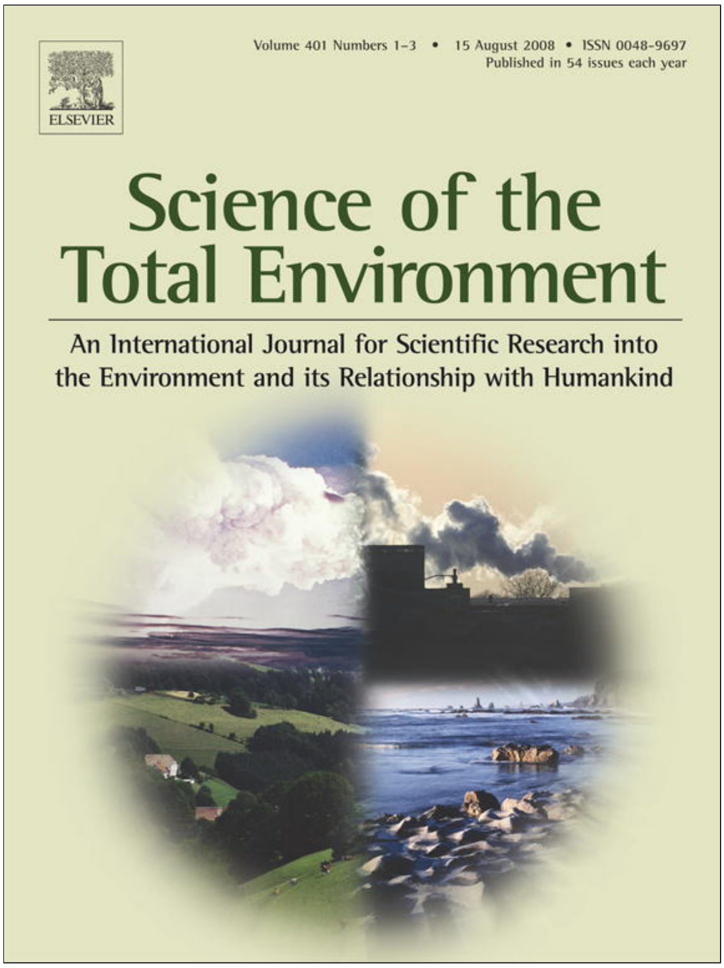
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Density currents in the Chicago River: Characterization, effects on water quality, and potential sources

P. Ryan Jackson[a,*], *Carlos M. García*[b], *Kevin A. Oberg*[c], *Kevin K. Johnson*[d], *Marcelo H. García*[e]

[a]Applied Ocean Physics and Engineering Department, Woods Hole Oceanographic Institution, Woods Hole, MA 02543, USA
[b]Instituto Superior de Recursos Hídricos, Universidad Nacional de Córdoba, Av. Filloy s/n. Ciudad Universitaria., Córdoba, 5000, Argentina
[c]U.S. Geological Survey, Office of Surface Water, 1201 W. University Ave. Urbana, IL 61801, USA
[d]U.S. Geological Survey, Illinois Water Science Center, 1201 W. University Ave. Urbana, IL 61801, USA
[e]Department of Civil and Environmental Engineering, University of Illinois at Urbana-Champaign, 205 North Mathews Ave. Urbana, IL 61801, USA

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ABSTRACT

Bidirectional flows in a river system can occur under stratified flow conditions and in addition to creating significant errors in discharge estimates, the upstream propagating currents are capable of transporting contaminants and affecting water quality. Detailed field observations of bidirectional flows were made in the Chicago River in Chicago, Illinois in the winter of 2005–06. Using multiple acoustic Doppler current profilers simultaneously with a water-quality profiler, the formation of upstream propagating density currents within the Chicago River both as an underflow and an overflow was observed on three occasions. Density differences driving the flow primarily arise from salinity differences between intersecting branches of the Chicago River, whereas water temperature is secondary 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. Water-quality assessments of the Chicago River may underestimate (or overestimate) the impairment of the river because standard water-quality monitoring practices do not account for density-driven underflows (or overflows). Chloride concentrations near the riverbed can significantly exceed concentrations at the river surface during underflows indicating that full-depth parameter profiles are necessary for accurate water-quality assessments in urban environments where application of deicing salt is common.

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1. Introduction

The present-day Main Branch of the Chicago River (hereafter MB) flows west from Lake Michigan, through downtown Chicago, Illinois, and joins the North Branch (hereafter referred to as NB) where it empties into the South Branch (hereafter SB) (Fig. 1). Flow in the MB was reversed in 1900 to keep sewage effluent from reaching Lake Michigan (Hill, 2000). The MB flow is now controlled by the Lockport Powerhouse and Controlling Works near Joliet, IL, by the Chicago River Controlling Works (hereafter referred to as CRCW) and by the Chicago Harbor Lock at Lake Michigan. During summer, water from Lake Michigan flows into the MB through sluice gates and lockages (the passage of ships through the lock) at the CRCW. This flow, called discretionary diversion, is used to preserve or improve the water quality in the MB, SB and the Chicago

* *Corresponding author*. Present address: U.S. Geological Survey, Illinois Water Science Center, 1201 W. University Ave. Urbana, IL 61801, USA. Tel.: +1 217 344 0037; fax: +1 217 344 0082.
E-mail address: pjackson@usgs.gov (P.R. Jackson).

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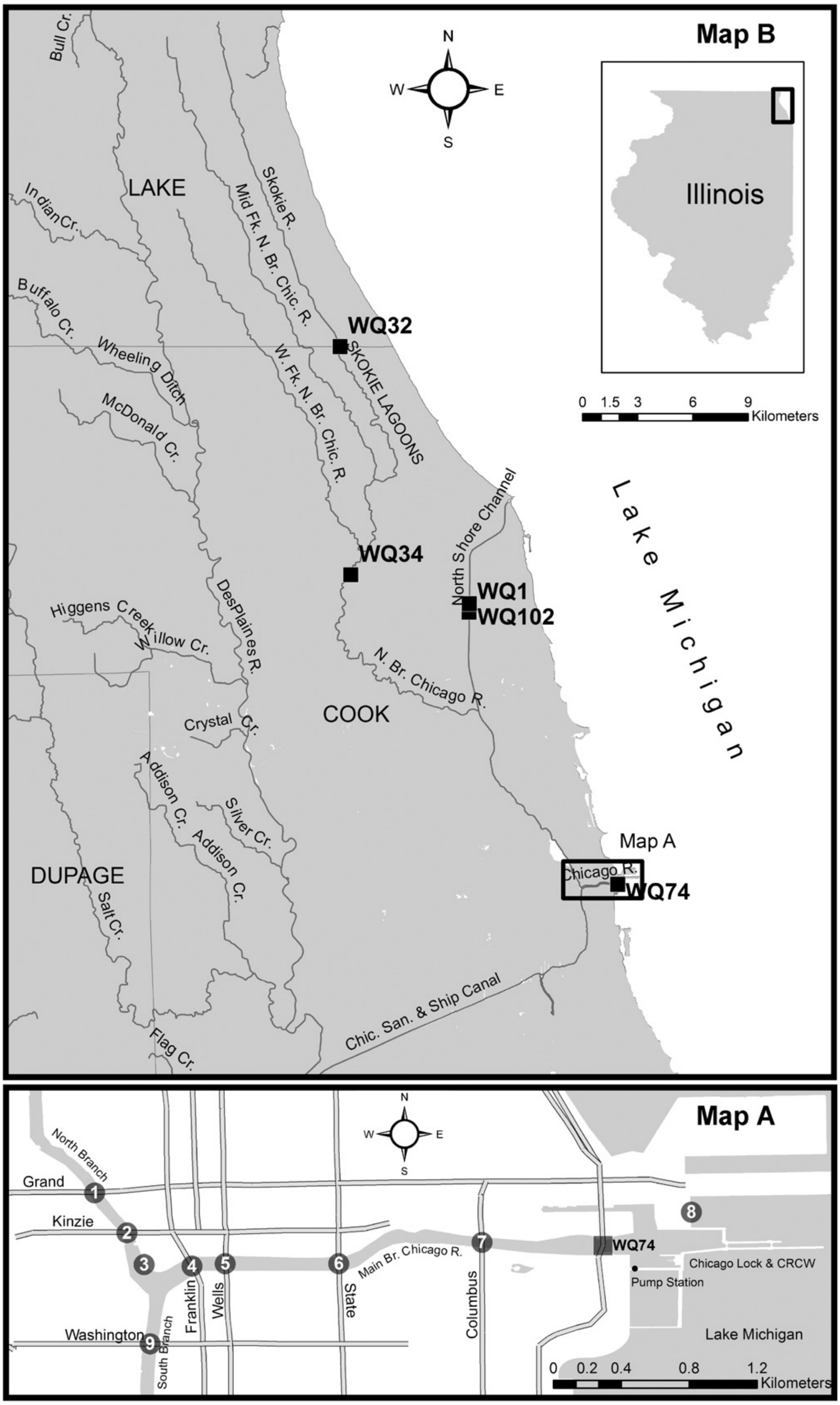

Fig. 1 – The Chicago River system, Chicago, Illinois. Circles on Map A show locations and identification of sampling stations (see Table 1) and squares show locations and identification of MWRDGC water-quality sampling stations (see Section 4).

