MEASUREMENTS OF LEAKAGE FROM LAKE MICHIGAN THROUGH THREE CONTROL STRUCTURES NEAR CHICAGO, ILLINOIS, APRIL–OCTOBER 1993

by K.A. Oberg *and* A.R. Schmidt

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CONTENTS

FIGURES

CONTENTS

TABLES

CONVERSION FACTORS AND VERTICAL DATUM

Multiply	By	To obtain
inch (in.)	25.4	millimeter
mile (mi)	1.609	kilometer
foot (ft)	0.3048	meter
square foot (ft^2)	0.09290	square meter
foot per second (ft/s)	0.3048	meter per second
cubic foot per second (ft^3/s)	0.02832	cubic meter per second
gallon per minute (gal/min)	0.06309	liter per second

Sea level: In this report, "sea level" refers to the National Geodetic Vertical Datum of 1929 (NGVD of 1929)—a geodetic datum derived from a general adjustment of the first-order nets of both the United States and Canada, formerly called Sea Level Datum of 1929.

Measurements of Leakage from Lake Michigan through Three Control Structures near Chicago, Illinois, April–October 1993

By K.A. Oberg *and* A.R. Schmidt

Abstract

Acoustic Doppler current profilers (ADCP's) and dye-dilution techniques were used to make 221 measurements of leakage at three control structures near Chicago, Ill. The three control structures are the Chicago River Controlling Works (CRCW), Thomas J. O'Brien Lock and Dam (O'Brien), and Wilmette Pumping Station (Wilmette). The CRCW consists of the Chicago Lock and two sets of sluice gates connected by a network of harbor walls. Lake Michigan water leaks through harbor walls, lock gates, and sluice gates at each of these control structures. The diversion of Lake Michigan water is regulated by U.S. Supreme Court decree, and the water leaking through each of these structures forms part of the diversion of Lake Michigan water by the State of Illinois.

Leakage measurements were made in April, May, July, September, and October 1993 by means of an ADCP. Dye-dilution measurements of leakage were made at the Chicago Lock in July 1993 to evaluate the discharges measured using the ADCP. The mean leakage measured by the ADCP for the Chicago Lock river gate was 133 ft^3/s (cubic feet per second); the standard deviation of the leakage measurements was 38 ft^3/s. The mean and standard deviation of the leakage measurements at CRCW were 192 and 73 ft^3/s, respectively. River-gate leakage accounted for more than half of the total leakage measured at CRCW. The mean and standard deviation of leakage measurements at O'Brien on September 17, 1993, were 21 and 10 ft^3/s, respectively. The mean leakage measured at Wilmette using the ADCP was 59 ft^3/s in April 1993; the standard deviation of the leakage measurements was 8 ft^3/s. After the pump bays at Wilmette were sealed in July 1993, the leakage decreased to less than 15 ft^3/s in September 1993.

Leakage through the river gate at the Chicago Lock was estimated by dye dilution on July 15, 1993. The discharge estimated by dye dilution was 160 ft^3/s; the standard deviation of the measurement was estimated to be 23 ft^3/s. The discharge estimated by dye dilution was within 12 ft^3/s, or 8 percent of the ADCP-measured discharge. Sensitivity analyses indicate that, for the leakages being measured, discharges are insensitive to the changes in the exponent of the power law for velocity distribution used to estimate the unmeasured flow near the channel bottom.

INTRODUCTION

Water has been diverted from Lake Michigan at Chicago into the Mississippi River Basin since the completion of the Illinois and Michigan Canal in 1848. At that time, the mean annual discharge of the diversion was about 500 ft^3/s. After construction of the Chicago Sanitary and Ship Canal (CSSC) was completed on January 17, 1900, the flow of the Chicago River was reversed and allowed to discharge into the Des Plaines and Illinois Rivers (Naujoks, 1946). On

December 5, 1901, the Secretary of War granted the State of Illinois a permit allowing a diversion of 4,167 ft^3/s through the CSSC. In October 1913, the United States filed a bill before the U.S. Supreme Court enjoining the State of Illinois from diverting more than 4,167 ft^3/s. In the ensuing years, however, the actual diversion increased, reaching a maximum of about 10,000 ft^3/s. In 1930, the U.S. Supreme Court entered a decree against the State of Illinois requiring that the diversion be reduced from a permitted 8,500 ft^3/s to 5,000 ft^3/s plus domestic pumpage by December 31, 1935, and 1,500 ft^3/s plus domestic pumpage by December 31, 1938 (Naujoks, 1946). The most recent U.S. Supreme Court decree (December 1, 1980) limits the diversion to a 40-year average of 3,200 ft^3/s. In addition, during the first 39 years, the cumulative algebraic sum of the average annual diversions minus 3,200 ft^3/s cannot exceed 2,000 ft^3/s.

The U.S. Army Corps of Engineers, Chicago District (Corps) has been charged with accounting for the amount of Lake Michigan water diverted each year by the State of Illinois. The acoustic velocity meter (AVM) on the CSSC at Romeoville, Ill. (fig. 1), is a key part of the Lake Michigan diversion-accounting procedure. Approximately 95 percent of the total diversion (including leakage) is measured at the Romeoville AVM. The U.S. Geological Survey (USGS) operates and maintains the AVM by agreement with the Corps. Prior to the installation of the AVM in 1984, the Lake Michigan diversion was measured at the Lockport Powerhouse at Lockport, Ill. Discharges were estimated by the Metropolitan Water Reclamation District of Greater Chicago (MWRD) using ratings for powerhouse turbines, powerhouse sluice gates, number of lockages, and controlling works sluice gates (located about 1 mi upstream from the powerhouse).

The Lake Michigan diversion consists of three components: direct diversion through three lakefront control structures, domestic pumpage from Lake Michigan for water supply and not returned to Lake Michigan, and stormwater runoff from the Lake Michigan watershed diverted from the lake. The direct diversion consists of four components: lockage, discretionary flow, navigation makeup flow, and leakage. Lockage is the amount of water used to lock vessels to and from Lake Michigan. Discretionary flows are used primarily for water-quality improvement in the Chicago River and CSSC. Occasionally, the water level in the Chicago River and CSSC is lowered in anticipation of a storm by increasing the discharge through the Lockport Powerhouse and Controlling Works. After the storm has passed, the sluice gates may be used to raise the water level in the Chicago River and CSSC. This component of the Lake Michigan diversion is referred to as navigation makeup. Leakage is that amount of water that leaks through or around the three control structures in an uncontrolled manner. The measurements described in this report were made to quantify this latter component of the diversion.

Recently, the Corps found that the State of Illinois has exceeded the 3,200 ft^3/s limit for each of the 1986-89 water years (U.S. Army Corps of Engineers, 1993, p. 18). (A water year is the 12-month period, October 1 to September 30, and is designated by the calendar year in which it ends.) In addition, at the end of the 1989 water year, the cumulative algebraic sum of the average annual diversions minus 3,200 ft^3/s was 2,189 ft^3/s. As a part of the accounting scheme, the Corps computes water budgets at various points in the diversion system using measured and simulated streamflow data. A rainfall-runoff model is used to estimate unmeasured diversion flows. The water budgets are used as an indication of the accuracy of diversion accounting and also indicate unmeasured or unsimulated flows. The average imbalance for water years 1986-89 was 454 ft^3/s. The Corps concluded that the annual budget imbalances were primarily a result of leakage through the lakefront control structures (U.S. Army Corps of Engineers, 1993, p. 18).

The water-surface elevation (stage) of Lake Michigan at each of the three control structures is normally higher than the stage of the Chicago and Calumet Rivers. The stage difference varies throughout the year, but it is usually largest in July when Lake Michigan is highest, and smallest in February, when Lake Michigan is lowest. Because of the stage difference at each of the lakefront control structures, a potential for leakage of water from Lake Michigan into the CSSC exists. The potential for leakage is greatest at the Chicago River Controlling Works (CRCW), which consist of the Chicago Lock and two sets of sluice gates at the mouth of the Chicago River. In the past, leakage through the lock gates at the Chicago Lock has been significant, primarily because of inadequate or missing gate seals. More recently, the gates have not been closing

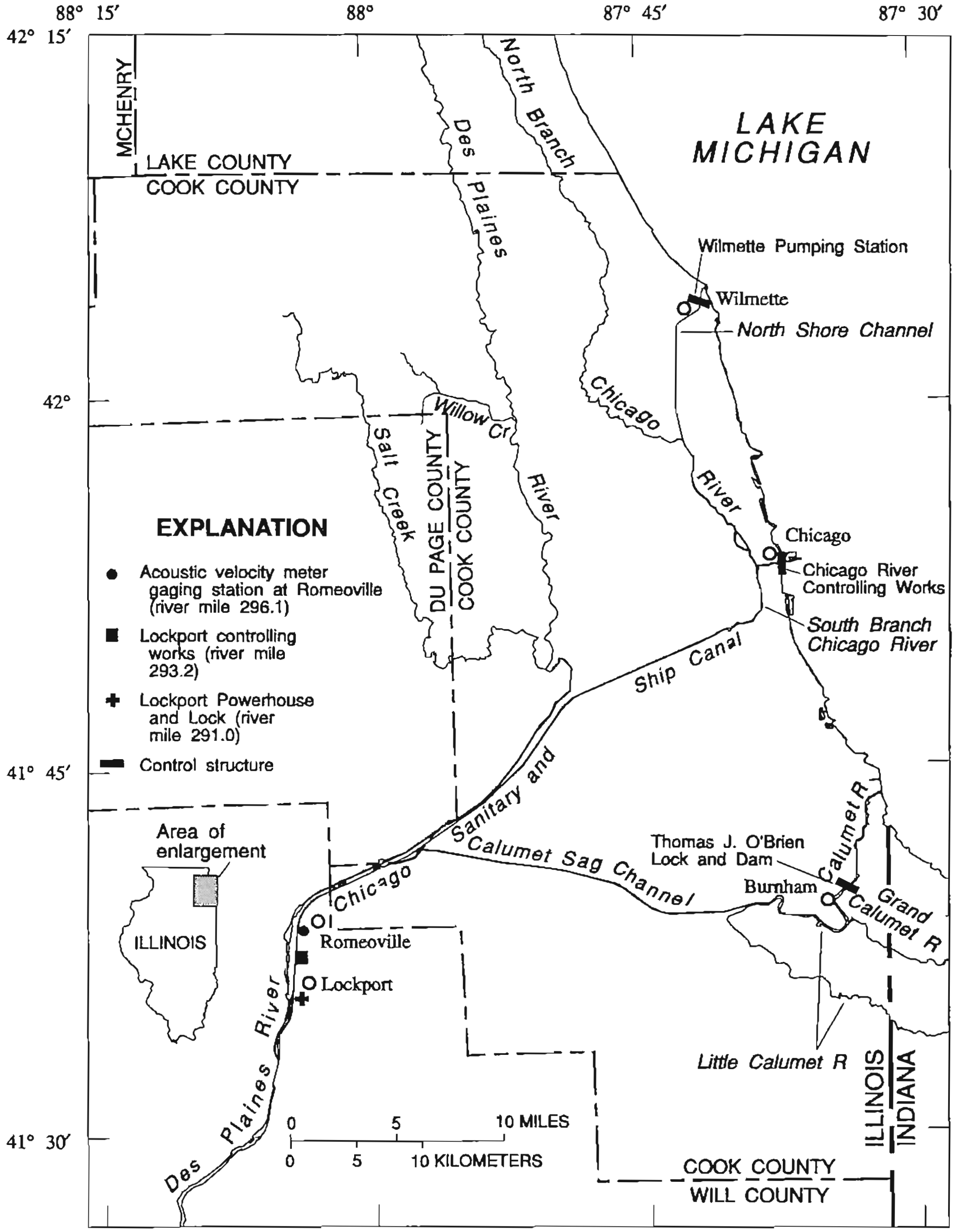


Figure 1. Location of study area and control structures near Chicago, Ill.

properly. The southeast (lake side) gate has been in especially poor condition. The opening between the two east gates, when closed as far as possible, has been as much as 24 in. The west gates (river side) were more water-tight than the east gates. The river gates normally control the amount of leakage because they are normally kept closed, except when opened to lower the water level in the lock chamber and when ships must pass through. Leakage at Thomas J. O'Brien Lock and Dam (O'Brien) and Wilmette Pumping Station (Wilmette) had been observed but was estimated to be less than that at CRCW.

