Observations of Hydraulic Controls on the Olentangy River, Columbus, Ohio

Senior Thesis

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By

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ABSTRACT

The Lower Olentangy River in Columbus, Ohio has a sharp change in slope and width near the crossing of the Henderson Rd. bridge. This sudden change in morphology had not been directly addressed, but previous studies suggest that these changes are results of the low-head dam near North Broadway, three kilometers downstream. The water surface elevation (WSE) is modeled by solving a gradually varied flow equation with input data collected by 16 stream gages in 2014, a nearby USGS gage station, and bathymetry data collected with a depth sounder in 2015. Two WSE profiles are computed, one using observed water elevation at the dam as a boundary condition, and the second using a boundary condition representing water elevation without the dam. The simulations using observed and lowered boundary conditions converge 2.2 and 1.7 km upstream at low and high flow. The effect of the dam does not extend to the sharp change in slope. At low flow, widths increase 15.5% in the influence of the dam, but at high flow width decreases by 1.65%. Bathymetry data show a 22.9% decrease in bed slope downstream of Henderson Rd., which contributes to the decreasing slope and increasing width.

Acknowledgements

First, I would like to thank my advisor, Dr. Michael Durand, for his guidance, knowledge, and enthusiasm for this thesis. Additionally, I thank his research group for being both welcoming, and helpful– I walked away from every group meeting with good advice and new ideas.

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INTRODUCTION

Background

The Olentangy River rises in northern Ohio, and is a tributary of the Scioto. Its watershed is 1,410 km^2. The river flows for 150 km before joining the Scioto in downtown Columbus, with an average gradient of 105 cm/km (Ohio EPA, 2007; FLOW, 2003). The Lower Olentangy flows through Columbus Ohio, and has been altered in many ways from its original form. The river has been relocated, channelized, and heavily dammed to build and protect roads, create reservoirs, and ironically, to make the river look more natural (FLOW, 2003). Using a gradually varied flow model and new bathymetry data, this research investigates the effect of a low-head dam on a short section of the Olentangy River.

Limited data are available for this section of the river. The U.S. Army Corps of Engineers surveyed the Olentangy 39 years ago for their 1977 Initial Flood Insurance Study. From that study, only twelve cross-sections were produced inside our 5.8 kilometer study area (FEMA, 2016), and newer editions of the report have not updated the model. These data were the basis for a more recent report on the effects of removing five low-head dams from the Olentangy (FMSM Engineers, 2005). While this report models the Olentangy River surface profile without dams, the dataset used is not spatially dense enough to address detailed questions. Variations in bathymetry, which affect surface slope, occur at much smaller spatial scales than sampled in the 1977 study.

Study Area

The bathymetry data were collected over a 5800 m stretch of the Olentangy River in Columbus, Ohio. The upstream and downstream ends are bound by low-head dams near Broad Meadows Park, and the North Broadway Bridge. The North Broadway Dam at the downstream end of the study area is 58m wide, and has a crest height of 1.9m (ODNR Division of Water Resources, 2016).

Flow is controlled by the Delaware Reservoir Dam 32 kilometers upstream of the study area. There is a USGS gauge station near the I-270 crossing of the Olentangy River about 4 km upstream of the study area's upstream end (USGS, 2016). No major tributaries join the Olentangy between the USGS gauge and the study area.

The study area has a significant change in slope at the approximate midpoint, near Henderson Rd. The downstream end is extremely flat, with a gradient of 17.8 cm/km. Upstream, the stream gradient is 70.3 cm/km. An increase in width downstream is also apparent from aerial photography of the River (Figure 1). This increase, however, is not sustained down to the North Broadway Dam; the width noticeably decreases after 1.1 km, upstream of a large channel bar and retaining wall on the left bank. The retaining wall's downstream end is 600m from the North Broadway Dam.

Figure 1: Map of the Olentangy River study area (OGRIP, 2013), with three road crossings for reference. Broad Meadows and N. Broadway are near the upstream and downstream ends, and Henderson road is near the dramatic change in surface slope and width.

Objectives

It is well established that rivers commonly reach equilibrium in concave-up profiles (Knighton, 1998; Sinha and Parker, 1996), and is reasonable that the change in surface slope observed is a natural progression. However, it is also reasonable that the decreased slope is impounded water from the low-head dam.

The objective of this research is to investigate the effect of the North Broadway dam on the Olentangy River profile. Specifically, the question this research aims to answer is: are the observed variabilities in slope, depth, and width primarily resulting from the dam impoundment or from other controls?

METHODS

Overview

The strategy employed for addressing the objectives is to model the river profile as is, and without the dam. The model requires data that describe width and cross-sectional area relationships with surface elevation at different points along the river. The model also requires bathymetry data, which were collected and processed to produce a thalweg profile. The differences between the two profiles are results of the dam, and the similarities between the profiles are results of other controls.

Gauges and time series data

In 2013, Dr. Durand's group installed 16 stream gauges in the study area. From the gauges, GPS measurements, and USGS data, a time series was created for width, elevation, area, and discharge. Width data were collected at multiple elevations using a laser rangefinder, and then a width-height relationship was modeled for each gauge by a linear fit. Elevations were calculated by combining data from pressure transducers at each gauge, and GPS measurements of the water surface elevation. The cross-sectional area time series was created using the elevation and the width-height relationship to form a trapezoid above reach-averaged low-flow area (A_0). Low-flow areas were calculated for each gauge by measuring the width of the river at low flow, and multiplying by the depth of the water; these were then averaged into four reaches. The cross-sectional area is the sum of A_0 and the trapezoid calculated with the height-width relationship.

$$A = A_0 + \left(\frac{W(h_1) + W(h_0)}{2}\right) * (h_1 - h_0)$$

Where A is the total cross-sectional area, $W(h)$ is the river width at elevation h, h_1 is the water surface elevation, and h_0 is the elevation at A_0.

Bathymetry data

Bathymetry data were collected with a Garmin 10272 depth sounder mounted to the bottom of a kayak and Garmin GPSMAP 441s chart plotter. The chart plotter pairs and saves each depth measurement from the depth sounder with location coordinates at a frequency of 1 Hz. With this setup, we were able to collect 15,000 depth measurements (Appendix A). The depth sounder has a minimum measureable depth of 0.3 meters, and was mounted 0.46 meters below below the surface of the water, making our minimum measureable depth 0.76 meters.

