ADCP Measurements of Gravity Currents in the Chicago River, Illinois

Carlos M. García[1]; Kevin Oberg[2]; and Marcelo H. García[3]

Abstract: A unique set of observations of stratified flow phenomena in the Chicago River was made using an upward-looking acoustic Doppler current profiler (ADCP) during the period November 20, 2003 to February 1, 2004. Water density differences between the Chicago River and its North Branch (NB) seem to be responsible for the development of gravity currents. With the objective of characterizing the occurrence, frequency, and evolution of such currents, the ADCP was configured to continuously collect high-resolution water velocity and echo intensity profiles in the Chicago River at Columbus Drive. During the observation period, 28 gravity current events were identified, lasting a total of 77% of the time. Sixteen of these events were generated by underflows from the NB and 12 of these events were generated by overflows from the NB. On average, the duration of the underflow and overflow events was 52.3 and 42.1 h, respectively. A detailed analysis of one underflow event, which started on January 7, 2004, and lasted about 65 h, was performed. This is the first time that ADCP technology has been used to continuously monitor gravity currents in a river.

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Introduction

In the late 1800s, flow from the North Branch Chicago River (NB) and the South Branch Chicago River (SB) [Fig. 1(A)] joined just north of present-day Lake Street in the city of Chicago, and flowed eastward into Lake Michigan [Fig. 1(B)]. Sewage discharged into the Chicago River caused serious health hazards during the mid and late 1800s when storm events transported the sewage into Lake Michigan, contaminating the City's drinking water supply. In 1900, a 45-km-long canal dug by the Sanitary District of Chicago, known today as the Chicago Sanitary and Ship Canal (CSSC), was completed, reversing the flow in the Chicago River and linking the Chicago River system (Lake Michigan basin) to the Des Plaines River (Mississippi River basin) [Fig. 1(A)].

Today the Chicago River (CR) flows west from Lake Michigan [Fig. 1(B)], through downtown Chicago, and joins the flow coming from the NB where it enters the SB and then the CSSC. Flow in the CSSC is controlled by the Lockport Powerhouse and Controlling Works near Joliet, Ill. [Fig. 1(A)] and by control structures near Lake Michigan such as the Chicago River Controlling Works (CRCW) [Fig. 1(B)]. Flow in the CR is primarily affected by regulation of the CRCW and the Chicago Lock. During the months of May through October, the sluice gates at CRCW are operated so that water from Lake Michigan flows into the CR. These flows, known as discretionary diversion, are used to maintain or improve the water quality in the CR, SB, and CSSC. Some flow enters the Chicago River through the Chicago Lock at CRCW as well, although this flow from locking boats constitutes only a small part of the net flow into the Chicago River. Flow from Lake Michigan into the CR during the remainder of the year is typically small ($<2.8\ m^3/s$), resulting from leakage through the sluice gates, lock gates, and sea walls at CRCW and water discharged from Lake Michigan when locking boats. The water level in the Chicago River at CRCW is maintained at an elevation less than the water level in Lake Michigan at Chicago, except during times of excessive runoff in the NB (U.S. Army Corps of Engineers 2005). For most of the year the water level is held at a constant elevation of 176.01 m (National Geodetic Vertical Datum of 1929). Other contributions to the CR discharge include water from direct precipitation and discharges of water used for cooling purposes from buildings along the river. The NB carries runoff from the watershed upstream and treated municipal sewage effluent released by the North Side Water Reclamation Plant (NS WRP) located 16 km upstream from the confluence of the NB and CR. Most, or all, of this effluent is transported down the SB into the CSSC and then to the Des Plaines and Illinois Rivers [Fig. 1(A)].

The United States Geological Survey (USGS) established a streamflow gauging station at Columbus Drive [Station Number 05536123 in Fig. 1(B)] in October 1996 for the purpose of monitoring the flows through CRCW and the Chicago Lock into the CR. Periodic discharge measurements made by the USGS beginning in 1998, indicated bidirectional flow in the CR. These measurements, along with local reports of changes in the color of water flowing in the CR, indicated that water from the NB might be flowing into the CR. The possibility of flow from the NB

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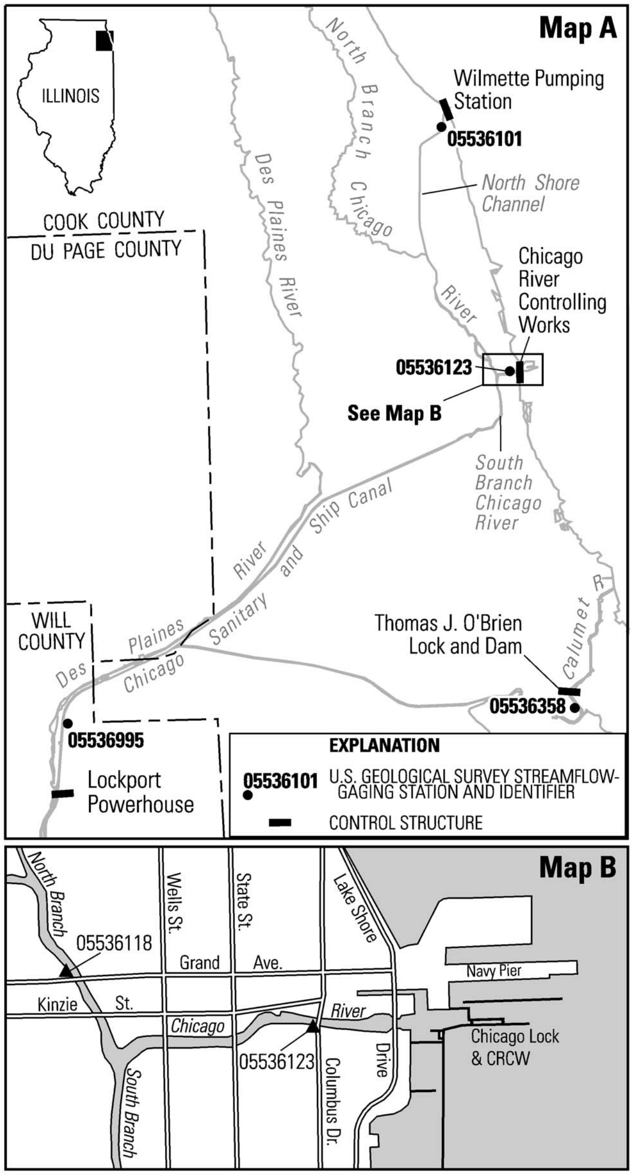

Fig. 1. Location of study area

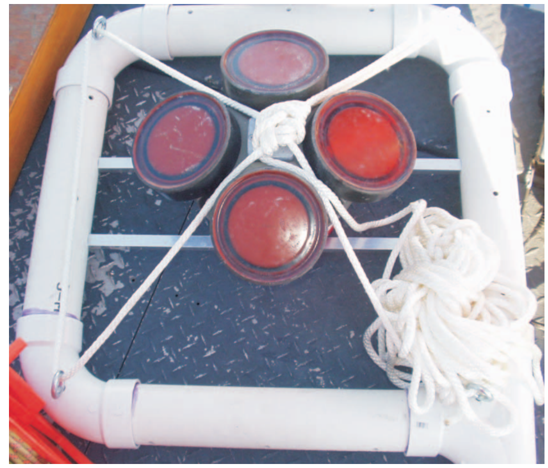

Fig. 2. (Color) 600-kHz acoustic Doppler current profiler and support frame installed at Chicago River at Columbus Drive, Chicago

entering the CR implied that water quality in the CR could be impaired. It was therefore necessary to determine the duration, frequency, and temporal variability of these bidirectional flows, the source of the bidirectional flows, and their impact on the CR.

