Measuring Gravity Currents in the Chicago River, Chicago, Illinois

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***Abstract*- Recent studies of the Chicago River have determined that gravity currents are responsible for persistent bidirectional flows that have been observed in the river. A gravity current is the flow of one fluid within another caused by a density difference between the fluids. These studies demonstrated how acoustic Doppler current profilers (ADCP) can be used to detect and characterize gravity currents in the field. In order to better understand the formation and evolution of these gravity currents, the U.S. Geological Survey (USGS) has installed ADCPs and other instruments to continuously measure gravity currents in the Chicago River and the North Branch Chicago River. These instruments include stage sensors, thermistor strings, and both upward-looking and horizontal ADCPs. Data loggers and computers installed at gaging stations along the river are used to collect data from these instruments and transmit them to USGS offices.**

I. INTRODUCTION

Historically, the North Branch Chicago River and the South Branch Chicago River (Fig. 1A) joined just north of present-day Lake Street in the City of Chicago, Illinois and flowed eastward into Lake Michigan (Fig. 1B). As the City of Chicago developed it began to rely upon Lake Michigan for its water supply. During storm events, untreated sewage was transported into Lake Michigan, contaminating the City's drinking water supply. These events are thought to be responsible for large outbreaks of dysentery, cholera, and typhoid. For example, in 1854, almost 6% of the City's population died from dysentery and cholera [2]. Various efforts to mitigate this problem were attempted, but with little success.

In 1900, a 45-kilometer (km)-long canal dug by the Sanitary District of Chicago was completed, reversing the flow in the Chicago River and linking the Chicago River (Lake Michigan basin) to the Des Plaines River (Mississippi River basin) (Fig. 1A). The primary purpose of this canal, known as the Chicago Sanitary and Ship Canal (CSSC), was to carry Chicago River water away from the City and its water supply into the Des Plaines and Illinois Rivers. With this change in the drainage system, the Chicago River began to flow westward from Lake Michigan (Fig. 1B), through downtown Chicago, joining the flow coming from the North Branch Chicago River where it enters the South Branch Chicago River and then the CSSC.

Flow in the CSSC is controlled by the Lockport Powerhouse and Controlling Works near Joliet, IL (Fig. 1A) and by control structures near Lake Michigan such as the Chicago River Controlling Works (CRCW) (Fig. 1B). Flow in the main stem of the Chicago River 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

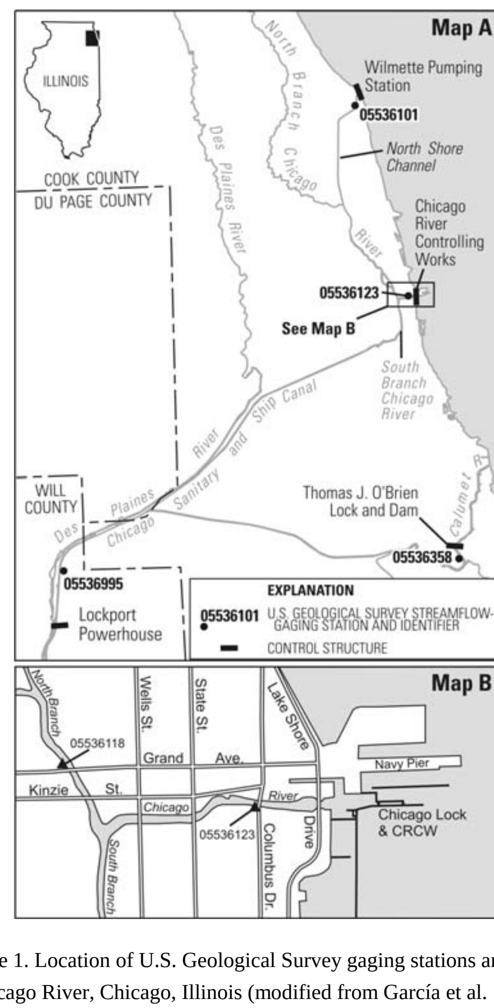

Figure 1. Location of U.S. Geological Survey gaging stations and the Chicago River, Chicago, Illinois (modified from García et al. [1]).