The strategy for data collection in the kayak was to complete four passes of the river. Three passes were longitudinal paths covering the thalweg and the banks, and one pass zigzagging between the banks. The two near-bank passes followed as close to the bank as possible, while still in water deeper than our minimum measureable depth. Due to inclement weather, our data collection was limited and many areas received only a zigzag pass.

The chart plotter only recorded coordinates and water depth. In order to estimate river bathymetry, a reference surface elevation is also required. Water surface elevation measurements were made with a Leica Viva GS15 GPS antenna, with a three-dimensional error of 3.5 cm or less. With these measurements, a set of gauge height measurements from the time series data could be chosen to best represent the water surface. Because the river discharge and stage were different from day to day, a different set of gauge measurements were picked for each day of data collection. The depths measured in the kayak were subtracted from the water surface elevations to give the bed elevation.

On one day of our data collection, we had enough people to operate the kayak and Leica antenna, and two people measuring cross sections of the river. The cross sections were measured using a tape measure for the distance across the river, and a folding ruler to measure depth. The cross-section data were appended to the larger dataset from the kayak.

Thalweg determination

In order to produce a profile of the thalweg elevation vs. flow distance for the river from the bathymetry data collected, it was necessary to determine which points represent the thalweg. The logic for creating the profile was modified from the methods described in Merwade et al. (2005) to accommodate incomplete data (Appendix B). The following steps were used to create the two-dimensional thalweg profile from three-dimensional bathymetry data:

1. Clear the data of any entries without elevations
2. Create a segmented centerline that extends from end to end of the desired profile.
3. Define search rectangles along each centerline segment with widths equal to the river width, and oriented perpendicular to the segment.
4. Locate and save the lowest elevation point inside each rectangle as a thalweg point. In sections of the river where the rectangle does not include any measurements, no thalweg point is picked.
5. Calculate distance between consecutive thalweg points. The distance to each point is the cumulative sum of all distances downstream of that point.

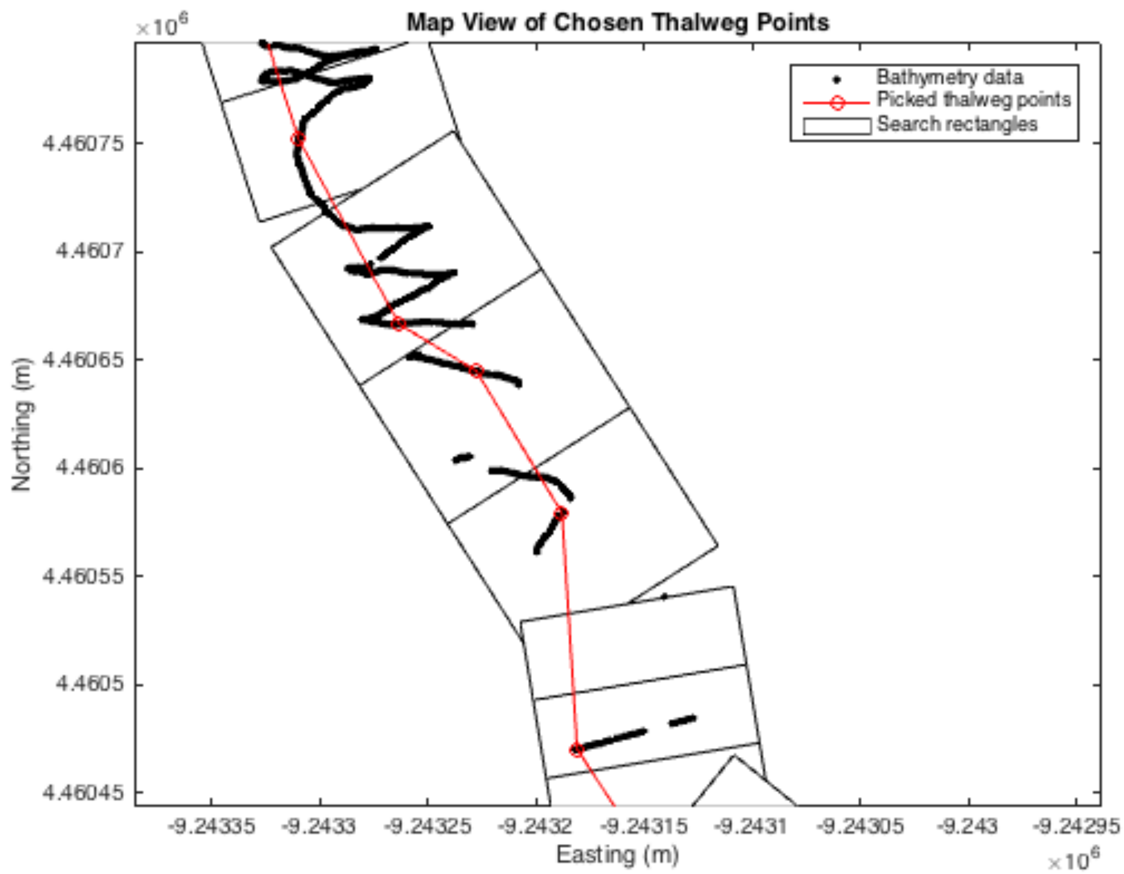

Figure 2: Illustration of thalweg finding method. Each centerline segment is divided in three rectangles, and the minimum elevation is found for each rectangle. This plot shows sections with typical coverage (top half), and sections with limited coverage (bottom half) where not every rectangle contains data.

