Protecting Our Water Environment

Metropolitan Water Reclamation District of Greater Chicago

RESEARCH AND DEVELOPMENT DEPARTMENT

REPORT NO. 03-26

HYDRAULIC MODEL STUDY OF CHICAGO RIVER DENSITY CURRENTS

Progress Report

Prepared By

Ven Te Chow Hydrosystems Laboratory
Department of Civil and Environmental Engineering
University of Illinois at Urbana-Champaign

December 2003

Metropolitan Water Reclamation District of Greater Chicago
100 East Erie Street Chicago, IL 60611-2803 (312) 751-5600

HYDRAULIC MODEL STUDY OF CHICAGO RIVER DENSITY CURRENTS

Progress Report

Prepared By

Ven Te Chow Hydrosystems Laboratory
Department of Civil and Environmental Engineering
University of Illinois at Urbana-Champaign

December 18, 2003

Research and Development Department
Richard Lanyon, Director

December 2003

Progress Report

Hydraulic Model Study of Chicago River Density Currents

By

Marcelo H. Garcia*, Claudia Manriquez**, Andrew R. Waratuke***
*Siess Professor, **Research Assistant, ***Research Engineer

Ven Te Chow Hydrosystems Laboratory

Department of Civil and Environmental Engineering

University of Illinois at Urbana-Champaign

Research Sponsor

Metropolitan Water Reclamation District of Greater Chicago

December 18, 2003

Introduction

Water quality in urban rivers is an issue of increasing importance at the beginning of the new millennium. Problems such as pollution due to solid urban waste, discharges of heated water from cooling systems, and contamination generated by industrial liquid effluents are quite often reported in the media and discussed in the specialized literature. At the same time, several previously "unforeseen" problems have appeared during the last few years that have an important impact on the management and operation of river systems. For instance, the Chicago River (CR) has recently experienced some interesting phenomena. Recent measurements performed by the Illinois District of the United States Geological Survey (USGS) have revealed bi-directional flow in the river during wintertime, a phenomenon not commonly reported in the leading literature of hydraulic engineering and water-quality assessment.

Motivated by these findings, the Metropolitan Water Reclamation District of Greater Chicago (MWRDGC), which manages the water flow and quality of the river, contacted researchers at the Ven Te Chow Hydrosystems Laboratory (VTCHL) at the University of Illinois at Urbana-Champaign, and co-sponsored, together with the Illinois Department of Natural Resources, a study to elucidate the causes and science of such phenomenon. Motivated by this request, the staff of the VTCHL submitted an explanation for the existence of bi-directional flow through the potential occurrence of density currents in the Chicago River.

Density currents are well known to be capable of transporting contaminants, dissolved substances, and suspended particles for very long distances (Garcia, 1993; 1994). If this is the case in the Chicago River, there could be a potential water-quality problem due to the potential for adverse impact on Lake Michigan.

The potential occurrence of density currents in the Chicago River is supported by the results from a three-dimensional hydrodynamic simulation conducted by Bombardelli and Garcia (2001). However, such phenomenon has yet to be directly observed and the USGS observations of bi-directional flow constitute the only “smoking gun.”

In order to test this hypothesis, a hydraulic model of the Chicago River system has been constructed in the VTCHL. The goal of this model study is to determine the conditions for which the bi-directional flow develops with the ultimate goal of determining the steps that need to be taken to prevent its formation in the future.

This report details the scaling, design, and construction of the physical model, as well as some theoretical considerations and preliminary experiments that have been performed in the Chicago River model. The overall objective of the study are to characterize the hydrodynamic conditions that lead to the generation of density currents and to assess different technologies that could be used to prevent such phenomenon from taking place.

Model Description

A physical model of the CR system has been constructed in the VTCHL. The model includes the Main Branch of the Chicago River (MBCR) extending to the North Pier Lock and Lake Michigan to the East, the North Branch (NBCR) extending to Grand Ave. to the North, and the South Branch (SBCR) extending to Monroe Street. A map of the area that has been modeled is presented in Figure 1. In order to be able to fit the 2.80 x 1.25 kilometer footprint of the prototype section within the laboratory space available, it was necessary to choose a horizontal scale factor of 1 to 250 with a vertical scale of 1 to 20. The distortion of the scales was necessary so that the flow depths would be measurable within the laboratory. Using a consistent scale of 1 to 250 would have resulted in a model depth of approximately 3 centimeters (for a prototype depth of 7 to 8 meters). The chosen scales resulted in a vertical distortion of 12.5, which is acceptable for this type of model studies (ASCE, 2000).