Chicago River. These flows are used to maintain or improve the water quality in the Chicago River, the South Branch Chicago River, and the 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 Chicago River during the remainder of the year is typically small (<2.8 cubic meters per second, 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 Chicago River. The North Branch Chicago River carries runoff from the watershed upstream and treated municipal sewage effluent released by the North Side Water Reclamation Plant (NSWRP) located 16 km upstream from the confluence of the North Branch Chicago River and the Chicago River. Most, or all, of this effluent is transported down the South Branch Chicago River into the CSSC and then to the Des Plaines and Illinois Rivers (Fig. 1A).

A gravity current is the flow of one fluid within another caused by a density difference between the fluids [5]. Examples of gravity currents include avalanches, seafloor turbidity currents, lahars, pyroclastic flows, and lava flows. This paper describes the instrumentation and techniques for measurement of gravity currents in the Chicago River. Previous work documenting measurements of gravity currents during the winter of 2003-2004 and the winter of 2005-2006 are first summarized. Acoustic Doppler current profilers (ADCPs), thermistors, and multi-parameter water-quality probes are being used to measure these currents. The location and configuration of these instruments at two locations along the Chicago River and the North Branch Chicago River are described, along with plans for future activities to measure gravity currents in the Chicago River system.

II. Gravity Currents in the Chicago River

The U.S. Geological Survey (USGS) established a streamflow gaging station at Columbus Drive (station number 05536123 in Fig. 1B) in October 1996 for the purpose of monitoring the flows through CRCW and the Chicago Lock into the Chicago River. As a part of its routine gaging station operation, USGS personnel made periodic measurements of discharge at this station at 6-8 week intervals. Beginning in 1998, discharge measurements made using an ADCP occasionally showed pronounced bidirectional flow in the Chicago River. This unexpected result raised questions about the cause of the bidirectional flow. Although it was possible that wind may have been responsible for a flow reversal near the surface, it seemed highly unlikely to be the primary cause as the flow reversal was present as deep as 3 meters (m) below the water surface.

Profiles of water temperature and specific conductance were obtained by USGS personnel during the winter of 1998-1999 in order to better understand the cause of these bidirectional flows. These profiles indicated that the river was sometimes stratified and, on several occasions, this stratification coincided with observations of bidirectional flow. At this same time the public occasionally reported that the river changed color during a day or over a period of several days. The cause for this stratification and color change was unknown, but it was hypothesized that flow from the North Branch Chicago River might enter the Chicago River. This hypothesis resulted in an investigation of the duration, frequency, and temporal variability of the bidirectional flows, their source, and their impact on the Chicago River.

García et al. [1] used measurements made with an uplooking ADCP, a thermistor string, and other information to identify 28 gravity currents in the Chicago River from November 2003 to February 2004. Sixteen of these events were generated by underflows from the North Branch Chicago River and 12 of these events were generated by overflows from the North Branch Chicago River. García et al. [1] found that underflows ranged from 5 hours to 228 hours in duration and overflows range from 11 hours to 114 hours in duration. On average, the duration of the underflow and overflow events was 52.3 hours and 42.1 hours, respectively. A detailed analysis of one underflow event, which started on January 7, 2004, and lasted about 65 hours, was also performed. It is believed that this was the first time that ADCP technology had been used to continuously monitor gravity currents in a river.

Subsequently, Jackson et al. [3] described synoptic measurements of water velocity, water temperature, and specific conductivity during an underflow and an overflow in the Chicago River during the winter of 2005-2006. Profiles of water velocity, water temperature, and specific conductivity were measured using a multi-parameter water-quality probe at selected locations along the Chicago River and the North Branch Chicago River during these events. They concluded that density differences responsible for driving the flows sampled primarily arise from salinity differences between the Chicago River and the North and South Branches of the Chicago River. Water temperature plays a secondary role in the creation of these currents. Deicing salts appear to be the primary source of salinity in the North Branch of the Chicago River, entering the waterway through direct runoff and effluent from a wastewater treatment plant in a large metropolitan area primarily served by combined sewers [3].

III. Measuring Gravity Currents

With the findings of [1] and [3], it has become apparent that gravity currents are common in the Chicago River. The presence of these currents creates challenges to making accurate measurements of streamflow. As a result the USGS has adapted its approach to the measurement of streamflow while also attempting to continuously monitor the river for gravity currents, to facilitate further research. The following sections provide an overview of the instrumentation installed at two gaging stations for continuous in-situ measurements and how these data are being collected.

