Abstract

During the winter months, the Chicago River in Chicago, Illinois, USA, is subject to bi-directional flows, and gravity currents are thought to be responsible for such flow behavior. The occurrence, frequency, and evolution of gravity currents in the Chicago River have been described using a unique set of field observations made using an upward-looking acoustic Doppler current profiler (ADCP) during the period November 20, 2003 to February 1, 2004. Detailed field observations performed on December 2005, based on both ADCP and water-quality measurements, are employed to validate hypotheses about the characteristics of the currents and the source of the denser water. Observations indicate bi-directional flow is a common condition in the Chicago River system, and that density differences driving the gravity currents are mostly due to salinity differences between the North Branch and the main stem of the Chicago River, whereas temperature differences do not seem to affect the creation of gravity currents.

1. Introduction

The present-day Chicago River (hereafter CR) flows west from Lake Michigan, through downtown Chicago, and joins flow coming from the North Branch of the Chicago River (hereafter NB) where it enters the South Branch of the Chicago River (hereafter SB). Flow in the CR is controlled by the Lockport Powerhouse and Controlling Works (near Joliet, IL) and by the Chicago River Controlling Works (hereafter CRCW) and the Chicago Lock. During the summer, water from Lake Michigan flows into the CR through sluice gates in the CRCW and, because of lockages, through the Chicago Lock at CRCW. Flow from Lake Michigan into the CR during the summer months, called discretionary diversion, is used to improve the water quality in the CR and the Chicago Sanitary and Ship Canal (hereafter CSSC). This has been the case since the reversal of the Chicago River in the early 1900’s, in order to protect the main water supply for Chicago (i.e. Lake Michigan). During the winter, flow from Lake Michigan into the CR is small, when compared to the summer, and typically results from leakage through the gates and sea-walls at CRCW and some sporadic lockages. Other contributions to the CR discharge include water from direct precipitation and discharges of water used for cooling purposes from neighbouring buildings. The NB carries runoff from the watershed up-stream and treated municipal and industrial wastewater released by a water-treatment plant located 16 km upstream from the confluence of the branches. The treated wastewater effluent accounts for as much as 75 percent of the discharge in the NB during the winter months (Manriquez et al., 2005).

Beginning in 1998, the U.S. Geological Survey (USGS) observed bi-directional flow conditions while making discharge measurements in the CR. Although the duration of this bi-
directional flow was not known, this flow indicated the possibility that water from the NB might be flowing into the CR and, perhaps, even into Lake Michigan. The possibility of NB water entering the CR meant that water quality in the CR, and, therefore, Lake Michigan could be impaired.

Since the discovery of such bi-directional flow, the USGS in cooperation with the University of Illinois have been working to better understand this stratified flow, including the conditions that lead to its development. Bombardelli and García (2001) and Manriquez (2005) summarized the main results obtained in this regard based on the use of 3D computational modeling and laboratory experiments, respectively. This paper summarizes the main results of an ongoing study based on field observations. First, a general characterization of the flow conditions observed in the CR near Columbus Drive (location 6 in Fig. 1) during the period November 20, 2003 to February 1, 2004, is presented. The frequency and duration of gravity currents detected during this period with the help of water velocity records at location 6 (see Fig. 1) are described. Then, detailed water-velocity and water-quality measurements obtained during the winter 2005-2006 at locations 1 to 7 (see Fig. 1) are employed to validate hypotheses about the fluid properties of the current and the source of the denser water. This work describes a particular density current event observed during December 2005.

2. Field Methods and Instrumentation

2.1 Field measurements performed during period November, 2003 to February, 2004

A 600-kHz acoustic Doppler current profiler (ADCP), manufactured by Teledyne RD Instruments, was installed in an upward-looking configuration on the bottom of the CR at Columbus Drive (location 6), in the center of the channel, approximately 0.8 km downstream from the Chicago River Lock. The CR is 55 m wide at this location. The water depth at location 6 is held at a nearly constant value of 7.0 m in the center of the channel throughout the year. The ADCP transducers were located about 0.30 m above the stream bed using a PVC frame. Continuous three-dimensional velocity profiles were collected at a sampling frequency of 0.2 Hz implying that an entire water-velocity profile was recorded every 5
seconds (s). Depth-cell size for the velocity measurements was 0.1 m and the blanking distance was set to 0.25 m. For the normal water depth at CR of approximately 7.0 m, valid water-velocity measurements in each profile were obtained for nearly 72 percent of the total depth. A temperature sensor located in the ADCP transducer face (0.3 m above the streambed) measured the temperature of the water close to the transducer at the same sampling frequency as the velocity data (0.2 Hz). Water temperature measurements from this sensor are used herein to characterize the water temperature of the underflows.