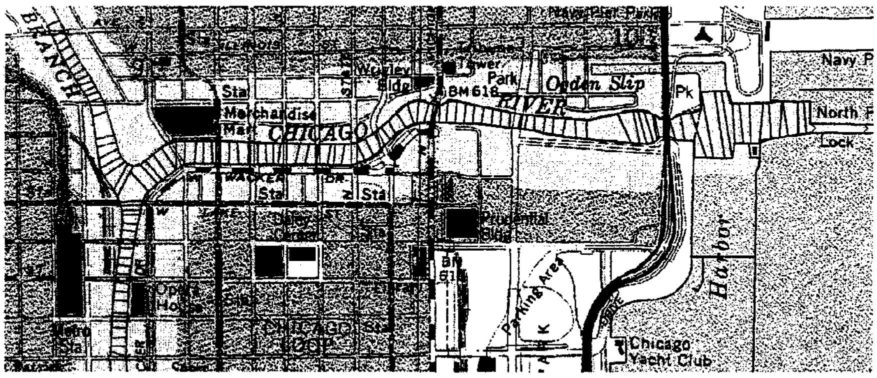

Figure 1: Map of the Chicago River showing Modeled Area

The model basin was constructed out of modular fiberglass sections manufactured by Engineering Laboratory Design Inc., Lake City, MN (Figure 2). Constructing the model in this manner had several distinct advantages over the more traditional method using plywood and cast concrete. First, manufacturing the model basin out of fiberglass made it simpler to represent accurately the plan shape of the river channel – in the area of interest, the CR system bends and turns a great deal. Constructing the concrete forms necessary to build this type of geometry out of concrete would have proven to be time consuming and labor intensive. Second, using fiberglass made it possible to build a very slender model basin with minimal space requirements. Constructing the same basin out of concrete would have required much more space in the laboratory. Third, the use of fiberglass made it possible to add several plexi-glass viewing windows in the side of the model. These windows are important because they will allow the project staff to perform visualization studies of the flow in profile, which is very important in the case of bi-directional underflows. In addition, the windows will provide an opportunity to make flow measurements using a technique known as PIV (Particle Image Velocimetry), a non-intrusive measurement technique in which a laser sheet and high-speed video camera are used to measure the velocity of the flow by tracking the movement of seeding particles suspended within the water column. Finally, the modular construction of the basin makes it possible to non-destructively disassemble the basin when this study is completed. Thus, should any future modeling work be required, the basin can be re-assembled with minimal time and effort.

Figure 2: Chicago River Model Basin in VTCHL

In order to accurately represent the geometry of the channel bottom, a survey of the channel bathymetry was conducted by the USGS. Bathymetric data was collected by boat along 112 plan lines (73 along the MBCR, 20 in the NBCR, and 19 along the SBCR – see Figure 1 for locations). After the data was collected, it was necessary to perform some manipulation so that usable cross sections could be generated and added to the model. While collecting the data, it was not always possible to remain on the planned line while piloting the boat. This sometimes resulted in extremely curved survey lines that could not be placed, as-is, in the model. For practical reasons, the cross-sections must be straight. Thus, it was necessary to project the survey data back onto the planned lines. After this was completed, the data was smoothed to remove any "noise" from the data. Finally, the width of the survey cross sections was adjusted so that it matched to channel width exactly.

The model basin was built so that it accurately represented the plan shape of the river system, but was built with a constant channel depth of 60 cm in order to facilitate construction of the channel bottom. After the cross-sectional data had been finalized, it was plotted out to scale and overlain on 1/4"-thick sheets of plywood (Figure 3). These cross sections were then cut out and placed at the appropriate location in the model basin and braced using 2 x 2 wood blocks (Figure 4).

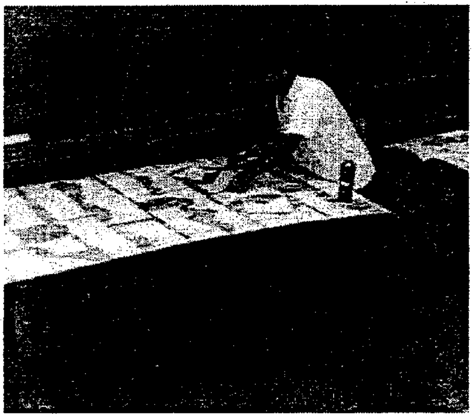

Figure 3: Laying Out Model Cross-Sections

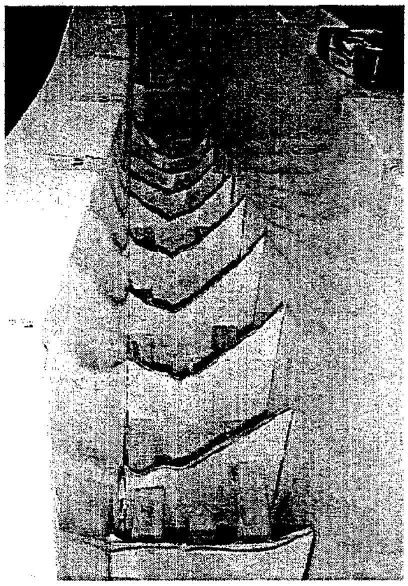

Figure 4: Model Cross-Sections in Place within the Basin

After placing all of the cross sections, it was necessary to fill the void space and construct the channel bottom between the cross sections. This was done by filling the space between the cross-section templates with pea gravel (Figure 5) and then capping it with mortar (Figure 6). The mortar was used for two reasons. First, the distortion to the vertical scale meant that sections of the channel bottom have slopes much greater than the accepted repose angle of sand or gravel (approx. 30 degrees). Thus, it was necessary to cap the pea gravel with a material that would maintain the steep slopes once cured. Also, capping the gravel with mortar insures that the channel bottom will remain static during testing. Finally, an asphalt-based sealant was used to seal any joint or cracks that were present in the mortar cap.