A. Chicago River at Columbus Drive

Data collection at Columbus Drive is motivated by two primary needs, (1) the need to accurately measure the evolution of gravity currents spatially and temporally and (2) the need to accurately measure the net discharge through this section of the river. The former need requires data to be collected at a relatively high frequency (1 minute or less) and with a vertical resolution that is as detailed as possible. The latter really requires only the mean velocity in the vertical at a time step of 5 to 15 minutes. If the ADCP was configured to collect data to meet only the latter need, it is doubtful whether the data would be of much use in understanding the formation of gravity currents.

The Columbus Drive gaging station is located approximately 0.8 km downstream from the Chicago River Lock (Fig. 1B). At this location the Chicago River is 55 m wide and the water is held at a nearly constant depth of approximately 7 m in the center of the channel throughout the year. The gaging station at Columbus Drive is equipped with a stage sensor, a string of thermistors, and an upward-looking ADCP. Two different recording devices are used to record data collected using these instruments.

Stage (water-surface elevation in the river) is measured by means of a gas-purge, pressure transducer system and recorded every 5 minutes. Stage measurements are necessary for computation of discharge at this location. In addition, a string of thermistors was installed along the south bank of the river for continuous measurements of water temperature. Water-temperature data obtained from the thermistors will be used to characterize gravity current events. Thermistors are located 0.2 m, 0.7 m, 1.3 m, 2.3 m, 3.0 m, and 3.7 m above the bed of the river. The thermistor string was installed in October 2007. Both stage and water-temperature measurements are recorded by means of a Campbell Scientific data logger located in the Columbus Drive bridge house on the south side of the river. (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.) A phone line in the bridge house is used to transmit these data to the USGS office in Urbana, IL for input into the USGS National Water Information System (NWIS) database.

A 600-kHz Teledyne RD Instruments ADCP (Fig. 2) is permanently installed in an upward-looking configuration on the streambed of the Chicago River approximately in the center of the channel. The center of the ADCP transducers are located about 0.2 m above the streambed.

Water velocity measurements are normally made using pulse-coherent water modes, known as water mode 5 or water mode 11 [6]. Water modes (WMs) 5 and 11 measure the Doppler shift using short phase-encoded broadband pulses separated by a long lag. Normally with WMs 5 and 11, when using bottom tracking, the lag is set 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. The ADCP determines how long to wait before transmitting the second pulse based on the water depth obtained from a bottom track measurement. This approach results in a very long lag with low instrument noise, typically less than 2 centimeters per second (cm/s) with a depth cell size of 10 cm for a 600-kHz ADCP. However, for the Chicago River installation, the ADCP was mounted in a fixed location on the streambed of the Chicago River looking upwards. Because the water surface is often relatively smooth, bottom tracking could not be reliably used in this application, requiring the lag between the pulses to be set to a constant value of 6.7 m (corresponding to a WM 5 ambiguity velocity command of 6 cm/s). This is slightly less than the water depth at Columbus Drive. The primary difference between WM 5 and WM 11 is the location of the ambiguity resolving bin used to help resolve the ambiguity and allow a lower ambiguity velocity than the actual velocity of the water [6]. In WM 5, the ambiguity resolving bin extends from the end of the blanking distance (area near transducer faces where no velocity measurements are made) to 0.6 m or 85% of the shallowest beam, whichever is less. In WM 11, the ambiguity resolving bin is centered between the end of the blanking distance and 85% of the shallowest beam and has a maximum length of 2.3 m. Rapid changes in velocity with depth (known as shear) can cause these WMs to fail. Depending on the location of the shear, sometimes WM 11 will work when WM 5 will not.

The ADCP at Columbus Drive is configured to collect continuous velocity profiles at a sampling frequency of 0.2 Hz to 0.1 Hz. The depth-cell size is set to 0.1 m and the blanking distance is set to 0.25 m. With the PVC 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, the valid velocity data are located approximately 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

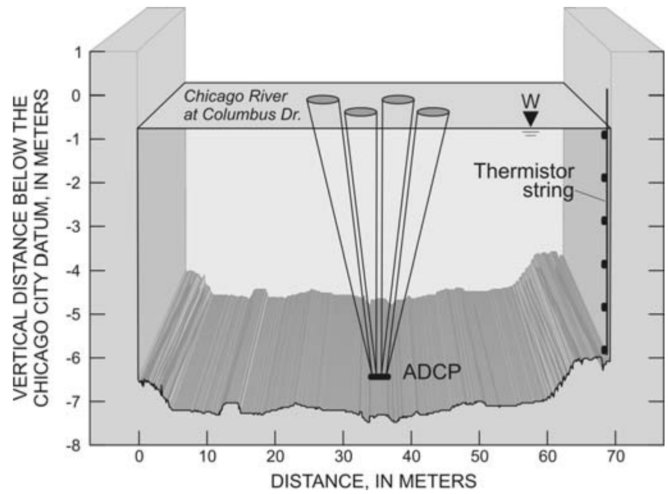

Figure 2. Cross section of Chicago River at Columbus Drive, Chicago, IL. Vertical scale exaggerated.