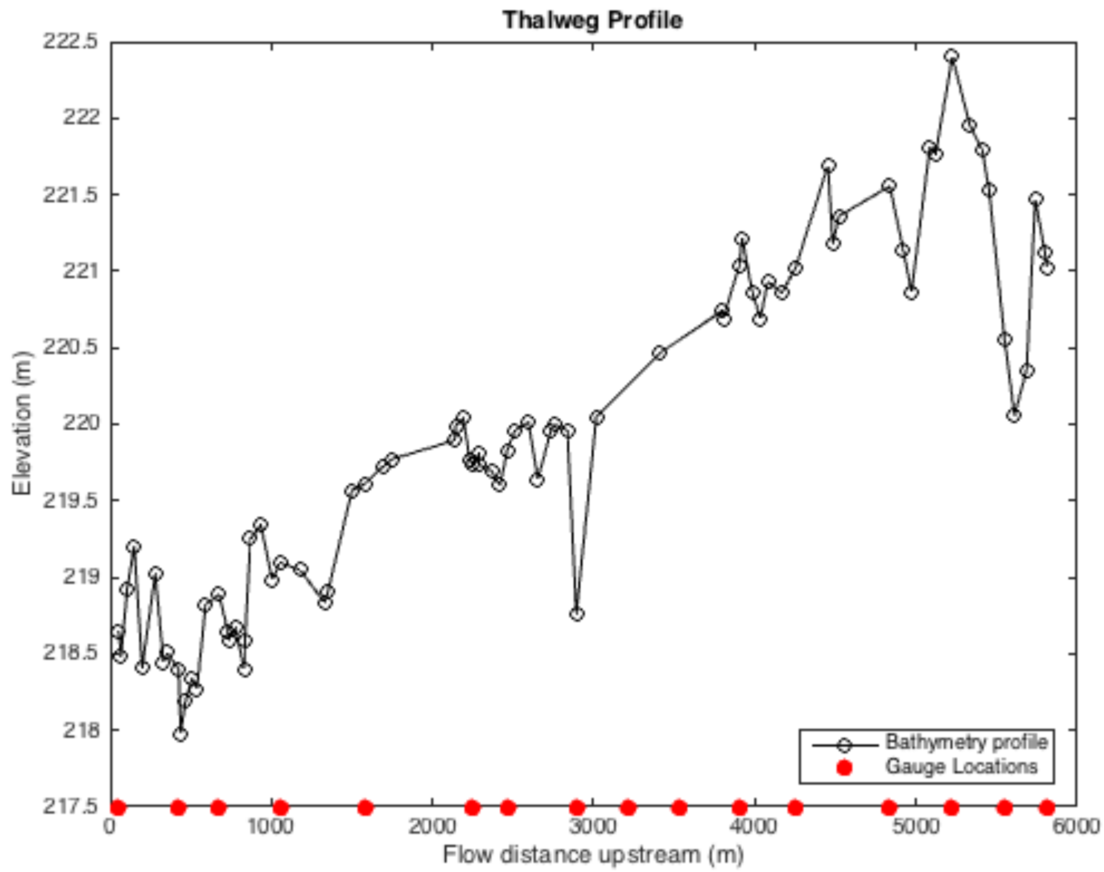

Figure 3: Thalweg profile resulting from the method in Figure 2. Flow distance is calculated as cumulative distance between thalweg points from downstream, with the 0 distance at the location of the dam. Large gaps between sampled points are due to missing data.

Model

The gradually varied flow (GVF) equation is a differential equation with no closed form solution, but can be solved iteratively to give WSE along the length of the bathymetry profile. The GVF flow equation is built on three relationships: continuity of mass equation, which assumes no water is gained or lost between successive points, an energy equation, which relates eddy and frictional losses to losses in hydraulic head, and Manning's equation, which describes uniform flow (Dingman, 2009). The GVF equation also requires steady-state flow, meaning the flow is temporally constant.

$$\frac{dh}{ds} = -\left(\frac{S_o - S_e}{\cos(\theta) - Fr^2} - S_o\right)$$

Where h is elevation, s is flow distance, S_o is channel slope, S_e is the energy slope, θ is the angle of the slope from horizontal, and Fr is the Froude number. The energy slope and Froude number calculations determine area and width as a function of height, and as a result, the GVF equation is a differential equation. Because the angle of the bed from horizontal is so small, the cos(θ) term is simplified to 1 by the small-angle approximation. The same principle allows using the measured vertical depth as depth normal to the bed.

$$S_e = \frac{n^2 q^2 P^{\frac{4}{3}}}{A^{\frac{10}{3}}}$$

Where n is Manning's roughness coefficient, q is discharge, P is the wetted perimeter, and A is cross-sectional area.

The energy slope (S_e) is also defined as the change in hydraulic head over a distance, or slope of the water surface. In uniform flow, this is the same as the channel slope ($S_e = S_o$). However, uniform flow is an unrealistic condition in a river system. Gradually varied flow describes steady-state, non-uniform flow, in which $S_e \neq S_o$ (Dingman, 2009).

$$Fr^2 = \frac{q^2 W}{gA^3}$$

Where W is river width, and g is the gravitational constant.

Flow is categorized as subcritical when the Froude number (Fr) is less than 1, critical when Fr equals 1, and supercritical when Fr is greater than 1. The Froude number can be described as the ratio of flow velocity to the wave celerity (Dingman, 2009). When the flow is in a subcritical state, hydraulic controls only influence flow upstream, which means computing a subcritical gradually varied flow profile starts downstream and solves upstream. Field observations and Froude number calculations agree that our study area is entirely subcritical, and the equations should be solved moving upstream.

Evaluation

The GVF model was evaluated using an ordinary differential equation (ODE) solver in MATLAB's ODE suite. The area and width used for solving the differential equation are interpolated both between gauge locations, and between measured surface elevations. In the flow distance (s) dimension, this is necessary because data were only measured at the 16 gauges, but our bathymetry was much higher resolution. In the elevation (h) dimension, when the ODE solver is checking a height within the range of elevations measured by the gauges, then the area and width are also interpolated from the time series data. However, when the elevation is outside the range measured at that location, area and width take on the minimum or maximum value. Consequently, the GVF solution's accuracy decreases with increased deviation from measured elevations.

When solving the equation, the ODE solver requires a boundary condition so that it can give a unique solution instead of a general form of the solution. In this case, the boundary condition changes the elevation of the water surface at the location of the N. Broadway dam. If the model and data are accurate, using a measured surface elevation as the boundary condition will produce a profile similar to the measured profile.

To answer my question, two boundary conditions were used: one at a measured height, and one set to an elevation closer to the normal depth without the dam. Calculation of normal depth requires the cross-sectional area, for which we have no data below the elevation of the dam. Instead, the elevation was lowered to an estimated normal depth, and the gradually varied flow solution will, over a distance, return to normal depth (Dingman, 2009). The model was run at both low-flow (3 m^3/s), and high-flow (10 m^3/s) conditions. For each profile, the model was calibrated with Manning's roughness coefficient (n) such that the calculated water surface with a measured initial condition matched the measured profile. For low-flow n = 0.05, and for high-flow n = 0.04. The resulting profiles will merge upstream at the extent of the dam's influence (Dingman, 2009), and the difference between them is the effect of the dam.