Because of the apparent increase in leakage at the CRCW and water-budget imbalances, the USGS, in cooperation with the Corps, completed a set of leakage measurements at the lakefront control structures. Although 95 percent of the total diversion is measured at the Romeoville AVM, it was not possible to determine how much of the diversion was from leakage through the lakefront control structures. In April 1993, the USGS, in cooperation with the Corps, began a study to determine whether or not accurate measurements of leakage could be made and, if so, to make leakage measurements for a range of lake and river stages at each structure.

Purpose and Scope

The purpose of this report is to document the methods used to measure leakage through the CRCW, O'Brien, and Wilmette control structures and the results of measurement analysis. These three structures control the flow of water from Lake Michigan into the Chicago and Calumet Rivers.

This report presents results from leakage measurements made using two methods: use of an acoustic Doppler current profiler (ADCP) and dye dilution. Leakage measurements were made at each of the control structures from April to October 1993. Dye-dilution measurements were made in the Chicago Lock during May and July 1993 to verify the results of the ADCP measurements. A description of the three control structures and the measuring locations is provided along with the methods used to measure leakage. The accuracy of the leakage measurements also is evaluated, and the results of the two measurement methods are compared. The report also includes suggestions for future leakage measurements.

Previous Work

The Corps made discharge measurements near each of the three control structures during July 23-27, 1990. Results of these measurements are summarized in a report by the Corps (U.S. Army Corps of Engineers, 1990). The sluice gates at each control structure were open when the measurements were made; therefore, the discharges measured by the Corps included both sluice-gate flow and leakage. Measurements were made from bridges near each structure using conventional methods (a Price AA meter with cable suspension) (Rantz and others, 1982). The average discharge measured by the Corps was 830 ft^3/s at CRCW, 709 ft^3/s at O'Brien, and 225 ft^3/s at Wilmette. The Corps concluded that the July 1990 measurements may be inaccurate because point velocity measurements were occasionally less than 0.10 ft/s and it was difficult to detect the direction of flow. No other measurements of leakage at or near the control structures using conventional, ADCP, or dye-dilution methods have been documented.

Gordon (1989) and Simpson and Oltmann (1993) describe the use of ADCP's to measure streamflow. It is believed, however, that the measurements described in this report represent the first attempt at using an ADCP to measure leakage through a control structure.

Acknowledgments

The assistance of the following personnel from the Corps is acknowledged. David Moughton and David Kiel assisted in making the leakage measurements and coordinated the measurements with MWRD personnel. During the May and September measurements, Rich Pickett provided invaluable assistance in coordinating measurements at the Chicago Lock with the work crew making repairs to the Chicago Lock.

The employees of IRD, Inc., the company responsible for the operation of the Chicago Lock, assisted during measurements in and near the lock. The employees of IRD provided storage space in one of the buildings at the lock, warned boat traffic during leakage measurements, and occasionally loaned equipment. We especially acknowledge Scott Baseman, John Mammano, and Chris Boyer for their cheerful assistance provided at any time of the day or night.

Lockmaster Doyle Jennings and personnel at O'Brien are acknowledged for assisting USGS personnel during the leakage measurements at O'Brien and also for providing space for equipment storage. Jim Vey, of the MWRD, assisted by providing stage data collected during each of the measurements. MWRD dispatchers also assisted the USGS by making the required changes in gate settings at each of the three control structures.

DESCRIPTION OF CONTROL STRUCTURES

Leakage measurements were made near three different control structures: the CRCW (which includes the Chicago Lock), O'Brien, and Wilmette. A description of each of these structures is given below.

Chicago River Controlling Works

The CRCW consists of the Chicago Lock and two sets of sluice gates located in the harbor walls surrounding Chicago Harbor. The CRCW and Chicago Harbor are located just south of Navy Pier, close to the original mouth of the Chicago River (fig. 2).

The CRCW was built in 1938 as a part of the construction of the Chicago Sanitary and Ship Canal and the diversion of the Chicago River. The harbor walls were constructed of rock-filled timber cribs and, in places, the walls have metal sheet piling on one or both sides of the wall. During 1987, the tops of most harbor walls were raised and capped with concrete to reduce overtopping by waves in Lake Michigan. As a result of the original construction technique, the walls are porous. Figure 3 shows leakage through the harbor wall on the northeast side of CRCW.

The Chicago Lock is located at the far eastern end of the harbor walls, about 1,800 ft east from the Lake Shore Drive bridge (fig. 2). The lock (fig. 4) is 600 ft long and 80 ft wide and also was constructed using rock-filled timber cribs with sheet piling and a concrete facade extending below the water line. Triangle gates, located at either end of the lock, are used to seal the lock chamber. Water levels in the lock chamber are raised or lowered by gradually opening the triangle gates. The Corps is responsible for the operation and maintenance of the Chicago Lock.

Two sets of sluice gates were constructed in the harbor wall: one located near the lock and another on the south harbor wall (fig. 2). A transverse section of a typical sluice gate at CRCW is shown in figure 5. The elevation of the concrete sill at the base of both sets of sluice gates is -16.0 ft Chicago City Datum (562.48 ft above sea level). Each sluice gate at CRCW is 10.5 ft wide and 10.5 ft high. During the summer, the sluice gates along the south harbor wall are opened to allow Lake Michigan water to flow into the Chicago River and down the CSSC to improve water quality in the CSSC. The sluice gates near the lock are used only for flushing ice down the Chicago River, for flow reversals, and when the south gates are inoperable. During storms, when the water-surface elevation of the Chicago River exceeds the elevation of Lake Michigan, both sluice gates may be opened to allow flow from the Chicago River to discharge into Lake Michigan. However, the sluice gates are used only infrequently for this purpose. The MWRD is responsible for the operation and maintenance of the sluice gates.

Thomas J. O'Brien Lock and Dam

O'Brien is located at river mile 326.5 (miles above the mouth of the Illinois River) on the Calumet River (fig. 6), about 7 river miles south from Lake Michigan near Burnham, Ill. A plan view of O'Brien is shown in figure 7. O'Brien was constructed by the Corps in 1959 with techniques similar to those used at CRCW. The lock at O'Brien is 110 ft wide and 1,200 ft long and provides access from Lake Michigan to the Calumet Sag Channel, the CSSC, and the Illinois River. Streamflow is regulated at the dam by use of combinations of the four sluice gates. The sluice gates at O'Brien are 10 ft wide and 10 ft tall and are constructed similar to those at CRCW (fig. 5). The concrete sill of the sluice gates has an elevation of -13.00 ft Chicago City Datum. The sluice gates at O'Brien also have the same dual purpose as at CRCW. They are used during the summer to divert water to improve the water quality in the Calumet Sag Channel and the CSSC. The sluice gates are opened during periods of high runoff to allow water to flow toward Lake Michigan in order to minimize flood-water damage along the Calumet Sag Channel and its tributaries. The Corps of Engineers, Rock Island District, is responsible for the operation of the lock and dam.

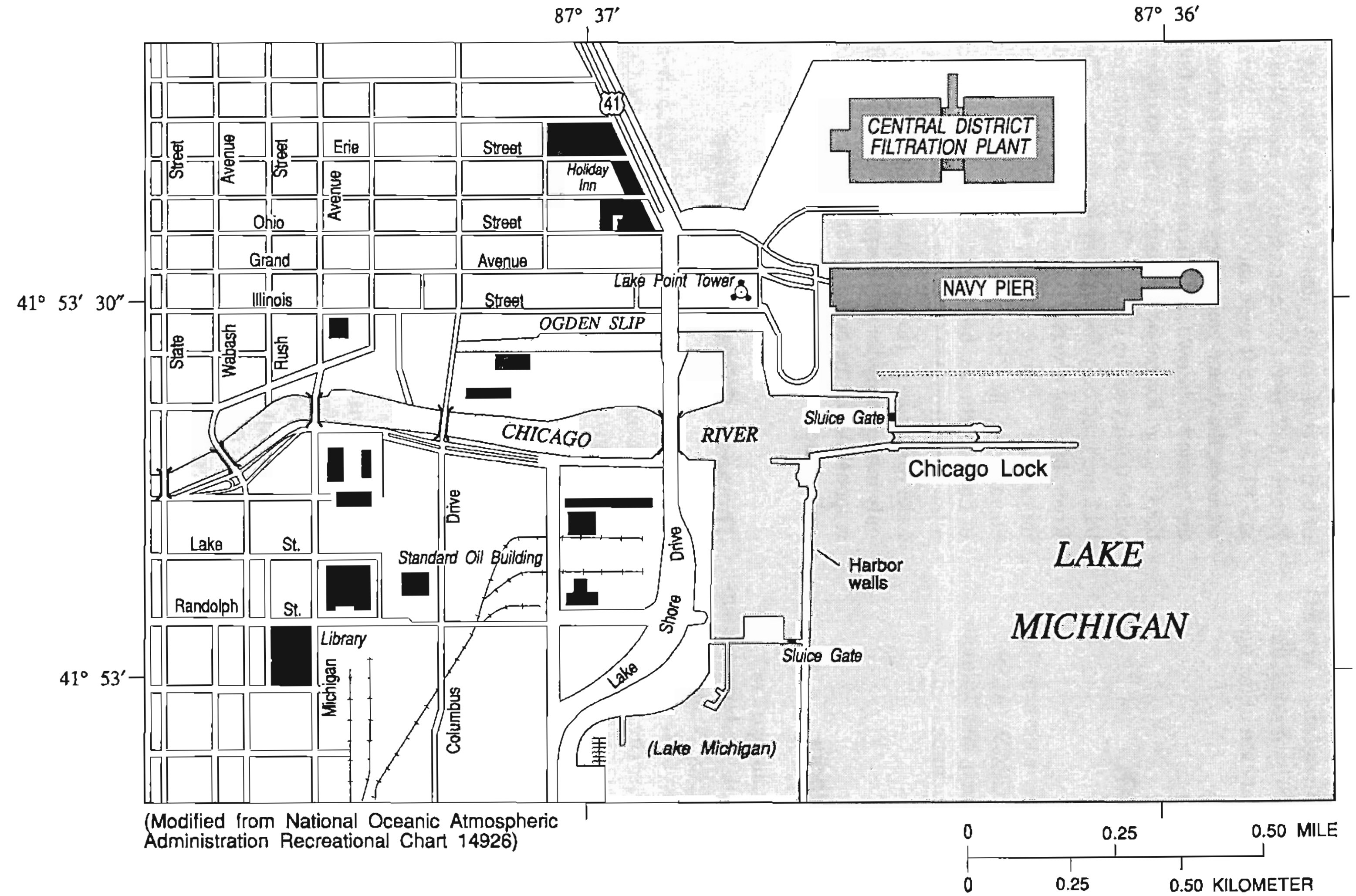


Figure 2. Location of the Chicago River Controlling Works, the Chicago Lock, and the Chicago River, Chicago, Ill.