Figure 5: Pea-Gravel Fill Material

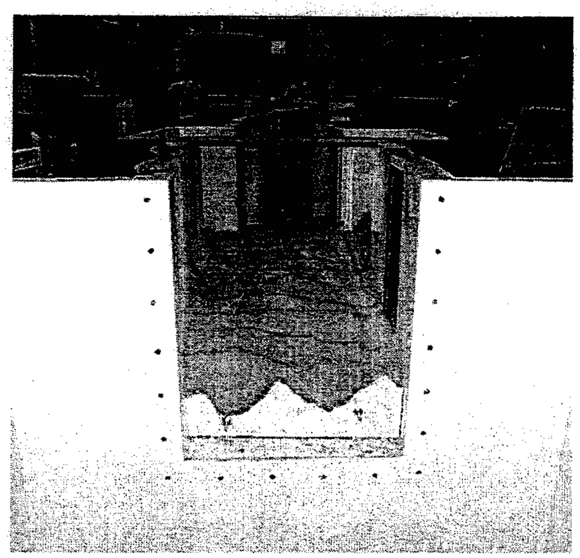

Figure 6: Mortar Cap in the Model Basin

Additionally, a hydraulic closed circuit was built to allow the flow of fresh and salty water through the model. It is composed of two independent lines, as it is shown in Figure 7. The in-line pumps salty water from the salt tank into the north branch tank and the out-line pumps water from the south branch tank into the salt tank or into a trench. One pump is manufactured by Goulds Pumps, Model SST (2" x 2" suction and discharge pipe sizes) while the second pump is manufactured by Teel Pumps (2" suction pipe, 1-1/2" discharge pipe). In both lines flow meters were installed to measure flow discharge. The flow meter of the outgoing line is an electromagnetic sensor manufactured by

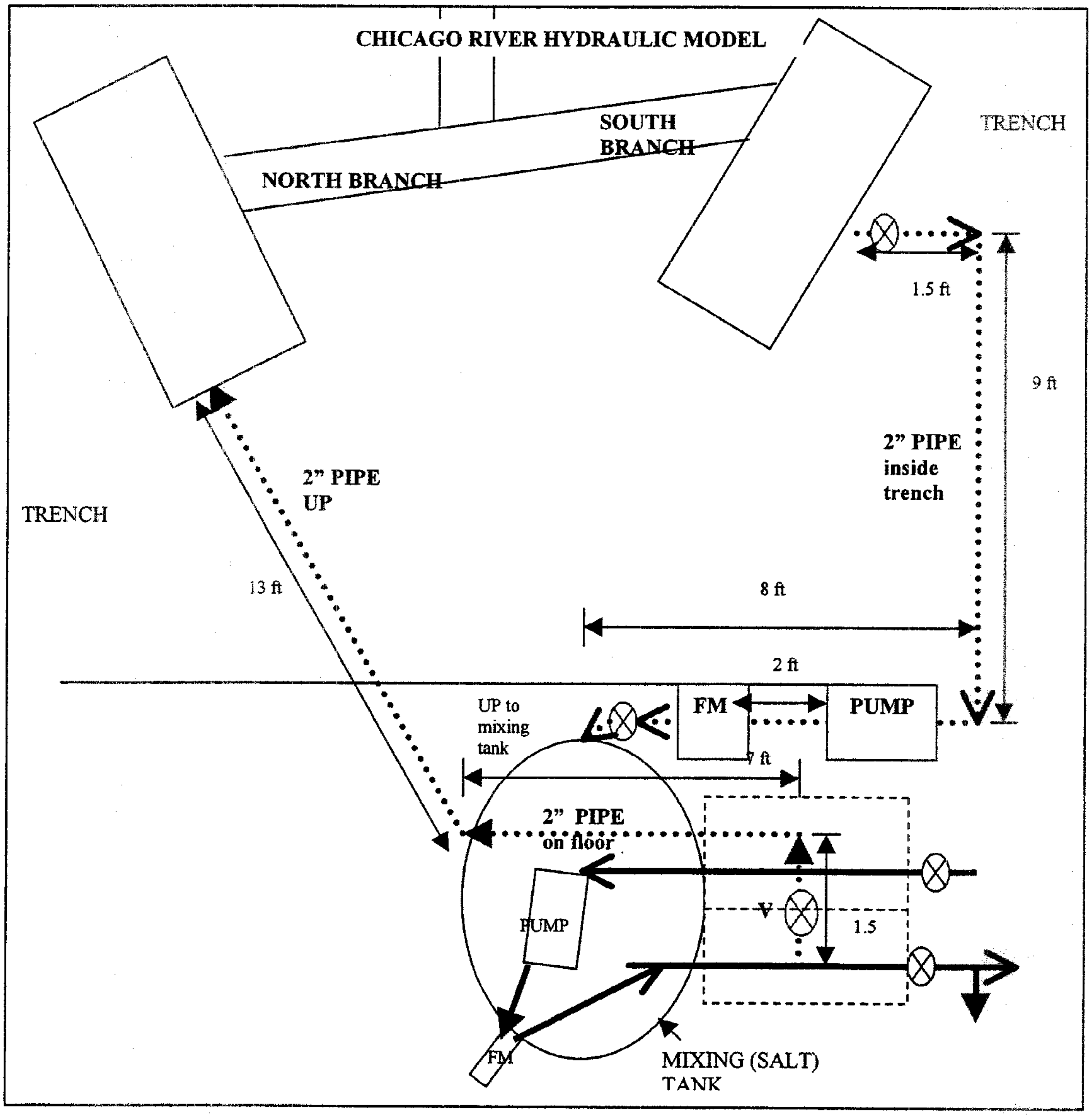

Fig.7: Schematic of the Hydraulic Circuit of the Chicago River Model.