Sanitary and Ship Canal (hereafter referred to as CSSC). During winter, diversions from Lake Michigan into the MB are small compared to summer and typically result from lockages and leakage through the gates and sea walls at CRCW. The NB carries watershed runoff and treated municipal sewage effluent from the North Side Water Reclamation Plant located on the North Shore Channel, 16 km upstream from the MB. Sewage effluent accounts for as much as 75% of the discharge in the NB during winter months (Manriquez et al., 2005).

During routine discharge measurements in 1998 as part of the discretionary diversion accounting, the U.S. Geological Survey (USGS) observed bidirectional flow in the MB at station 7 (see Fig. 1, Map A). Bidirectional flow consists of two layers moving in opposite directions (i.e. one layer flowing downstream while the other layer flows upstream). Such flow irregularities introduced large uncertainty into discharge measurements made at this station using an acoustic velocity meter and the index velocity technique (Morlock et al., 2002). Motivated by the 1998 field observations, Bombardelli and García (2001) used a three-dimensional numerical model to test the hypothesis that density currents (buoyancy-driven flows arising from density differences) created bidirectional flows in the Chicago River. Whereas the duration and frequency of the bidirectional flows were not known, the observed and modeled flows indicated the possibility that water from the NB might be flowing into the MB and affecting water quality. Concerns were also raised about the potential effects of these currents on the water quality in Lake Michigan should the pump station located on the Chicago inner harbor turning basin cutoff wall near the lock (see Fig. 1, Map A) ever be utilized. The pump station was designed to return water to Lake Michigan from the Chicago River during the period November to April to make up for excessive diversion from Lake Michigan.

Based on data from an uplooking acoustic Doppler current profiler (ADCP) and available meteorological and limited water-quality data for the period from November 2003 to February 2004, García et al. (2007) concluded that bidirectional flows occurred in the MB because of currents driven by differences in density ρ between waters from the NB and MB. They hypothesized that the density differences might be caused by temperature differences, high concentrations of dissolved salts, suspended-sediment concentrations, or by some combination of these three factors. Bombardelli and García (2001) proposed an equation of state that accounted for the relative contribution of all these factors to density differences in the Chicago River, and indicated that density underflows would be most common during the winter months. García et al. (2007) found that bidirectional flows were common in the Chicago River system; over a period of 2.5 months, 28 bidirectional flow events were observed with underflows ($\rho_{NB} > \rho_{MB}$) measured 47% of the time and overflows ($\rho_{NB} < \rho_{MB}$) measured 30% of the time.

Previous studies of bidirectional flow in the Chicago River have only speculated about the source of the density anomaly in the river (Bombardelli and García, 2001; García et al., 2007). The present work introduces a new set of synoptic field data recorded during bidirectional flow events in the Chicago River system. Data are used to validate previous hypotheses about the fluid properties of the density currents, to characterize the currents, and to propose possible sources of the dense water. Two density current events (an underflow and an overflow) are characterized based on data collected during field measurements performed in December 2005 and January 2006. In addition, an event in late January 2006 is presented showing the transition from an underflow to an overflow condition. The potential sources of the dense water are discussed and recommendations are given for future work.

2. Data collection

In December 2005, a field program was initiated by the USGS and the University of Illinois at Urbana-Champaign (UIUC) to investigate bidirectional flows in the Chicago River. Synoptic field measurements included velocity and water-quality profiles measured at seven locations in the Chicago River system (Table 1, Fig. 1). The profiles were collected on December 19, 2005, and on January 11, 2006, by measuring from bridge crossings. In addition, the temporal evolution of the velocity profile in the MB was captured at station 7 using an uplooking ADCP.

Simultaneous velocity and water-quality profiles were measured at stations listed in Table 1 using (1) an Oceanscience River Boat equipped with a Teledyne RD Instruments 600 kHz ADCP and (2) a YSI data sonde. (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.) Velocity profiles were not recorded at all stations. The same ADCP sampling configuration was adopted for all water-velocity measurements: a bin size of 0.10 m, a blanking distance of 0.25 m, the ADCP submerged to about 0.09 m, a pulse pulse-coherent water-velocity measurement mode (mode 11), a sampling interval of between 0.6 and 0.64 s, and single ping configuration to obtain both the water water-velocity and boat velocity measurements (one profile at station 7 used mode 12, 25 cm bins, and a sampling interval of 0.99 s).

Temperature and conductivity profiles were measured using a YSI Model 600xl multi-parameter data sonde with a thermistor (range: −5 °C to 45 °C; accuracy: 0.15 °C) 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 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 (0.3 m at stations 5 and 6 on December 19, 2005) with an error in the depth of less than 0.5 m due primarily to layback (wire angle) of the graduated deployment wire while sampling. Salinity was computed in accordance with national and international standards (Clesceri et al., 1998; Fofonoff and Millard, 1983) under the assumption that sodium chloride (NaCl) is the major constituent contributing to the high conductivity. This assumption is reasonable because NaCl is the primary road salt used in the Chicago area (Friederici 2004) and elevated chloride concentrations (above background levels) in the NB have been observed during winter (García et al., 2005). Density was computed using the United Nations Educational, Scientific and Cultural Organization (UNESCO) 1983 equation of state for seawater that is valid at the observed temperatures (Fofonoff and Millard, 1983). For comparison, densities were also computed with a simplified equation of

Table 1 – Sampling stations and instrumentation

Station	Name	Profile start times Dec. 19, 2005	Profile start times Jan. 11, 2006	Approximate distance DS from station 1 (m)	Width (m)	Sampling location	Instrumentation	Figure symbol
1	Grand	13:15	11:18	0	56	Right [a] Bank, Center line [b]	YSI [a,b], tethered ADCP [b]	○
2	Kinzie	13:36	11:42	297	52	Center line	Tethered ADCP [a,b], YSI [a,b],	+
3	DS Kinzie	13:52	12:04	419	65	Left Bank	YSI [a,b]	×
4	Franklin	N/A	12:50	515	71	Center line	Tethered ADCP [b], YSI [b]	✡
5	Wells	14:08	12:34	863	79	Center line	Tethered ADCP [a,b], YSI [a,b]	△
6	State	14:50	13:10	1358	84	Center line	Tethered ADCP [a,b], YSI [a,b]	◇
7	Columbus	11:58	10:15	2006	57	Center line	Tethered ADCP [a,b], YSI [a,b], uplooking ADCP [a,b]	□
8	Lake Michigan	15:30	N/A	2800	N/A	Bank	YSI [a]	N/A
9	Washington	N/A	13:44	845	65	Center line	Tethered ADCP [b], YSI [b]	✳

Along-stream distances given are measured distances downstream (DS) from station 1. Profile start times refer to the YSI water-quality measurements. Synoptic velocity profiles were gathered within the sampling period of the YSI measurements.
[a] December 19, 2005 event.
[b] January 11, 2006 event.

state used by Bombardelli and García (2001) resulting in slightly higher densities (<0.1% difference). The UNESCO 1983 equation of state was ultimately used to keep with recognized standards.

The temporal evolution of the velocity profiles at station 7 was measured with an uplooking 600-kHz Teledyne RD Instruments ADCP deployed on the channel bottom (from 6.7 to 6.8 m depth) along the approximate channel center line. An underwater cable connected the ADCP to a computer in the nearby USGS streamflow-gaging station (05536123), allowing full remote operation of the instrument including real-time data access. This ADCP was deployed intermittently starting in August 1999 and has operated continuously since May 2003 (with the exception of servicing periods). The uplooking ADCP provided three component, continuous profiles of velocity at a sampling frequency of 0.1 Hz. The uplooking ADCP was configured using the mode 5 pulse-coherent technique for RDI profilers, 10 cm depth cells, and a 0.05 m blanking distance. The deepest valid velocity measurement was approximately 0.40 m above the streambed and no data in the top 1 m of the flow were used in this analysis because of side-lobe interference and decorrelation near the surface (Simpson, 2001). With these limitations, about 79% of the depth in each profile contained valid water-velocity measurements. A temperature sensor (range from −5 °C to 45 °C, precision of 0.4 °C, resolution of 0.01 °C) mounted between the ADCP transducers (0.3 m above the streambed) measured near-bed water temperature at sampling frequency of 0.1 Hz.

Data collected during this study allowed the characterization of the observed density currents. Layer-averaged velocity U and layer depth H were computed using a set of moments (García, 1994, García et al., 2007) with the upper limit of the underflow taken as the zero velocity line for the integration. Excess fractional density was computed as $(\rho-\rho_0)/\rho_0$ (expressed as a percent) where ρ and ρ_0 are the mean densities of the density current and ambient water, respectively. The Reynolds number $Re=UH/\nu$, the Richardson number $Ri=g'H/U^2$, and the densimetric Froude number $Fr=U/(g'H)^{0.5}$ were computed, where ν is the kinematic viscosity, $g'=g(\rho-\rho_0)/\rho_0$ is the reduced gravity, and g is the gravitational acceleration. The density ratio, or the ratio of the contributions from temperature and salinity to the density, was computed to determine the primary contributor to the density anomaly driving these currents. The contribution to density from each scalar was computed by taking the difference in density over the depth from each scalar while holding the other scalar constant at its depth averaged value.