2.2 Field measurements performed on December 2005

Measurements of water-velocity profiles and water-quality profiles (i.e. temperature, conductivity) were made at seven locations in the Chicago River system (Table 1) yielding the most complete data set to date. The profiles were gathered over the course of 4 hours on December 19, 2005. In addition to these measurements, the temporal evolution of the velocity profiles was also captured using deployed ADCPs at other locations in the Chicago River system, as shown in Table 1 below.

**Table 1: Sampling locations and instrumentation used in the CR system**

<table>
<thead>
<tr>
<th>Location (Figure 1)</th>
<th>Profile Time on Dec. 19, 2005</th>
<th>Approximate Distance from Location 1 [m]</th>
<th>Sampling Location</th>
<th>Instrumentation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Grand Ave.</td>
<td>0</td>
<td>Right Bank</td>
<td>YSI</td>
</tr>
<tr>
<td>2</td>
<td>Kinzie St</td>
<td>13:36</td>
<td>297</td>
<td>Center line</td>
</tr>
<tr>
<td>3</td>
<td>DS Kinzie</td>
<td>13:52</td>
<td>419</td>
<td>Left Bank</td>
</tr>
<tr>
<td>4</td>
<td>Wells St.</td>
<td>14:08</td>
<td>863</td>
<td>Center line</td>
</tr>
<tr>
<td>5</td>
<td>State St.</td>
<td>14:50</td>
<td>1358</td>
<td>Center line</td>
</tr>
<tr>
<td>6</td>
<td>Columbus Dr.</td>
<td>11:58</td>
<td>2006</td>
<td>Center line</td>
</tr>
<tr>
<td>7</td>
<td>Lake Michigan</td>
<td>15:30</td>
<td>2800</td>
<td>Bank</td>
</tr>
</tbody>
</table>

Simultaneous water-velocity and water-quality profiles were measured at locations 2, 4, 5, and 6 (Fig. 1) using an Ocean-science tethered River Boat with a Teledyne RD Instruments 600 kHz ADCP and a YSI data sonde, respectively. Only water-quality data were recorded at locations 1, 3, and 7. The same ADCP sampling configuration was adopted for all the cited locations: a bin size of 0.10 m, a blanking distance of 0.25 m, the ADCP submerged to about 0.09 m, sampling mode 11 for velocity measurements and mode 5 for bottom tracking (RD Instruments, 2001), a sampling interval of 0.64 s, and 1 ping per ensemble was averaged for both the water-velocity measurements and bottom tracking.

Temperature and conductivity profiles were measured using a YSI Model 600xl multi-parameter data sonde with a thermistor (range: from -5º to 45ºC, accuracy +/- 0.15ºC) and a 4 electrode cell conductivity probe (range 0 to 100 mS/cm, accuracy +/- 0.5% of reading + 0.001 mS/cm). A YSI 650 Multiparameter Display system (YSI 650 MDS) allowed real-time display of the temperature and conductivity readings refreshed every second. Profiles were recorded by measuring at discrete points in the vertical and allowing enough time at each point for the readings to stabilize. Vertical resolution of the measurements generally was limited to 0.6 m, but at State Street and Wells Street, multiple profiles were measured with offset depth increments allowing vertical resolution to be increased to 0.3 m.
3. Gravity Currents Observed From November 20, 2003 to February 01, 2004

Flow conditions in the Chicago River system were analysed for the period from November 20, 2003 to February 1, 2004 (a 1,704 hour period). This period was selected based on the hypothesis that gravity current events in the CR are more likely to occur during cold weather periods because discharge from Lake Michigan into the CR system (at CRCW) is low and the differences between water properties (such as water temperature) in the NB and CR are greatest. The time series of 3-dimensional water velocity profiles from the uplooking ADCP at location 6 were analysed to characterize the flow conditions during such period. The temporal evolutions of the vertical profiles of water velocity in the easterly direction measured at location 6 are shown in Figure 2a for a fraction of the entire period analysed. This data subset as shown in Figure 2a consists of a 69.4 hour (250,000 second) record beginning on January 1, 2004 at 0:05:55 AM. High temporal variability in the vertical structure of the flow at location 6 (see Fig. 1) can be observed in Figure 2a, including the presence of bidirectional flow generated by gravity currents.

Two bidirectional flow events generated by underflows of water from the confluence with the North Branch (designated UF1 and UF2) were observed in the period shown in Figure 2a. In addition, a bidirectional flow event generated by overflows from the confluence with the North Branch was observed (designated OF2). Instantaneous velocity profiles in the easterly direction measured at location 6 during these three gravity current events are shown in Figure 2b. Event UF1 is the strongest gravity current event of the three observed ones, with the measured velocity magnitudes for all three events being less than 10 cm/s.