RESULTS

Profile slopes

As expected, the profiles with gauge height as the initial condition follows gauge measurements reasonably well. Both lowered profiles merge with the gauge height profiles, but the shape of each is very different (Figures 4 and 5). In both flow conditions, a sharp change in slope is apparent. At low flow, the break in slope occurs at 3000 m, and at high flow it occurs at 3500 m. The lowered boundary conditions remove the influence of the dam from the GVF solution, but both high and low flow profiles display the sharp change in slope originally observed by the gauges (Table 1).

While there is much variation in the channel bed slope, a general flattening trend is apparent around 3000 m upstream. Upstream of 3000 m, the gradient is 63.4 cm/km, and downstream the gradient is 51.2 cm/km. This is a 22.9% decrease in slope.

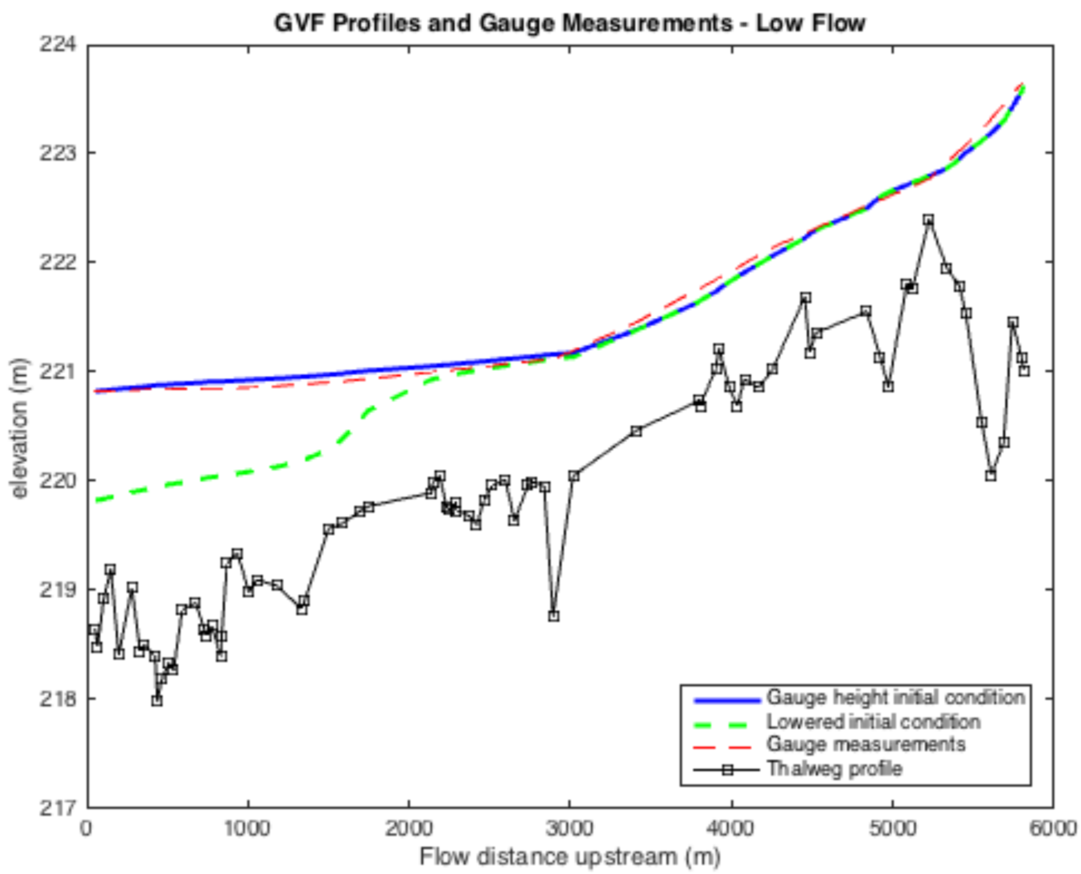

Figure 4: Plot of both GVF profiles at low-flow, gauge measurements with same discharge, and the bathymetry profile. A noticeable change in surface slope is at 3000 m.