Meteorological data from the National Climatic Data Center were analyzed to characterize the boundary conditions present in the Chicago River system during the sampling period. Data included time series of air temperature, wind speed, and wind direction reported hourly by the O'Hare airport meteorological station (WBAN Station 94846, Chicago, IL).

3. Data analysis

3.1. *Characterization of an underflow event: December 19, 2005*

On December 19, 2005, an underflow event was observed in the Main Branch of the Chicago River. The bidirectional flow data from the uplooking ADCP at station 7 for the 4-hour period starting at approximately 11:30 AM Central Standard Time (CST) is presented in Fig. 2b. The velocity data indicate a sustained underflow with a thickness of about 2 m and a layer-averaged velocity of approximately 3 cm/s traveling east toward Lake Michigan and the surface flow to the west at approximately 2 cm/s. There is excellent agreement between the time-averaged uplooking ADCP profile and the synoptic velocity profile from the tethered boat (Fig. 2b). The sampling period used in averaging the uplooking ADCP data (from 11:32:28 to 15:24:08, 1391 ensembles) included the 6.5-minute long sampling period (620 ensembles) for the tethered boat (starting at 12:05:00). Southwesterly winds (winds originating from the southwest) prevailed throughout the data record with speeds ranging between 9 and 14 mph (14.5–22.5 km/h) and may be responsible for the brief eastward surface flows. Air temperatures remained near −13 °C during the sampling period.

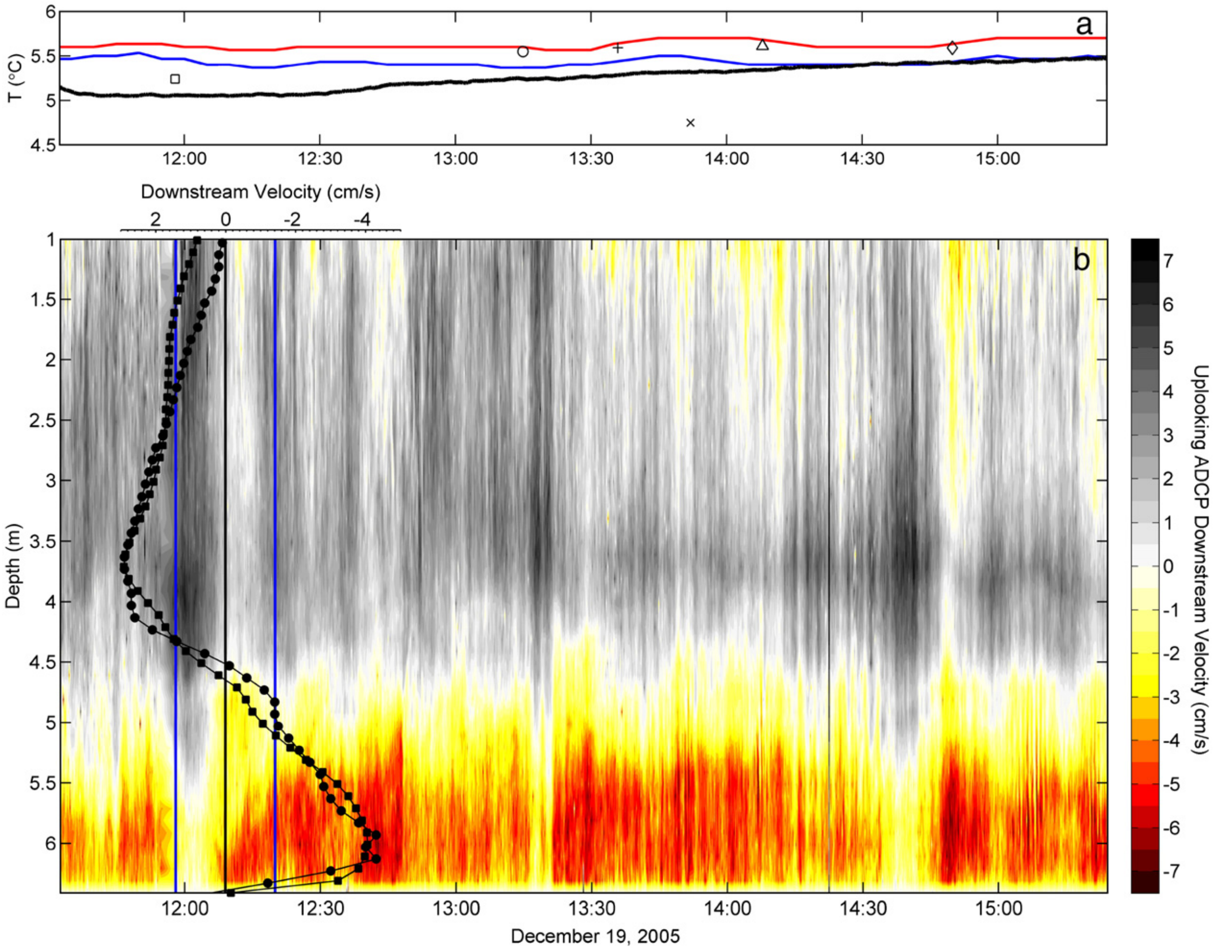

Fig. 2 – December 19, 2005, underflow event. (a) Water temperature in the NB at station 1 (blue line, surface; red line, near bed) and MB at station 7 (black line, near bed). Near Near-bed (YSI) water temperatures are also shown for most stations (symbols given in Table 1). Station 3 (×) measurement was made from the bank at 4.75 m depth. (b) Contour plot of downstream water velocity (in cm/s) recorded by the uplooking ADCP at station 7 for an underflow event. The downstream direction is away from the lake (west). Mean downstream water-velocity profiles recorded at station 7 by both the uplooking ADCP (squares; averaged over the entire record shown) and the tethered ADCP (circles; averaged over 6.57 min starting at 12:05) are overlaid. Vertical blue lines show the time limits of the synoptic YSI measurements at station 7 (which encompass the tethered tethered-boat velocity profiles).

With the exception of small areas near the lock at Lake Michigan (Fig. 1, Map A), no ice coverage was observed on the river.

Water-quality profiles confirm the NB is the source of the dense water driving the underflows in the MB of the Chicago River. Profiles of temperature, salinity, density and downstream velocity for most of the stations listed in Table 1 (Table 1 includes sample location information and sample times for each profile) are illustrated in Fig. 3. The collapse of the temperature and salinity profiles near the streambed reveals warm, saline water from the NB invading the MB as an underflow. General flow circulation within density currents pumps dense water to the head of the current along the lower boundary while most of the mixing takes place at the front of the current and along its upper boundary (Garcia and Parker, 1993; Kneller et al., 1999). The relatively fresher, colder water in the density current at station 7 and the observation of a flow reversal below the velocity maximum in the current (see Fig. 3) indicates that the profile at station 7 may have been taken close to the front of the current where entrainment (dilution) and mixing take place. Temperature records from the uplooking ADCP at station 7 (Fig. 2a) indicate that the water temperature near the bed in the MB rose to levels consistent with NB upper layer water within several hours following the collection of water-quality profiles. This observation not only directly links the water masses in the NB and the underflow, but it also indicates that the underflow observed at station 7 is evolving and has not yet reached equilibrium conditions. The collapse of the water-property profiles in the underflow in Fig. 3 indicates that lower quality water from the NB (relative to the MB) is capable of reaching the lock at Lake Michigan with little dilution; such a density current can negatively affect water quality in the Chicago River and, potentially, Lake Michigan.

In contrast to the relatively uniform water properties of the underflow at all stations (station 7 excluded), the ambient water properties show a horizontal (stream-wise) gradient along the length of the MB with the densest water in the NB and the lightest water at station 7. This horizontal density variation is a direct result of mixing between MB and NB water.