McCrometer Inc. Also, a gate at the exit of the North Branch tank was placed to separate the incoming flow from the water that is stored in the model.

Initial operation of the model revealed the need for additional bracing to maintain the integrity of the channel walls. Such bracing does not affect the modular construction and the disassembly and re-assembly of the model.

Model Scaling

In order to maintain similarity between the prototype and model systems for a density-driven flow, it is necessary to set the ratio of the densimetric Froude number, F_d, or Richardson number, Ri, between the prototype and model equal to one. The Richardson number is related to the densimetric Froude number and is defined as:

$$Ri = \frac{g \frac{\Delta\rho}{\rho} h}{U^2} = \frac{1}{F_d^{\,2}} \tag{1}$$

Where g is the acceleration of gravity, $\Delta\rho/\rho$ is the excess fractional density, h is the mean flow depth, and U is the cross-sectional mean velocity.

Keeping the ratio of the Richardson numbers equal to one ($Ri_r = Ri_p / Ri_m$, where the subscripts r, p, and m denote ratio, prototype scale, and model scale, respectively), gives the following relationship for discharge:

$$Q_r = \left(\frac{\Delta\rho}{\rho}\right)_r W_r h_r^{3/2} \tag{2}$$

where Q_r is the ratio of mean discharges, W_r is the ratio of the horizontal scales, and h_r is the ratio of the vertical scales.

Setting $(\Delta\rho/\rho)_r = 1/100$, $W_r = 250$, and $h_r = 20$ gives a discharge ratio of 2236. Based upon an analysis of streamgage data collected along the North Branch Chicago River at Grand Avenue (USGS gage 05536118, North Branch Chicago River at Grand Avenue), the average daily flow for the period between November 4, 2002 and February 12, 2003 was 260 cubic feet per second (cfs). Using the above factor, the scaled flow rate for the model is 0.116 cfs, or 3.28 liters per second (l/s).

Derivation of the Scale Factors

Scaling of flow and density gradients was achieved by maintaining the same densimetric Froude number, F_d, in the model and prototype or the same Richardson number, Ri. Thus, the ratio of the Richardson numbers should equal one.

$$\frac{Ri_p}{Ri_m} = Ri_r = \frac{\left(\frac{\Delta\rho}{\rho}\right)_r h_r}{U_r^2} = 1 \tag{3}$$

This equation has three degrees of freedom, $\Delta\rho_r$, h_r, and U_r. In order for this equation to have a unique solution, it is necessary to set two of the parameters, in this case $\Delta\rho_r$ and h_r. With the fixed geometric scaling used for the model ($h_r = 250$ and $W_r = 20$), there are two possible approaches to the scaling, detailed below.

First approach - set $(\Delta\rho/\rho)_r = 1$

The appropriate scaling factors can be obtained by inspection of the Richardson number, for the case when the excess fractional density in the prototype is set equal to the one in the model, as follows:

$$Ri_r = \frac{h_r}{U_r^2} = 1 \therefore U_r = L_r^{1/2} \tag{A1}$$

The discharge, Q, is defined as $Q = U \times A$. Thus,

$$Q_r = U_r \times A_r \text{, where} \tag{A3}$$

$$A_r = h_r \times W_r \tag{A4}$$

Therefore, substituting (A2) and (A4) into (A3) gives

$$Q_r = U_r \times A_r = h_r^{1/2} \times h_r \times W_r = h_r^{3/2} \times W_r \tag{A5}$$

Substituting in the values for h_r and W_r ($h_r = 20$ and $W_r = 250$) gives a value of $Q_r = 22{,}360$. Thus, for a mean daily flow discharge of 260 cfs in the Chicago River, the model flow would need to be 0.0116 cfs (0.3 liters/s). With a mean model depth and width of 35 centimeters, the mean velocity at this flow rate would be approximately 0.25 cm/s, too small to be measured accurately. Thus, it is necessary to change the excess fractional density ratio to get a measurable channel velocity in the physical model.

Second approach - set $(\Delta\rho/\rho)_r = 1/100$

An alternative is to increase the excess fractional density in the model with respect to the prototype so that the resulting flow velocities can be measured. This approach yields,

$$Ri_r = \frac{\left(\frac{\Delta\rho}{\rho}\right)_r h_r}{U_r^2} = 1 \therefore \left[\left(\frac{\Delta\rho}{\rho}\right)_r h_r\right]^{1/2} = U_r \tag{A6}$$

Substituting (A6) and (A4) into (A3) gives

$$Q_r = \left[\left(\frac{\Delta\rho}{\rho}\right)_r h_r\right]^{1/2} \times h_r \times W_r = \left(\frac{\Delta\rho}{\rho}\right)_r^{1/2} \times h_r^{3/2} \times W_r \tag{A7}$$

Substituting in the values for $(\Delta\rho/\rho)_r$, h_r, and W_r gives a value of $Q_r = 2{,}236$. The model flow discharge is therefore 0.116 cfs (3 l/s) and the mean channel velocity is 2.5 cm/s. These values of flow discharge and mean flow velocity can be accurately measured in the model with the help of particle-image-velocimetry (PIV) and acoustic Doppler Velocimeters (ADVs).

