A Physical Model Investigation of Sediment Deposition and Circulation Patterns for Kalamazoo Lake (a.k.a. Saugatuck Harbor)

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I. Introduction / Background

The Saugatuck Harbor is located in Allegan County in the state of Michigan at the outflow of the Kalamazoo River into Lake Michigan. Kalamazoo Lake is a drowned river mouth lake just upstream from the harbor that serves a vital role to the local communities of Saugatuck and Douglas. However, Kalamazoo is experiencing very shallow water depths in certain locations due to the deposition of sediment carried by the Kalamazoo River. Historical records reveal that deposition within the lake has been a recurring issue impacting the navigability of the harbor. The local community is interested in evaluating possible alternatives for solving the sedimentation problem while also preserving the natural beauty of the waterway.

Figure 1: Satellite View of Saugatuck Harbor (Yahoo Maps)

The flow enters Kalamazoo Lake from the southeast and exits to the north. Prior to the harbor, the Kalamazoo River represents a watershed of over 2000 square miles (USGS). A USGS stream gauging station is located on the Kalamazoo River about six miles upstream, but has a limited data record. Station 04108670, also referred to by name as Kalamazoo River near New Richmond, has collected sediment concentration and daily discharge data from April 1994 to October 1995 and October 2002 from present. The daily average discharge from this short duration record is 2320 cubic feet per second (cfs) with a 10 % exceedance flow of 3940 cfs, a 50 % exceedance of 2020 cfs and a 90 % exceedance of 1110 cfs. A comparison of flows at upstream gauging stations over the same time period with their long term statistics suggests that the above numbers may be biased towards the high end.

Other USGS data can be used to estimate the sediment input from the Kalamazoo River. A series of sediment concentration measurements were made (approximately 80 individual measurements from 1974-1986) in the river near the inlet to Kalamazoo Lake and transport rates are reported in tons per day. Taking the numerical average of the individual measurements, and converting to cubic yards per year provides an estimated inflow rate of 23,000 cubic yards per year. Given the uncertainty due to the limited data, this number is consistent with estimated deposition rates obtained from changes in volume within the lake (*JJR and RMT 2007*). It is therefore reasonable to presume that the vast majority of sediment entering Kalamazoo Lake through the river ends up deposited within the lake. Precipitation events result in sediment being transported with the runoff from this large watershed. Solution techniques to eliminate the sediment contributions throughout the entire watershed would be helpful but are probably not feasible within regulatory and economic constraints. In-situ management techniques to handle the sediment inflow are limited to maintenance dredging or providing a solution that will transport a significant fraction of the sediment through the lake without deposition. Options to achieve the latter are considered to be limited.

One of the suggested alternatives for solving the Kalamazoo Lake sedimentation problem is the construction of a seawall near the river entrance into the lake on the south side of the inlet extending from the Blue Star Bridge out into the lake as shown in Figure 2. The main goal of the seawall is to direct the flow toward the far end of the lake rather than allow the velocities to slow down as the present inflow spreads out after entering the lake. The majority of the sediment would hypothetically be carried out into Lake Michigan, reducing the amount of deposition within the Kalamazoo Lake.