Bombardelli and García (2001a,b) suggested that bidirectional flows could indicate the presence of gravity currents in the CR. A gravity current is the flow of one fluid within another caused by a density difference between the fluids (Simpson 1982). These gravity currents in the CR could develop because of density differences between waters from the NB and CR. Density differences may be caused by water temperature differences, or by the presence of salt or sediment in suspension or some combination thereof.

The hypothesis of gravity currents in the CR was supported initially by the results from a three-dimensional hydrodynamic simulation conducted by Bombardelli and García (2001a,b) and from laboratory experiments in a scale model of the Chicago River system (Manriquez et al. 2005). Field information is presented herein to support this hypothesis through the analysis of a unique set of water-velocity measurements (vertical profiles of three-dimensional water-velocity components) collected continuously by the USGS using an acoustic Doppler current profiler (ADCP) near Columbus Drive on the CR [Station Number 05536123 in Fig. 1(B)] since November 2003. In addition, hydrological, water-quality, and meteorological data collected by the USGS and the Metropolitan Water Reclamation District of Greater Chicago (MWRDGC) are used as complementary information to both characterize the flow conditions in the NB and to evaluate the boundary conditions (such as NB discharge, air temperatures, wind speed and direction, etc.) in the CR.

In this paper, we first present a description of the instruments used to measure the flow field generated by gravity currents, the location and configurations of the instruments, along with the data available for analyzing gravity currents in the Chicago River system (CR, NB, and SB). A general characterization of the flow conditions observed in the CR near Columbus Drive (CR_CD) during the period November 20, 2003, to February 1, 2004, is then presented. The frequency and duration of gravity currents detected in water-velocity records at CR_CD are described, as well as the meteorological and hydrological conditions (boundary conditions) in the Chicago River system when they occurred. Finally, one gravity current event is characterized in detail, including an estimation of the density difference inducing the underflow and the description of the time evolution of the vertical velocity profiles. Analysis of the boundary conditions in the CR system is used to establish hypotheses regarding causes for the gravity currents observed.

Instrumentation and Data Description

A 600-kHz ADCP, manufactured by Teledyne RD Instruments (Fig. 2), was installed in an upward-looking configuration on the bottom of CR_CD, in the center of the channel, approximately 0.8 km downstream from the Chicago River Lock [Fig. 1(B)]. The CR is 55 m wide at this location. The water depth at CR_CD is held at a nearly constant value of 7 m in the center of the channel throughout the year. The center of the ADCP transducers was located about 0.3 m above the streambed using the frame shown in Fig. 2. The ADCP was connected to a computer in the USGS streamflow gauging station located on the south side of the CR_CD by means of an underwater cable. Data measured by the

ADCP were transferred from the computer to the USGS office in Urbana, Ill., using a dedicated high-speed Internet connection.

A pulse-coherent technique, known as water mode 5 (Teledyne RD Instruments, Inc. 2001), was used to measure water velocities at CR_CD. Water mode 5 (WM5) is most commonly used for velocity and discharge measurements in rivers with an ADCP mounted to a moving boat and configured for bottom tracking. WM5 measures the Doppler shift using two phase-coded broad-band pulses separated by a long lag. The lag is equal to the time for the first pulse to travel to the streambed and back. After the signal from the first pulse is received at the transducer face, the ADCP transmits the second pulse. This approach results in a very long lag with low instrument noise, typically less than 2 cm/s with a depth cell size of 10 cm for a 600-kHz ADCP. When bottom tracking is used with WM5, the ADCP adjusts the lag dynamically as the water depth changes. However, at CR_CD, the ADCP was mounted in a fixed location on the streambed of the CR looking upwards. Bottom tracking could not be used in this setting, requiring the lag between the pulses to be set to a constant value. Therefore, the ADCP at CR_CD was configured to collect data using a constant lag of 6.7 m (slightly less than the water depth at CR_CD), by setting the mode 5 ambiguity velocity command to 6 cm/s.

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 s. Depth-cell size for the velocity measurements was 0.1 m and the blanking distance was set to 0.25 m. With the frame, depth-cell size, and blanking distance, the deepest velocity measurement was made in a depth cell centered approximately 0.65 m above the streambed. Therefore, no velocity data were available for analysis in the first 0.65 m above the streambed. Velocity measurements were also not possible near the water surface because of side-lobe interference, decorrelation near the surface, and some interference between the two Mode 5 pulses at the surface (Simpson 2001). The latter occurred because the lag was slightly less than the water depth for most of the measurements. The unmeasured region extended 1.3 m below the free surface for most of the water-velocity vertical profiles analyzed. For a water depth at CR of approximately 7 m, valid water-velocity measurements in each profile were obtained for nearly 72% of the total depth.

The temperature of the water near the ADCP transducers (about 0.3 m above the streambed) was measured at the same sampling frequency as the velocity data (0.2 Hz) using the integrated temperature sensor in the ADCP. Technical specifications provided by the manufacturer state that the temperature sensor operates in a temperature range from −5 to 45°C, with a precision of 0.4°C and a resolution of 0.01°C (Teledyne RD Instruments, Inc. 2001). Water temperature measurements are used by the ADCP to compute the speed of sound at the transducer face (Teledyne RD Instruments, Inc. 2001). Water temperature measurements from this sensor are also used in this paper to characterize the water temperature in the underflows.

Complementary hydrological and meteorological data are analyzed herein to characterize the flow conditions at the NB and to evaluate the boundary conditions (i.e., flow discharge at NB, wind speed and direction, air temperature) in the CR system during gravity current events. Discharge and water temperature are measured at a USGS stream gauging station, North Branch Chicago River at Grand Avenue [Station Number 05536118 in Fig. 1(B)] located on the right bank upstream from the Grand Avenue bridge and about 1,000 m upstream from the confluence with the main stem of the CR. This stream gauging station is hereafter referred to as NB_GA. A SonTek/YSI Argonaut-SL acoustic Doppler velocity meter (ADVM) at NB_GA is used to measure horizontal water velocity profiles across the NB and to compute discharge in the NB by the index-velocity method (Morlock et al. 2002). The ADVM is located on the right bank at about one-half of the bank depth (right bank depth is about 3.5 m). The maximum water depth in the thalweg of the NB at this cross section is about 6.5 m, therefore the ADVM measures velocity in the upper part of the total flow depth at this site (about 4.8 m from the bed in the thalweg). In addition, a string of six thermistors are used to measure the water temperature at various elevations along the right bank at Grand Avenue. The thermistors are located at 0.6-m increments in the vertical, with sensor T6 being the lowest in the water column (located at 0.15 m above the streambed at the wall) and sensor T1 being the highest. Water temperatures for each of the thermistors were recorded at a sampling frequency of 5 min. Daily effluent discharges to the NB from North Side Water Reclamation Plant (NS WRP), located 16 km upstream from NB_GA, were also used to validate the discharges computed at NB_GA. On average, more than 75% of the observed discharge measured at NB_GA is composed of the NS WRP effluent discharge (Manriquez et al. 2005). The NS WRP has a design capacity of 1,249 million l/day (daily discharge of 14.5 m^3/s).

The meteorological conditions during the period analyzed were characterized using data recorded at the Chicago O'Hare International Airport meteorological station (ORD), located 24 km northwest of CR_CD. Wind speed and direction, air temperature, and snow depth are available in 3-h intervals at the ORD station (NOAA, National Climatic Data Center, http://www.ncdc.noaa.gov/). In addition, data from a Great Lakes Environmental Research Laboratory (GLERL) meteorological station were used to characterize the wind speed and direction. The GLERL station is located approximately 5 km offshore from the City of Chicago and is equipped with an anemometer and air temperature probe. The anemometer is located 25.9 m above station elevation. Meteorological measurements are made every 5 s at the station and then averaged together and recorded every 5 min (http://borris.glerl.noaa.gov/metdata/chi/).