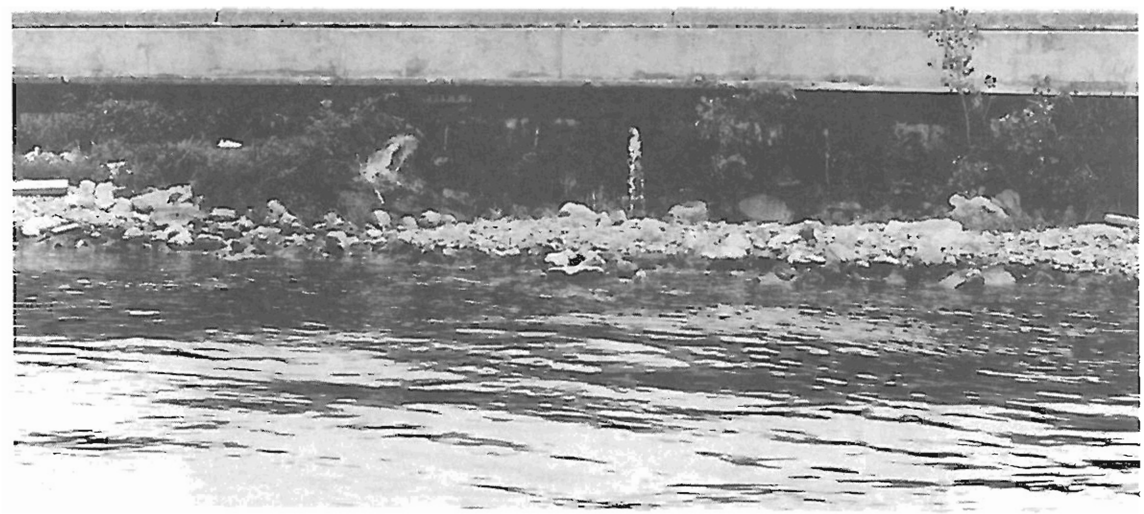


Figure 3. Leakage through southeast harbor wall at Chicago River Controlling Works, view looking east, July 10, 1993.

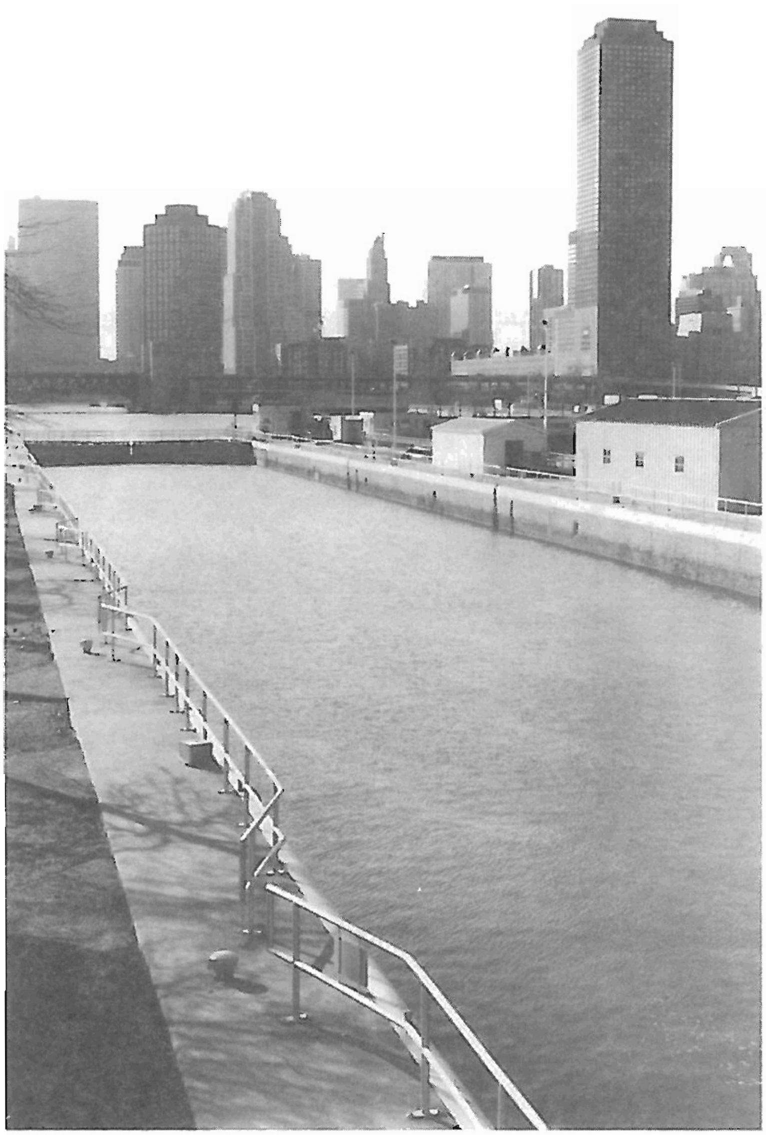


Figure 4. Chicago Lock, Chicago, Ill., looking east to west, September 1993.

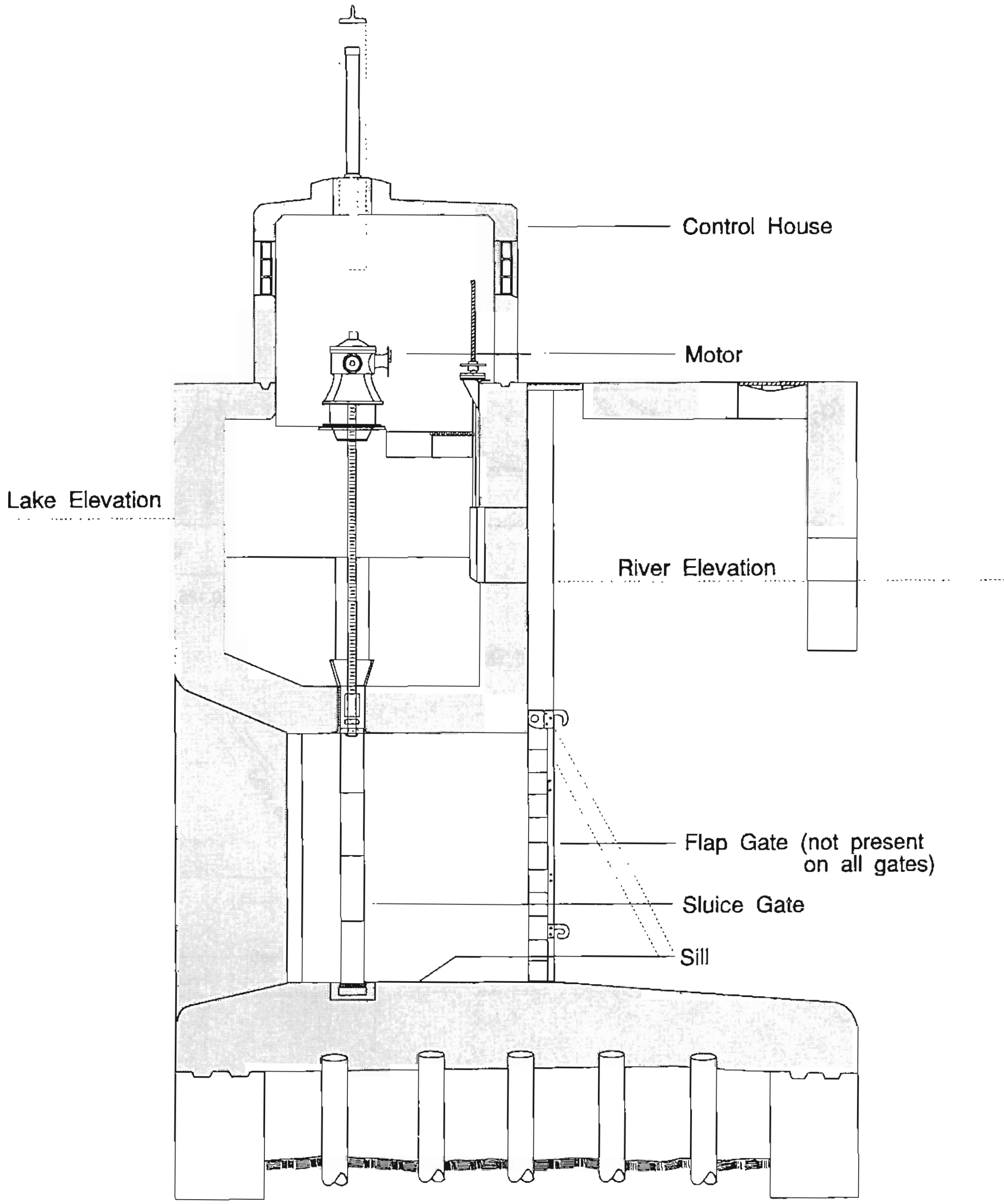
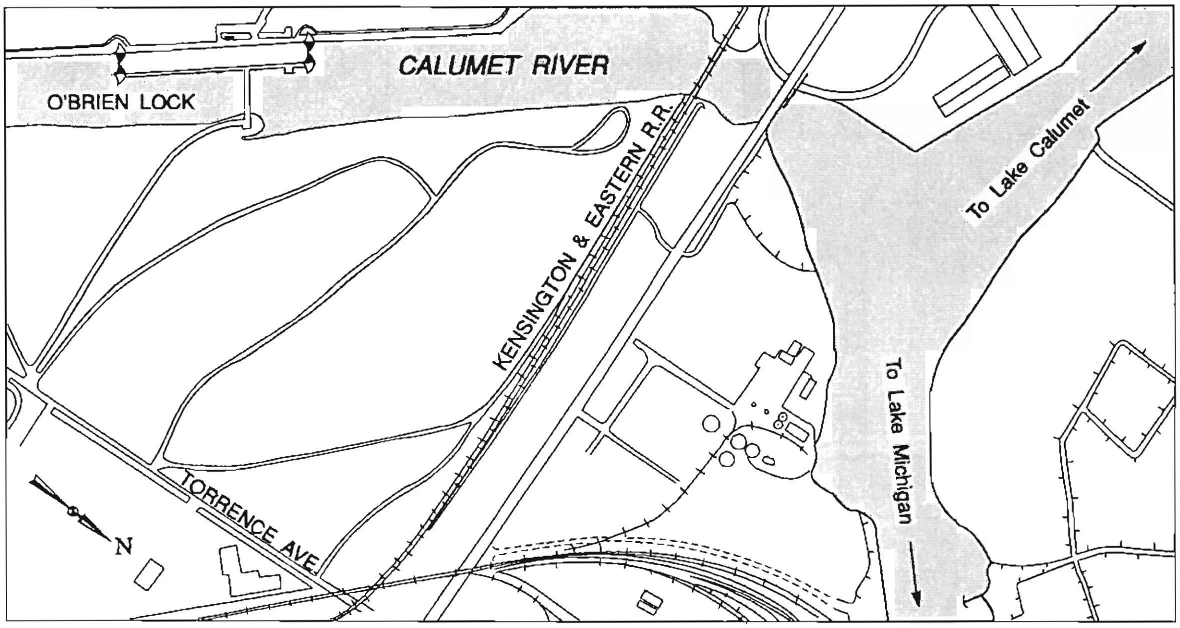


Figure 5. Typical sluice-gate configuration at Chicago River Controlling Works and Thomas J. O'Brien Lock and Dam.



(Modified from U.S. Army Corps of Engineers Charts of the Illinois Waterway, Chart 76)

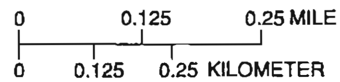


Figure 6. Location of Thomas J. O'Brien Lock and Dam, Burnham, Ill.