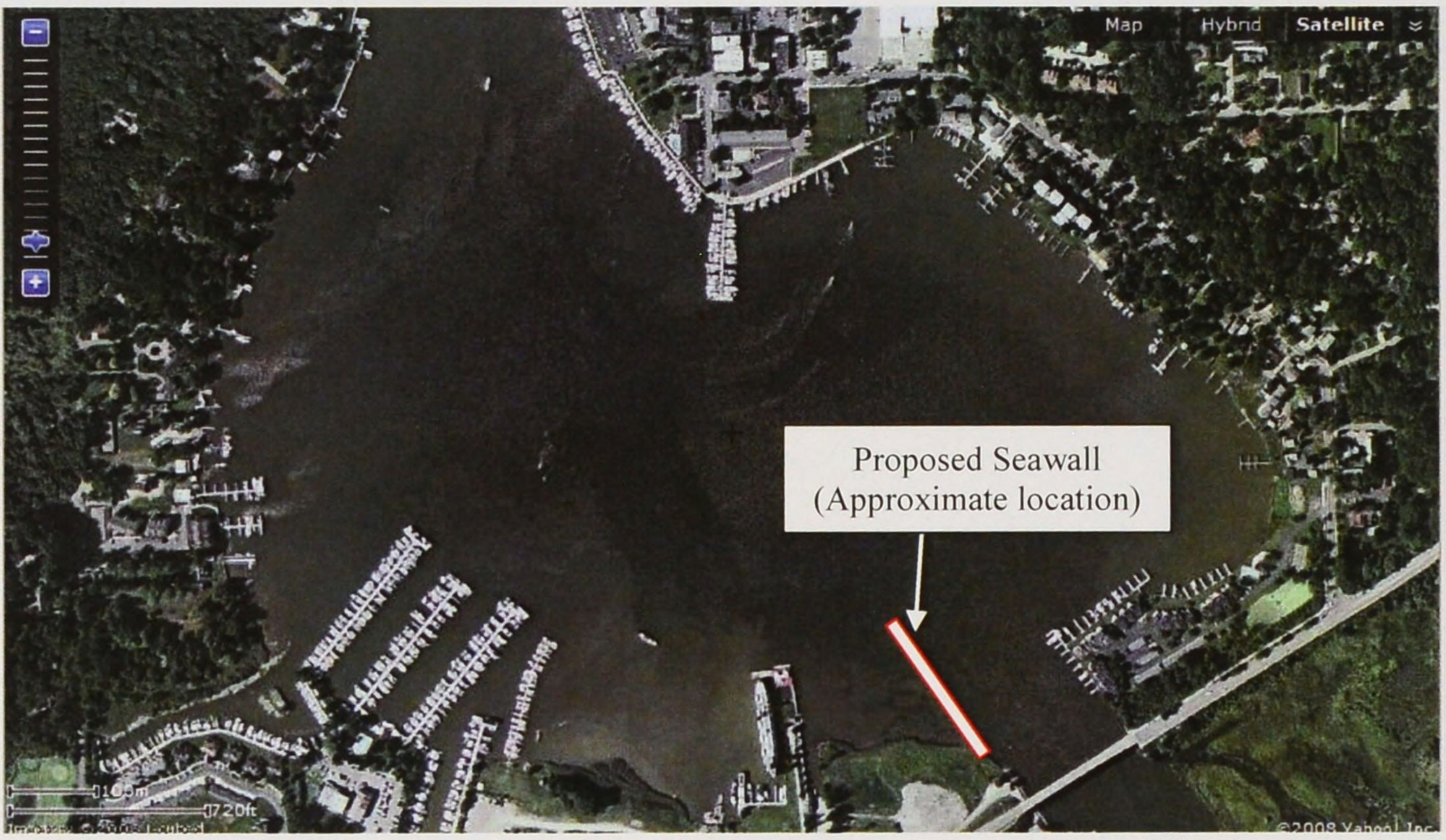

Figure 2: Approximate Location of the Proposed Sea Wall

The purpose of this research investigation was to construct a physical model of the Kalamazoo Lake and observe the effects of installing the proposed seawall. The physical model was used to observe the flow circulation and the sediment deposition patterns of the overall Harbor with and without the proposed seawall. This report describes the construction and testing of the physical model in detail as well as the results of the tests. A discussion is provided with recommendations based on the results.

II. Physical Model

Froude Number Scaling

The physical model was scaled from the actual site conditions using dimensional analysis. The hydraulic regime of the harbor is free-surface flow which implies that the elements of the model will be scaled using the dimensionless Froude number (*Henderson p.489*). The model scale was chosen based on laboratory space and surface tension effects. The available space in the laboratory allows for a model scale ratio of 1:150 in the horizontal direction. Using this scale in the vertical direction would introduce unwanted surface tension effects due to the very small water depths. Most of the lake is less than 1.5 m (5 ft) deep and a 1:150 vertical scale would produce depths less than 0.5 inches. Therefore, the vertical scaling is chosen different from the horizontal scaling. A reasonable vertical scale based on the depths of the lake and the capacity of the recirculation pump was 1:30. Table 1 presents the relationships between key model variables and the chosen length scales:

Table 1: Froude Number Distorted Model Scaling
(Subscripts: p = Prototype, m = Model)

Variable	Relation	Scaling Ratio
Length (horizontal)	$(L_m / L_p)_h$	1/150
Length (vertical)	$(L_p / L_m)_v$	30 / 1
Velocity	$v_m / v_p = (L_m / L_p)_v^{1/2}$	$v_m / v_p = (1/30)^{1/2}$
Discharge	$Q_m / Q_p = (v_m / v_p)\ (A_m / A_p)$	$Q_m / Q_p = (L_m / L_p)_h (L_m / L_p)_v^{1.5}$ $= (1/150)\,(1/30)^{1.5}$