Results

Flow conditions in the Chicago River system were first analyzed for bidirectional flow during a period from late November 2003 through the beginning of February 2004. Subsequently, one of the bidirectional flow events was analyzed in detail.

Gravity Currents Observed from November 20, 2003, to February 01, 2004

Flow conditions in the Chicago River system were analyzed for a 1,704-h period from November 20, 2003, to February 1, 2004. This period was selected for analysis based on the hypothesis that gravity current events in the CR are more likely to occur during cold weather periods when 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 (Bombardelli and García 2001b). The average daily air temperature for the months of November 2003, December 2003, and January 2004, were 5.5, −0.2, and −6.5°C, respectively.

The time series of three-dimensional water-velocity profiles from the up-looking ADCP at CR_CD were analyzed to charac-

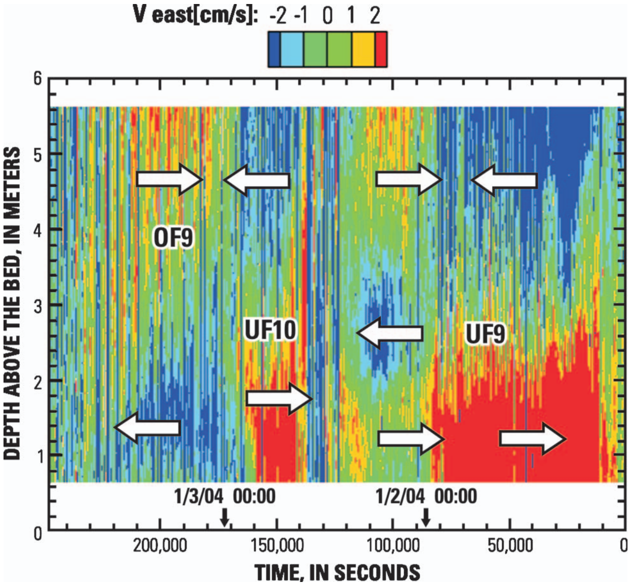

Fig. 3. (Color) Contour plot of water velocity in easterly direction measured at Chicago River at Columbus Drive, Chicago. Time=0 s corresponds to January 1, 2004, at 00:05:55. Arrows indicate flow direction in each region and bidirectional flow events are named as in Tables 1 and 2.

terize the flow conditions during the period. The temporal evolution of the vertical profiles of water velocity in the easterly direction measured at CR_CD are shown in Fig. 3 for a fraction of the entire period analyzed. This subset of data shown in Fig. 3 consists of a 69.4-h (250,000 s) record beginning on January 1, 2004, at 00:05:55. The shape of the velocity profile varies through time, and the presence of bidirectional flows generated by gravity currents carrying water from the NB may be seen. Gravity current events are hereafter designated as underflow or overflow events. An *underflow* event is one in which denser water flows from the NB into the CR. An *overflow* event is one in which less dense water flows from the NB into the CR.

Two bidirectional flow events generated by ***underflows*** of water from the confluence with the North Branch (designated UF9 and UF10, respectively, in Table 1) were observed during the period shown in Fig. 3. In addition, one bidirectional flow event generated by an ***overflow*** from the confluence with the North Branch was observed (designated OF9 in Table 2). Fig. 4 shows instantaneous velocity profiles in the easterly direction measured at CR_CD, at selected times during the three gravity current events, with the measured velocity magnitudes for all three events being less than 10 cm/s.

An interesting shape of the velocity profile can be seen in Fig. 3 at about 100,000 s. During this time, water is flowing eastward near the water surface and near the bed, but westward in the middle of the water column. The shape of the velocity profile during this period indicates the effect of a strong easterly wind during an *underflow* event. Prior to January 1, 2004, at 2000 hrs (corresponding to 71,644 s in Fig. 3) and during an ongoing *underflow* event (UF9), the wind was blowing out of the south. At 20:00, the wind began to blow from the west for several hours with maximum observed wind velocities of 51 km/h and average wind velocity of 26 km/h. The wind continued to blow from the west until January 2, 2004, at 10:00 (corresponding to 122,044 s in Fig. 3). This strong wind out of the west caused the top part of

Table 1. Characteristics of Bidirectional Flow Events in the Chicago River at Columbus Drive Caused by Underflows of Water from the North Branch of the Chicago River

Event number	Starting date and time	Duration (h)	Water temperature[a] (°C) NB_GA[b]	Water temperature[a] (°C) CR_CD[c]	Mean daily flow at NB_GA (m^3/s)	Mean air temperature (°C)
UF1	November 21, 11:40	23.9	12.8	10.9	13.5	7.2
UF2	November 26, 11:36	33.0	9.6	10.1	12.3	6.2
UF3	December 12, 15:16	90.2	7.4	6.6	14.3	−2.1
UF4	December 18, 02:56	14.7	7.9	6.9	12.2	−4.7
UF5	December 20, 00:09	35.6	7.4	4.6	10.5	−2.9
UF6	December 22, 22:31	7.6	8.3	5.0	9.4	2.4
UF7	December 24, 06:36	138.2	8.8	4.1	9.3	1.4
UF8	December 30, 14:18	16.0	9.8	4.5	9.1	4.6
UF9	January 1, 01:50	21.1	8.5	4.8	9.7	3.3
UF10	January 2, 15:19	5.0	9.3	4.6	9.5	14.3
UF11	January 4, 03:41	24.0	10.1	4.7	9.2	−1.2
UF12	January 7, 13:37	64.7	6.0[d]	2.5	8.9[e]	−5.1
UF13	January 13, 12:18	21.8	7.9	4.0	10.5	−1.8
UF14	January 15, 11:23	56.6	6.9	2.9	9.8	−2.8
UF15	January 19, 12:45	55.4	6.1[d]	2.4	9.0[e]	−7.5
UF16	January 23, 23:21	228.3	4.6[d]	2.8	8.8[e]	−10.8

[a]Water temperature before the gravity current event occurred.

[b]North Branch Chicago River at Grand Avenue, Chicago (05536118).

[c]Chicago River at Columbus Drive, Chicago (05536123).

[d]Stratified conditions in NB during the event at CR_CD.

[e]Discharge estimated using discharge from NS WRP.

Table 2. Characteristics of Bidirectional Flow Events in the Chicago River at Columbus Drive Caused by Overflows of Water from North Branch of the Chicago River

Event number	Starting date and time	Duration (h)	Water temperature (°C)[a] NB_GA[b]	Water temperature (°C)[a] CR_CD[c]	Mean daily flow at NB_GA (m^3/s)	Mean air temperature (°C)
OF1	November 20, 00:07	34.7	13.4	10.0	17.2	9.7
OF2	November 23, 00:09	83.4	12.9	10.9	18.8	3.2
OF3	November 27, 20:33	114.4	10.7	9.9	12.2	1.6
OF4	December 5, 20:32	87.3	11.1	6.2	12.5	2.7
OF5	December 10, 15:09	48.1	12.7	5.1	24.7	−5.4
OF6	December 16, 09:26	22.8	8.0	6.2	12.6	−2.3
OF7	December 21, 21:35	10.7	7.3	4.7	10.4	4.0
OF8	December 29, 01:12	36.7	9.1	4.6	9.9	1.5
OF9	January 2, 21:44	15.0	9.5	4.8	9.6	7.1
OF10	January 12, 14:28	11.1	7.3	4.3	10.8	0.6
OF11	January 14, 10:07	13.8	7.9	4.3	9.5	−2.5
OF12	January 17, 17:59	27.6	6.9	2.7	9.5	−7.6

[a]Water temperature before the gravity current event occurred.