Originally, water refrigeration was to be used to produce density gradients. However, an evaluation of the flow rates needed in the model suggested the need for a fairly large piece of heat-transfer equipment. The refrigeration units that were available turned out to be faulty so a decision was made to use an existing tank for mixing of salt and water. Heat can be lost to the air above the river model, but salt is a conservative contaminant thus facilitating its control and monitoring in the laboratory. Fine silt and clay particles will also be used in combination with the salt, so that the fate of solids particles in the river can be both visualized and studied in detail.

Preliminary Experiments

In order to test the potential occurrence of density currents in the Chicago River, a preliminary experiment was carried out to create a density current in the model and to measure flow depths and flow velocities. The experimental conditions are given in the table below.

Experimental Conditions for Preliminary Run					
	Model		Scale conversion	Prototype	
Discharge	0.116	cfs	2236	**260**	cfs
Temperature	14	(°C)			
Density of water-salt mixture	1.01				
Density of river water	1.001				
Δρ/ρ	0.009		0.01	**0.0001**	
Flow velocity			0.447		
Vertical elevation			20		

Once the denser water-salt mixture coming down the North Branch got to the junction with the Chicago River, it plunged and a density current developed along the bottom, slowly flowing towards lake Michigan. An acoustic Doppler velocimeter (ADV) was used to measure the vertical flow velocity distribution at a river-cross section located at Columbus Drive. The observed velocity profile was converted to prototype scale and is plotted in Figure 8 together with observations made by the USGS at the same location. Even though, the values of flow velocity are not exactly the same, the velocity distribution in the vertical is quite similar in the model and the prototype. It is important to keep in mind that the conditions used in the model for this preliminary experiment are not necessarily the same ones that existed in the Chicago River the day the measurements where taken by the USGS. Flow discharge is the most reliable parameter but the density differences that might have been present are more difficult to estimate. However, these results are encouraging since they clearly point out that density currents are quite likely to develop in the Chicago River. The model observations also support the trend of the field measurements obtained by the USGS.

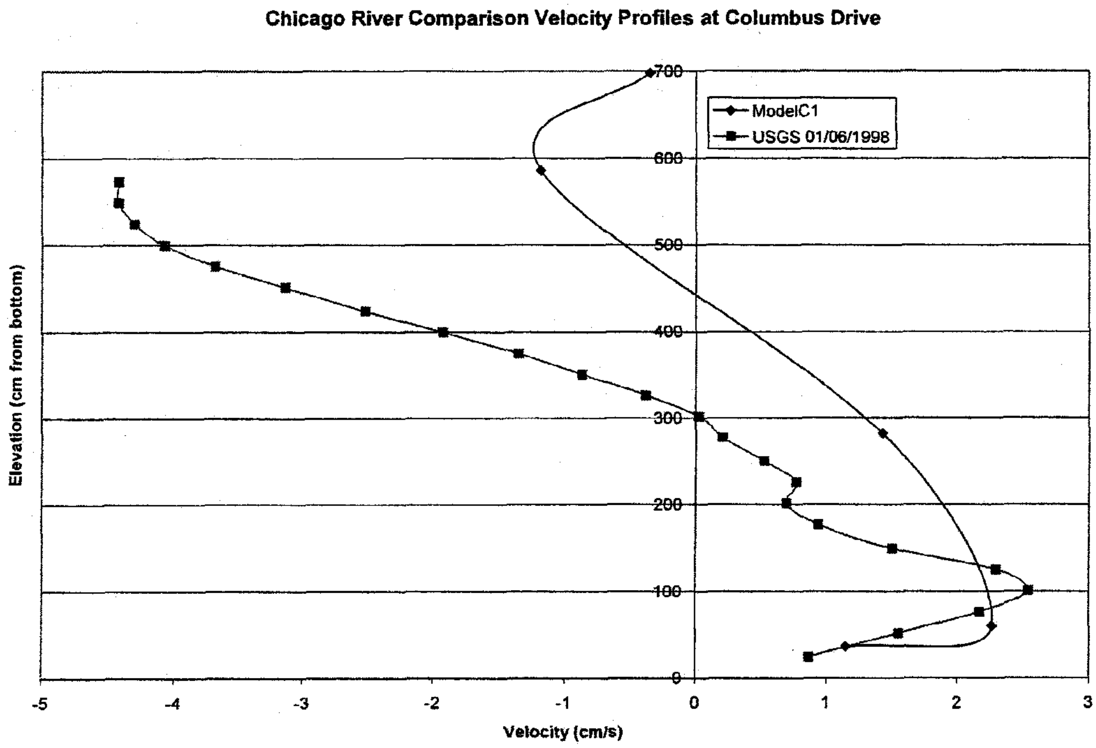

Figure 8. Comparison of flow velocity distribution observed in the model and in the field.

Future Experimental Work and Analysis of Field Data

While the results obtained so far are promising, it is clear that more experiments are needed in order to assess the dynamics of density currents in the Chicago River and the conditions that lead to their development. Field data can be used to compare and interpret the experimental observations made so far, and to select future experimental conditions. In particular, a theoretical analysis of the measurements of the event occurred in March 18, 1998, will serve as guide to determine relevant parameters such as plunging point conditions, density differences, flow velocities, discharges, flow depths and Richardson number. This analysis is presented below.