Physical Model Construction

The physical model was constructed in the Civil Engineering Hydraulics Laboratory at the University of Michigan. The first step of construction was to set up concrete blocks around the model lake perimeter. Plastic sheets were then taped along the inside of the blocks and along the floor to create a seal for holding water. Sand was carefully filled and compacted on top of the plastic to be used for matching the bathymetry of the model to the actual lake. The bathymetry data used came from a combination of US Coast Guard Navigational Charts (*NOAA 2005*) and data obtained by the Great Lakes Center for Environmental and Molecular Sciences (*Coastal Dynamics 2003*). A grid was laid out over this bathymetric data to create squares of 75 feet x 75 feet (6 inches x 6 inches in the model). For each intersection of these grid lines a depth was transferred from the bathymetric data to the physical model. Measurements were made downward from an established reference datum to adjust the sand to the correct height. The sand was compacted and smoothed between node locations. Dry cement was sprinkled over the top of the sand and wetted to solidify the lake bottom. The lake was filled very carefully the first time to avoid any disturbance to the bottom surface before the cement set.

Water was re-circulated from the downstream outlet back to the upstream inlet using a 1 horsepower pump and 2 in. diameter PVC pipe. Reservoir areas were constructed at the inlet and outlet ends of the physical model to maintain entrance and exit velocity distributions that were not overly influenced by the concentrated flows at the re-circulating pipe inlet and outlet. The flow was regulated using a 2 inch ball valve. Flow was measured at the re-circulation outlet by collecting water in a bucket over a measured time interval. Repetitions were performed to ensure the precision of this measurement. Three different flow rates were used during the testing procedure as shown in Table 2 based on the expected maximum and minimum daily mean flow values of the Kalamazoo River according to *JJR and RMT2007*.

Table 2: The Three Tested Lake Flow Rates

Label	Prototype Flow (cfs)	Model Flow (cfs)
Low	1010	0.041
Medium	2155	0.087
High	3300	0.134

III. Experimental Procedure

There were two main objectives of the experiments: observe the flow circulation and observe the sedimentation patterns. The experimental procedure was relatively straightforward in accomplishing these objectives. The lake was filled until the level was at the correct elevation. The pump was turned on to initiate the re-circulating flow. The discharge was measured using a bucket and stopwatch; three repetitions were conducted to check each flow rate. Once the correct flow rate through the recirculation pipe was established for each test, the flow was then allowed to run undisturbed for approximately 10 minutes to allow a steady-state condition to be established. Small pieces of Styrofoam were sprinkled on the surface at the inlet to observe the flow circulation. Fine-grained quartz powder was also sprinkled at the inlet of the physical model to observe the sedimentation patterns. Video recordings of each experimental scenario were taken. A summary of the experiment tests is presented in Table 3.

Table 3 - Experimental Conditions

Label	Model Flows (cfs)
Original Conditions (no seawall)	0.041, 0.087, 0.134
With Squared Seawall	0.041, 0.087, 0.134
With Single Arm Seawall	0.041, 0.087, 0.134

IV. Results

General Flow Patterns

The main results were in the form of video recordings for each test. Figure 3 shows an example snapshot from the video of the constructed physical model. Some general observations can be made about the general flow circulation patterns based on the results of the physical model study. The results are discussed based on an orientation from the downstream-facing perspective, in other words from standing on the Blue Star bridge overlooking the Kalamazoo Lake.