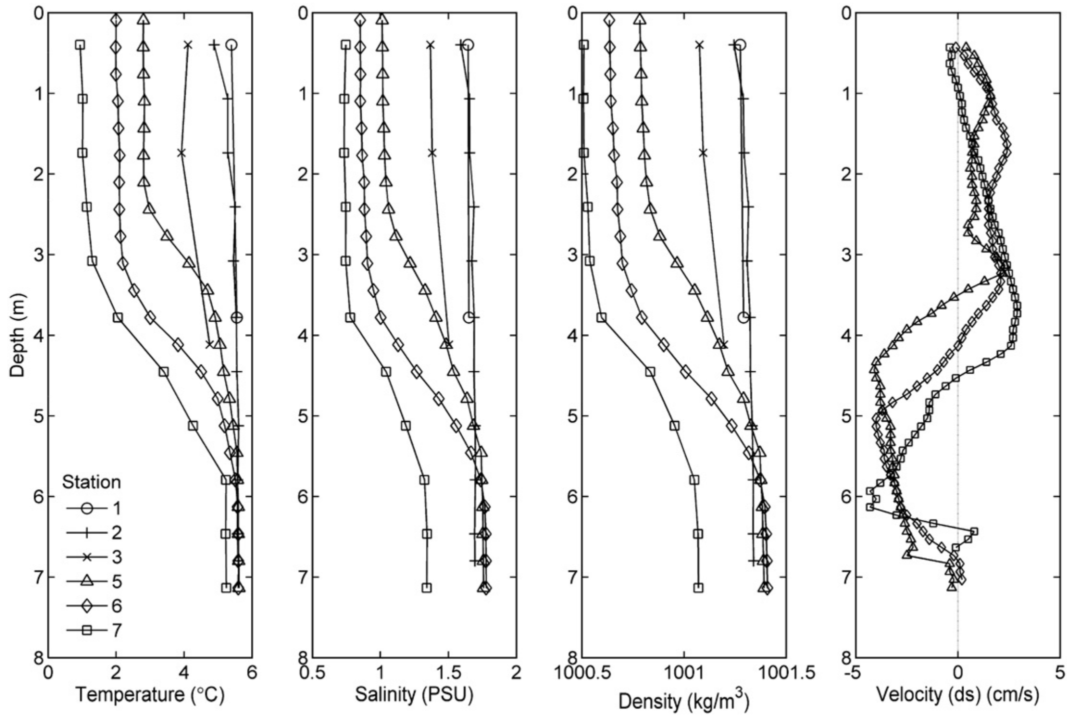

Fig. 3 – Water-quality and velocity profiles at stations along the Main Branch and North Branch of the Chicago River during the December 19, 2005, underflow event. Station locations are given in Fig. 1, Map A. Velocity is given with the downstream (ds) component taken as positive. Single point samples for Lake Michigan (at 1.3 m depth; station 8): T=0.06 °C, S=0.315 PSU (Practical Salinity Units), ρ=1000.108 kg/m^3. The sampling periods for the velocity measurements at stations 5, 6 and 7 were 10.17 min (957 ensembles), 13.35 min (1266 ensembles), and 6.57 min (620 ensembles), respectively.

Near the confluence, the MB mixes more efficiently with NB water compared to the reach close to the lake creating streamwise gradients. Influx of fresh water from Lake Michigan (leakage, lockage, diversion) can strengthen this horizontal gradient.

While stations 1 and 2 in the NB display uniform water-quality profiles, station 3 just upstream from the confluence with the MB shows signs of mixing between NB and MB water. This result indicates that the plunging point for this underflow, the point at which the dense water plunges below the lighter water creating a flow convergence (see García et al., 2007), was upstream from station 3 and downstream from station 2. Field notes taken during measurements on December 19, 2005, indicate a line of debris on the water surface between stations 2 and 3. The flow convergence associated with the plunging point would form such a debris line at the location of plunging (Largier, 1992).

The depth of the velocity interface (the zero velocity point) for each profile approximately coincides with the mean of the density profile and the middle of the interfacial layer in density. The broad and almost linearly stratified interfacial region indicates relatively strong mixing at the head of the density current and a wake region behind the head in which the scalar concentrations linearly vary (Britter and Simpson, 1978; Parsons and García, 1998; Kneller et al., 1999; Cantero et al., 2007). Effects of the no-slip boundary condition imposed by the lower boundary and the influence of a wind-induced surface stress at the upper boundary are also seen in Fig. 3. For clarity, the velocity profile from station 2, which had a mean downstream velocity of about 3 cm/s and showed no signs of bidirectional flow, has been omitted from Fig. 3.

The observed underflow was subcritical (Fr<1) with increasing Froude numbers towards the head of the current (Table 2A). The relatively low Froude numbers observed within the body of the current indicate buoyancy-dominated flow and are consistent with the Froude numbers measured in the saline density current of Fernandez and Imberger (2006) under equilibrium conditions. The increase in the Froude number (decrease in Ri) at station 7 indicates that the current may not have been under equilibrium flow conditions at station 7 during sampling, an assumption made by García et al. (2007) to estimate the excess density of a strong underflow event from a different set of water water-velocity measurements. The higher Froude number (lower Ri) at station 7 indicates a greater rate of entrainment and mixing characteristic of the front of a density current. Previous measurements (García et al., 2007) may have been made farther from the head of the current where equilibrium conditions could be achieved. However, the Froude number at station 7 in the present observations was less than unity (characteristic of critical flow conditions at the front (e.g. Garcia and Parsons, 1996)) indicating that the observations were made in the body of the current, but prior to reaching equilibrium conditions.

Bombardelli and García (2001) observed an increase in the excess fractional density along the length of the MB from the confluence to the lock. The present observations show a similar trend (Table 2A, Fig. 3). With the exception of station 7, the density change over the channel depth increases from

Table 2 – Density current parameters characterizing the underflow and overflow events in the Main Branch of the Chicago River

Station	Depth (m)	Interface depth (m)	*H* (m)	*U* (cm/s)	Excess density (%)	*Re* $UH/\nu \times 10^3$	*Ri* $g'H/U^2$	*Fr* $U/(g'H)^{0.5}$	Density ratio
A. December 19, 2005 underflow									
5	7.33	3.5	3.11	−3.15	0.046	64	14.3	0.26	0.038[a]
6	7.33	4.2	2.14	−3.05	0.060	43	13.6	0.27	0.004[a]
7	6.74	4.5	1.57	−2.94	0.046	30	8.2	0.35	0.102
B. January 11, 2006 overflow									
1[b]	6.03	4.4	1.19	−0.58	0.002	4.6	5.6	0.42	0.04
5	7.33	2.7	1.92	−1.86	0.007	24	3.8	0.51	3.12
6	7.18	1.5	0.77	−1.66	0.006	8.4	1.5	0.81	0.98

Negative *U* indicates upstream flow.
[a] Temperature profile was unstably stratified.
[b] Observations and parameters at station 1 on January 11, 2006 (NB) are for the observed underflow.

station 1 to station 6 (Fig. 3) and station 7 would have likely been similar had the profile been taken under equilibrium conditions. The increase in the excess density along the current from the tail to the head is a result of two factors: 1) the efficiency of the current in pumping dense water to the head as demonstrated by the collapse of the scalar profiles in the underflow, and 2) the stream-wise gradient in the ambient water density along the length of the MB resulting from mixing. The ambient water in a small volume receiving body such as the MB can become tainted by intruding density currents leading to an increase in the excess fractional density toward the head. However, many density currents issuing into large, uniform ambient environments show a decrease in the excess density towards the head of the current because of entrainment and mixing (e.g. Fernandez and Imberger, 2006).

The low density ratios computed for this underflow (i.e. R_ρ<0.1) reveal that the density differences are mainly due to salinity rather than temperature. The saline contribution to the density is between 10 and 250 times the thermal contribution. Temperature only minimally affects the density change because the temperatures in the upper and lower layers straddle the 4 °C density maximum for pure water (slightly lower for the brackish water in the MB) leading to only small density differences because of temperature (e.g. station 6). The temperature profiles at stations 5 and 6 were unstably stratified (identified by a negative thermal contribution to the density change in the computation of the density ratio) and salt acted to stabilize the density profile (Bombardelli and García (2001) observed similar scalar profiles). This result indicates that double diffusive mixing processes often observed in the ocean may be important in the Chicago River system (Turner, 1973, Parsons and García, 2000).

Finally, analysis of five grab samples collected between 09:30 and 10:20 on December 19, 2005, using a Niskin bottle in both the underflow and the ambient upper layer reveal higher chloride concentrations at station 1 (430 mg/l) and in the underflow at station 7 (284 mg/l) and lower concentrations in the upper layer water at station 7 (147 mg/l). Station 8 on the shore of Lake Michigan had a chloride concentration of 15 mg/l. Cation analysis was not performed because of limited sample size. Recall that synoptic measurements were made at station 7 prior to the underflow reaching an equilibrium state. Following the synoptic measurements, the temperature of the underflow at station 7 increased through the day to eventually match the temperature of the NB water (Fig. 2a). These temperature observations combined with the collapse of the temperature and salinity profiles within the underflow at all other stations (Fig. 3) indicates that the near-bed chloride concentration at station 7 may have increased through the day to match the NB chloride concentration (430 mg/l). Chloride concentrations in the observed underflow were about a factor of 1.9 (and perhaps up to a factor of 3) higher than upper layer concentrations. The potential sources of salt and the implications of the vertical chloride gradient for routine sampling procedures are discussed further in Section 4 of this paper.