Twenty-eight bidirectional flow events generated by gravity currents were observed at location 6 for the period from November 30, 2003 to February 1, 2004. Gravity current events carrying water from the NB either as an underflow or an overflow are hereafter designated underflow and overflow respectively. These bidirectional flows conditions (generated by underflows and overflows) were observed during 77% of the time during the period analysed, indicating that gravity currents occur frequently at location 6. Sixteen of these bidirectional
flow events (observed during 47% of the total time) were generated by underflows and twelve of these bidirectional flow events (observed during 30% of the total time) were generated by overflows.

3. Gravity Currents Observed on December 2005

The temporal evolution of vertical profiles of east water velocity recorded by the ADCP uplooker at location 6 (Figure 1) over the course of 4 hs on December 19, 2005, are shown in Figure 4. A bi-directional flow was clearly observed during the sampling period with the lower water layer moving east towards Lake Michigan and the upper portion of the flow moving west towards the confluence. The interface between the two layers was located about 2 m above the streambed and fluctuated during the sampling period between 1 m and 3 m above the bed. When first observed in ADCP discharge measurements in 1998, the bi-directional flow was thought to be due to wind action. However, the cause of this bi-directional flow event observed in Figure 4 could not be due to wind because the direction of the wind was opposite to the upper layer flow direction (winds out of the west, upper layer flow to the west). However, a shallow layer of water moving to the east towards Lake Michigan is intermittently observed at the top of the water column, which could be driven by the wind effect.

![Figure 4: Contour plot of east water velocity recorded by the ADCP uplooker at location 1 (Figure 1). Dark colors represent water flowing to the confluence (West) and light colors show flow to the lake (East). Elapsed time = 0s corresponds to 11:32:28 on 12/19/05. Arrows represent flow direction.](image)

To capture the spatial extent of the density current in the Chicago River system, the tethered ADCP was used in combination with water-quality profiles at various locations throughout the system. Velocity profiles measured using the tethered ADCP at locations 4, 5, and 6 are presented in Figure 5b for comparison with density profiles. The sampling period for the velocity measurements at locations 4 and 5 were 13 minutes (1266 ensembles) and 10 minutes (957 ensembles), respectively.

To investigate the driving forces behind the density current, water-quality profiles were measured at six locations along the Chicago River system (Figure 1). Conductivity and temperature measurements were combined to compute salinity under the assumption that sodium chloride (NaCl) is the major constituent contributing to the high conductivity. This is a valid assumption because NaCl is the primary road salt used in the Chicago area to melt down ice and snow in winter and chloride concentrations have been shown to be higher than background concentrations in North Branch water samples during winter (Garcia et al., 2005). Density was computed using the temperature and salinity measurements and an equation of state proposed earlier by Bombardelli and Garcia (2001) for numerical modelling of density currents in the Chicago River. In addition to vertical and horizontal temperature stratifications in the CR, the sonde profiles revealed similar stratifications in conductivity and salinity. The full and partial density profiles measured during the study at locations 4, 5, and 6 are
presented in Figure 5b. Density and velocity profiles shown in Fig. 5a and 5b are typical of density currents (Garcia, 1994). There is excellent agreement between the density interface and the zero velocity point in these figures.

![Figure 5. a) Density profiles computed using data from each location (Fig. 1): 1 ○; 2 +; 3 x; 4 Δ; 5 ◇; 6 □; 7 ■, b) Vertical profiles of east water velocity recorded by the tethered ADCP at locations 4 Δ; 5 ◇; 6 □.](image)

**Conclusions**

During winter months, the Chicago River experiences bi-directional flows and several analyses indicate that density currents are responsible for these flow variations. This paper presents detailed field measurements using three different ADCP instruments and simultaneous water-quality measurements. Because of the unique flow conditions, mainly the bi-directional nature and low velocities of the flow, multiple ADCP instruments and configurations were used to capture the dynamics accurately. Observations indicate the formation of density currents within the Chicago River and density differences are mostly due to salinity differences between the North Branch and the main stem of the Chicago River, whereas temperature difference does not seem to significantly affect the formation of density events. Potential sources of higher water temperature, conductivity, and salinity values in the North Branch should be addressed in future studies.

The use of trade, product, or firm names in this paper is for descriptive purposes only and does not imply endorsement by the U.S. Geological Survey. The help of Kevin Johnson (USGS) and Ryan Jackson (WHOI) with the December 2005 measurements and the continuous support of the Metropolitan Water Reclamation District of Greater Chicago (MWRDGC) for studies on the Chicago River are both gratefully acknowledged.

**References**