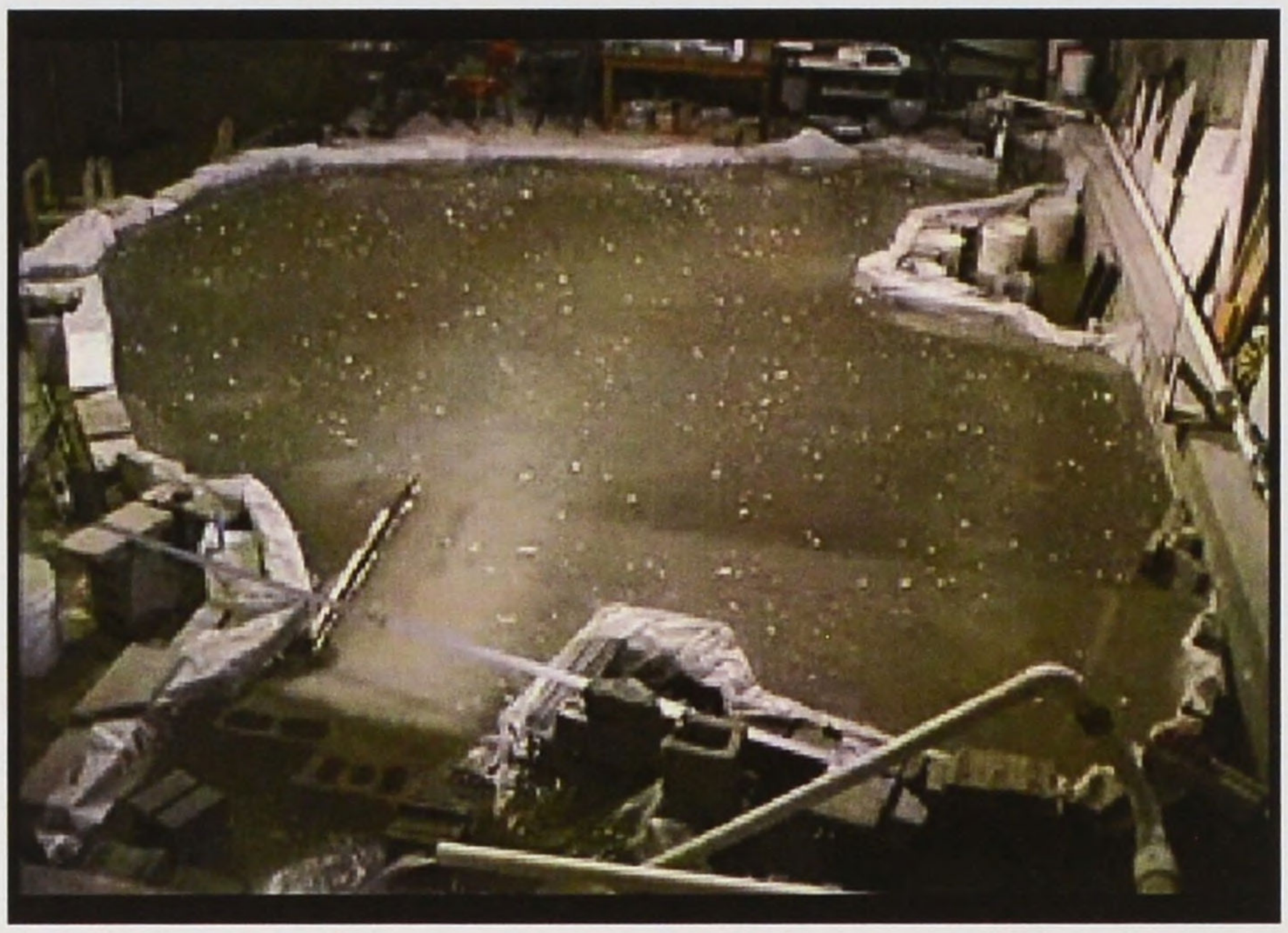

Figure 3 – Constructed Scale Model of Kalamazoo Lake
(Including single arm seawall)

Figure 4 below shows the normal circulation patterns which develop for the current conditions. In general, the flow veers slightly to the left about halfway through the lake before turning back to the right near the outlet. This is especially noticeable for low flow rates. The majority of the flow travels directly along this path and exits accordingly, however some flow enters the slow-moving eddies which exist in certain areas of the lake. There is a large counter clockwise eddy which develops at the west/northwest corner as the flow reaches the opposite side of the lake. A significant amount of flow is diverted into this eddy, especially for the highest discharge condition. Similarly, there is a smaller clockwise eddy which develops on the right side of the outlet and carries a small fraction of flow. Another large clockwise eddy exists in the northeast region of the lake. A counter-clockwise eddy of approximately 4 feet diameter (600 feet prototype) occasionally forms about halfway down on the left side and is especially noticeable for the lowest flow rate.

Figure 4 – Normal Circulation Patterns before Seawall
(From scale model observations)

Effect of Seawall Installation

To construct the seawall, a thin (1/4") wood panel was shaped to match the bottom bathymetry and stabilized in place to stand vertically. A squared wall was first implemented, made of two of these panel sides forming a 90 degree corner. The results of the single arm wall and the squared wall were equal based on our observations. Although the exact optimization of the angle and length of the proposed seawall which would be most cost-efficient for this situation is relatively difficult to determine, it is possible to make some general recommendations. An original suggestion as to the seawall orientation was basically to follow the line of the left bank of the entering river.

This original orientation of the seawall to form a 95 degree angle with the Blue Star Bridge caused a large amount of flow to be directed into the northeast pocket of the lake. The most reasonable angle based on our observations is to place the seawall parallel to the bathymetric contours on the bottom of the lake as shown in Figure 5. This will allow for the greatest amount of flow to be passed directly across and through the lake. For the NOAA 2005 data used in this study, this would mean that the seawall forms approximately a 105 degree angle with the Blue Star bridge.