3.2. *Characterization of an overflow event: January 11, 2006*

Simultaneous water-quality and velocity profiles captured an overflow event in the Chicago River on January 11, 2006. The velocity time series from the uplooking ADCP is compared with the synoptic velocity profile at station 7 in Fig. 4b. Water temperatures in the NB and MB during the sampling period are shown in Fig. 4a. In contrast to the December 19, 2005, underflow event (previous section), the bidirectional flow on this day was primarily upstream flow (to the lake) at the surface and downstream flow near the bottom. The early part of the record shows an intrusion with weak upstream velocities of about 1 cm/s near mid-depth bounded by downstream flows near the top and bottom. The low-flow profile during this period was captured well by the uplooking ADCP, but the tethered boat failed to resolve the intrusion. This result highlights the benefits of a bottom-mounted uplooking ADCP for low and variable flow situations. By midday, the flow transitioned to a 3.5 m thick overflow that gradually increased in strength before peaking at about 14:00. Winds varied in speed from 9 to 15 mph (14.5 to 24.1 km/h) throughout the day with southwesterly winds in the morning followed by southerly winds in the afternoon. While winds may have triggered the upstream surface flows early in the day, the relatively strong overflow late in the day is inconsistent with wind forcing. Winds of a similar speed and direction were observed on December 19, 2005, and January 24, 2006, and no sustained overflow events occurred in those records. Air temperatures

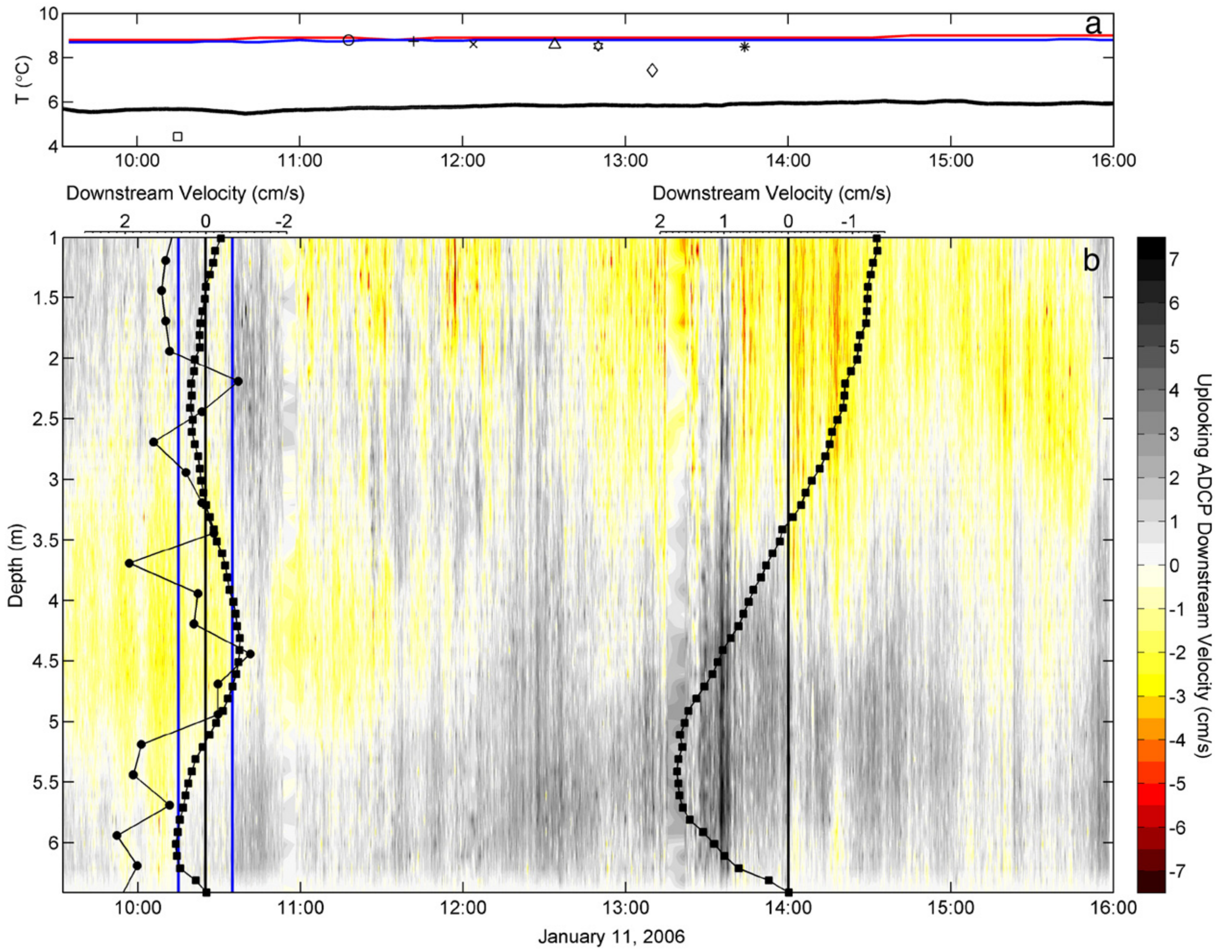

Fig. 4 – January 11, 2006, overflow event. (a) Water temperature in the NB at station 1 (blue line, near surface; red line, near bed) and MB at station 7 (black line, near bed). Near surface-water temperatures are also shown for various stations (symbols given in Table 1). (b) Contour plot of downstream water velocity (in cm/s) recorded by the uplooking ADCP at station 7 for an overflow event. The downstream direction is away from the lake (west). Simultaneous mean downstream water-velocity profiles recorded at station 7 by both the uplooking ADCP (squares) and the tethered ADCP (circles) are overlaid. Uplooking ADCP profiles averaged over two periods (from 9:32 to 12:00, left; from 12:00 to 16:00, right). Vertical blue lines show the time limits of the synoptic YSI measurements at station 7 (which encompass the tethered tethered-boat velocity profiles).

remained about 4 °C throughout the sampling period. No ice was present in the Chicago River system at the time of the measurements.

The scalar profiles measured during the overflow event showed similar trends to those measured during the December 19, 2005, underflow event, in spite of opposite directions of the currents. Profiles of temperature, salinity, density and velocity are shown at various locations along the NB, MB, and SB of the Chicago River in Fig. 5. Similar to the underflow event, the water in the NB was warmer than the water in the MB for the overflow. A temperature drop from the NB to the MB seems to be a common occurrence in the Chicago River system (García et al., 2007). The temperature change between these two reaches was comparable to that during the December 19, 2005, underflow (4 to 5 °C); however, the water temperatures were above the 4 °C density maximum allowing the temperature difference to control more of the density change. With the exception of the bottom water at station 7, the salinity also generally decreased moving from the NB to the MB. This, too, is similar to the observed underflow event; however, the change in salinity along the river was only about 20% of that during the December 19, 2005 underflow event. At station 7, the deep water was relatively saline (compared to the rest of the Chicago River system); a likely result of the lateral trapping of lower quality, dense water from previous underflow events and local runoff. Water-quality measurements by the Metropolitan Water Reclamation District of Greater Chicago near the lock (Fig. 1, Map A, WQ74) show a gradual increase in the chloride concentrations in the MB throughout the winter (see Section 4, Fig. 7) indicating trapping of dense water and insufficient flushing by Lake Michigan water during winter.

In contrast to the December 19, 2005 underflow event, the density profiles for this overflow event reveal a density increase from the NB to the MB. The density was lower in the NB despite the fact that water in the NB had a higher salinity because temperature controlled the density stratification (noted by a density ratio above unity, see Table 2B). As the overflow reached the MB, the trapped dense water in the MB was replaced by less dense NB water resulting in partial flushing of the MB. The scalar

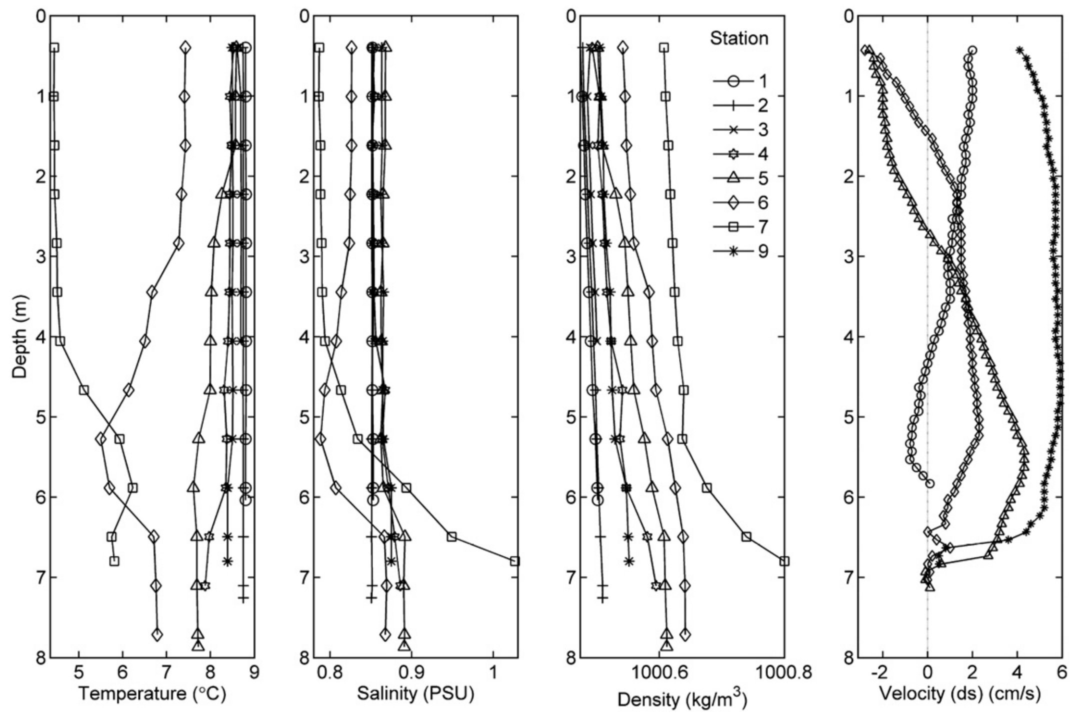

Fig. 5 – Water-quality and velocity profiles at stations along the Main Branch, North Branch, and South Branch of the Chicago River during the January 11, 2006 overflow event. Station locations are given in Fig. 1, Map A. Velocity is given with the downstream (ds) component taken as positive. The sampling period for the velocity measurements at stations 1, 5 and 6 were 10.05 min (974 ensembles), 13.26 min (1251 ensembles), and 11.02 min (1040 ensembles), respectively.