From this analysis, it follows that:

- In the hydraulic model, the density difference will be best achieved by the incorporation of salty water. Therefore, a system of inflows and outflows of water having different density (see Figure 7), will be used in the model to maintain the stable stratification in the system. Series of experiments will be conducted to determine the range of flow discharges and density differences required to originate density currents. Also, the temporal evolution of the system will be studied.

- The equations for prediction of the plunging point and lock exchange show results that are consistent with the few available field observations. Thus they will be applied in the hydraulic model to analyze simple cases, and to compare the observed values of the location of the plunging point near the junction, and average flow depths of the under- and over-flow along the Chicago River.

- Further experiments will be carried out to capture the complexity of the bed and its interaction with the flow to predict the profile of the underflow depth.

Theoretical analysis of field data

The Chicago River presents a very irregular bed, with differences in elevation of the order of 1 m that is within the order of magnitude of the flow depth (7.3 m). Thus, depending on the reach the slope could be treated as favorable or adverse to the flow. For this exercise, the bottom slope was estimated as an average slope with a value of 0.0001. The mean bottom elevation of the Chicago River slopes down from the junction towards Lake Michigan. The gradient is very small and different values can be obtained depending on how it is estimated. However, it is large enough to promote the movement of denser water coming down the North Branch, towards the lake as a density current.

The flow depth, flow velocities and discharges were obtained by analyzing field measurements of velocity, conductance and temperature in three cross sections along the river, taken by the USGS on March 18, 1998. From the junction with the North Branch going towards the lake these sections are La Salle Bridge, Wabash Bridge and Mc Clurg Court (Fountain). Figures 9, 10 and 11 show these measurements and Table 1 summarizes the parameters obtained from the analysis of the data.

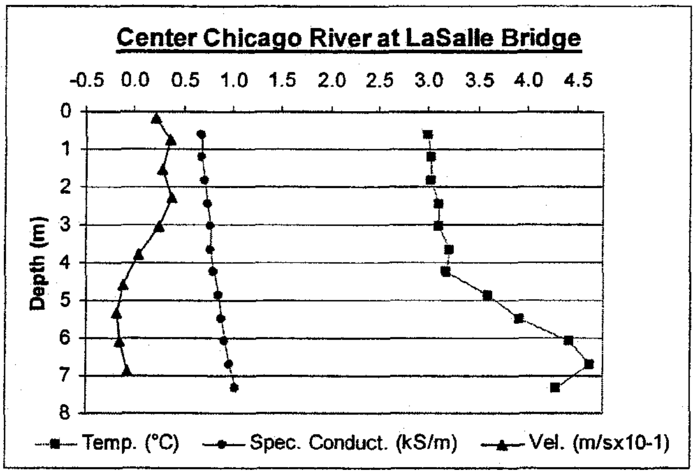

Figure 9: Field measurements of temperature, velocity and conductance at La Salle.

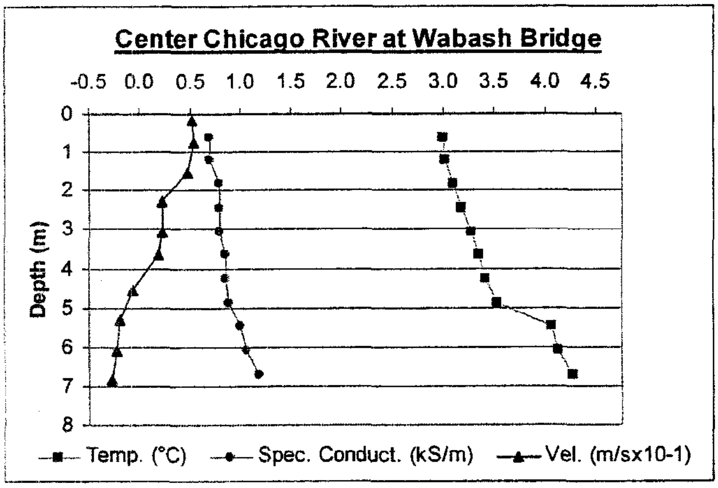

Figure 10: Field measurements of temperature, velocity and conductance at Wabash.

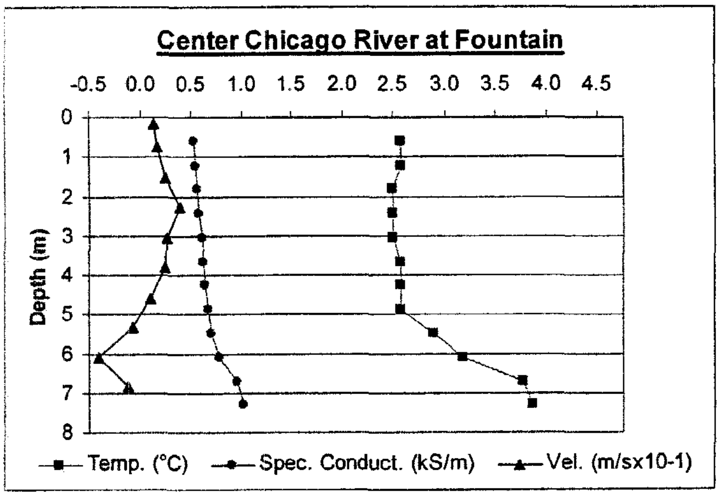

Figure 11: Field measurements of temperature, velocity and conductanc. at Court(Fountain)

If the flow is assumed to be an underflow over a virtual uniform bed located 7.3 m underneath the free surface, the measurements can be interpreted as follow: the eventual plunging point could be located upstream of La Salle and the underflow develops from that point towards the lake. The underflow depth is in the order of 2.4 m and the velocity of the front is of the order of -0.03 m/s, which decreases downstream. The latter might occur due to bottom friction losses. The discharge of the underflow is approximately equal to 0.04 $m^3/s/m$. Notice that the free surface of the river can be considered as horizontal for practical purposes.