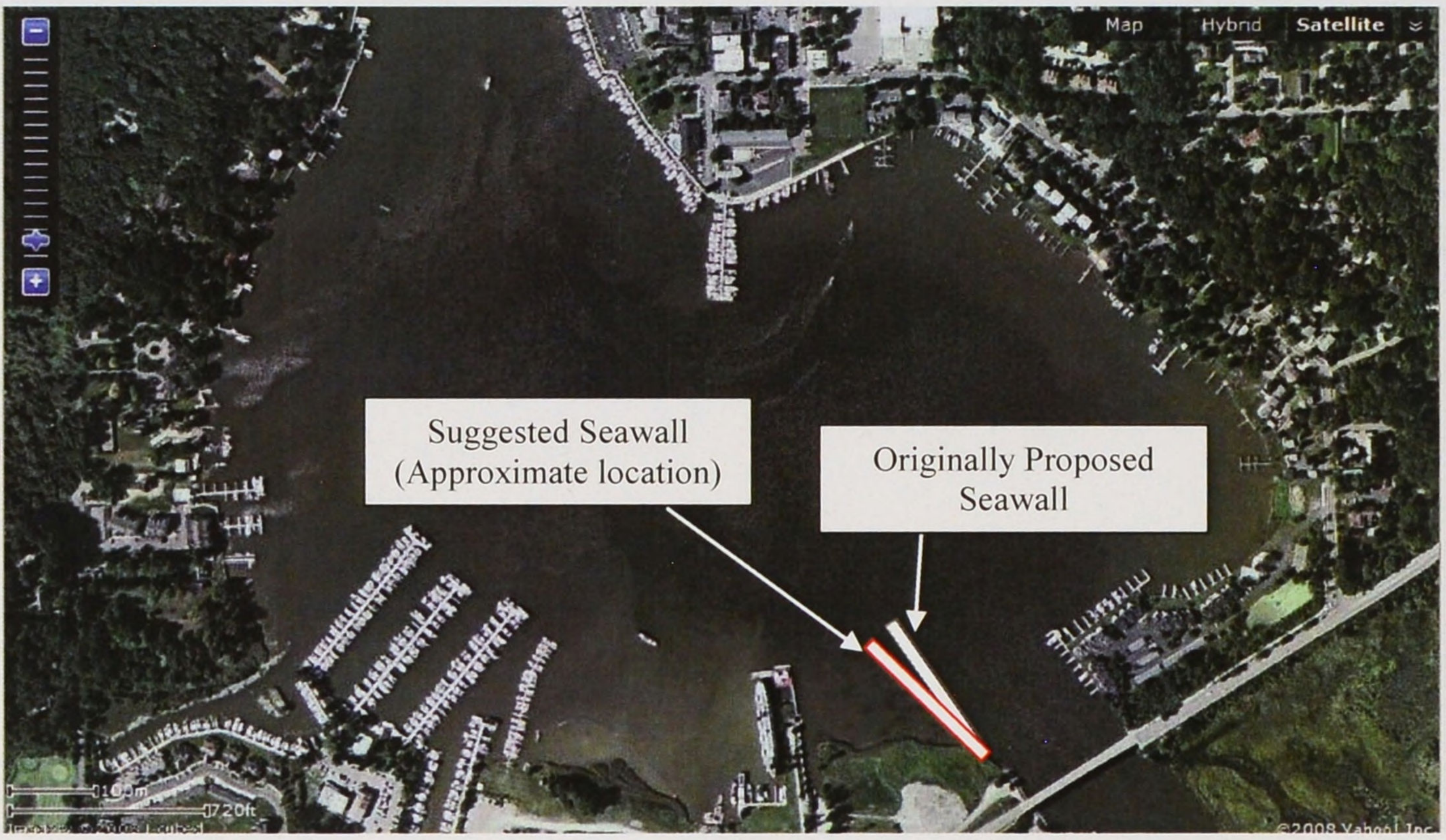

Figure 5: Recommended Seawall Location on Kalamazoo Lake

When tested at the proposed 105 degree angle, the seawall was effective in keeping the velocity higher as the flow enters the lake. Figure 6 shows the observed velocities comparing the "seawall" vs. "without seawall" results for the medium flow rate tests. Adjustments to the length of the seawall seem to have a limited influence on the overall objective of reducing sediment deposition. Lengths between 400 and 600 feet seem appropriate to accomplish the overall objective but distinguishing within this range is difficult.