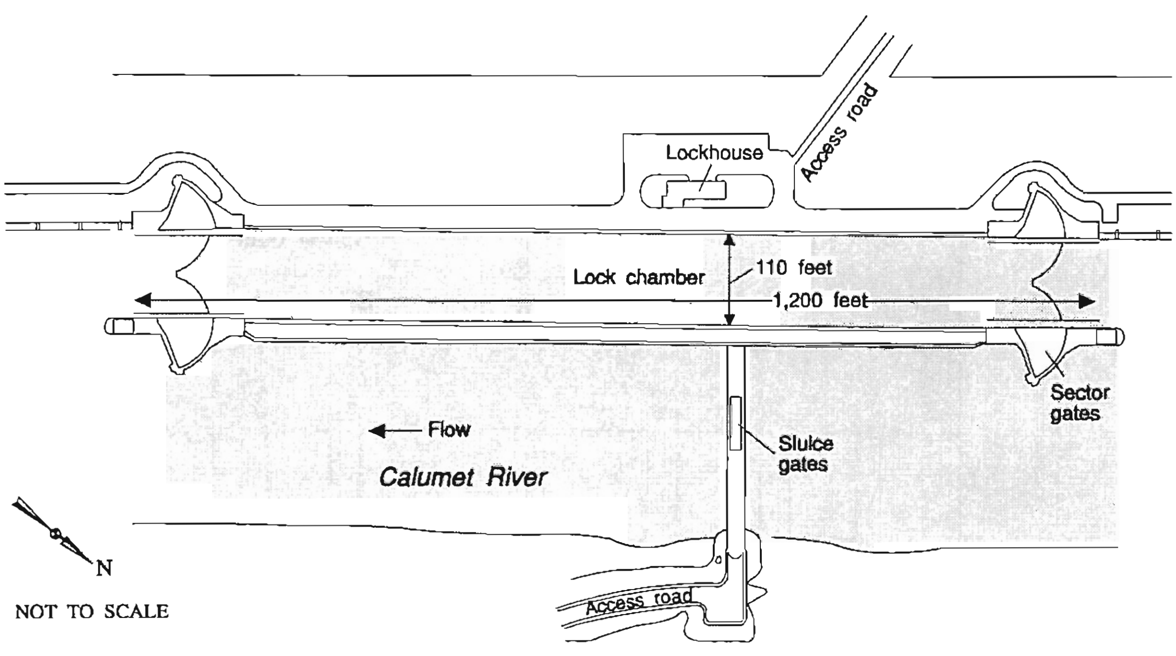


Figure 7. Thomas J. O'Brien Lock and Dam, Burnham, Ill.

The MWRD, however, has the responsibility for determining the settings for the sluice gates at O'Brien.

Wilmette Pumping Station

In 1910, the 8-mi-long North Shore Channel was constructed and connected to the CSSC (fig. 1) to carry wastewater away from north shore communities near Chicago and to provide additional Lake Michigan water for dilution of the wastewater. MWRD also constructed a pumping station and a small lock in 1910 where the North Shore Channel intersects Lake Michigan (fig. 8). At the time of construction and until the completion of CRCW in the late 1930's, the water level in the North Shore Channel was higher than Lake Michigan. The pumping station, located under the Sheridan Road bridge, was used to pump Lake Michigan water into the North Shore Channel in order to create enough head to convey wastewater down the Chicago River and the CSSC. The pumps at the pumping station were not used after the completion of the part of the Deep Tunnel project under the Chicago River (Robison, 1986). In July 1993, MWRD removed the pumps and sealed the pump bays to reduce leakage.

During the 1970's, MWRD removed the lock gates at Wilmette and installed a sluice gate at the downstream end of the lock (fig. 9). The Wilmette sluice gate is structurally somewhat different from the sluice gates at CRCW and O'Brien, but functions similarly. As at O'Brien and CRCW, the sluice gate is raised during the summer to improve water quality in the North Shore Channel and the CSSC. During periods of extremely high flow, water will sometimes overtop the lock gate at Wilmette and flow into Lake Michigan. The MWRD is responsible for the operation and maintenance of Wilmette.

MEASUREMENT METHODS

As previously mentioned, the Corps measured discharge downstream from each of the three control structures in July 1990. The discharges measured by the Corps were 352 ft^3/s greater than flows computed from MWRD sluice-gate ratings for the same period (U.S. Army Corps of Engineers, 1990, p. 25). On the basis of these measurements and other information available to the Corps, the leakage at CRCW was estimated to be between 200 and 400 ft^3/s. It is likely that the amount of leakage at CRCW and other control structures varies with the stage difference between Lake Michigan and the Chicago River. If the leakage at CRCW is assumed to be 200 ft^3/s and the cross-sectional-flow area of the Chicago River at Lake Shore Drive is approximately 5,000 ft^2, the average velocity would be 0.04 ft/s.

Because Price AA meters cannot accurately measure velocities less than 0.25 ft/s, other methods for measuring leakage were necessary. Few instruments are able to accurately measure water velocities less than 0.04 ft/s. Price AA meters have been fitted with an optic head to increase the accuracy of low-flow velocity measurements. However, optic-head meters are not rated for velocities less than 0.10 ft/s and cannot be used to determine flow direction, except at the surface. An acoustic or electromagnetic velocity meter is necessary to measure velocities less than 0.10 ft/s and to determine flow direction. However, acoustic or electromagnetic meters have the disadvantage of measuring point velocities only; therefore, measurements cannot be made any faster than with a Price AA. The ADCP was considered advantageous because it can quickly obtain measurements of discharge from a moving boat. In April 1993, therefore, trial leakage measurements were made with an ADCP. Results of the trial measurements indicated that an ADCP could be used to measure leakage at each of the three control structures.

Several dye-dilution leakage measurements were made at the Chicago Lock in order to evaluate the results from simultaneous ADCP measurements. Because of the poor measuring conditions, the dye-dilution measurements cannot provide a strict verification of ADCP-measured leakage. However, the dye-dilution measurements provide an approximate check on ADCP-measured discharges. The two methods for measuring leakage are described in the following sections.

Acoustic Doppler Current Profiler

ADCP's have been in use for more than 10 years. They have been used primarily in the study of ocean currents and estuaries. Within the last 5 years, ADCP's have been used to measure streamflow, especially in rivers or canals where conventional discharge-measurement techniques are either very expensive or impossible to apply. Recently, a more advanced ADCP has been developed to measure

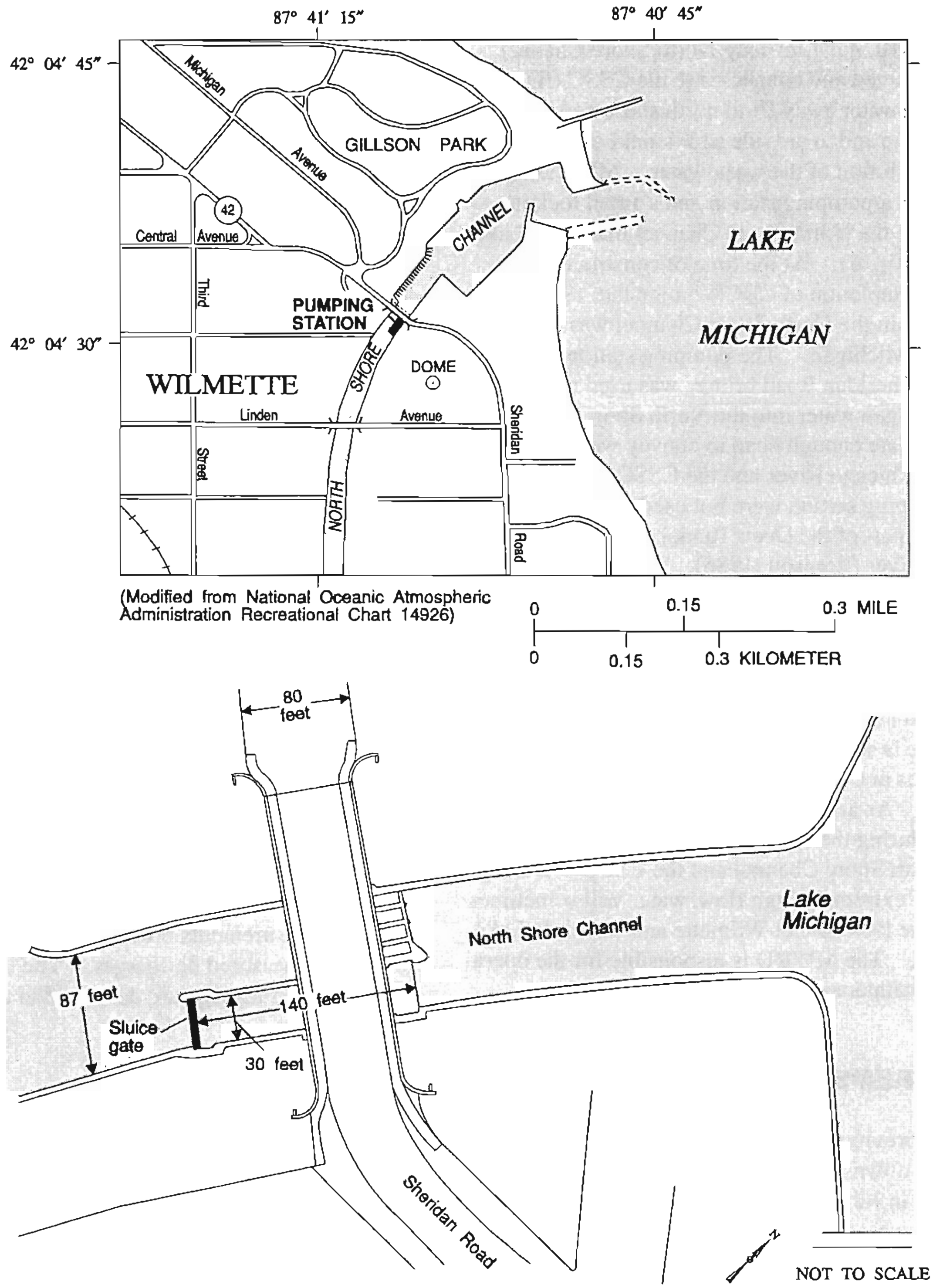


Figure 8. Wilmette Pumping Station, Wilmette, Ill.

Figure 9. Wilmette Pumping Station, Wilmette, Ill., view looking northeast, September 1993.

discharge in shallow water (as shallow as 5 ft) and with a greater vertical resolution. This type of instrument, called a Broadband ADCP (hereafter referred to as an ADCP), was used for these measurements. A brief description of how an ADCP is used to measure discharge is provided below. For a detailed description of the ADCP and its application to streamflow measurement, the reader is referred to RD Instruments (1989, 1993), Gordon (1989), and Simpson and Oltmann (1993).

An ADCP measures vertical profiles of water velocities from a moving boat. Water velocities are measured by the ADCP using transducers that transmit short, phase-encoded acoustic pulses along four narrow beams at a known, fixed frequency (from 75 to 1,200 kilohertz (kHz), depending on the transducer). These beams are positioned 90 degrees apart horizontally and at a known angle (usually 20 degrees) from the vertical. The ADCP detects and processes the echoes reflected by suspended material from successive volumes (depth cells) along the beams and determines the time-lag change and frequency shift. The time-lag change and difference in frequency (shift) between transmitted and reflected sound is proportional to the relative velocity between the ADCP and suspended material in the water that reflects the beam back to the ADCP (back scattering). This frequency shift is known as the Doppler effect. An autocovariance method is used to compute the mean value or first moment of the Doppler frequency. Using simple trigonometry and water velocities calculated from adjacent beams, the ADCP can compute water speed and direction. The size or height of the depth cells can be set by use of ADCP software parameters. Most of the measurements described in this report were made using 9.8 in. (0.25 m) depth cells.

Because water-velocity measurements are made relative to the movement of a boat, the ADCP also must measure the velocity of the boat. This process is referred to as bottom tracking. The boat velocity relative to the river bottom is computed by the ADCP using a flux-gate compass and the results of measurements of the Doppler shift of acoustic pulses reflected off of the river bottom. Bottom-tracking measurements can be made with greater accuracy than water-velocity measurements because a longer pulse is used for bottom tracking and return echoes from the bottom are much stronger than echoes from most particulates suspended in the water column. In addition to measuring boat velocity, the depth of the river is estimated by use of the amplitude of the bottom-track echoes (echoes returned from the bottom).

When the ADCP is used to measure discharge, a series of acoustic pulses known as pings are transmitted. Pings for measuring water velocities are referred to as water pings; pings for measuring the boat velocity are referred to as bottom-tracking pings. Normally, water and bottom-tracking pings are interleaved during transmission. A group of interleaved water and bottom-tracking pings is referred to as an ensemble. The number of water and bottom-tracking pings per ensemble is set by the user. An ensemble is analogous to one vertical in a conventional discharge measurement. Most leakage measurements described in this report were made with five water pings and four bottom-tracking pings. Some measurements were made with 10 water pings and 9 bottom-tracking pings. Increasing the number of pings per ensemble slows down the rate at which the ADCP makes measurements but does not necessarily increase measurement accuracy. A single discharge measurement, called a transect, is a collection of ensembles for a measuring section. A single transect typically will contain 50-60 ensembles.