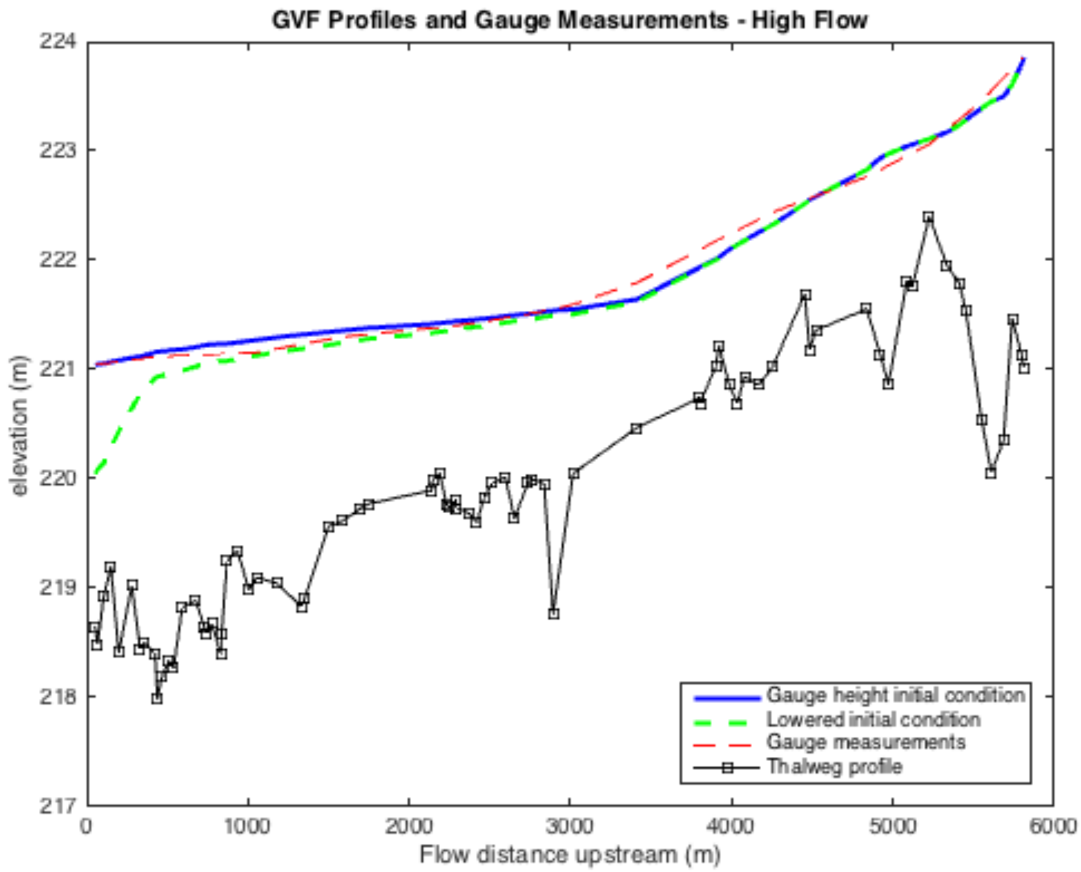

Figure 5: Plot of both GVF profiles at high-flow, gauge measurements with same discharge, and the bathymetry profile. The noticeable change in surface slope moved upstream to 3500 m compared to 3000 m at low flow.

Table 1: Comparison of lowered boundary condition slopes

Flow Profile	Gradient (cm/km)	Change in gradient (%)
Low Flow*		
Upstream	81.7	
Downstream	52.6	-35.6
High Flow†		
Upstream	84.4	
Downstream	28.4	-66.3

*Downstream and Upstream are relative to break in slope at 3000m
†Downstream and Upstream are relative to break in slope at 3500m

Profile Comparison

Before comparing the gauge height and lowered height profiles, the results were densified to give one meter intervals on the calculated surface. This removes increased influence of sections with higher density of thalweg measurements. A threshold of 10 cm separation between observed boundary condition and lowered boundary condition profiles was used to find the upstream extent of the dam's influence. This threshold occurs 2,248 m and 1,722 m upstream of the dam for low and high flows. In both the high and low flow profiles, upstream of the threshold the mean difference is small and has little variation (Table 2). Downstream of the threshold, however, the mean difference of the low flow profile is almost three times the mean difference of the high flow profile (Table 2).

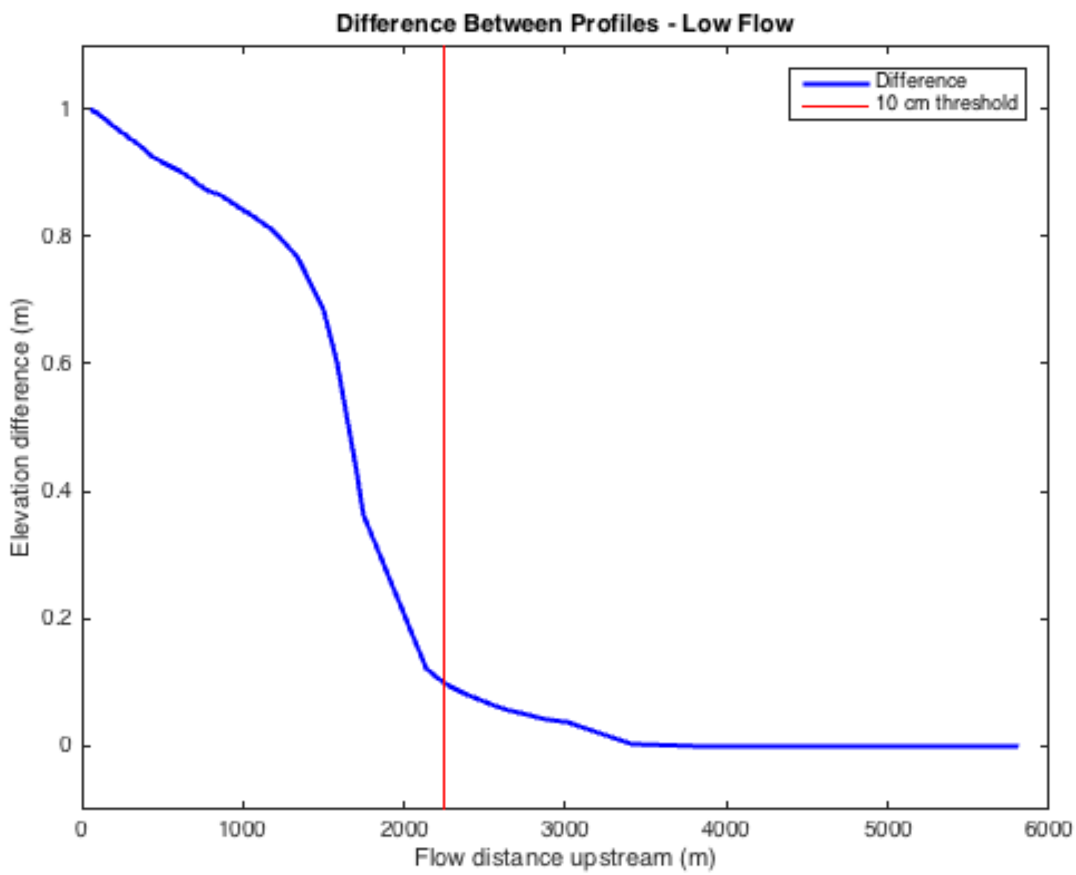

Figure 6: Difference between low-flow profiles. 10 cm separation is at 2,248 m upstream.