The net discharge equals 0.07 $m^3/s/m$, shows that there is a flow from the CR into the South Branch. This flow might be due to water leaking from Lake Michigan, because these measurements were done before the reparation of the gate locks was completed.

Assuming a value of $\Delta\rho/\rho$ equal to 0.0005, which is in the range of values (0.0001 to 0.001) calculated by Bombardelli and Garcia (2001), the Richardson number is approximately equal to: 1200 (F^2=0.0008) upstream of the plunge point, 83 downstream of the plunge point and 42 along the underflow and the critical Richardson number is equal to 5. Also, the entrainment rate is within the range of 10^{-6} to 10^{-5}. These numbers indicate that density stratification effects are far more important than inertial terms, thus entrainment of less dense water from above into the underflow can be safely neglected. Moreover, the slope of the bed is mild, $S<Sc=0.007$, and the underflow is a subcritical flow, controlled by downstream conditions. This result indicates that in the physical model the boundary conditions at both Lake Michigan and the South Branch need to be set carefully in order to reproduce the behavior observed in the prototype.

Table 1 : Summary of Relevant Parameters.

Location	La Salle	Wabash	Fountain
Distance from Lake Michigan (m)	1650	1150	300
Total depth flow = d (m)	7.3	7.3	7.3
Position of interface from the surface (m)	4.2	4.9	4.9
Underflow depth measured from bottom,=h (m)	3.0	2.4	2.4
h/d	0.41	0.33	0.33
Avg. Vel. overflow (m/s)	0.03	0.03	0.02
Avg. Vel. underflow (m/s)	-0.01	-0.03	-0.02
Max. Vel. underflow(m/s)	-0.02	-0.03	-0.04
Discharge overflow (m3/s/m)	0.10	0.13	0.11
Discharge underflow(m3/s/m)	-0.04	-0.04	-0.04
Net discharge (m3/s/m)	0.07	0.08	0.07
Qnet (width=70m) (m3/s)	4.70	5.90	4.80
Densimetric Froude number (squared) ($\Delta\rho/\rho$=0.0005)	0.012	0.024	0.024
Richardson number	83	42	42

Note : Negative velocities indicate flow towards the lake.

Prediction of plunge point conditions

Table 2 shows plunge point depths estimated with the formulas reviewed and values of coefficients recommended by Akiyama and Stefan (1981). Considering that the plunge point depth should be smaller than 7.3 m and higher than the underflow depth, i.e. 2.3 m, depending also on the bed elevation, for an average excess fractional density $\Delta\rho/\rho$ equal to 0.0005, formulas number 1 and 5 predict reasonable values of this parameter. Also for lower values of $\Delta\rho/\rho$ formulas number 3, and 5 yield acceptable results and for values of $\Delta\rho/\rho$ closer to 0.001 formulas number 1 and 5 estimate reasonable depths. In addition, in order to have plunge-point depths of the order of 7.3 m, formulas 1 and 5 yield values of excess fractional density within the range of the field data.

Table 2: Plunge point depth (hp) and densimetric Froude number (Fp)

qo=0.04 m3/s/m.

Bottom Slope	0.0001						0.0001
$\Delta\rho/\rho$	0.0001		0.0005		0.001		hp=7.3 m
Formula Number/Author	Fp	hp (m)	Fp	hp (m)	Fp	hp (m)	$\Delta\rho/\rho$
1. Akiyama and Stefan(1984)	0.06	7.6	0.03	**4.4**	0.02	**3.5**	1E-04
2. Elder and Wunderlich (1973)	0.50	1.9	0.50	1.1	0.50	0.9	2E-06
3. Savage and Bringberg(1975)	0.14	**4.5**	0.14	2.6	0.14	2.1	1E-06
4. Jain (1978)	0.59	1.7	0.59	1.0	0.59	0.8	1E-06
5. Hebbert et al. (1979)	0.005	**7.0**	0.003	**5.1**	0.002	**4.4**	8E-04
6.Akiyama and Stefan (1987) (Fp=0.68)	0.68	1.5	0.68	0.9	0.68	0.7	3E-06

Moreover, if a larger flow discharge is considered, for example 0.07m3/s/m, formulas 1,3 and 5 yield coherent values of the plunge point depth.

Backwater profile for the underflow.

Applying the formula for the variation of the underflow depth along the river considering an internal hydraulics approach (Garcia, 1993) for downstream boundary conditions between of 0.1 and 2.3 m, the first set arbitrarily and the second is the underflow depth measured at Fountain, the following profiles were obtained (Figure 12).