The ADCP cannot measure water velocities near the top and bottom of the water column. Water velocities near the surface cannot be measured for two reasons. The ADCP must be deployed so that the transducers remain under water during the course of a measurement (fig. 10). In addition, the physical characteristics of the transducers are such that accurate velocity measurements cannot be made within at least one depth cell away from the transducer. With 9.8-in. depth cells, usually no velocity measurements are made within 20 in. of the transducers. The first depth cell for the measurements described in this report ranged from 2.4 to 5.5 ft below the water surface.

Water velocities near the bottom of the water column cannot be measured because of a phenomenon known as side-lobe interference. The return signals from particulates near the bottom are distorted by echoes from the riverbed directly below the ADCP (see figure 10). This distortion occurs because the strong bottom reflection from a weak side-lobe signal overwhelms the weak backscattered reflection of the strong main beam signal. Gordon (1989, p. 929) and Simpson and Oltmann (1993, p. 6) provide more details on side-lobe interference and its effect on water-velocity measurements. For a 1,200 kHz

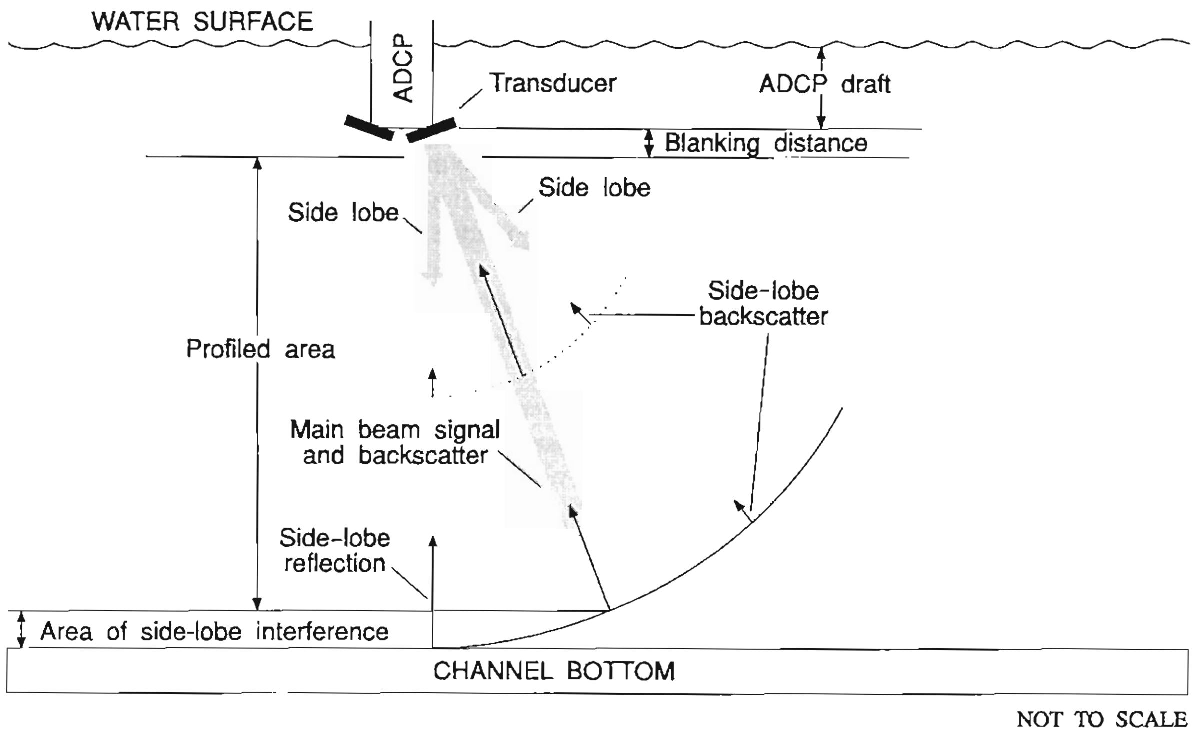


Figure 10. Beam pattern of acoustic Doppler current profiler (ADCP), showing side-lobe interference.

ADCP with a 20-degree beam angle, about 6 percent of the profiling range is lost because of side-lobe interference. The ADCP software automatically rejects water-velocity data beyond about 94 percent of the distance to the bottom.

Water velocities near the surface or near the bottom of the water column can be estimated by the constant-velocity method or the power-law method. With the constant-velocity method, the velocity at the surface or the bottom is assumed to be equal to the velocity of the first or last measured depth cell, respectively. The constant-velocity method is conceptually better for estimating velocities near the surface than the power-law method, because, in open-channel flow, the velocity approaches a constant value near the surface. However, the constant-velocity method is considered inappropriate for estimating the velocities near the bottom because typical vertical-velocity distributions for open-channel flow are not accurately represented. In open-channel flow, the velocity approaches zero near the bottom. The power-law method is based on the power law for velocity distribution presented by Chen (1989, 1991). With the power-law method, a least-squares fit of the measured water velocities is obtained using the power law for velocity distribution. The exponent of the power law can be selected by the user. The exponent is typically set to 1/6, based on the 1/6 power law suggested by Chen (1989). Chen has shown that Manning's formula is essentially the same as the 1/6 power law. The power law is then used to estimate velocities in the unmeasured parts of the water column. Conceptually, the power-law method is better than the constant-velocity method for estimating the unmeasured portion of the water column near the bottom. In this study, the constant-velocity method was used to estimate the unmeasured portion of the water column near the surface, and the power method with an exponent of 1/6 was used to estimate the unmeasured portion of the water column near the bottom.

The ADCP cannot measure water velocities near the edges of the section. This is primarily because the ADCP cannot accurately measure velocity in shallow water. ADCP water-profiling mode 2 or 4, used in this study, requires a 4.7-ft minimum depth for velocity measurement. A new water-profiling mode (currently being tested) will allow ADCP measurements in water as shallow as 3 ft. If the unmeasured discharge section is assumed to be triangular, the estimated velocity for the unmeasured section, V_e, is estimated by Simpson and Oltmann (1993, p. 9) with the equation

$$V_e = 0.707 V_m, \quad (1)$$

where V_m is the mean velocity at the first or last ADCP-measured subsection. The assumption that the unmeasured flow area is triangular is reasonable for many river cross sections where the bottom gradually slopes upwards toward the edge of water.

Sometimes the edge of water is a vertical wall such as a sea wall. Water velocities also cannot be accurately measured by the ADCP near a vertical wall. For example, assume that the acoustic signals transmitted by the ADCP are sent out at a 20-degree angle from the vertical. As the ADCP approaches a vertical wall, the acoustic beam will impinge on the wall and cause a false bottom return. The ADCP will then calculate flow for a depth shallower than the actual depth at that location. The horizontal distance at which the acoustic beam impinges on the vertical wall depends on the depth of water near the vertical wall and the orientation of the transducers on the ADCP relative to the wall. For example, the beam will impinge on the wall sooner if two of the transducers are oriented perpendicular to the wall than if the transducers are oriented at a 45-degree angle to the wall. Most measuring locations in this study had at least one vertical wall in the measuring section. For most measurements described in this report, the transducers were oriented at 45 degrees to the wall. With this orientation, it was determined that for measurement locations, the ADCP could be brought within 8 ft of the vertical wall. Velocities for the unmeasured edge sections could then be estimated by setting $V_e = V_m$; however, this is not entirely accurate because the velocity decreases to zero near the wall. Therefore, for the measurements described in this report, velocities near vertical walls were estimated by the equation

$$V_e = 0.91 V_m. \quad (2)$$

The coefficient of 0.91 was estimated from data presented in Rantz and others (1982, p. 82) showing the relation between mean velocity in the vertical and distance from a smooth wall expressed as a ratio of the depth.

Estimates of V_e are sensitive to the value of V_m obtained from the first of last ensemble, and therefore the estimates of V_e may have unrealistic values. The result of velocity measurements from multiple ensembles may be averaged in space or time (referred to as ensemble-averaging). Sometimes the average velocity measured for the last ensemble has a sign that is opposite to the predominant flow direction. Ensemble-averaging is done so that a more consistent estimate of edge discharge can be obtained, rather than estimating the edge discharge based on the average velocity from a single ensemble. Typically, three to four ensembles were averaged, especially near the edges. For measurements made in the Chicago River, the velocity measurements from individual ensembles were averaged laterally (across the section) every 6 ft. The resulting V_m was used to estimate V_e. At all other locations, ensemble-averaging was performed every 3 ft and was used to estimate V_e. The edge discharge may then be estimated using the equation

$$Q_e = (C\ V_e\ L\ d_m), \quad (3)$$

where

Q_e = estimated edge discharge,
C = 0.707 for triangular-shaped edge section, 0.91 for vertical wall,
L = distance to the shore from the first or last ADCP-measured subsection, and
d_m = depth at the first or last ADCP-measured subsection.

The variable d_m is measured by the ADCP; L is measured using a tagline or a similar measuring device.

ADCP measurements were made at each location for a range of lake- and river-level conditions. Lake Michigan levels usually are highest during July and are lowest during February. Water levels in the Chicago and Calumet Rivers are relatively constant throughout the year. Immediately prior to a storm, river levels will decrease initially in response to increased flow at Lockport. Then, river levels will increase in response to rainfall and runoff. Occasionally, during large storms, levels in the Chicago and Calumet Rivers will be higher than in Lake Michigan. In order to measure leakage, ADCP measurements were made during dry periods when the river levels were not changing rapidly during the measurements.

Two ADCP's were used for making the leakage measurements described in this report. Both ADCP's were equipped with 1,200-kHz transducers mounted 20 degrees from the vertical. The ADCP used to make measurements in April and May 1993 was equipped with firmware version 3.20. The ADCP used to make measurements in July, September, and October 1993 was equipped with firmware version 3.90. The main difference between firmware versions is that a new water-profiling mode was added and problems with ambiguity errors were corrected in the latter version (J. R. Marsden, RD Instruments, oral commun., 1993). The two ADCP's were otherwise identical. A metal bracket was used to suspend the ADCP from the boat and hold it steady in the water. During the April and May ADCP measurements, the bracket used contained ferrous metal. The flux-gate compass in the ADCP is affected by nearby ferrous metal. The result is that velocity directions computed by the ADCP are offset by some constant amount, provided that the ferrous metal object does not move relative to the ADCP. This, however, does not invalidate the discharges measured by the ADCP (J. R. Marsden, RD Instruments, oral commun., 1993). An aluminum bracket was used to hold the ADCP in all subsequent leakage measurements.

Normally, streamflow measurements using an ADCP are made from a moving boat without the use of a tagline. The average velocity in the Chicago River and at the Chicago Lock was estimated to be as low as 0.04 ft/s. Water velocities were presumed to be similar at Wilmette and O'Brien. Initial attempts to measure leakage at CRCW indicated that a trolling motor moved the boat too fast across the channel. In order to obtain accurate, consistent ADCP measurements, it was necessary to cross the channel with a boat speed approximately equal to the average water velocity. A tagline was used to slowly pull the boat by hand from one shore to the other in order to obtain the proper rate at which the boat crossed the channel. During measurements made in July-September 1993, a windlass winch was mounted on the boat and was used to pull the boat across the measuring section at a relatively constant speed. The windlass assembly is shown in figure 11.