some interference between the two WMs 5/11 pulses at the surface. This latter interference is a result of the lag being fixed at a value somewhat less than the water depth. The unmeasured region extended 1.3 m below the free surface for most water-velocity measurements.

The water temperature is also measured by a thermistor located near the ADCP transducers at the same frequency as the velocity data. Water-temperature measurements are used in the ADCP to compute the speed of sound at the transducer face [6]. However, these water-temperature measurements are also used to describe variation of water temperature in the gravity currents.

The ADCP was connected to a computer in the USGS streamflow-gaging station by means of an underwater cable. Teledyne RD Instrument's software, VMDAS [7] is used for data acquisition and display. A dedicated high-speed Internet line is also installed in the gaging station in order to facilitate real-time control of the ADCP and data transfer. By means of software for remotely controlling a computer across the Internet, USGS personnel can change ADCP configuration parameters in response to changes in flow conditions. USGS personnel can remotely access the gaging station computer, determine whether a gravity current is flowing, and plan synoptic surveys or other on-site measurements. ADCP data files created by VMDAS are transferred from the gaging-station computer to the USGS office in Urbana, IL, for permanent storage and archival, using the Internet connection.

A time series of velocities measured during three gravity current events are shown in Figure 3. This time series shows three gravity current events, one underflow that occurs between two overflows. During the two overflows, water from the North Branch Chicago River is not as dense as the water in the Chicago River (originally from Lake Michigan) and flows eastward towards the Lake, while the water in the Chicago River flows westward along the bed towards the channel junction. During the underflow, denser water from the North Branch Chicago River flows eastward along the bed towards the Lake, while Chicago River water flows westward near the surface towards the channel junction. García et al. [1] provide a detailed description of similar events and analyze an underflow event in detail. Data shown in Figure 3 are indicative of the kind of velocity records available for analysis.

B. North Branch Chicago River at Grand Avenue

Data collection at Grand Avenue was originally motivated primarily by the need to measure the streamflow at that location. The instrumentation originally installed did not allow for measurement of bidirectional flows. However, since García et al. [1] showed that the plunging point for underflows can move upstream from Grand Avenue, it has become necessary to install an upward-looking ADCP for accurate measurement of streamflow and in order to better study the formation of gravity currents in the Chicago River system.

The Grand Avenue gaging station (station number 05536118 in Fig. 1B) is located on the right bank upstream from the Grand Avenue bridge and about 1,000 m upstream from the confluence of the North Branch Chicago River with the main stem of the Chicago River. The gaging station was originally established in 2002. The North Branch Chicago River is 50 m wide at Grand Avenue and the maximum water depth in the thalweg is about 6.5 m. The gaging station at Grand Avenue is presently equipped with a stage sensor, a string of thermistors, an upward-looking ADCP, and a horizontal acoustic Doppler velocity meter (ADVM).