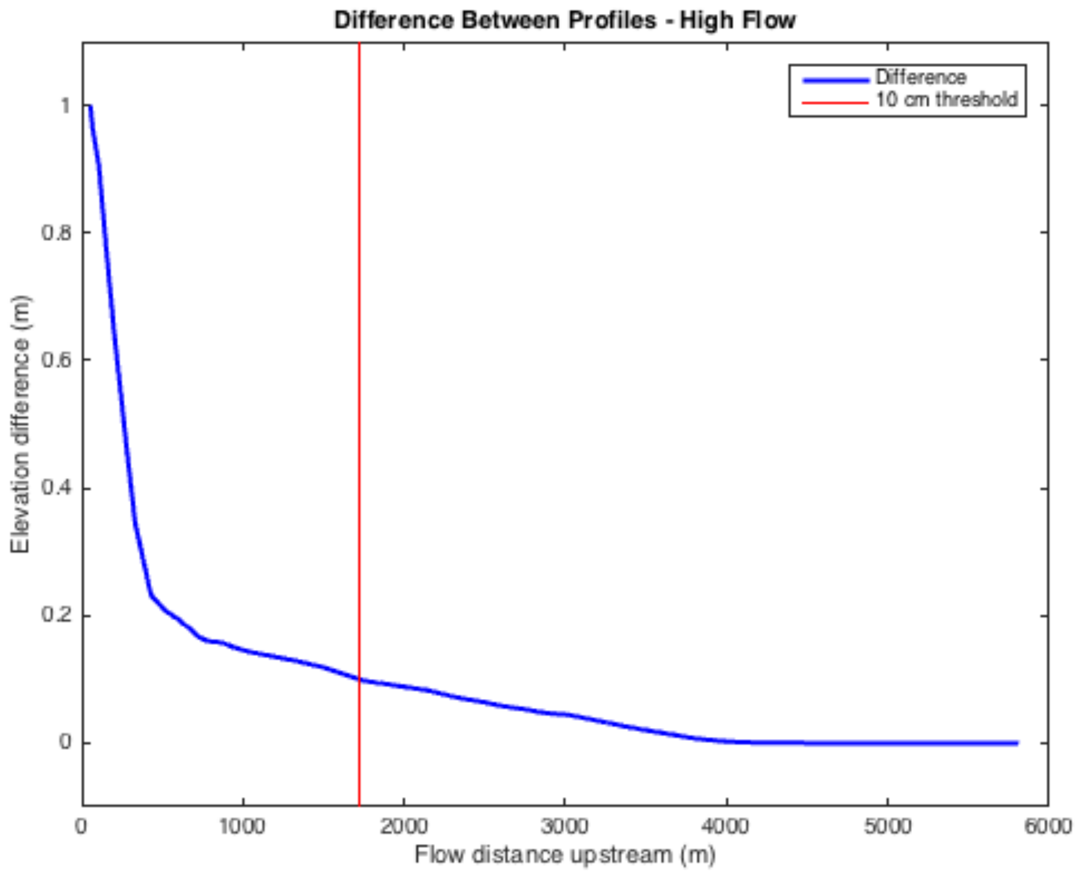

Figure 7: Difference between high-flow profiles. 10 cm separation is at 1,722 m upstream.

Table 2: Comparison of computed profiles upstream and downstream of threshold

Flow Profile	Mean elevation difference (m)	Standard Deviation (m)
Low Flow		
Downstream	0.6826	0.2872
Upstream	0.0156	0.0262
High Flow		
Downstream	0.2447	0.2135
Upstream	0.0275	0.0325

Discussion

Influence of the Dam

As discussed earlier, the mean difference for the high-flow is almost a third of the mean difference at low-flow (Table 2), and that the influence of the dam extends more than 500 m further at low flow. These results show the dam has more control on the river's elevation at low flow than at high flow. An earlier study on the flood control of dams on the Olentangy found the dams had some control for a 1-year flood level, but almost no control at the 500-year flood level (FMSM Engineers, 2005).

The model does not predict widths outside the range of measurements. As a result, we can only compare widths for the gauge height boundary condition (Figures 8 and 9). At low flow, there is a 15.5% increase in average width downstream of the threshold. At high flow, however, there is almost no change (Table 3). From 250 to 1250 m behind the dam, the river shows a decrease in width to a minimum of 34.86 meters at both high and low flow. In part of this section, a retaining wall was built on the left bank, and further upstream a large channel bar is near the left bank.

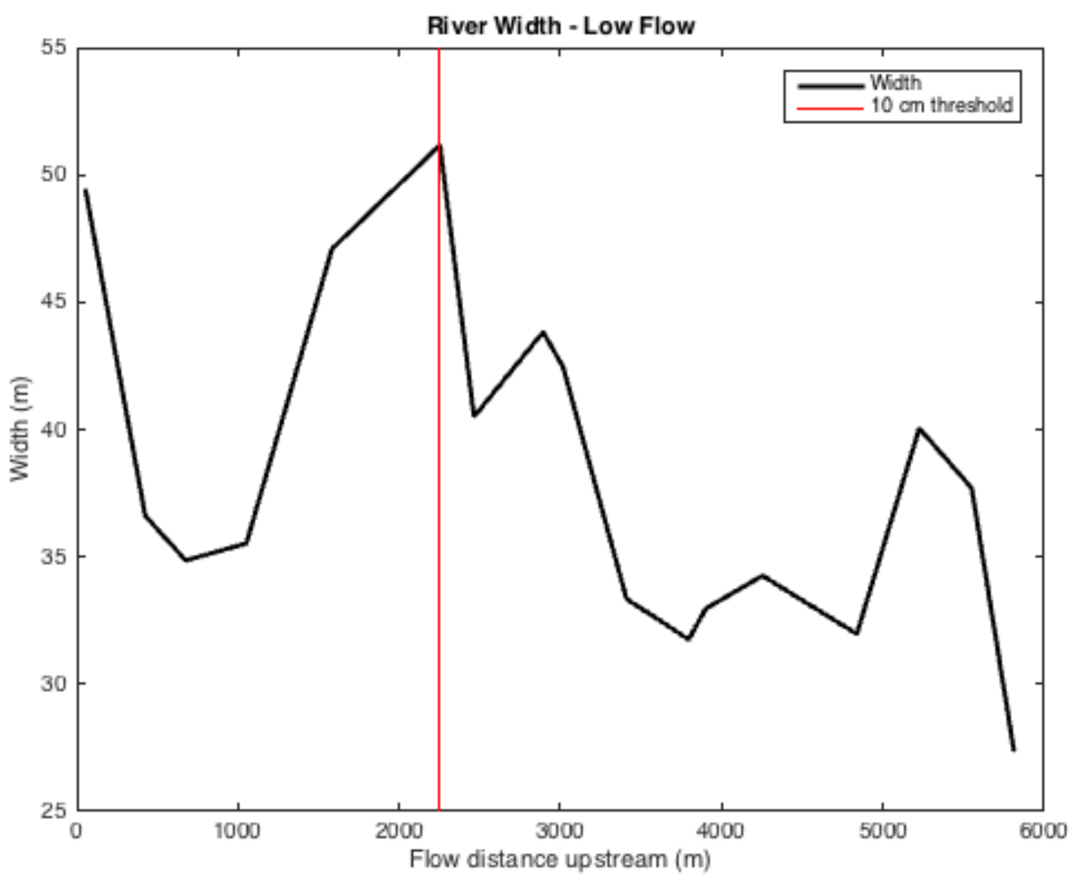

Figure 8: Width of Olentangy river at low-flow over the study area's length from gauge measurements.