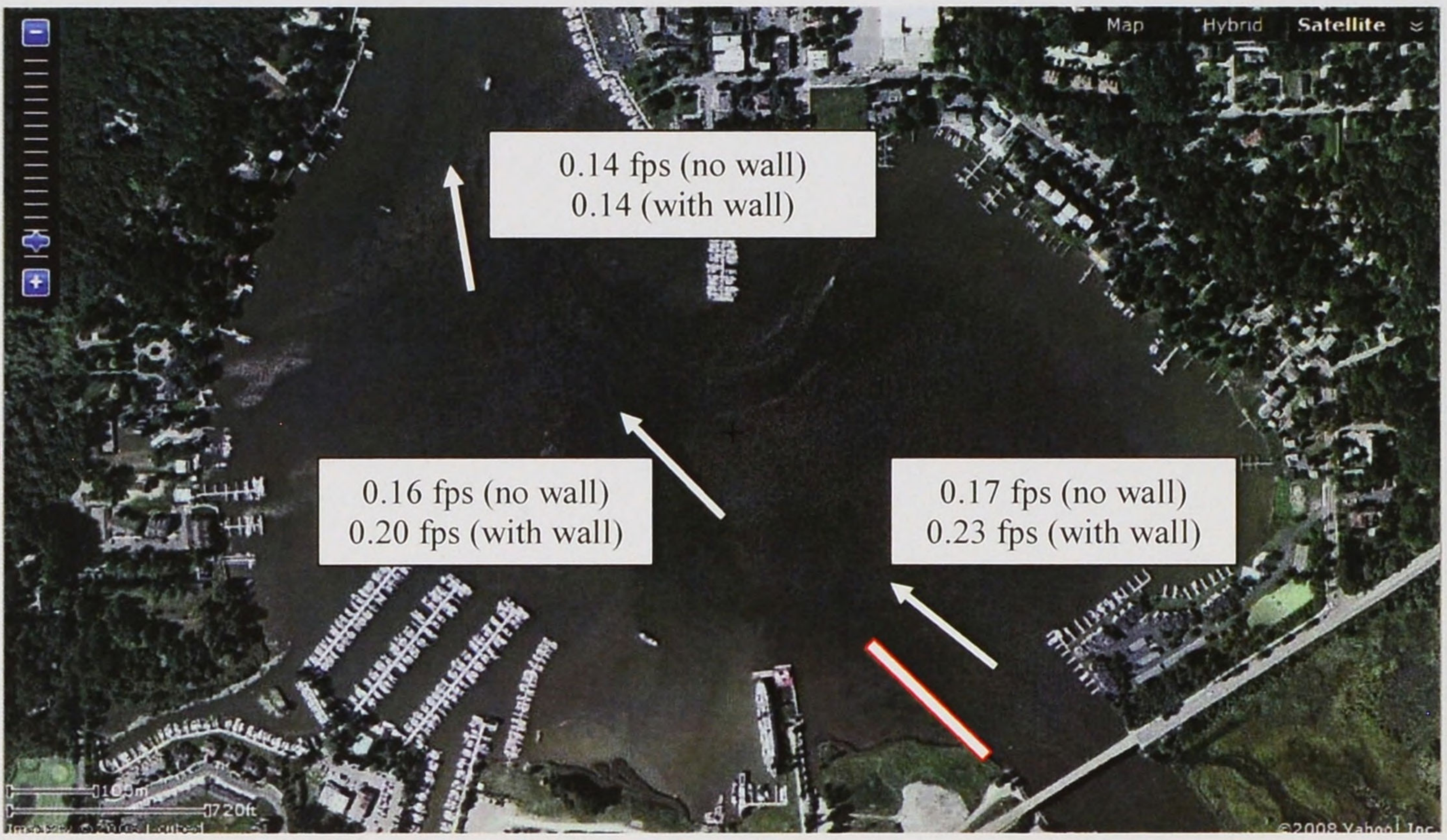

Figure 6: Observed Model Velocities for the Medium Flow Test Case (fps = ft/sec)

Sediment Transport Calculations

Sediment samples were taken by Atlantic Testing Laboratories in 2000 and included in the JJR and RMT 2007 technical report. The samples were withdrawn from the dredge spoils lagoon, located near the Tower Marine Marina. The dredge material originated from "the turning basing, Saugatuck city dock, chain ferry and Tower Marina in Kalamazoo Harbor" (*JJR and RMT 2007*). The sediment properties are summarized in the Table 4 below.

