of this location was that the weir could be attached to the existing concrete structure, thereby eliminating problems with scour that could have plagued a weir in the channel. The only modification to the concrete structure was the addition of a steel wing-wall on one side that serves to prevent water from cutting around the edge of the structure with the increased pond depth.

We decided that steel would be the best material for weir construction, and we were fortunate enough to have Jim Robinson, the shop manager at Nakoma Golf Club, fabricate the weir for us. To necessitate easy installation and removal, rather than bolting the weir to the concrete, we opted for a bracket and clamp system that allows the weir to be slid into place and secured. The installation consisted of cleaning the concrete, adding gasket material to the weir, and sliding the weir into place. After a few weeks it was working properly with minimal leaks or noticeable changes to the pond.

Calibration

While the existing structure at the golf course provided good conditions for the installation of our weir, it was, nonetheless, a good idea to get an independent confirmation of the results in case there is any discrepancy from the ideal weir equation.

The Cipoletti weir equation is $Q = 3.367Lh^{1.5}$, where Q is discharge in cfs, L is the length of the weir nappe in feet, and h is the head in feet. Ideally the equation is expected to be accurate to around 5%, however there are a number of restrictions on the installation which can affect this accuracy. In our case, we were unable to install the weir with sufficient clearance between the bottom of the upstream channel and the nappe of the weir. For this reason, it was important to confirm that the weir was performing as expected.

In order to verify the accuracy of the weir, we made an independent measurement of stream discharge by determining the time required to fill a 8.5 gallon container. From the weir equation we estimated the flow at 0.238 cfs. If correct, we expected the container to fill completely in approximately 4.8 seconds. The difficulty in measuring volumes and times this small was not inconsiderable, so we estimated that time was measured to 0.5 second accuracy and volume to 0.5 gallon accuracy.

Four repeated measurements yielded a consistent result of 5 ± 0.5 seconds to fill the given volume, for a discharge of 0.227 cfs; the previously estimated uncertainties give:

$$Q = 0.227 \pm 12\%\ cfs$$

The weir result, then, was consistent with the measured value. While it is unfortunate that we are unable to reduce the uncertainty of the direct measurement to the level of uncertainty inherent in the weir, it is our recommendation that the weir be treated as accurate to the expected (5%) level. It is to be expected that any uncertainties resulting from the installation will be strongly correlated between subsequent measurements, so while the absolute discharge may not be known to this degree of accuracy we can assume that the change in discharge between measurements will be accurately determined.

Nakoma Golf Course Field Measurement Instruction

1. Measure the distance (d) from the top of the weir to the water surface.

2. Convert this measurement into feet.

3. Convert measurement to head as $h = 0.656 - d$

3. Use the following equation to compute discharge:

$$Q = 3.367 \times L \times h^{1.5}$$

where $L = 0.75$ft; Q in cubic feet per second

4. Measurements should be taken monthly and effort should be taken to avoid storm events.

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