profiles do not collapse in the upper overflow layer indicating that there was appreciable entrainment and mixing along the overflow acting to dilute the current along its stream-wise axis (in contrast to the underflow on December 19, 2005, which showed little dilution). However, such an observation could also result from the unsteadiness of the current over the period of the synoptic measurements (see Fig. 4).

The synoptic velocity profiles in the MB (stations 5 and 6) show an overflow toward the lake with interfacial depths of about 1.4 m and 2.4 m, respectively, whereas the mean overflow thickness at station 7 based on the uplooking ADCP data was about 3.5 m (Fig. 4b). The variability in the thickness of the overflow along the MB is attributed to the unsteadiness of the current over the sampling period. The synoptic velocity profile at station 7 (Fig. 4b) had numerous flow reversals with layer depths of about 0.5 to 1.5 m possibly indicating interleaving (the temperature profile at station 7 was unstable indicating potential double diffusive processes). Interleaving is the dovetailing of two water masses along a front separating the masses creating an alternating series of intrusions of one mass into the other. Whereas the tethered-boat profile at station 7 was ultimately inconclusive because of the low velocities and poor vertical resolution, the uplooking ADCP data show alternating layers of upstream and downstream flow consistent with interleaving (Fig. 4b). Mean layer thicknesses were from 1 to 1.5 m, slightly larger than those seen in the synoptic measurements. The resolution of the density profile is far too low to verify the existence of steps in the profile consistent with these layers.

Finally, data from station 1 indicate an underflow in the NB progressing upstream during the overflow event in the MB. Just as the plunging point in the underflow draws MB water along the surface upstream in the NB, the “rising point” for the overflow has similar tendencies. In this case, relatively dense water may have been drawn upstream along the bottom of the NB by the entrainment associated with the detachment and rising of the overflow. The density signature of this underflow is virtually undetectable compared to the stronger events in the MB, perhaps because of the enhanced mixing along the bottom boundary combined with the relatively weak excess density. The density ratio at station 1 was very low (Table 2B) indicating that the excess density of the underflow at this station was primarily due to salt. No bidirectional flows were observed downstream from the confluence at station 9 (Fig. 5).

Characterization of the overflow event reveals a much weaker, more diluted density current compared to the December 19, 2005, underflow event (Table 2). The excess fractional density was an order of magnitude smaller than the observed underflow event. The small and decreasing Richardson number (increasing Froude number) along the current indicates greater entrainment and mixing; thus, supporting the previous observation of a less homogeneous current in terms of water properties. Station 6 appeared to be close to the head of the overflow as the Richardson number and Froude numbers approached unity and the current was relatively thin (and nonexistent at station 7 for the time of the profiling).

The density ratios observed in the MB for the overflow event reveal that temperature controlled the density stratification at station 5 and temperature and salinity equally contributed to the density stratification at station 6. At station 7 (not shown in Table 2B) the high salinity water near the bed controlled the density stratification and temperature was unstably stratified. This stream-wise variation in density ratio (temperature controlled density stratification in the MB near the confluence and salinity controlled the stratification near the lock) likely arose from the trapping of dense, saline water in the MB during previous underflow events. The water near the confluence was flushed relatively easily compared to the water near the lock (2.5 km away from the confluence) resulting in a gradual increase in salinity along the MB.

3.3. *Transition from an underflow to an overflow: from January 23, 2006, to January 27, 2006*

The December 19, 2005, and January 11, 2006, events described above document a variable and fluctuating density in the NB of the Chicago River. As “slugs” of dense water are transported down the NB to the SB of the Chicago River, the MB acts as a lateral trap for the dense water. These slugs of dense water may be well defined or diffuse with a long leading edge and trailing tail in response to mixing and shear dispersion upstream. Under the right conditions, a well-defined slug will lead to a sharp transition between an underflow and an overflow as seen in Fig. 3 of García et al. (2007), whereas a diffuse slug will form a well-defined intrusion in the transition from an underflow to an overflow (García et al., 2007, Fig. 8).

Based on past water-velocity data, intrusions often mark the transition from an underflow event to an overflow event in the Chicago River. The transition of an underflow to an overflow for the period from January 23, 2006, to January 27, 2006, captured by the uplooking ADCP at station 7 is shown in Fig. 6. One possible explanation for this 3.5-day transition is a gradual decrease in the density of the NB water and the gradual increase in the density of the MB water through mixing. We hypothesize that at the point when the underflow detached from the bottom (about 00:00 on January 25, 2006), the density of the NB water reached a density equal to that of the MB bottom water. Further decreases in the density of the NB water led to the subsequent propagation of an intrusion into the MB at the level of neutral density (the density at which the intrusion is neither positively or negatively buoyant). The level of neutral density decreased in depth as the water in the NB continued to decrease in density until the point at which the NB water was lighter (less dense) than the MB water and an overflow formed. Moreover, the horizontal gradients in density

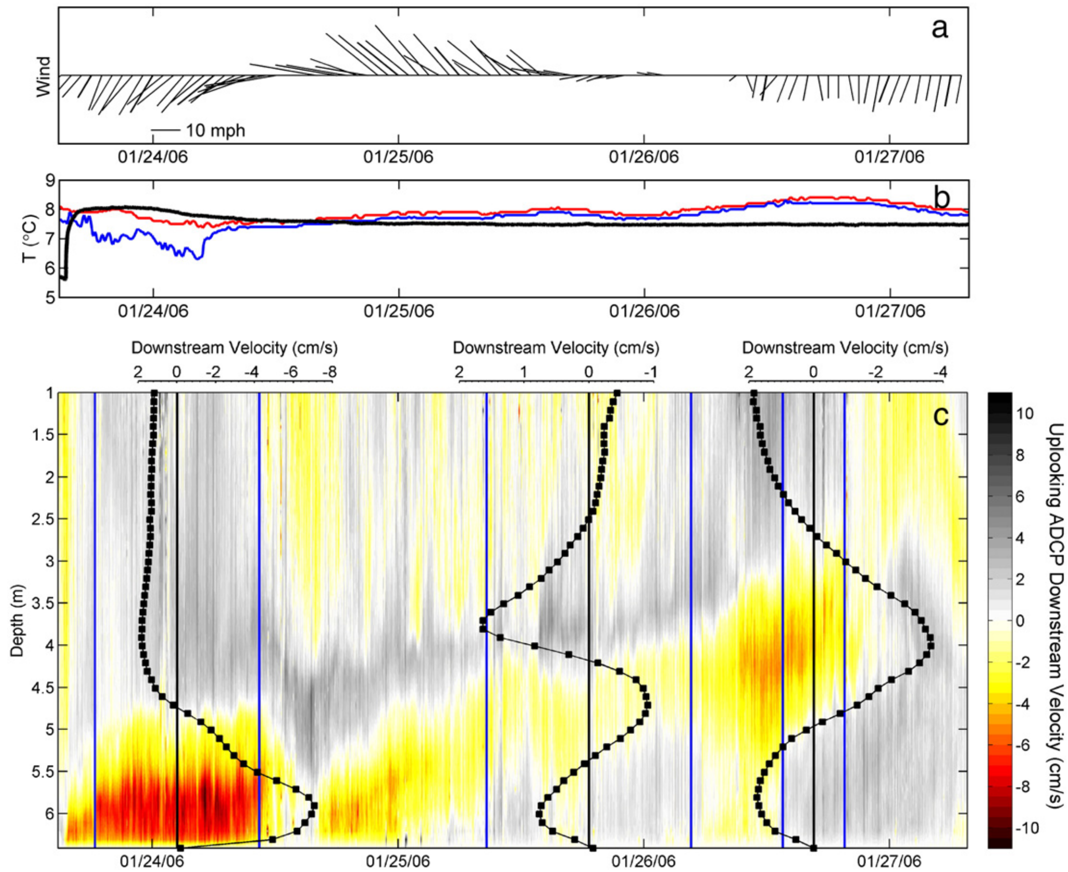

Fig. 6 – Transition from an underflow event to an overflow event on January 23–27, 2006. (a) Stick plot of surface wind observed at O'Hare International Airport (sticks point into the wind, north is to the top). (b) Water temperature in the NB at station 1 (blue line, near surface; red line, near bed) and MB at station 7 (black line, near bed). (c) Contour plot of downstream water velocity (in cm/s) recorded by the uplooking ADCP at station 7 for a transition event. The downstream direction is away from the lake (west). Mean downstream water-velocity profiles recorded at station 7 by the uplooking ADCP (squares) are overlaid. Vertical blue lines show the time limits for each of the averaging periods.

throughout the MB (Figs. 3 and 5) likely caused the current to continually adjust its position in the water column as it traveled along the MB and searched for the level of neutral density.