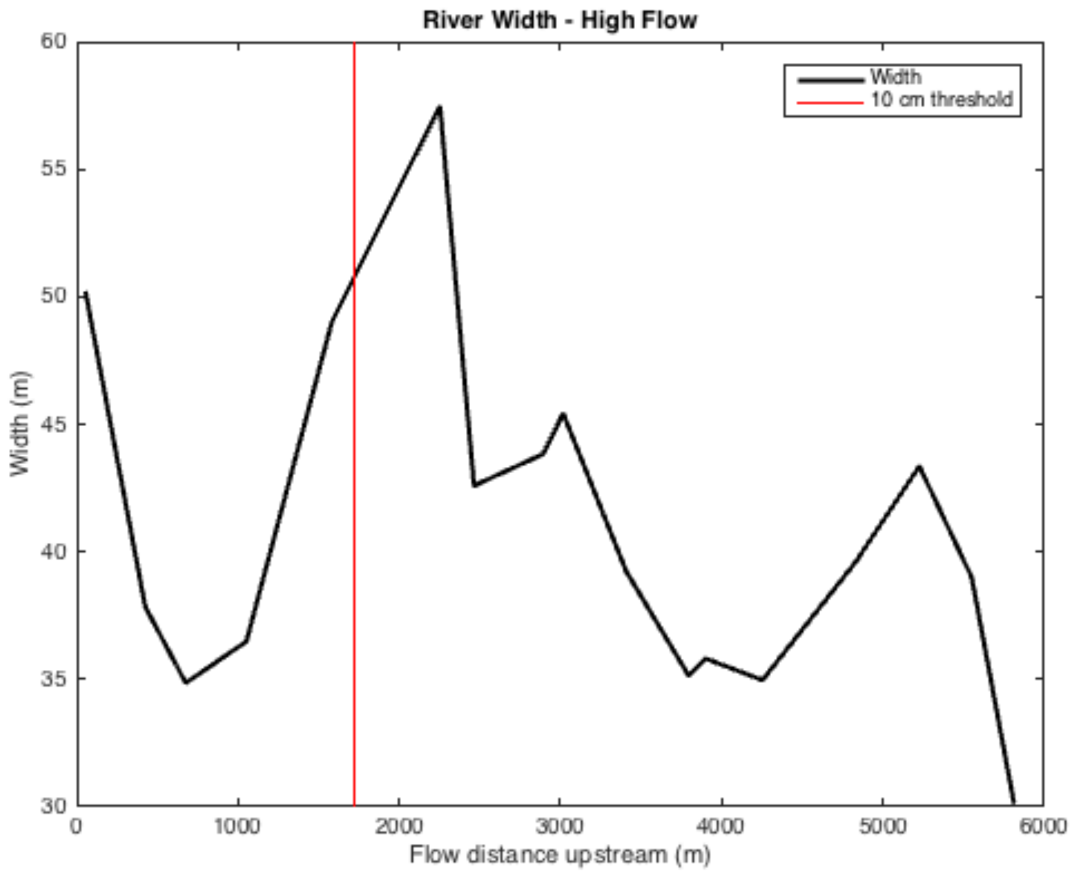

Figure 9: Width of Olentangy river at high-flow over the study area's length from gauge measurements.

Table 3: Statistics of surface width variability

Flow Profile	Mean width (m)	Min. width (m)	Max. width (m)	Variance (m)
Low Flow				
Downstream	42.29	34.86	51.14	16.28
Upstream	36.62	27.34	51.16	23.82
High Flow				
Downstream	41.08	34.86	50.78	15.92
Upstream	41.77	30.12	57.47	27.35

Bathymetric Control

In the two profiles where the water surface was lowered below the dam, the slopes were reduced by 35.6% at low flow and 66.3% at high flow (Table 1). In the high-flow simulation, the lowered boundary condition remains lower than the observed boundary condition, but the slopes are similar after the first 500m (Figure 7). If the dam were the sole cause of the flat slope seen in the gauge measurements, there should be a continuation of the upstream slope when the dam's influence is removed. However, the results show that without the dam in place, the sudden decrease in slope remains.

Previous studies on dam removal on the Olentangy River have shown the slope of the surface to be similar to the upstream sections upon removal of the N. Broadway dam (FMSM Engineers, 2005). This was caused by the bathymetry data used, as previous data show a continuous channel slope across Henderson Rd. The results of the research presented herein suggest that the break in surface slope observed is partially a result of the 22.9% decrease in bed slope.

CONCLUSIONS

The work in this thesis has shown that the N. Broadway Dam is not the only cause of the sudden change of slope near Henderson Rd. While the dam does increase the depth of the river at low flow by an average of 68.26 cm, the surface slope still decreases downstream when the dam is removed from the model by 35.6%. At high flow, the mean difference is diminished to 24.47 cm inside the extent of the dam's influence, and the surface slope is 66.3% less than upstream of Henderson Rd. The average width at low flow does increase by 5.67 m as a result of the dam, but at high flow, the width decreases by 0.69 m. The model provides enough evidence to conclude that the dam is not solely causing the decreasing surface slope downstream, does not control the width of the river, and has limited control of the river depth at high flow. As a consequence, much of the river flow is still a result of bathymetry and other hydraulic controls.

Recommendations for Future Work

While the quantity of bathymetry data collected was much greater than previously existing data, the new data are still sparse in shallower sections of the river due to the limitation of the depth sounder. Reducing the minimum measureable depth or combining conventional cross section methods to cover these shallow areas would improve spatial continuity of the data. With greater data coverage, three-dimensional analysis of the bathymetry could provide additional insight.

Estimates of area and width values outside of the time series would improve the model's accuracy when the elevation is above or below what was observed. This could be done with the bathymetry data collected, or by extrapolation of the time series data.

While not an issue for a short river section, application of this model to a longer, more diverse section of a river would require spatially varying discharge and Manning's roughness coefficient.