[b]North Branch Chicago River at Grand Avenue, Chicago (05536118).

[c]Chicago River at Columbus Drive, Chicago (05536123).

the water column to flow eastward. After this time, the wind direction changed again and blew from the south. Wind effects on the observed velocity profiles are discussed in a subsequent section of this paper.

An inventory of all the bidirectional flow events generated by gravity currents and observed at CR_CD is shown in Tables 1 and 2, for the period from November 30, 2003, to February 1, 2004. *Underflow* events are shown in Table 1 and *overflow* events are shown in Table 2. Both tables include the following characteristics for these bidirectional flow events: starting date and time (in military time); duration of the bidirectional flow events at CR_CD; the water temperature before the gravity current event occurred at both the thermistor nearest to the streambed at NB_GA and at the ADCP transducer at CR_CD; the mean daily discharge at NB_GA; and the mean air temperature during the event.

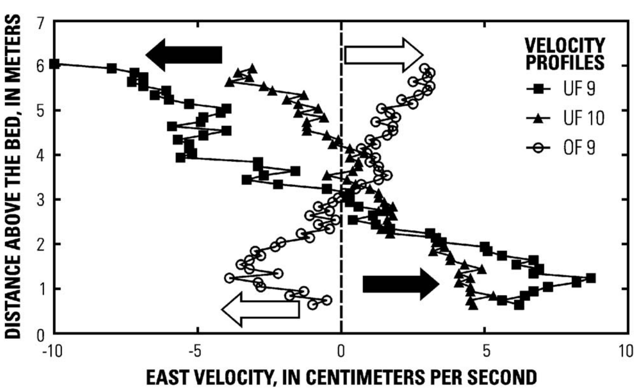

Fig. 4. Instantaneous velocity profiles in easterly direction measured at selected times during gravity current events shown in Fig. 3, Chicago River at Columbus Drive, Chicago. Symbols: (■) velocity profile from January 1, 2004, at 07:05:35 (UF9); (▲) velocity profile from January 2, 2004, at 16:39:00 (UF10); and (○) velocity profile from January 3, 2004, at 05:13:55 (OF9).

Twenty eight bidirectional flow events generated by gravity currents were observed at CR_CD for the period from November 30, 2003, to February 1, 2004. These bidirectional flow events (generated by *underflows* and *overflows*) were observed 77% of the time during the period analyzed, indicating that gravity currents occur frequently at CR_CD. Sixteen of these bidirectional flow events (observed during 47% of the total time) were generated by *underflows* and 12 of these bidirectional flow events (observed during 30% of the total time) were generated by *overflows*.

The total time during which a bidirectional flow generated by *underflows* was observed at CR_CD increased from 21.6% of the time in November 2003, to 40.6% of the time in December 2003, and to 59.3% of the time in January 2004. The average duration for these events was 52.3 h, with a minimum duration of 5 h and a maximum duration of 228.3 h (more than 9.5 days). More than half (56.3%) of these events were initiated between the hours of 11:00 and 16:00.

The total time during which a bidirectional flow generated by *overflows* was observed at CR_CD decreased from 88.1% of the time in November 2003, to 27.6% of the time in December 2003, and to 9.1% of the time in January 2004. The average duration for the *overflow* events was 42.1 h, with a minimum duration of 10.7 h and a maximum duration of 114.4 h (more than 4.7 days). No trend in the time when *overflow* events were initiated was observed. Bidirectional flows generated by *overflows* were observed at CR_CD even when air temperatures were less than −7 °C.

The average water temperature from the six thermistors at NB_GA was greater than the water temperature recorded near the streambed at the centerline of the CR_CD for most of the gravity current events analyzed. Three temperature stratification events were observed at NB_GA during the period from November 30, 2003, to February 1, 2004. All of these events occurred during January 2004. The time series of water temperatures recorded during January 2004 for the near-bed (T6) and the near-surface (T1) thermistors at the NB_GA stream gauging station are shown in Fig. 5. The temperature stratification events at NB_GA occurred simultaneously with the gravity current events UF12,

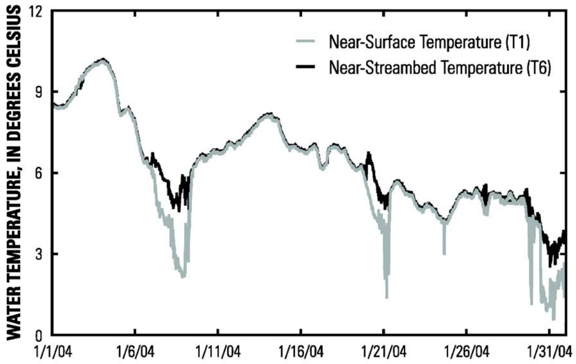

Fig. 5. Near-surface (T1, gray line) and near-streambed (T6, black line) water temperatures during January 2004, North Branch Chicago River at Grand Avenue, Chicago

UF15, and UF16. The maximum observed water temperature differences (T6 minus T1) at NB_GA for the gravity currents UF12, UF15, and UF16, were 3.8, 3.7, and 3.0°C, respectively. For each event, the upper part of the water column was coldest. Meteorological data also indicate that the 3 days with the lowest mean daily air temperature for January 2004 occurred at the beginning of each of these three events.

During the periods when thermal stratification was observed at NB_GA, it appears that bidirectional flows were also present at this location. Small or even negative velocities measured by the ADVM during periods of thermal stratification at NB_GA confirm this hypothesis (Fig. 6). Negative velocities recorded by the ADVM indicate that water was flowing upstream at the elevation of the ADVM. Discharges at NB_GA computed using the measured ADVM velocities with the index-velocity method (Morlock et al. 2002) result in small or negative net discharge for these time periods (Fig. 7). This result, however, does not agree with the records of the effluent discharge from the NS WRP located 16 km upstream (Fig. 7). For these events, the discharges computed using the measured index velocities are not valid and the values for discharge at NB_GA reported in Table 1 were estimated using the daily mean effluent discharge recorded at the NS WRP.

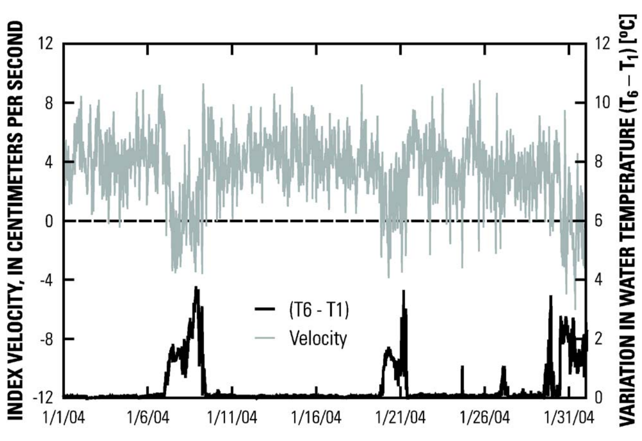

Fig. 6. Index velocities (gray line) and difference between near-bed (T6) and near-surface (T1) water temperatures (black line), North Branch Chicago River at Grand Avenue, Chicago