Fig. 12 shows that the results are consistent with the expected behavior of the backwater curve, i.e., the flow depth decreases upstream and the slope of interface decreases as the downstream depth approaches a depth value of 2.3 m. This behavior is also observed for higher values of Δρ/ρ, with the consideration that the downstream height must be larger than 1. On the other hand these profiles are only valid within some distance downstream of the plunging point, where the flow depth varies rapidly. Since there are uncertainties in the determination of the downstream condition, the reach where these profiles apply, the determination of the bed slope, and the violation of the assumption that the flow over the underflow is stagnant and that the thickness of the underflow is much smaller than the total flow depth, these results should be considered with caution.

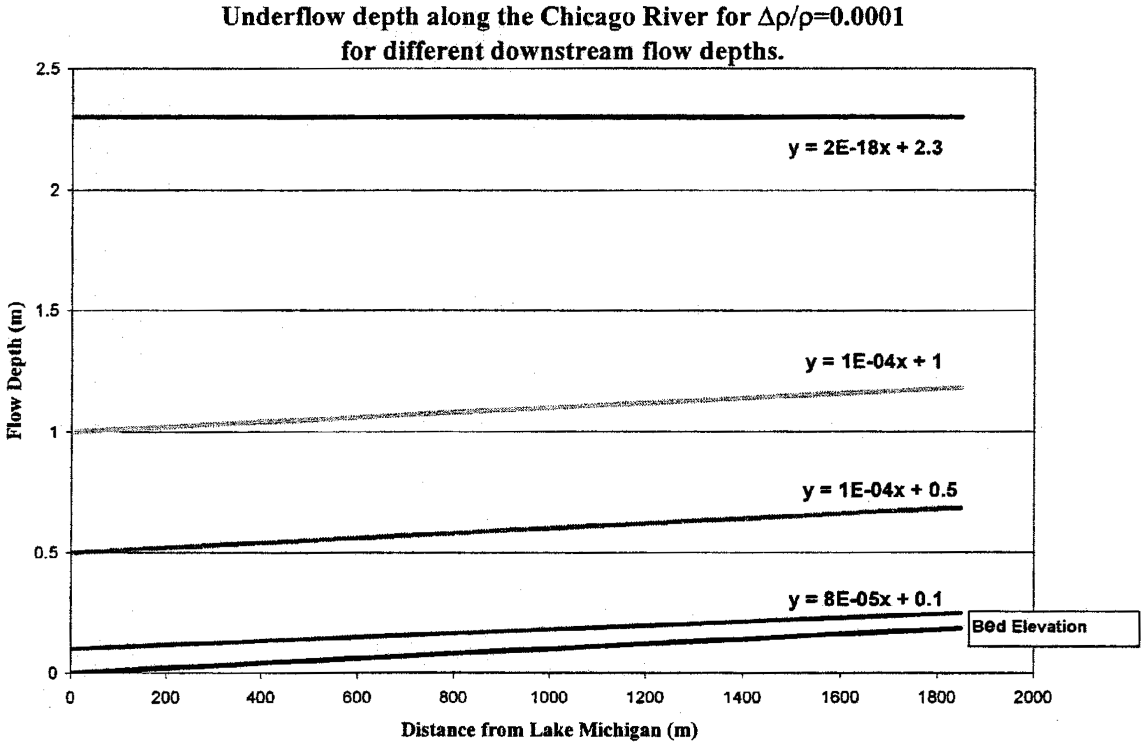

Figure 12: Underflow depth in the Chicago River for Δρ/ρ=0.0001.

Goal of Future Experiments

The main goal of the experiments to be conducted in the next phase of the study will be to characterize the hydrodynamic conditions that lead to the development of density currents in the Chicago River. Once the phenomenon is well understood, different alternatives measures (e.g. bottom sill, bubble screen, etc.) that could be implemented to prevent the development of density currents will be analyzed in detail with the help of the hydraulic model.

References:

- Akiyama, J. and Stefan, H. (1981) Theory of plunging flow into a reservoir. Internal Memorandum No. IM-97. Saint Anthony Falls Hydraulic Laboratory. University of Minnesota.
- ASCE (2000), Hydraulic Modeling: Concepts and Practice, ASCE Manuals and Reports on Engineering Practice No 97, Reston, Virginia, 390p.
- Bombardelli F. and Garcia, M.(2001) Three-dimensional hydraulic modeling of density currents in the Chicago River, Illinois". Civil Engineering Studies, Hydraulic Engineering Series N-68, Ven Te Chow Hydrosystems Laboratory, department of Civil and Environmental Engineering. UIUC, Illinois.
- Garcia, M.H. (1993), "Hydraulic Jumps in Sediment-Laden Bottom Currents," Journal of Hydraulic Research, American Society of Civil Engineers, 199:1094-1117.
- Garcia, M.H. (1994), "Depositional Turbidity Currents Laden with Poorly-Sorted Sediment," *Journal of Hydraulic Engineering*, American Society of Civil Engineers, 120:1240-1263. (*Received the 1996 Karl Emil Hilgard Prize for best publication in the Journal of Hydraulic Engineering*)
- Nino, Y and Garcia M. CEE 498 Environmental Hydrodynamics, Department of Civil and Environmental Engineering, UIUC, Urbana, Illinois, Spring 2003.