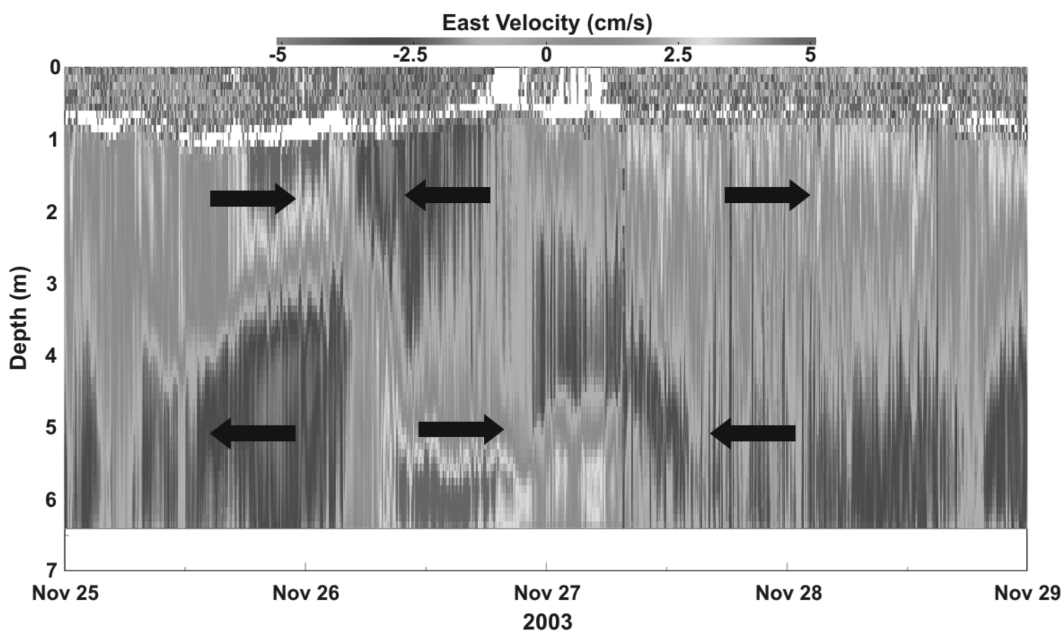

Figure 3. Contour plot of water velocity in the easterly direction measured at the Chicago River at Columbus Drive, Chicago, IL, for a 5-day period beginning November 25, 2003.

Stage in the North Branch Chicago River is measured by means of a gas-purge, pressure transducer system. A string of six thermistors are used to measure the water temperature at various elevations along the right (west) bank at Grand Avenue. Water-temperature data obtained from the thermistors have been used to help characterize gravity current events by García et al. [1]. The thermistors are located at 0.6-m increments in the vertical, with the near bed thermistor located at 0.15 m above the streambed at the wall (Fig. 4). The thermistor string was installed when the gage was established in 2002. Both stage and water-temperature measurements are recorded at a 5-minute sampling frequency by means of a Campbell Scientific data logger located in the Grand Avenue gage house on the west side of the river.

A SonTek/YSI Argonaut-SL ADVM is used to measure horizontal water velocity profiles across the North Branch Chicago River [4]. The 1,500 kHz 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 North Branch Chicago River 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). The ADVM is also equipped with an acoustic stage sensor, providing redundancy in stage measurement at this site. It was originally thought that accurate flow records could be computed for this site using the index-velocity method [4] with the velocity record from ADVM and the stage record as inputs. In the index-velocity method, two ratings are developed and maintained, a stage-area rating and an index-velocity rating. The stage-area rating is developed by surveying a stable cross section in the stream near the permanently mounted ADCP. The channel area for a given stage can then be determined from the surveyed cross section. An index-velocity rating is also developed using the relation between the measured mean velocity in the cross section and the simultaneous index velocity measured using a permanently mounted ADVM or ADCP. Using these two ratings, the continuous time series of stage and index (ADVM) velocities, one can compute a continuous record of discharge. However, the use of the ADVM with this method at Grand Avenue was invalidated when García et al. [1] found that the plunging point for gravity currents could move upstream from Grand Avenue. When this occurs, the velocity measured by the ADVM can be negative and therefore is not a good index of the mean flow in the river.

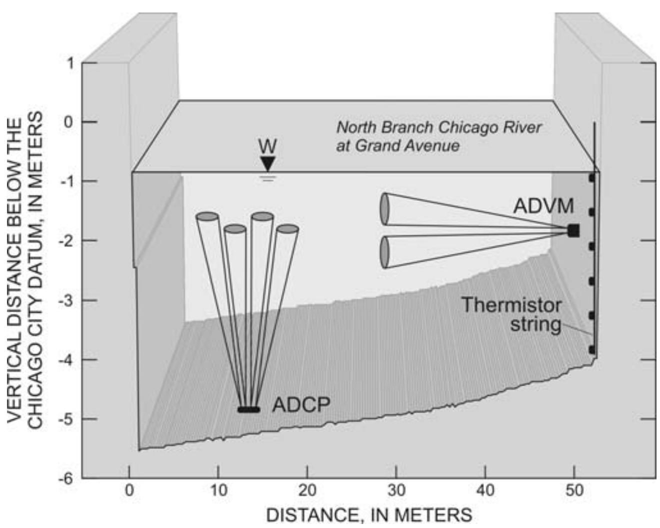

Figure 4. Cross section of North Branch Chicago River at Grand Avenue, Chicago, IL. Vertical scale exaggerated.