Table 4: Sediment Properties

Sample No.	D95 (mm)	D60 (mm)	D50 (mm)	D30 (mm)	D10 (mm)
33241	2.00	0.13	0.07	0.009	.0026
33233	0.40	0.21	0.18	0.114	.0522
33231	2.30	0.28	0.23	0.152	.0421
33229	0.25	0.12	0.10	0.080	.0462
33227	0.38	0.19	0.17	0.066	.0131
33226	2.00	0.36	0.10	0.011	.0014
33232	2.00	0.35	0.12	0.027	
33240	1.20	0.22	0.19	0.140	.0671
33228	3.00	0.07	0.05	0.026	
33230	2.80	0.05	0.037	0.007	
33237	3.00	0.18	0.13	0.030	.0033
33236	2.80	0.14	0.055	0.007	
33235	2.30	0.08	0.04	0.005	
33238	1.00	0.16	0.12	0.011	
33239	5.00	0.29	0.21	0.090	.0151
33234	1.70	0.10	0.06	0.034	.0054
Average	**2.00**	**0.18**	**0.12**	**0.051**	**0.0249**
Geo. Mean	**1.55**	**0.16**	**0.10**	**0.029**	**0.0124**

Sediment transport calculations are performed based on the observed velocities from Figure 6 to determine the approximate size of sediment grains that would be transported. These calculations assume a gravitational constant $g = 9.81$ m/s^2, a median grain size $d_{50} = 0.10$ mm, a sediment density $\rho_s = 2.65$ g/cm3, and a water density $\rho = 1.00$ g/cm^3. The kinematic viscosity, v, changes as a function of temperature so two values will be used:

Temperature	Kinematic Viscosity
5°C (37°F)	1.519×10^{-6} m^2/sec
15°C (59°F)	1.141×10^{-6} m^2/sec

The Reynolds number is calculated using $\mathrm{Re} = \frac{uh}{v}$ where h = depth of water, u = velocity, and v = kinematic viscosity. From this, an equation can be used based on the work of Nikuradse, and of Colebrook and White to find the friction factor f:

$$\frac{1}{\sqrt{f}} = 2.0\log_{10}\left(\frac{\mathrm{Re}\sqrt{f}}{2.51}\right)$$

Then the shear velocity can be calculated using: $u_* = u\sqrt{\frac{f}{8}}$. The grain Reynolds number is then: $\mathrm{Re}_* = \frac{u_* d_{50}}{\nu}$. In 1963 Bonnefille approximated the Shields curve by using piece-wise relationships relating the Reynolds number to the dimensionless grain size.

$$\begin{aligned}
D_* &= 2.33\,\mathrm{Re}_*^{0.79} && \mathrm{Re}_* < 1 \\
D_* &= 2.33\,\mathrm{Re}_*^{0.85} && 1 < \mathrm{Re}_* < 5 \\
D_* &= 2.78\,\mathrm{Re}_*^{0.74} && 5 < \mathrm{Re}_* < 10 \\
D_* &= 3.96\,\mathrm{Re}_*^{0.584} && 10 < \mathrm{Re}_* < 100
\end{aligned}$$

The formula for the dimensionless grain size is:

$$D_* = \left(\frac{\rho_s - \rho}{\rho}\frac{gd^3}{\nu^2}\right)^{1/3}$$

Solving for the sediment diameter produces the results found in Table 5 below. The *d* column represents the sediment size which is transportable by the corresponding velocities.

Table 5: Sediment Transport Calculations and Properties

Observed Model Velocity (ft/sec)	Real / Prototype Velocity (m/s)	Prototype Depth (m)	*d* (mm) cold	*d* (mm) warm
0.14	0.234	2.1	0.098	0.101
0.16	0.267	1.8	0.109	0.114
0.17	0.284	1.8	0.114	0.119
0.20	0.334	1.8	0.128	0.135
0.23	0.384	1.8	0.143	0.151

There was a very small difference between using the 5°C and the 15°C kinematic viscosity values. The sediment transport relations are directly dependent on the velocity of the fluid, so the slight increase in velocity due to the installation of the seawall would result in only a slight increase in the size of sediment particles which would be transported through the lake.

Assuming that the sediment samples from the dredged material is representative of the sediment carried into the lake, roughly half of the sediment is able to be transported through the center of the lake during medium flow conditions. Using the geometric mean of the soil data, we see that the outlet velocity (.234 m/s prototype) is only able to transport roughly 50% of the incoming sediment. This outlet velocity is not influenced by the construction of the seawall which implies that half of the sediment may still be deposited somewhere within the lake, only perhaps in a different location due to the seawall. The increased velocity due to the seawall at the start of the lake is able to transport roughly 58% of the incoming sediment. Without the seawall, roughly 53% of the sediment is able to be transported. During periods of large flow through the lake, this difference in velocity may result in slightly less sediment deposition near the lake inlet due to the increased velocity from the seawall. Although it would be expected that less sediment deposition will occur in the vicinity of the river discharge into the lake due to the construction of the seawall, it appears unlikely that this action alone will result in a significant decrease in deposition within the lake.