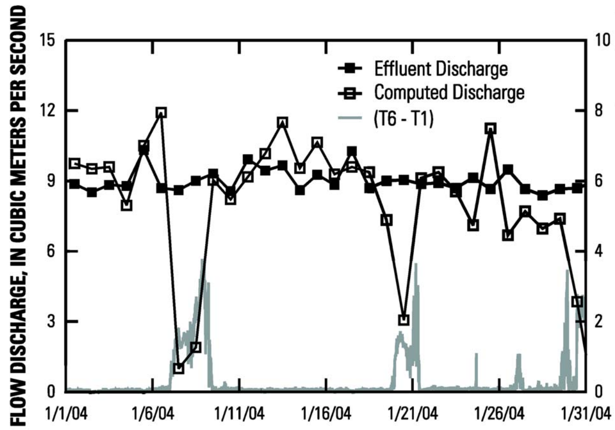

Fig. 7. NS WRP effluent discharge (black line ■) and discharge computed using index-velocity method, North Branch Chicago River at Grand Avenue, Chicago (black line □), and difference between near-bed (T6) and near-surface (T1) water temperatures (gray line) at Grand Avenue

Detailed Characterization of January 7, 2004 Gravity Current Event

A bidirectional flow event generated by an *underflow* of water from the NB (Event UF12, Table 1) beginning on January 7, 2004, was characterized in detail. The average air temperature recorded at ORD meteorological station during this event was −5.1°C and the minimum was −9.4°*C*. Fig. 8 shows a contour plot of velocity in the easterly direction from profiles recorded by the ADCP for a 200,000 s period beginning on January 7, 2004, at 12:13. During this *underflow* event at CR_CD, the water near the bed was flowing east (towards the lake), whereas the water near the surface was flowing west (towards the confluence). These bidirectional flow conditions persisted at CR_CD for more than 64 h.

As the *underflow* began (January 7, 2004, at 13:37), the water

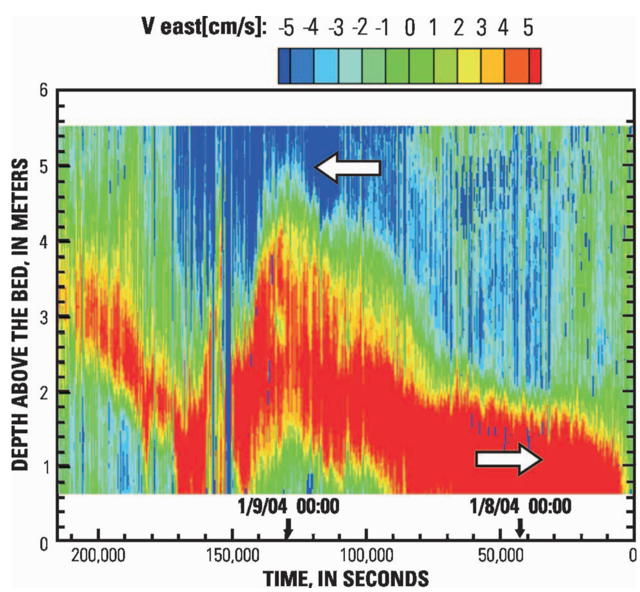

Fig. 8. (Color) Water velocity in easterly direction measured at the Chicago River at Columbus Drive, Chicago, during underflow event beginning January 7, 2004, at 12:13:50

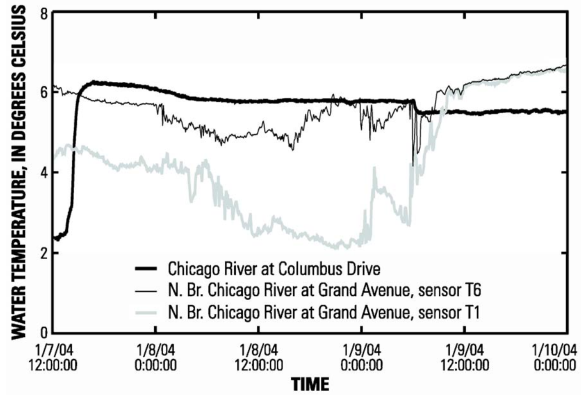

Fig. 9. Water temperature measured at North Branch Chicago River at Grand Avenue (NB_GA) and Chicago River at Columbus Drive (CR_CD thick black line), Chicago. For NB_GA, sensor T6 (thin black line) is located nearest to streambed and T1 (thick gray line) is located nearest to water surface.

temperature recorded by the ADCP at the centerline at CR_CD increased from 2.4 to 6.2°C (Fig. 9). This water temperature (6.2°C) was approximately the same as that concurrently recorded by the T6 sensor located nearest to the streambed at NB_GA. This suggests that water coming from the NB is present as an *underflow* at CR_CD.

The instantaneous velocity profiles observed at two different times during the underflow event UF12 are shown in Figs. 10(A) and 10(B). Characteristics for each profile are summarized in Table 3, including: sampling date and time (in military time), discharge per unit width in the *underflow* q_u, depth of the *underflow* H, the layer-averaged velocity in the *underflow* U, and the Reynolds number of the *underflow* R. The layer-averaged velocity U, and the depth of the *underflow* H, are defined from the observed east velocity (V_{east}) profiles via a set of moments (García 1994), through ratios [Eqs. (3*a*) and (3*b*) below] of the integrals indicated in Eqs. (1) and (2) below

$$UH = \int_0^h V_{\text{east}} \cdot dy \tag{1}$$

$$U^2H = \int_0^h (V_{\text{east}})^2 \cdot dy \tag{2}$$

Table 3. Flow Characteristics Observed at Chicago River at Columbus Drive, Chicago, for Two Selected Times during Gravity Current Event UF12, Starting January 7, 2004

Profile number	Sampling date and time (hrs)	q_u (m^2/s)	H (m)	U (m/s)	R
1	January 8, 01:25	0.138	1.37	0.101	93,497
2	January 8, 15:22	0.128	2.18	0.059	86,480

$$U = \frac{U^2H}{UH} \tag{3a}$$

and

$$H = \frac{(UH)^2}{U^2H} \tag{3b}$$

where h=depth above the streambed where a change in the direction of the easterly water velocities was observed (i.e., zero mean velocity). The Reynolds number of the *underflow* R, is computed as $\mathsf{R}=UH/\nu$, where ν=kinematic viscosity of water (equal to 1.48×10^{-6} m^2/s) computed using the observed *underflow* water temperature (about 6°C for event UF12).

The excess fractional density causing the *underflow* $R_0=(\rho_u-\rho_0)/\rho_0$, (where ρ_0 and ρ_u=ambient and *underflow* water density, respectively) was estimated using the observed east velocity profile. In order to estimate R_0, it was assumed that the gravity *underflow* or density current is close to the so-called normal or equilibrium condition, which implies that the Richardson number $\mathsf{Ri}=gR_0H/U^2$ is a constant or equilibrium value Ri_n along the longitudinal direction (Ellison and Turner 1959). An underflow gravity current over a uniform slope reaches a normal flow condition a short distance downstream from the source (Fernandez and Imberger 2006). Given that bed slope of the CR is relatively constant and the measurement location (CR_CD) is about 1,200 m away from the source (the NB in Fig. 1), a normal flow condition can be assumed. The normal value of the Richardson number Ri_n was estimated as (García 1996)

$$\mathsf{Ri}_n = \frac{E + C_D}{S_1 S - \frac{1}{2} S_2 E} \tag{4}$$

where C_D=bed friction coefficient; E=coefficient of water entrainment from above into the *underflow*; S=mean bottom slope (equal to 0.0004 for the CR); and S_1 and S_2=shape factors, which