In order to measure streamflow more accurately and to facilitate investigation of gravity currents, a 600-kHz Teledyne RD Instruments ADCP was also permanently installed in an upward-looking configuration on the streambed at Grand Avenue in October 2007. The installation is similar to that at Columbus Drive, except that the ADCP is located at approximately 40 m from the right bank (Fig. 4). The ADCP is configured similar to the ADCP at Columbus Drive. As at the Columbus Drive gaging station, pulse-coherent WMs (5 and 11) are used to measure water velocity. For the computation of streamflow records, the velocities measured by the ADCP will be used to develop a new index-velocity rating. The water velocity measurements made by the ADCP will also be used for further research on the formation of gravity currents.

In terms of the measurement approach at the Grand Avenue gaging station, there are only two major differences as compared to the Columbus Drive gaging station. At present (February 2008), high-speed Internet access and AC power have not been installed at the gaging station. It is unlikely that AC power will be installed because of the high installation cost. However, installation of a high-speed Internet connection powered by batteries and solar power is planned. Because Internet access is not yet available for this gaging station, remote monitoring and control of the ADCP is not available yet.

IV. Future Work

Work by García et al. [1] and Jackson et al. [3] has demonstrated how ADCPs can be used to continuously monitor gravity currents in the Chicago River. Water-temperature measurements from thermistor strings installed in the North Branch Chicago River have been used to help understand the source, and to some extent, the evolution of the currents. Jackson et al. [3] conducted synoptic surveys to determine the driving forces for the gravity currents and the causal sources for these currents. Despite this progress, our understanding of the formation and evolution of these currents in the Chicago River system is still quite limited. García et al. [1] and Jackson et al. [3] have identified the following questions that require additional research and monitoring:

- Are the causal sources for gravity currents different during summer periods (as opposed to the winter periods analyzed to date)?
- What are the mechanisms for triggering gravity current events? While it is clear from previous work that density plays the primary role in driving these currents, wind and air temperature may also play an important role in the initiation and evolution of these currents.

- Since it appears likely that underflows will travel downstream in the South Branch Chicago River, how far do they travel and how do they affect water quality in that portion of the river?
- How can water-quality measurements be more accurately made to account for the presence of bi-directional flows caused by gravity currents?

In order to address some of these issues, the USGS and colleagues from the University of Illinois, Urbana-Champaign, plan to conduct several synoptic surveys during gravity flow events. These synoptic surveys will be similar to those conducted by Jackson et al. [3], but will also involve deployment of additional ADCPs to monitor currents in the South Branch Chicago River and in the vicinity of the channel junction. Detailed water-quality profiles and physical water samples will be obtained to help characterize the driving forces for gravity currents for summer periods, as well as winter periods.

V. SUMMARY

The Chicago River has undergone many changes since the late 1800s. These changes have resulted in the reversal of the Chicago River so that water in the Chicago River and the North Branch Chicago River now flows into the Mississippi River basin. Periodic streamflow measurements made by the USGS in the Chicago River at Columbus Drive beginning in 1998 indicated pronounced bidirectional flow. These bidirectional flows observed in the Chicago River at Columbus Drive are caused by gravity currents in the Chicago River [1]. Jackson et al. [3] showed that the gravity currents they measured during the winter of 2005-2006 were driven by density differences attributed primarily to salinity. An ADCP has been shown to be a valuable tool for detecting and characterizing gravity currents in the field. These field observations have made it possible to describe the evolution of gravity currents and to document their frequency and duration.

Instrumentation has been installed to measure flows and gravity currents in-situ along the Chicago River and the North Branch Chicago River. The streamflow gaging station at Columbus Drive is equipped with a stage sensor, a string of thermistors, and an upward-looking ADCP permanently mounted on the bed of the Chicago River. Pulse-coherent techniques (water modes 5 and 11) are used to make accurate water-velocity measurements using the ADCP. The streamflow gaging station at Grand Avenue is equipped with a stage sensor, a string of thermistors on the right bank, a horizontal ADVM mounted about 1.7 m above the bed along the right bank, and an upward-looking ADCP permanently mounted on the bed of the North Branch Chicago River. These instruments are being used to measure streamflow records continuously, but also to provide the means for characterizing the formation of gravity currents in the Chicago River system. Future monitoring activities include several planned synoptic measurements of water velocity, water temperature, and water-quality parameters at multiple locations along the Chicago River during gravity current events.

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