Dye Dilution

Dye-dilution methods to measure discharge are based on a mass-balance calculation for the flow (Kilpatrick and Cobb, 1985). A harmless, fluorescent dye, known as rhodamine WT, was used for the dye injections described in this report. This section describes a continuous, steady-state dye injection into a steady, uniform flow at the Chicago Lock. For these conditions, the dye concentration at the sampling section will rise with time until a steady plateau concentration is reached (Kilpatrick and Cobb, 1985, p. 4-5). The time required to reach the plateau concentration depends on the dispersion in the flow. The dye concentration should remain steady once the plateau concentration is reached, provided the injection rate and concentration and the flow rate do not change. For this situation, the discharge can be calculated by use of the equation

$$Q + i = k\frac{iC_i}{C_s}, \tag{4}$$

where

- Q is the discharge in the stream,
- i is the injection rate of the dye,
- C_i is the concentration of the injected dye solution,
- C_s is the concentration of dye in the samples from the flow, and
- k is a constant to convert to a consistent system of units.

As the injection rate is far less than the discharge in the stream, this equation can be simplified to

$$Q = k\frac{iC_i}{C_s}. \tag{5}$$

For i, measured in milliliters per minute, and Q, measured as cubic feet per second, the units-conversion constant

$$k = 5.885 \times 10^{-7}\ \frac{ft^3/min}{mL/s}.$$

Most applications of dye-dilution methods to measure discharge involve highly turbulent flows where mixing is not a problem. The application discussed in this report involved the use of dye-dilution methods to measure small discharges through the closed gates of the Chicago Lock between Lake Michigan and the Chicago River. An initial attempt to measure discharge by dye dilution in May 1993 proved unsuccessful because of inadequate mixing. Therefore, a manifold had to be designed to mix the dye in the flow.

The dye-injection apparatus used in this study was planned to provide continuous, uniform mixing of a small volume of dye in an open channel 80 ft wide

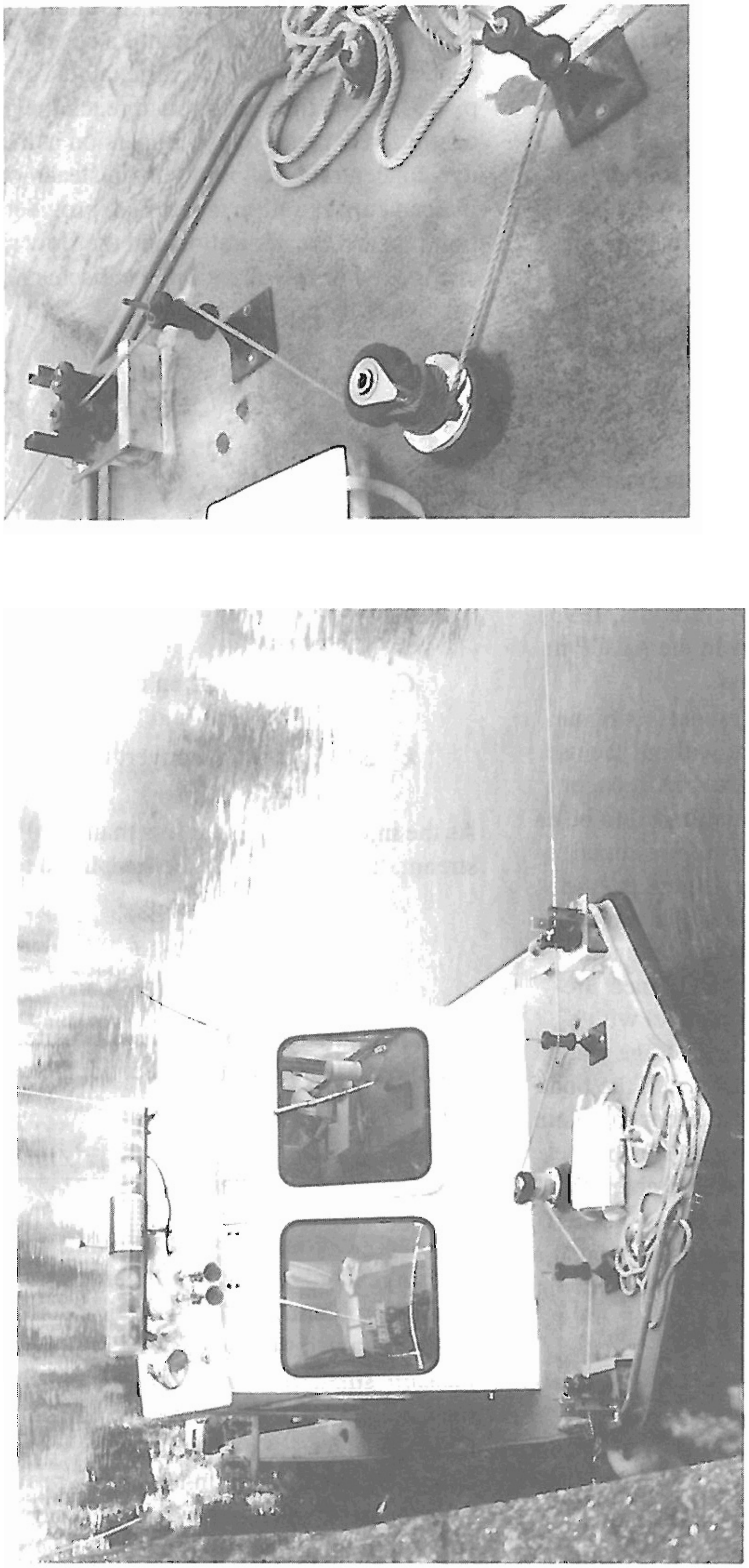


Figure 11. Boat and windlass used to move boat across a measurement section.

and 25 ft deep. The dye was metered into the outlet of a centrifugal pump with a constant-rate, positive-displacement metering pump. The centrifugal pump took water from outside the Chicago Lock and pumped it, together with the injected dye, through a manifold into the lock. The purpose of the centrifugal pump was to provide enough flow through the manifold to mix the dye solution through the entire cross section. The metering pump controlled the dye-injection rate, resulting in a steady injection of dye into the flow despite any fluctuations in the pumping rate of the centrifugal pump. The dye was pumped from a 6-L holding tank with a scale indicating the volume of dye remaining. Measurements of the volume of dye in the holding tank at intervals throughout the injection indicated the injection rate and any variance. Figure 12 shows the dye-injection apparatus.

The manifold was designed of 2-in. diameter polyvinyl-chloride pipe suspended in the lock about 50 ft west from the lake gate and about 1 ft above the bottom of the lock. The manifold had ports pointing upwards and spaced at 5-ft intervals along the length of the manifold. Theoretical mixing characteristics of each jet from the manifold are listed in table 1 and computed from Fisher and others (1979). At depths greater than 4 ft, the flow from adjacent jets should overlap. The diameter of the ports was increased with distance along the manifold to maintain a consistent flow from all ports. The total area of all the ports was 40 percent of the cross-sectional area of the pipe.

Table 1. Theoretical characteristics of jets from dye-injection manifold used in the Chicago Lock, July 13-15, 1993
[ft, feet; <, less than]

Depth below water surface (ft)	Width of jet (ft)	Dilution factor	Percentage of channel width included in jet
0	6.1	260	64
2	5.6	240	63
6	4.6	190	52
10	3.6	150	40
14	2.5	110	28
18	1.5	65	17
22	.5	22	6
24	.03	0	< 1

The manifold was modified from the original design because of mechanical difficulty in joining adjacent sections of the manifold. The manifold was 45 ft long with 9 ports rather than the original at 75 ft long with 17 ports. The manifold was centered in the channel less than 1 ft above the channel bottom. Figure 13 shows the manifold suspended 2-3 ft below the water surface and the resulting jets at the water surface.

Dye standards were prepared from the dye lot used for the injection solutions. Five cuvettes were used for the fluorometric analysis for dye concentrations. All of the cuvettes were used for blank (deionized water) samples as part of calibrating the fluorometer to ensure that the fluorescence did not vary among cuvettes. The fluorometer was calibrated by analyzing six to nine standard solutions prior to analyzing any water samples. The fluorometer was recalibrated after the samples were analyzed. If the analyses extended over several hours, an extra calibration was done part way through the analyses. Fluorometer-calibration curves were estimated using ordinary-least-squares regression. The fluorometer-calibration readings are listed in appendix 1. The calibration curves are listed in table 2.

Samples were collected 500 ft downstream from the injection location at four locations across the channel and at three depths at each location. Samples were collected at depths of 6, 12, and 18 ft with a Kemmerer bottle to isolate samples from the different depths. Samples were collected 10, 30, 50, and 70 ft from the left edge of the lock (facing west). The average concentration in each vertical was calculated by two methods: (1) the mean of the three samples from that vertical and (2) the depth-weighted average of the samples. The depth-weighted average for each vertical was calculated by dividing the vertical into "bins" represented by each sample (fig. 14). The concentration of the sample is weighted by the vertical size of the bin, and the total for all samples is divided by the total depth of the vertical.

Each day, one set of samples was collected prior to starting the dye injection. These samples, referred to as background samples, were used to determine the background fluorescence of the water flowing through the lock. Samples to determine the steady dye concentration at the plateau of the concentration curve were collected at about 1/2-hour intervals starting

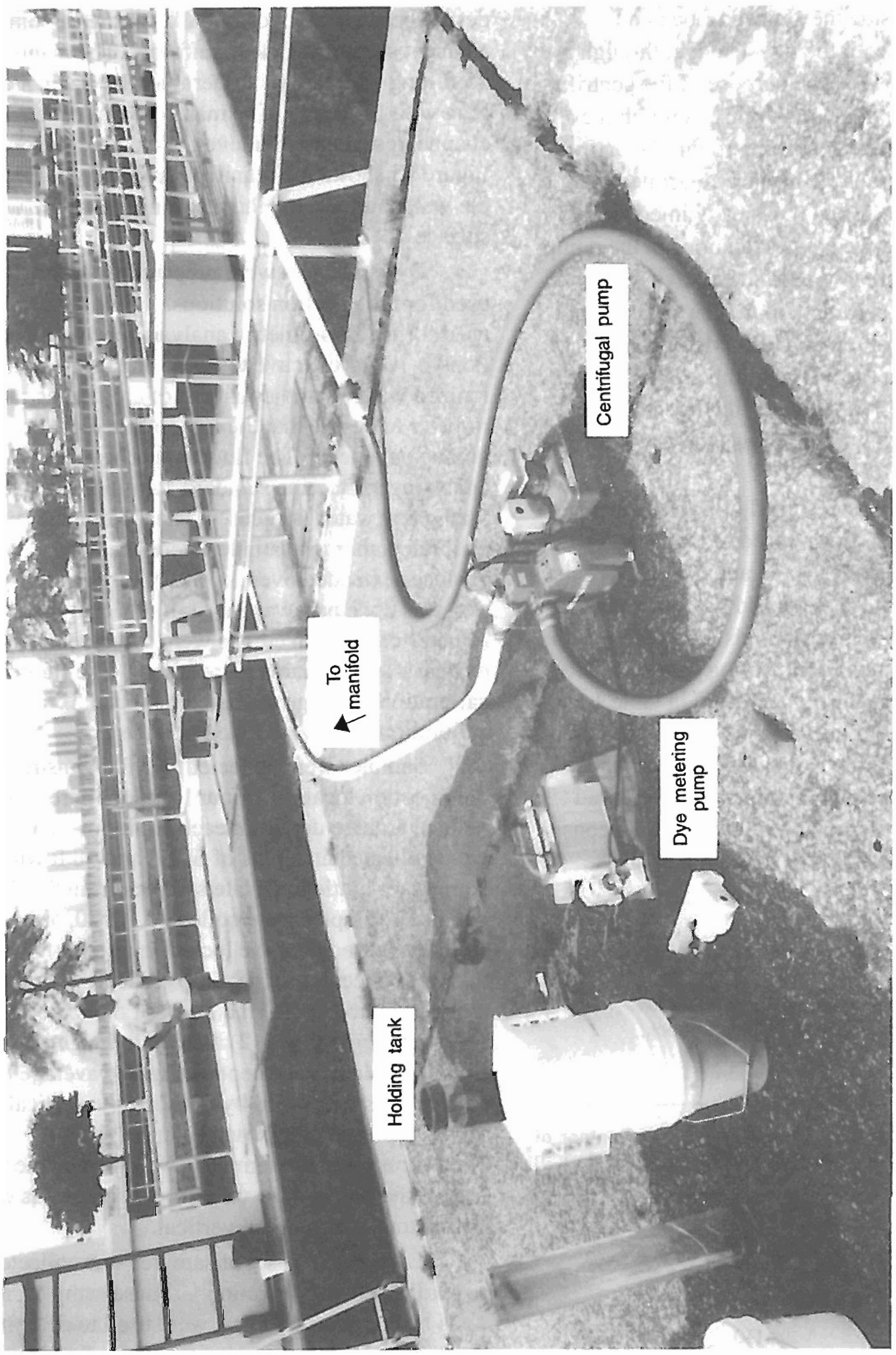


Figure 12. Apparatus used to inject dye mixture into the Chicago Lock, July 13-15, 1993.