At the present time, there is insufficient instrumentation and a lack of data to verify the transition behavior as theorized above. No concurrent time series of the velocity in the MB and density stratification in the NB exist. However, the two events described in this paper capture the two states of the Chicago River system—an underflow ($\rho_{NB} > \rho_{MB}$) and an overflow ($\rho_{NB} < \rho_{MB}$). Based on this evidence, there must be a state at which the NB water has a density equal to that at mid-depths in the stratified MB. At this point an intrusion would form and propagate in the MB along the neutral density surface. The duration of the intrusion is dependent on the strength of the stratification in the MB and the time rate of change of density in the NB.

García et al. (2007) hypothesized that wind has an effect on the thickness of an underflow. The eastward surface flow in the middle of the velocity record illustrated in Fig. 6 appears to be a result of westerly winds at sustained speeds of 15–25 mph (Fig. 6a). While it may be fortuitous, the underflow ceases as the winds shift from southerly to westerly and proceeds again when the winds shift to the northwest. Wind can generate turbulence that is capable of enhancing the mixing and entrainment at the density current interface (Kranenburg, 1985). The eastern surface flows penetrated down to a depth of 4 m, thinning the current and apparently disabling the underflow (Fig. 6). As the wind-induced flow at the surface varied, the current appears to have responded. Periodic reattachment of the intrusion to the bottom after the initial separation appears to be correlated with the relaxing of the wind-driven eastward (upstream) surface currents. The response of the system to wind forcing indicates that seiching may be an important factor in the dynamics of density currents in this partially closed system (partially closed by the lock at Lake Michigan), although the velocity profiles are inconsistent with purely wind-driven currents (Bombardelli and García, 2001). More simultaneous observations of wind conditions in the presence of bidirectional flows are needed to assess the effect of wind on bidirectional flows, including its effect on mixing in the Chicago River.

4. Discussion

Synoptic measurements revealed that salinity has the greatest effect on density current formation in the Chicago River. Because salinity appears to play a vital role in the development of underflow and overflow events, determining the source of this saline water in the NB of the Chicago River is now a primary goal.

The most probable ways in which salt can be introduced to the NB is through 1) direct runoff of deicing salts, 2) effluent from wastewater-treatment plants, and 3) industrial discharge. Naturally occurring salt loading such as weathering of chloride-rich rocks is unlikely in this area of the country. Repeated measurements by MWRDGC show that the highest chloride concentrations are present in the NB upstream from the North Shore channel (i.e. upstream from any lake diversions) in winter and the lowest concentrations are observed in summer (Fig. 7). Natural weathering and routine municipal and industrial effluent would produce a less variable load throughout the year. The seasonal variability in the chloride concentration is consistent with direct runoff of deicing salts to surface water and combined sewer systems (Kaushal et al., 2005). Chloride concentrations in the MB of the Chicago River increase over the winter when lockages and diversions are at a minimum (Fig. 7). Lock exchanges and discretionary diversion flush the MB causing chloride concentrations to rapidly decrease when lock exchanges become more frequent in early spring. In contrast, reaches upstream from lake diversions can have chloride concentrations near or above the U.S. Environmental Protection Agency's 2006 recommended chronic chloride criterion (230 mg/l, USEPA, 2006) even in summer (Fig. 7).

More than 140,000 tons of deicing salts (primarily NaCl) are applied to the six-county area making up greater Chicago in a given year (Friederici, 2004). Of that salt, about 55% is transported to surface water by runoff and the remainder is left to infiltrate the soil and groundwater (Church and Friesz, 1993). In areas like Chicago that are served by combined sewers, much of the runoff and associated deicing salts are collected and contained in the effluent from the water-reclamation plants. Weekly and monthly water-quality measurements by the MWRDGC in the North Shore Channel at the outfall of the North Side Water Reclamation Plant (WQ1) and upstream from the outfall (WQ102) show high chloride concentrations in winter at both sites (Figs. 1 and 7). The winter chloride concentrations upstream from the plant generally equaled (or on one occasion exceeded) the outfall concentrations indicating significant chloride contamination upstream from the plant (Fig. 7), perhaps a result of direct runoff of deicing salts or density currents propagating upstream from the outfall. The chloride concentration dropped significantly in summer upstream from the plant to levels consistent with concentrations in Lake Michigan water (about 15 mg/l). The flushing of the North Shore Channel during summer months is consistent with increased discharge at the lake front because of discretionary diversion of Lake Michigan water by the Wilmette Pumping Station (Duncker et al., 2006).

In the NB and its tributaries, impairment is caused, in part, by high total dissolved solids and/or chlorides (Fig. 8, Illinois Environmental Protection Agency, 2004). One of the primary sources of impairment is urban runoff/storm sewers (Illinois Environmental Protection Agency, 2004). Other sources include municipal point sources and combined sewer overflows. Along with other pollutants and chemicals, deicing salts are directly entering the NB and its tributaries via urban runoff and combined sewage effluent. The low winter discharge allows chloride to accumulate in the upstream tributaries (Fig. 7). During periods of increased flow, such as precipitation periods and snowmelts, chloride-rich water can be flushed downstream creating a density anomaly (Marsalek, 2003). Evidence of insufficient flushing can be seen in Fig. 7 during the summer of 2005 when chloride concentrations in the upstream reaches of the NB remained excessively high (well above the U.S. Environmental Protection Agency's 2006 chronic chloride recommendation of 230 mg/l). Spring through fall of 2005 was the driest on record for the Chicago area and this followed the 8th wettest January on record where significant snowfall likely increased salt use.

Based on the above evidence, the authors hypothesize that the main source of the high chloride (saline) water in the NB may be the direct runoff of deicing salts to upstream reaches (primarily the Skokie River, the West Fork of the North Branch,

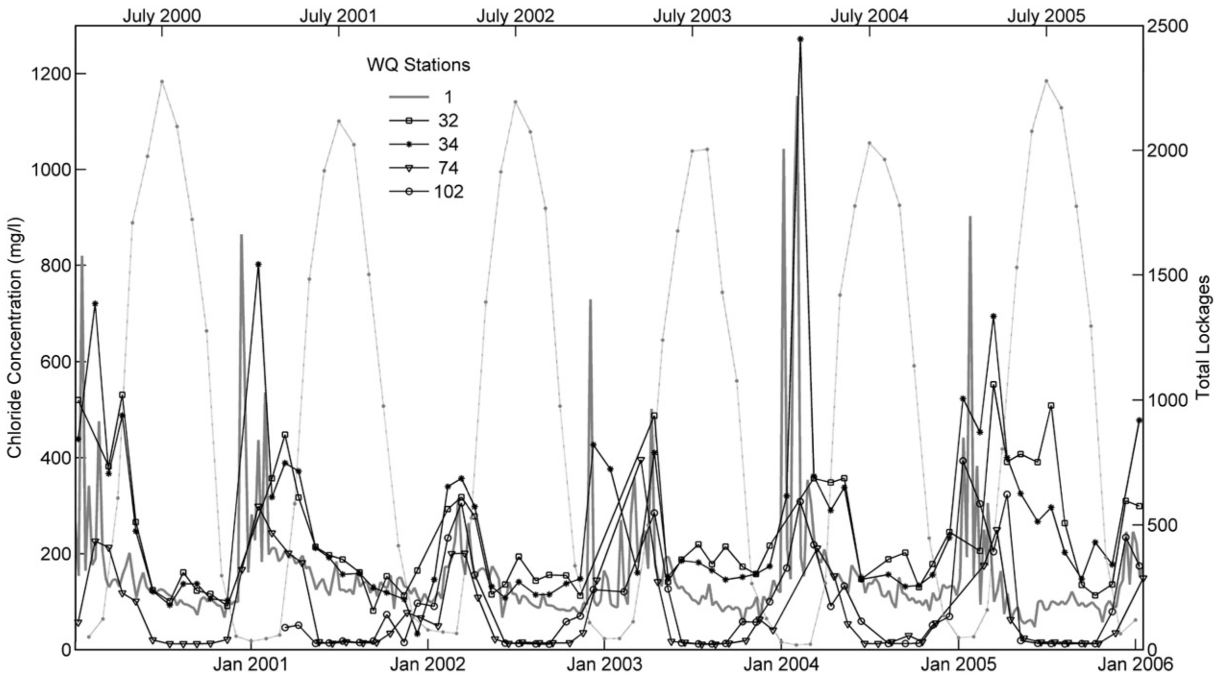

Fig. 7 – Total chloride concentrations measured in the Chicago River system (left axis) and total lockages at the Chicago Harbor Lock (right axis, grey line, dot markers) for the period 2000 to 2006. Water-quality monitoring station locations are given in Fig. 1. Data provided by the MWRDGC and the U.S. Army Corps of Engineers.