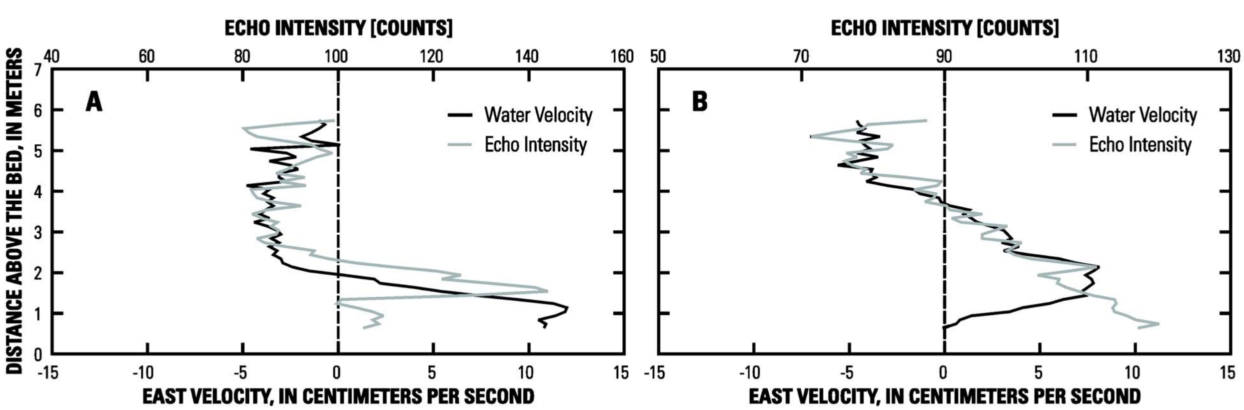

Fig. 10. Instantaneous water velocity in easterly direction (black) and echo intensity (gray) profiles measured January 8, 2004, at Chicago River at Columbus Drive, Chicago, at two different times during gravity current event UF12: (A) 01:25; (B) 15:22

can be approximated equal to 1 based on experimental observations (García 1996). Values of C_D for density and turbidity currents have been found to vary between 0.002 and 0.05 (Parker et al. 1987); the lower values correspond to observations in reservoirs and the higher values are associated with laboratory experiments. Parker et al. (1987) introduced a graph summarizing available experimental data showing values of C_D as a function of the *underflow* Reynolds number R. Using this plot and the range of values of R observed for the event UF12, C_D was estimated to be about to 0.003. The following expression was proposed by Parker et al. (1987) to estimate the value of E using data for turbidity currents and conservative saline currents

$$E=\frac{0.075}{(1+718\mathrm{Ri}_n^{2.4})^{0.5}} \tag{5}$$

Eqs. (4) and (5) were solved simultaneously to estimate Ri_n and E and from these parameters, the excess fractional density causing the *underflow* R_0 was estimated as

$$R_0=\frac{\Delta\rho}{\rho}=\frac{\rho_u-\rho_0}{\rho_0}=\frac{\mathrm{Ri}_n U^2}{gH} \tag{6}$$

The normal Richardson number Ri_n estimated at CR_CD was equal to 10.1 and the entrainment coefficient E was 1.74×10^{-4}. Hebbert et al. (1979) obtained values of the same order (17 and 1.9×10^{-4}, respectively) for entrainment studies associated with river *underflows* in reservoirs. The densimetric Froude number F_d estimated using $\mathsf{F}_d=1/\mathrm{Ri}_n^{0.5}$ was equal to 0.31 indicating subcritical flow conditions in the *underflow* at CR_CD during the event UF12. Finally, the buoyancy flux $\Phi=gRHU$ was computed as $\Phi=\mathrm{Ri}_n U^3$. The R_0 and Φ values estimated from the equations included above and the characteristics of the velocity profiles recorded on January 8, 2004, at 01:25 (Table 3) were 0.0077 and 0.0105 m^3/s^3, respectively.

Time series of east water-velocity values recorded by the ADCP at different depths during event UF12 were also analyzed in order to determine whether the water velocity signals recorded by the ADCP could be used to describe the flow turbulence generated by gravity currents at CR_CD. Even when the ADCP configuration is optimized for velocity measurements like this, the recorded signals still has a noise level, intrinsic to the Doppler measurement technique, which adversely affects the computed values for the turbulence parameters. The power spectrum computed from all the water velocity signals recorded at CR_CD showed a flat plateau, which indicates the presence of uncorrelated noise (white noise), at frequencies higher than $f=0.01$ Hz (see Fig. 14 in García et al. 2005b, p. 198). Assuming that the white noise and turbulent fluctuations are decorrelated (Garcia et al. 2005a), the spectrum (or total energy) of the resulting measurement is the sum of the turbulent spectrum (turbulent energy) plus the noise level (noise energy). The presence of a flat plateau spectrum for frequencies larger than $f=0.01$ Hz indicates that no description of the turbulence can be made because at this scale, where the turbulence production occurs, the total energy is dominated by the noise energy.

Wind data recorded at the Chicago meteorological station operated by GLERL were analyzed to evaluate the boundary conditions at the CR during different times within the *underflow* event UF12. The wind blew from west to east at speeds ranging between 5 and 10 m/s during the first 16 h of the event UF12. Then, the wind speed dropped dramatically for about 7 h. After that and for the rest of the time, the wind changed direction and blew from east to west at an average wind speed of about 10 m/s. Wind data from the ORD meteorological station confirmed the time evolution of the wind speed and direction observed at GLERL (García et al. 2005b).

In addition to water velocity and temperature, echo intensity data recorded by the up-looking ADCP at CR_CD were used as an indicator of the vertical distribution of suspended sediment in the flow (Gartner 2004). Sound emitted from the ADCP is scattered by sediment and other material suspended in the water. The ADCP measures the intensity of echoes returned to the instrument, called echo intensity, using an arbitrary scale of 0–255. Profiles of echo intensity and water velocity in the easterly direction are shown in Figs. 10(A) and 10(B) for two selected times during the gravity current UF12. Echo intensity values are greater near the bed as the *underflow* begins to develop at CR_CD. This, in turn, indicates higher concentrations of suspended sediment in this region of the flow. The presence of apparent higher suspended sediment concentrations in the *underflow* during the density current event agrees with an increase in the suspended solids in the NB (from about 10 to 20 mg/L) according to daily water-quality measurements of the treated effluent from the NS WRP (Catherine O'Connor, MWRDGC, written communication, 2005).

Discussion

Schematics of the flow conditions for *underflows* and *overflows* [Figs. 11(A) and 11(B)] illustrate generalized flow conditions in the NB and the CR during these stratified flow events. Flow conditions in the NB and CR during gravity current events UF12, UF15, and UF16 are shown in Fig. 11(A). Other *underflow* events were observed at CR_CD when no temperature stratification was observed at NB_GA. It is likely that for such events, the plunging point for the *underflow* was located downstream from NB_GA. The location of the plunging point depends on the relative density difference of each gravity current and the NB flow discharge. Laboratory experiments performed by Manriquez et al. (2005) on a distorted physical model (horizontal scale 1:250; vertical scale 1:20) of the CR system were used to analyze this behavior. Manriquez et al. (2005) found that for the same discharge at NB, increasing the density of the *underflow* caused the plunging point to migrate upstream in the NB, sometimes upstream from NB_GA. Therefore, for the weakest *underflow* event, neither bidirectional flow nor temperature stratification is likely to be observed at NB_GA.

The presence of bidirectional flow at NB_GA results in errors in the discharges computed using the index-velocity method (Fig. 7) and the single ADVM. In order to compute discharge accurately under these conditions, an additional side-looking ADVM or an up-looking ADCP should be installed and both devices used to compute discharge at this gauging station. Flow conditions in the NB and CR during *overflow* events are illustrated in Fig. 11(B). Neither temperature stratification nor bidirectional flows are expected at NB_GA during these events.