V. Conclusions

The following statements can be made based on this physical model study:

- Based on the limited information available, it appears that much of the sediment carried in by the Kalamazoo River gets deposited within the Kalamazoo Lake.

- The seawall, especially if aligned with the current bottom contours of the channel through the lake, tends to concentrate the flow and results in higher velocities near the inflow of the Kalamazoo River into the lake.
- Once the flow crosses the lake, the changes in velocity are very small, implying that the change of overall deposition within the lake is negligible.
- We expect that locations of deposition would change with the seawall construction but would not expect significant change in the amount deposited. In particular, less deposition is expected in the vicinity of the proposed seawall and somewhat less on the south side of the lake due to a reduction in eddies shed as inflow enters the lake.

VI. References

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AIIM SCANNER TEST CHART # 2

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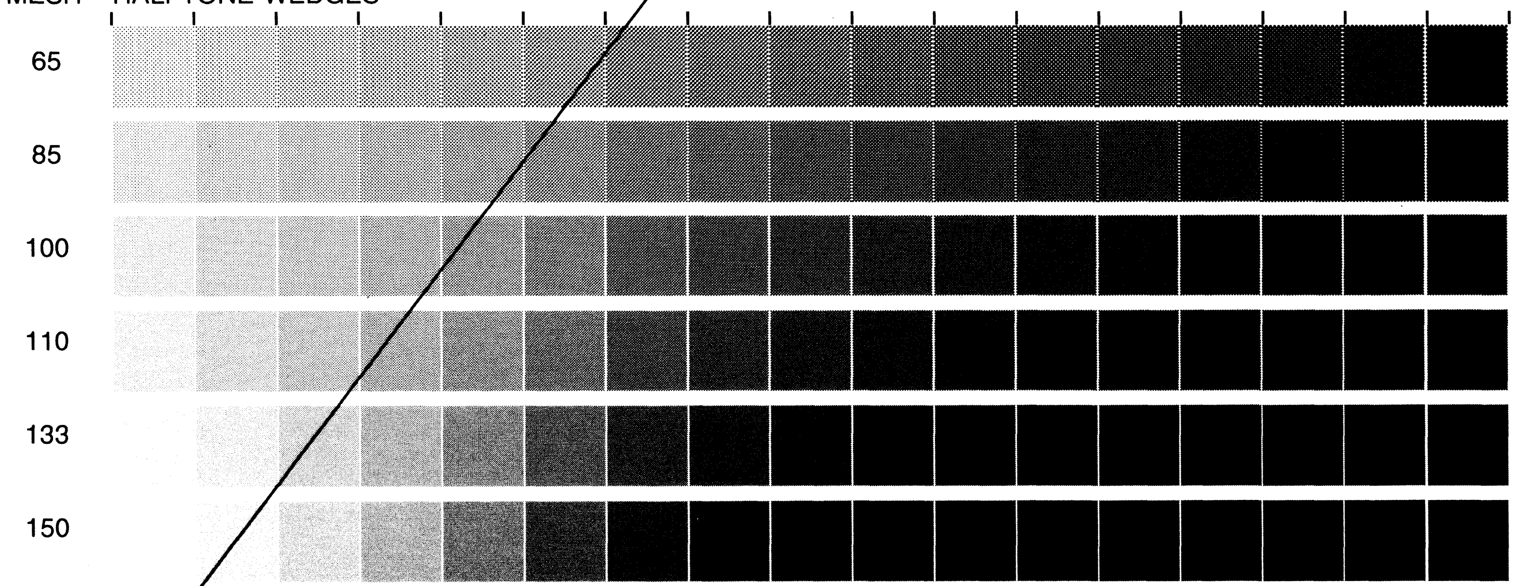

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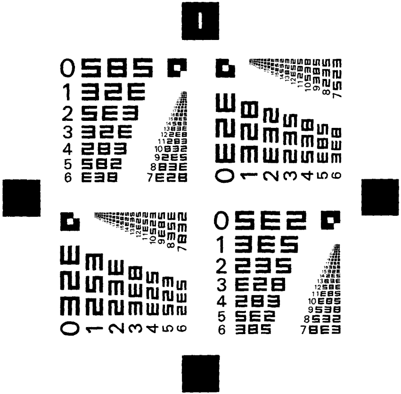

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