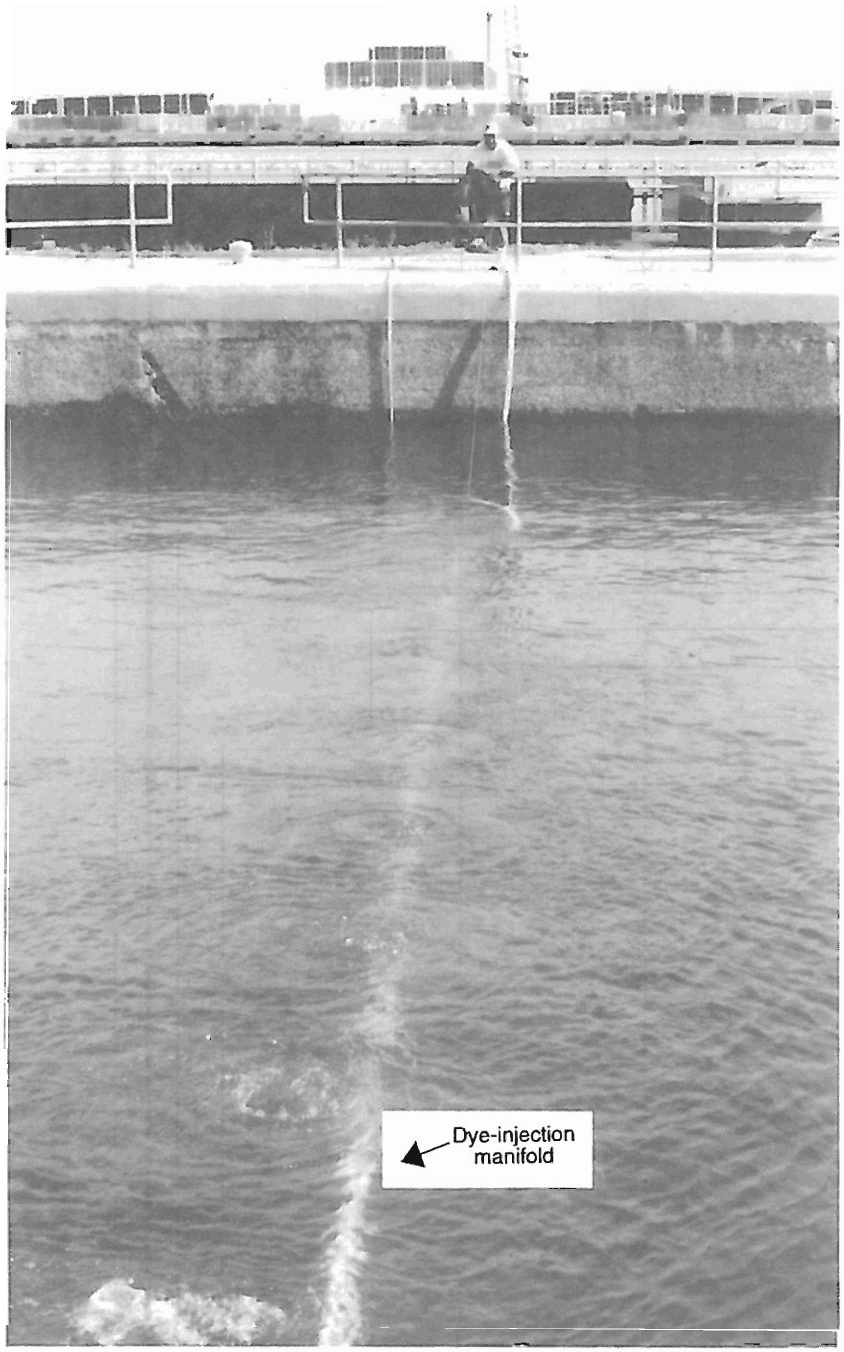


Figure 13. Dye-injection manifold in Chicago Lock, view looking north, July 13-15, 1993.

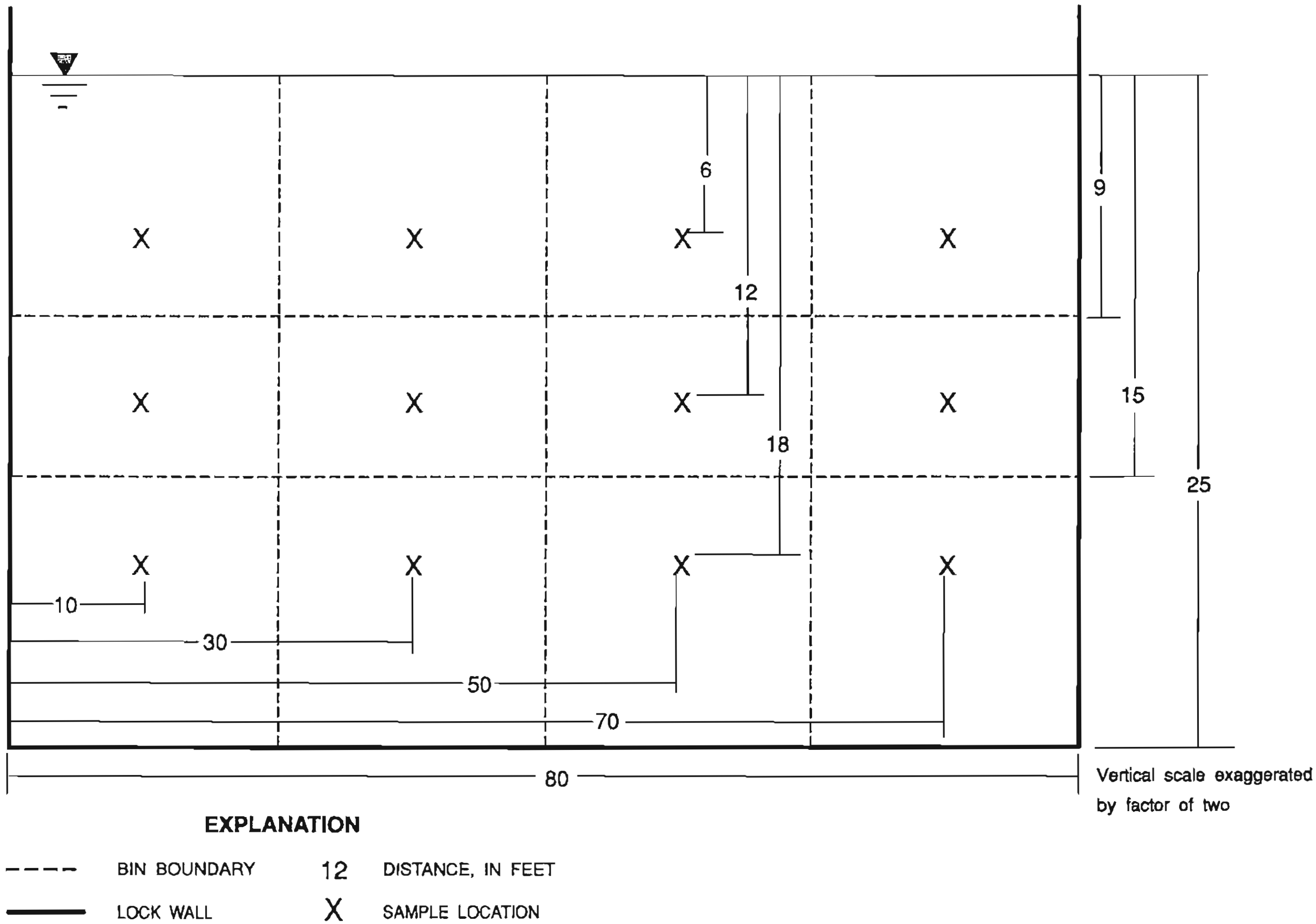


Figure 14. Generalized cross section of Chicago Lock channel showing the sample locations and bins used to calculate depth-weighted average dye concentrations.

Table 2. Calibration curves for fluorometric analyses of dye samples collected in the Chicago Lock, July 13-15, 1993

[ppb, parts per billion; ppb/unit, part per billion per unit fluorometer reading; calibrations are based on linear regression of the concentrations of standard solutions with the fluorometer readings for those standards (listed in appendix 1). These calibrations give the concentration in parts per billion for a given fluorometer reading.]

Calibration number	Calibration date	Calibration time (hours)	Intercept (ppb)	Slope (ppb/unit)	Fluorometer reading for zero concentration	Correlation coefficient	Number of samples	95-percent confidence interval for slope: Lower	Upper
1	July 13	1535	0.096	1.349	-0.071	0.999	9	1.321	1.378
2	July 13	1658	-.203	1.382	.147	.999	8	1.343	1.422
2.5	July 13	1818	-.177	1.389	.127	.999	8	1.354	1.423
3	July 14	1036	-.373	1.331	.280	1.00	8	1.304	1.358
3.5	July 14	1513	-.269	1.384	.194	.999	7	1.337	1.430
4	July 15	0930	-.066	1.281	.052	.999	7	1.245	1.317
5	July 16	0912	.228	1.473	-.155	.999	7	1.427	1.518
5.5	July 16	1101	-.121	1.559	.078	.999	6	1.511	1.607

about 1.5 times the estimated traveltime between the injection and sampling locations.

The dye concentration of each sample was calculated by multiplying the fluorometer reading by the slope of the regression line and adding the constant from the regression line for the calibrations before and after the sample was analyzed. The two resulting concentrations were weighted by the time between the calibration and the analysis, and the time-weighted average listed as the concentration for that sample. Dye samples are listed in appendix 2.

Quality-assurance samples were collected regularly to verify the accuracy of the sampling and analytical techniques. Split samples were collected by filling two sample bottles from the same sample of water. Split samples identify the variance in the sample analysis. Replicate samples were obtained by collecting two or more samples from the same point at about the same time. Replicate samples identify the variance in the sampling. Blank samples were collected by filling a sample bottle with distilled water and then handling the bottle exactly like the other samples. Blank samples identify contamination of the samples from handling and processing.

MEASUREMENTS OF LEAKAGE

Leakage measurements were made at CRCW, O'Brien, and Wilmette in April, May, July, September, and October 1993 by use of an ADCP. Two sets of dye-dilution measurements were made at Chicago Lock in May and July 1993. The results of all ADCP leakage measurements, the dye-dilution measurements in July, and the accuracy of the measurements are presented in the following sections. The results of the May 1993 dye-dilution measurements are not presented because the method used for dye injection did not result in complete mixing. Stages for Lake Michigan, the Chicago and Calumet Rivers, and the North Shore Channel are shown in table 3. The values in table 3 are the mean stages for the periods of the ADCP and dye-dilution measurements and are not daily mean stages.