and the Middle Fork of the North Branch) and chloride-rich effluent from the North Side Water Treatment Plant in the North Shore Channel. Numerous impoundments of water are present along the northern reaches of the watershed and may act as salt storage reservoirs during the winter (Marsalek, 2003). Underflow events that have been observed before the first snowfall of the year (before deicing begins) (García et al., 2007) may be due to releases of chloride-rich water during precipitation periods. Evidence of this chloride storage is seen in Fig. 7 as NB chloride concentrations are between 4 and 16 times greater than those concentrations in the MB during summer months. Whereas the reaches upstream from the North Shore Channel have some of the highest chloride concentrations in the system, the North Shore Channel appears to have a significant contribution to the total chloride load in the NB because of its high concentrations and discharge. Analysis of the weekly and monthly water-quality measurements can lend insight into the sources of chloride-rich water, yet one must use caution when comparing the results to formation of density currents that have a time scale on the order of days. To truly determine the primary sources of the saline water, daily water-quality samples are needed in conjunction with discharge estimates.

Sharp gradients in salinity that accompany the density currents in the MB and confirmation that the currents are composed of NB water raises concerns about water-quality assessments of the Chicago River. Water-quality samples in the Chicago River are currently collected just below the surface and are used by the U.S. Environmental Protection Agency for water-quality assessments. Because there are higher water-quality standards for the MB than the NB and SB (primary as opposed to secondary contact), it is important that the water-quality assessment be accurate. However, these results indicate that samples taken at the surface do not accurately represent the water quality within the stratified MB because of the intrusion of density currents. Conductivity and chloride measurements presented above show that underflows can have concentrations that exceed surface water by a factor of 3 (and perhaps greater) and other constituents would likely have a similar vertical distribution. Whereas surface water may meet recommended water-quality standards, near near-bed water may significantly exceed these standards leading to underestimation of the impairment of the Chicago River. While the impacts of these currents on aquatic life are currently unknown, concentrations of chloride-rich water at and near the river bottom will likely have the greatest effect on benthic species. Inland urban waterways in northern communities that apply road salt for deicing may need to modify their sampling procedures to include deep, near-bed water samples and vertical parameter profiles to accurately assess the water quality.

More work needs to be done to evaluate the mechanisms triggering initiation of density currents in the Chicago River system. While it is clear that density plays the primary role in driving these currents, wind and air temperature may be important in initiating, and perhaps opposing, the currents. Climate data indicate that neither wind nor air temperature can be solely responsible for driving all the observed currents, although more localized observations are needed. A significant amount of data has yet to be analyzed and these data, when combined with meteorological data, may provide answers to the remaining questions concerning the effect of atmospheric forcing in density current formation. In addition, a better understanding of the mixing and exchange of waters between the NB and the MB

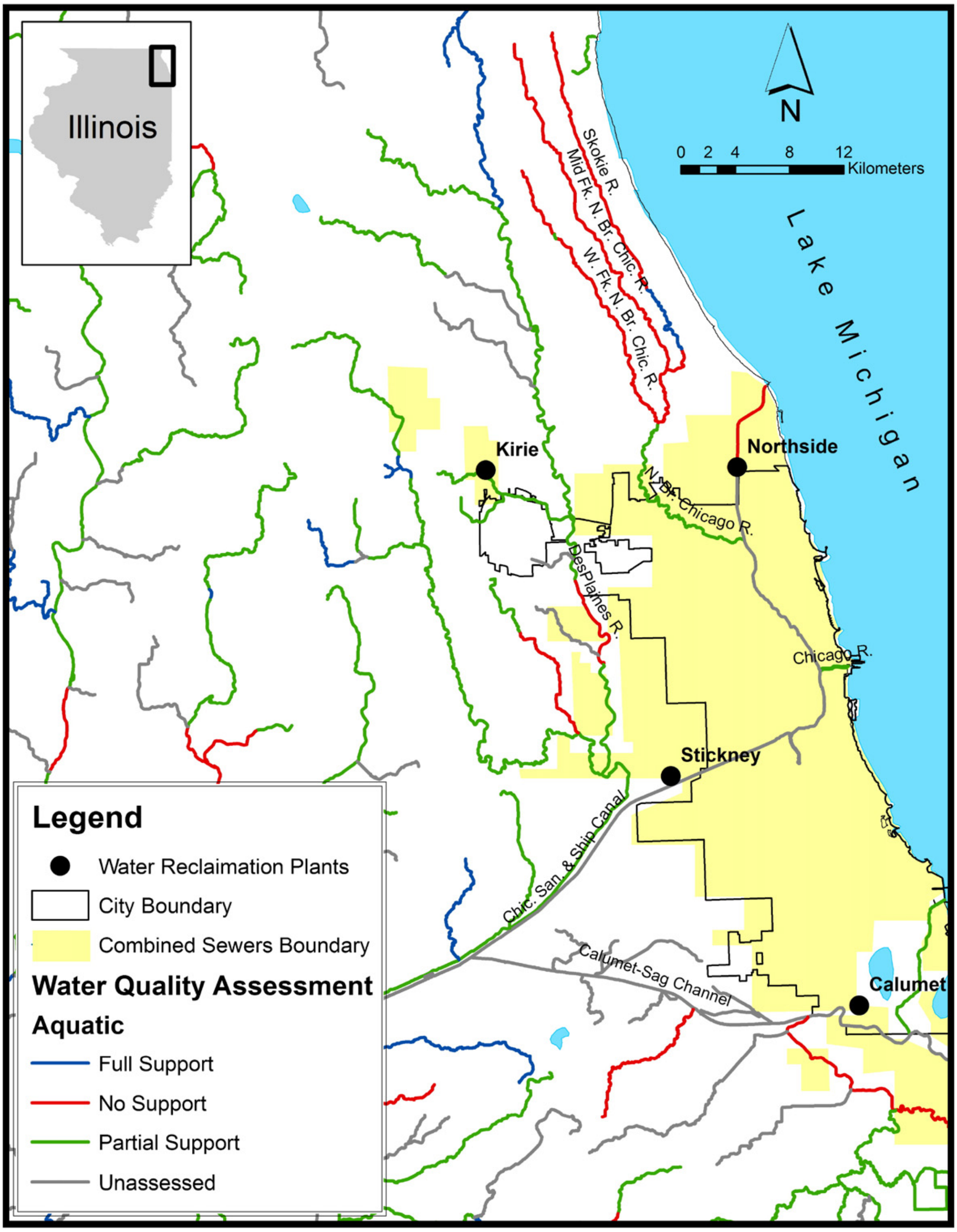

Fig. 8 – The Illinois Environmental Protection Agency's steam water-quality assessment (Illinois Environmental Protection Agency 2004). Water-quality assessment shows the support levels for aquatic life. The yellow areas show the approximate extent of combined sewers served by the Metropolitan Water Reclamation District of Greater Chicago (digitized from an MWRDGC publication).

could be determined from a tracer or dye release study combined with high spatial and temporal resolution water-quality and velocity profiles. Tagging the NB water with dye prior to plunging and tracking the dye as it moves through the system would be a useful tool to understand and quantify mixing, exchange and retention in this system. Placement of thermistor and conductivity strings in the NB and MB of the Chicago River would provide much needed information about the temporal variability and evolution of the density in these branches and would aide in assessing the role of seiching in the generation of bidirectional flows. Finally, a continuation of the modeling effort started by Bombardelli and García (2001) using recent observations and data sets to initialize and force the system would complement the field observations and provide a means to analyze the sensitivity of the Chicago River system to atmospheric forcing, boundary conditions, internal hydraulics, and lockages.

5. Conclusions

Bidirectional flows in the Chicago River are a result of density currents driven by differences in water density primarily attributed to salinity. Synoptic measurements of hydrography and water velocity revealed the occurrence of both underflows and overflows in this branched, urban channel. The source of the salinity in this freshwater system is likely road-salt contamination of upstream reaches. The road salt appears to be entering the system as direct runoff and through effluent from a large water-reclamation plant that treats combined sewage. These density-driven currents have an effect on water quality within the Chicago River as lower quality water, composed of 75% treated effluent, flows into the MB and to the lock at Lake Michigan. Current water-quality monitoring programs that sample only the top layer of water do not account for these stratified flow events and can underestimate the impairment of the Chicago River system. Water-quality sampling procedures in urban, freshwater streams and rivers in areas in which road-salt application occurs should include bottom water samples or parameter profiles in routine monitoring procedures.

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