Several factors may contribute to induce the gravity current events at the CR including differences in temperature, salinity, and suspended-sediment concentration. Water temperatures at NB_GA are always higher than at CR_CD in the period analyzed, according to historical data for both NB and CR (James J. Duncker, USGS, written communication, 2005; see also Tables 1

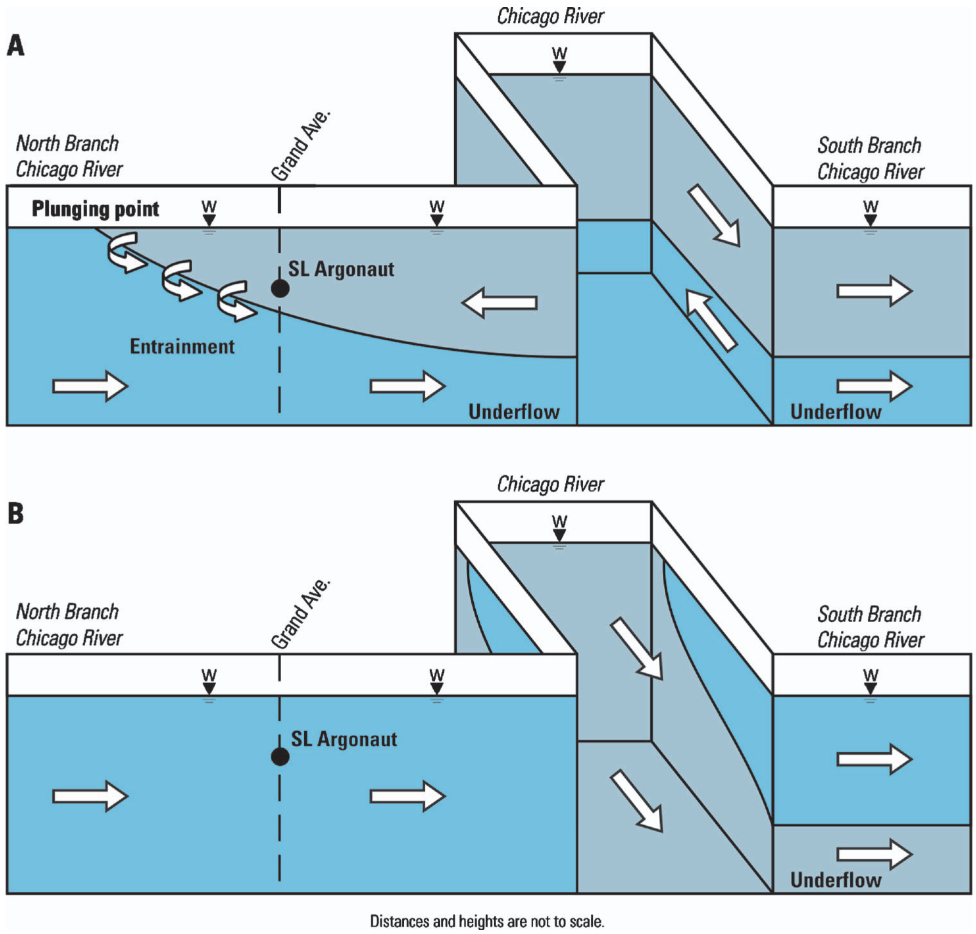

Fig. 11. (Color) Schematic illustrating flow conditions at junction of Chicago River (CR), North Branch Chicago River (NB), and South Branch Chicago River (SB), Chicago, during underflow event: (A); *overflow* event (B). Distances and heights are not to scale and arrows indicate flow direction.

and 2). Flow at NB_GA consists mostly of effluent discharge from the NS WRP. The average daily temperature of the effluent during January 2004 was 11.8°C with a standard deviation of 1.1°C. The only time that warmer water has a greater density (without the presence of high suspended-sediment concentrations or salinity) is when the water temperature is between 0 and 4°C. The maximum possible relative difference in the density ratio R_0 (assuming temperatures of 4 and 0°C for the NB and CR, respectively), is 0.012%, smaller than the values of R_0 estimated for the UF12 event. This indicates that other factors are causing the difference in density. An increase in suspended-solid concentration of the effluent of the NS WRP similar to the increase observed for the *underflow* event UF12 started at January 7, 2004, was observed for events UF15 and UF16. This increase was also detected in the echo intensity profiles.

The application of salt to roads during and after snowfalls, and the subsequent inflow to water treatment plants or direct discharge into streams, could result in an increase in salinity in the treated effluent or in the stream. On January 5, 2004, 0.1 m of snow depth was measured at the ORD meteorological station, and the snow remained on the ground (decreasing in depth) until January 14, 2004. It seems likely that salt was applied to the roadways because of this snowfall. Water-quality data for the NS WRP indicate elevated chloride concentrations (above normal levels) for at least two of the eight density current events observed in January 2004 (events UF12 and UF16).

The *underflow* event UF12 analyzed in detail in this paper is one of the strongest density current events observed during the period analyzed. The shape of the bidirectional vertical velocity profile changes during the event. Different processes were investigated as a possible cause of the unsteady behavior in the vertical profiles of easterly water velocity during the *underflow* event UF12. A quasi-uniform underflow discharge per unit width observed in profiles recorded within the event UF12 (see Table 3) would indicate that the unsteady behavior does not result from changes in the difference in density-driven flow. It is possible that the steadiness could result because of backwater effects from the locks, which would result in the depth (thickness) of the *underflow* being less at the beginning and greater towards the end for the entire event. The January 15, 2004, event (UF14) indicated an inverse time evolution (the depth of the underflow was greater at the beginning and less towards the end). An analysis of event UF14, similar to the one performed for event UF12, showed the same pattern in the relation between the depth of the *underflow* and the wind speed and direction: wind blowing in the downstream or upstream direction would generate *underflows* that have a greater or smaller thickness, respectively. Thus, wind speed and direction provided the best explanation as to the time evolution of the east velocity profiles for this *underflow* event.

Summary and Conclusions

A unique set of observations of stratified flows was made using an upward-looking ADCP in the Chicago River at Columbus Drive (CR_CD) from late November 2003 to early February 2004. This ADCP was deployed in response to previous measurements of bidirectional flow by the USGS and the application of a hydrodynamic model (Bombardelli and García 2001a, b) and a physical model (Manriquez et al. 2005) of the Chicago River system. These models and measurements suggested that the bidirectional flows were caused by gravity currents induced by density differences between the Chicago River and its North Branch (NB). Data collected using the up-looking ADCP were analyzed and used to characterize the occurrence, frequency, and evolution of gravity currents in the Chicago River during this time period.

The ADCP was configured to collect high-resolution measurements of velocity and backscatter profiles and water temperatures near the streambed. A pulse-coherent measurement mode (mode 5) was used to collect profiles every 5 s, with a 0.1 m depth cell size in a water depth of about 7 m. A continuous record of water velocity and backscatter with the above-mentioned vertical and temporal resolution made it possible to accurately characterize the gravity currents, which can vary greatly in time and space. This is the first time that ADCP technology has been used to continuously monitor gravity currents in a river.

In addition, continuous records of streamflow, water velocity, and water temperatures from a stream gauging station located just upstream from Grand Avenue on the North Branch Chicago River were also used to help determine the formation mechanism and driving force for the gravity currents analyzed, along with their spatial extent. Meteorological data from two stations, located 24 and 5 km away from Columbus Drive, were also used to characterize the meteorological conditions during the period analyzed and to evaluate the effect these conditions may have on the formation of the gravity currents.