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Appendix A

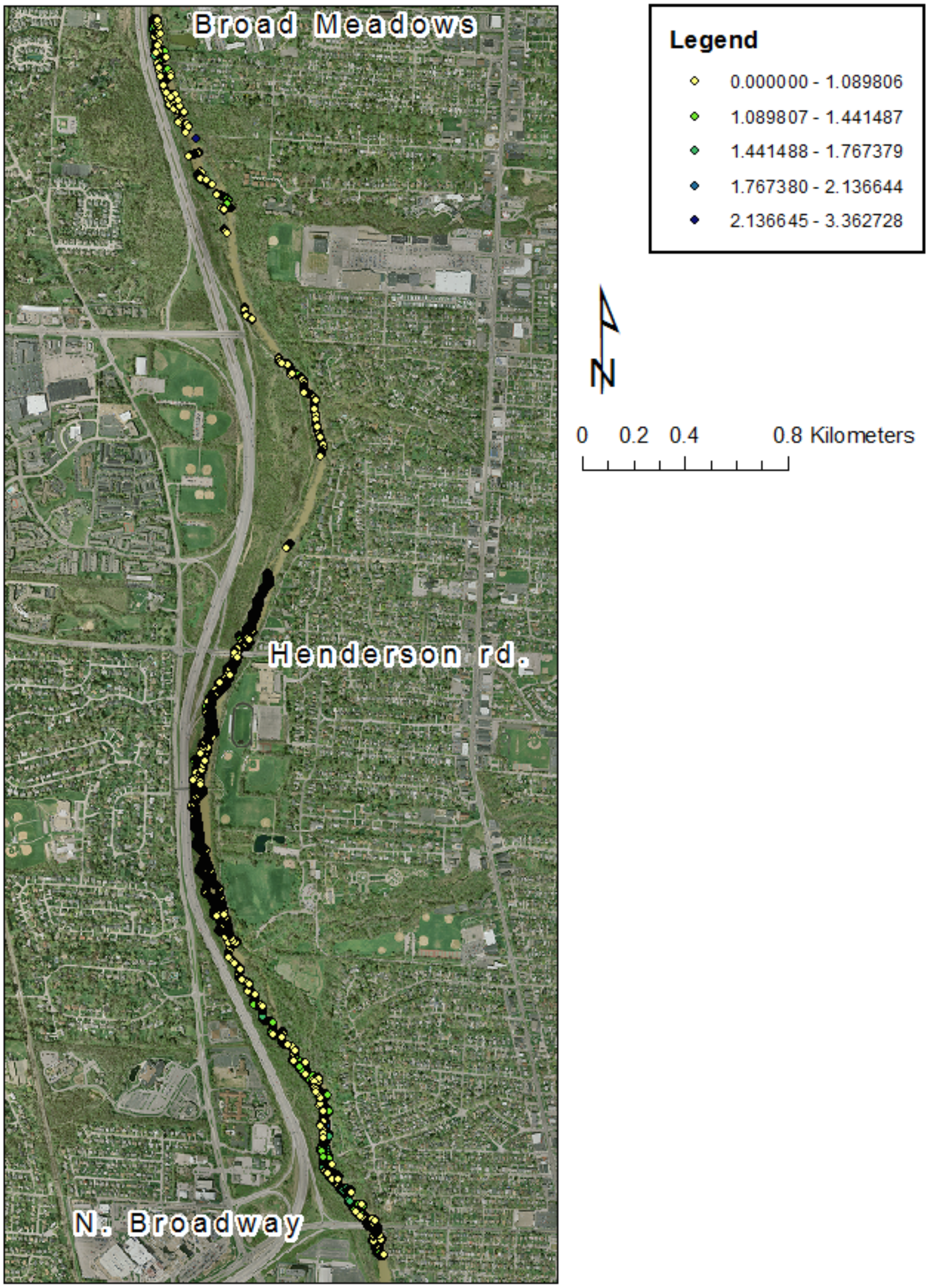

Figure A1: Map of study area (OGRIP, 2013) with bathymetry data as depth in meters overlain. Gaps between data are from the depth sounder not recording a depth as the kayak passed.

APPENDIX B

```
%% find_thalweg.m
%written by Ted Langhorst, 2016
%finds local minimums in bathymetry data and saves as thalweg variable
clear
close all

%% Variables
N=4; %N-1 search rectangles per segment
w=100; %width of search rectangle [m]
R=6378100; %radius of earth [m]

%% Data
load Points.mat %b_xyz=[x y z] of bathymetry data
b_xyz=[Point_Dat(:,7) Point_Dat(:,6) Point_Dat(:,8)];
b_xyz(any(isnan(b_xyz),2),:)=[]; %get rid of any row with NaN
b_xyz(:,[1 2])=b_xyz(:,[1 2])*(pi/180)*R; %convert from degree coords to meters

load Center.mat %segmented centerline
cx=center.X'; %xy coordinate of centerline verticies
cy=center.Y'; %saved as vars because structures giving me grief
cx(isnan(cx))=[]; %get rid of NaN
cy(isnan(cy))=[];
cx=cx*(pi/180)*R; %convert from degree coords to meters
cy=cy*(pi/180)*R;

%% locate thalweg

%create N points between vertices of segmented centerline
for i=1:length(cx)-1
   x_pt((i-1)*N+1:i*N)=linspace(cx(i),cx(i+1),N);
   y_pt((i-1)*N+1:i*N)=linspace(cy(i),cy(i+1),N);
end

xv=zeros(4,1); %xy vertices for inpolygon thalweg search
yv=zeros(4,1);
thalweg=zeros(length(x_pt),3);
md=zeros(length(x_pt),3);

%define 4 corners of search polygon, find all points in polygon and then
%save the minimum elevation as thalweg
for i=1:length(x_pt)-1
    m=(y_pt(i+1)-y_pt(i))/(x_pt(i+1)-x_pt(i)); %slope of centerline
    theta=atan(-1/m);   %angle from centerline point to vertices
    dx=(w/2)*cos(theta); %change in x from center point to vertices
    dy=(w/2)*sin(theta);
    xv=[x_pt(i)-dx x_pt(i)+dx x_pt(i+1)+dx x_pt(i+1)-dx]; %polygon vertices
    yv=[y_pt(i)-dy y_pt(i)+dy y_pt(i+1)+dy y_pt(i+1)-dy];

    in=inpolygon(b_xyz(:,1),b_xyz(:,2),xv,yv); %check for points inside
    [z,zi]=min(b_xyz(in,3)); %minimum elevation and index of that pt.


    if any(z) %make sure an elevation exists in the polygon
        inside=b_xyz(in,:);
        thalweg(i,:)=inside(zi,:); %save thalweg as bathy pt. at zi
    end
end
```