During the period November 20, 2003, to February 01, 2004, a total of 28 gravity current events were observed at CR_CD, lasting a total of 77% of the time during this period. Sixteen of these bidirectional flow events (representing 47% of the total time) were generated by *underflows* of water from the NB. Twelve events (representing 30% of the total time) were generated by *overflows* of water from the NB. The percentage of the total time when *underflows* from the NB occurred at CR increased from 21.6 to 59.3% during the period. The average duration for the underflow events was 52.3 h. More than half (56.3%) of these events were initiated between the hours of 11:00 and 16:00. The percentage of the total time when *overflows* from the NB occurred at CR_CD decreased from 88.1 to 9.1% during the period. The average duration for the *overflow* events was 42.1 h.

During the period analyzed, temperature stratification was observed at NB_GA on three occasions, all occurring during January 2004. During these periods, bidirectional flow was also observed in the NB_GA, indicating that the plunging point for the underflows was upstream from the stream gauging station at NB_GA. Wind speed and direction strongly affect the shape of velocity profiles and the thickness of gravity currents, but are not the driving force behind the currents observed. Other meteorological data (air temperature, snowfall, snow depth, etc.) were used to corroborate the explanation for the development of the gravity currents.

The use of an ADCP for detecting and characterizing complex flows has proven to be a valuable field measurement tool. The velocity profile data obtained from the up-looking ADCP installed at CR_CD are unique in the writers' experience. These field observations made it possible to describe the evolution of gravity currents at CR_CD, and to document their frequency and duration. The characteristics of the observed events indicate that there is no single cause for the development of gravity currents in the Chicago River. For the *underflow* event of January 7, 2004 (UF12), which was analyzed in more detail, the difference in temperature, suspended sediment, and salinity all contributed to induce the *underflow*.

Local water resource managers have given some consideration to the design of a system to inhibit or minimize the occurrence of gravity currents in the CR. It has been shown that the occurrence of gravity currents is not restricted to the main stem of the CR only, but they also travel upstream on the North Branch (NB). The greater the density difference between CR and NB water, the farther upstream on the NB the plunging point is observed. The presence of both *underflows* and *overflows* in the period analyzed therefore has strong implications regarding any method used to minimize the presence of water flowing from the NB. For example, the use of a physical barrier, thought to be efficient to control *underflows*, will have little or no effect on *overflows* in the CR.

The following suggestions are offered regarding any future work on the occurrence of gravity currents in the CR and the NB and SB:

1. Water-quality measurements should be made during both *underflow* and *overflow* events to confirm the estimates of the driving forces for each event;
2. The causal sources creating density differences in the NB and CR (temperature, salinity, or suspended sediment) should be explored;
3. Water velocity measurements should be made throughout the entire Chicago River system to validate the hypothesis regarding the equilibrium or normal condition of the *underflow* and the location of the plunging point;
4. The methods used to compute streamflow at the North Branch Chicago River at Grand Avenue (USGS Station 05536118) should be reconsidered to account for the presence of bidirectional flows, using multiple ADVMs or an up-looking ADCP;
5. The use of alternative measurement devices, such as a Modular Acoustic Velocity Sensor (MAVS) or an acoustic Doppler velocimeter (ADV), for characterizing the flow turbulence in the *underflow* and the induced bottom shear stresses should be explored; and
6. The period analyzed should be extended through warm weather periods (summer).

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Disclaimer. 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. Government.

Notation

The following symbols are used in this paper:

C_D = friction coefficient;
E = coefficient of entrainment;
F_d = densimetric Froude number;
f = frequency;
g = acceleration of gravity;
H = depth of underflow;
h = depth above streambed where change was observed in direction of easterly water velocities;
q_u = discharge per unit width in underflow;
R = Reynolds number;
Ri_n = normal or equilibrium value of Richardson number;
R_0 = estimate of relative difference in density inducing underflow;
S = mean bed slope;
S_1 and S_2 = shape factors;
U = layer-averaged velocity in underflow;
V_{east} = easterly water velocity;
y = vertical distance above bed;
ν = kinematic water viscosity;
ρ_0 and ρ_u = ambient and underflow water density, respectively; and
Φ = buoyancy flux.

References

Bombardelli, F. A., and García, M. H. (2001a). "Simulation of density currents in urban environments. Application to the Chicago River, Illinois." *Proc., 3rd. Int. Symp. on Environmental Hydraulics*, IAHR, Tempe, Ariz.

Bombardelli, F. A., and García, M. H. (2001b). "Three-dimensional hydrodynamic modeling of density currents in the Chicago River, Illinois." *Civil Engineering Studies, Hydraulic Engineering Series No. 68*, Ven Te Chow Hydrosystems Laboratory, Dept. of Civil and Environmental Engineering, University of Illinois at Urbana-Champaign, Urbana, Ill.

Ellison, T. H., and Turner, J. S. (1959). "Turbulent entrainment in stratified flows." *J. Fluid Mech.*, 6, 423–448.

Fernandez, R. L., and Imberger, J. (2006). "Bed roughness induced entrainment in a high Richardson number underflow." *J. Hydraul. Res.*, 44(6), 725–738.

García, M. H. (1994). "Depositional turbidity current laden with poorly-sorted sediment." *J. Hydraul. Eng.*, 120(11), 1240–1263.

García, M. H. (1996). *Environmental hydrodynamics*, Publications Center, Universidad Nacional del Litoral, Santa Fe, Argentina (in Spanish).

García, C. M., Cantero, M. I., Niño, Y., and García, M. H. (2005a). "Turbulence measurements with acoustic Doppler velocimeters." *J. Hydraul. Eng.*, 131(12), 1062–1073.

García, C. M., Manriquez, C. P., Oberg, K., and García, M. H. (2005b). "Density currents in the Chicago River, Illinois." *Proc., of the River Coastal and Estuarine Morphodynamics Conf.*, IAHR, Urbana, Ill.

Gartner, J. W. (2004). "Estimating suspended solids concentration from backscatter intensity measured by acoustic Doppler current profiler in San Francisco Bay, California." *Mar. Geol.*, 211(3–4), 169–187.

Hebbert, B., Patterson, J., Loh, I., and Imberger, J. (1979). "Collie River underflow into the Wellington reservoir." *J. Hydr. Div.*, 105(5), 533–545.

Manriquez, C. P., García, C. M., Jackson, P. R., and García, M. H. (2005). "Hydraulic model study of Chicago River density currents." *Civil engineering studies, hydraulic engineering series No. 77*, Ven Te Chow Hydrosystems Laboratory, Dept. of Civil and Environmental Engineering, Univ. of Illinois at Urbana-Champaign, Urbana, Ill.

Morlock, S. E., Nguyen, H. T., and Ross, J. H. (2002). "Feasibility of acoustic Doppler velocity meters for the production of discharge records from U.S. Geological Survey streamflow-gaging stations." *U.S. Geological Survey Water-Resources Investigation Rep. 01-4157*, Indianapolis.

Parker, G., García, M. H., Fukushima, Y., and Yu, W. (1987). "Experiments on turbidity currents over an erodible bed." *J. Hydraul. Res.*, 25(1), 123–147.

Simpson, J. E. (1982). "Gravity currents in the laboratory, atmosphere, and ocean." *Annu. Rev. Fluid Mech.*, 14, 213–234.

Simpson, M. R. (2001). "Discharge measurements using a broad-band acoustic Doppler current profiler." *U.S. Geological Survey Open-file Rep. 01-01*, ⟨http://pubs.usgs.gov/of/ofr0101/⟩ (June 28, 2005).

Teledyne RD Instruments, Inc. (2001). *Workhorse installation guide, P/N 957-6152-00*, Teledyne RD Instruments, San Diego.

U.S. Army Corps of Engineers. (2005). "Code of Federal regulation, Title 33—Navigation and navigable waters, 33CFR207.420." ⟨http://edocket.access.gpo.gov/cfr_2005/julqtr/pdf/33cfr207.420.pdf⟩ (May 1, 2006).