Table 3. Control-structure stage data for leakage measurements during April-October 1993
[CRCW, Chicago River Controlling Works; O'Brien, Thomas J. O'Brien Lock and Dam; Wilmette, Wilmette Controlling Works; Lake, Lake Michigan; River: Chicago River (CRCW), Calumet River (O'Brien), and North Shore Channel (Wilmette); dashes indicate no data available]

	Mean stage (feet, Chicago City Datum)					
	CRCW		O'Brien		Wilmette	
Date	Lake	River	Lake	River	Lake	River
04/05/93	0.56	-1.53	--	--	--	--
04/06/93	.36	-1.46	--	--	1.22	-0.38
04/07/93	.39	-1.57	0.88	-1.77	--	--
05/04/93	1.10	-1.84	--	--	--	--
05/05/93	1.02	-1.60	--	--	--	--
05/10/93	1.07	-1.48	--	--	--	--
07/12/93	1.54	-1.40	--	--	--	--
07/13/93	1.60	-1.46	--	--	--	--
07/14/93	1.80	-1.77	--	--	--	--
07/15/93	1.74	-1.44	--	--	--	--
07/16/93	--	--	--	--	--	--
09/13/93	--	--	1.28	-2.03	--	--
09/14/93	--	--	1.59	-1.36	--	--
09/15/93	--	--	1.93	-1.12	--	--
09/16/93	--	--	1.81	-1.10	--	--
09/17/93	--	--	1.61	-1.36	--	--
09/20/93	1.35	-1.77	--	--	--	--
09/21/93	1.52	-1.49	--	--	--	--
09/23/93	--	--	--	--	1.87	-1.14
10/04/93	1.18	-1.54	--	--	--	--
10/05/93	.91	-1.29	--	--	--	--
10/06/93	.59	-1.51	--	--	--	--

Control Structures

Chicago River Controlling Works

As mentioned previously, the CRCW consists of a network of harbor walls that include the Chicago Lock and two sets of sluice gates (fig. 2). In recent years, leakage through the Chicago Lock has increased because of worn gate seals and gates not fully closing. Considerable leakage through the harbor walls can result because of the construction techniques used. In order to measure the total leakage through CRCW, ADCP measurements were made in the Chicago River at or immediately west of Lake Shore Drive (fig. 2). Separate ADCP and dye-dilution measurements were made in the Chicago Lock in order to quantify leakage through the Chicago Lock as a percentage of the total leakage at CRCW.

Chicago Lock

Recently, the Corps has had problems operating the triangle gates at Chicago Lock. One of the lake gates would not fully close, sometimes resulting in an opening as wide as 24 in. Figure 15 shows leakage through the lake gates on April 5, 1993. In May 1993, the Corps initiated emergency repairs at Chicago Lock because of problems closing the triangle gates at both the east (lake) and west (river) ends of the lock. Debris was removed from the tracks on which the gates roll, gate seals were temporarily repaired, and the gates were adjusted for better closure. After repairs were completed, the lake gates closed so that there was little or no space between the gates. Nevertheless, leakage around gate seals and through holes in one of the gates still exists. However, after these repairs the lake gates sealed better than the river gates. Further repairs were made in September 1993, when the gate rollers from the river gates were removed and repaired. The Corps plans to completely rehabilitate the Chicago Lock in the near future.

ADCP measurements were made at several locations in and near the lock (fig. 16). All ADCP leakage measurements in April 1993 were made in the lock, halfway between the lake and river gates. In May, ADCP measurements of lake-gate leakage were made outside the lock, about 90 ft east of the lake gates (fig. 16). River-gate leakage measurements were made 70 ft upstream from the river gates. In July, all ADCP measurements were made in the lock halfway between the lake and river gates (fig. 16). In April and May, measurements were made by pulling the boat with the attached ADCP across the lock with a steel tagline cable. The ADCP measurements in July were made by pulling the boat with a nylon rope and a windlass mounted to the boat deck.

Ninety-five ADCP measurements were made in April, May, and July to quantify the leakage through the river gates. Measurements of leakage through the river gates were made with the river gates closed and the lake gates open. During the April and May river-gate leakage measurements, the lake gates were left in a fully open position. During the July leakage measurements, the lake gates were opened partially or kept closed. On July 13, the leakage through the river gates of the lock was measured with the lake gates opened about 3 ft so the water level in the lock was the same as in Lake Michigan. During July 14 and 15, the leakage was measured with both the river and lock gates closed. After the repairs to both sets of gates in May, the river gates leaked more than the lake gates so that between lockages, the stage in the lock was somewhat less than Lake Michigan stage and greater than

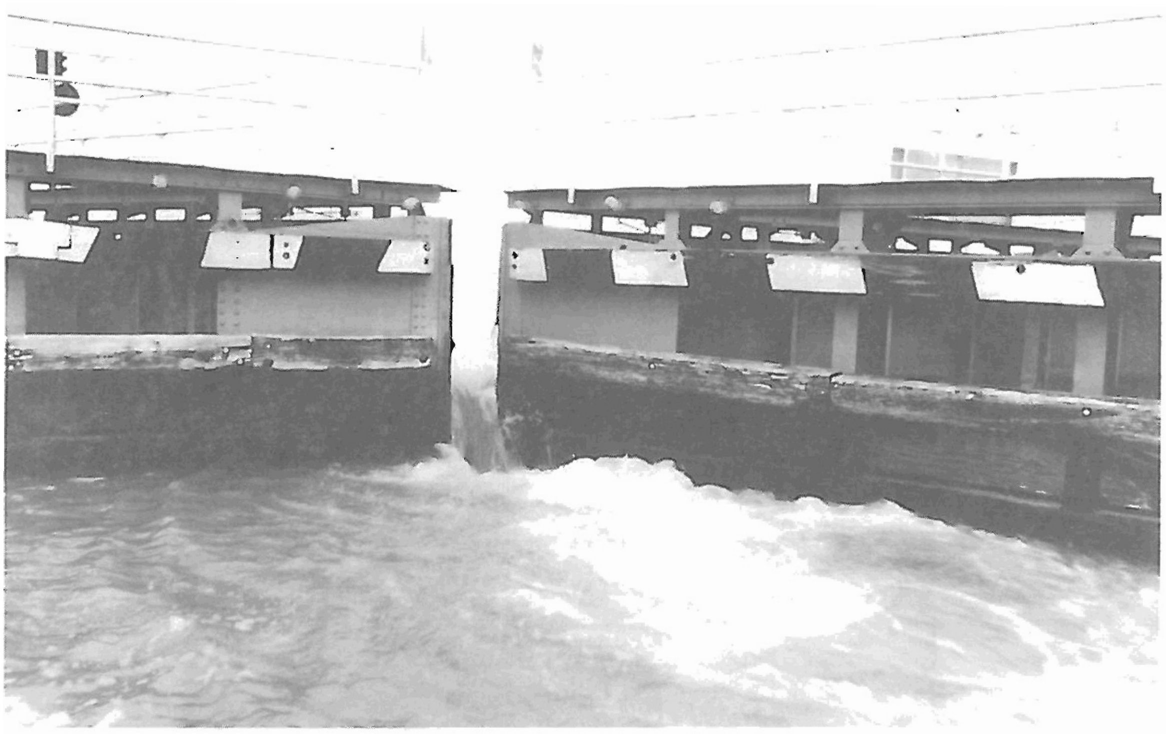
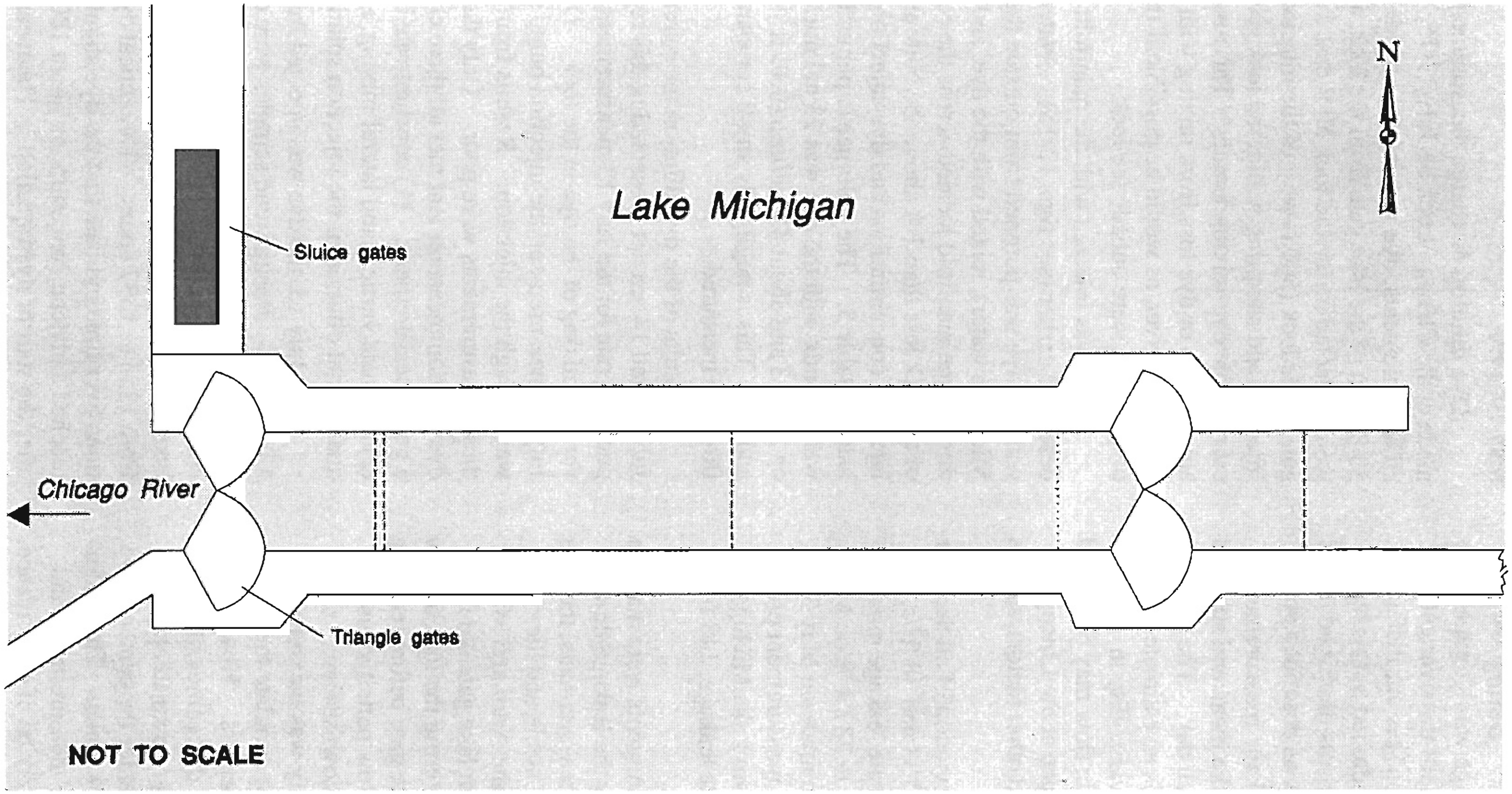


Figure 15. Leakage through lake gates at Chicago Lock, view looking east, April 5, 1993.

Figure 15. Continued.



EXPLANATION

· · · · · · · · DYE-INJECTION LOCATION

- - - - - - - - ACOUSTIC DOPPLER CURRENT PROFILER MEASUREMENT LOCATION

=========== ACOUSTIC DOPPLER CURRENT PROFILER AND DYE MEASUREMENT LOCATIONS

Figure 16. Measurement locations, Chicago Lock, Chicago, Ill.

the Chicago River stage. Prior to the repairs, the stage in the lock chamber normally was equal to the Lake Michigan stage. Measurements were made on July 14-15 after the water level in the lock stabilized between the lake and river levels. During April, measurement of river-gate leakage was attempted outside of the lock, about 20 ft west of the river gates. However, this measuring location was unsatisfactory, and the measurements are not included in this report. All river-gate leakage measurements described in this report were made inside the lock as described above.

The results of specific leakage measurements are shown in table 4, including the mean and standard deviation of the transects for each day. The standard deviation of the total discharge is an estimate of both measurement error and natural variability in discharge. Natural variability in flow may be caused by variation in the stage difference at the Chicago Lock (or any other structure) and other factors, such as wind speed and direction.

The mean and standard deviation of all the river-gate leakage measurements are 133 and 38 ft^3/s, respectively. The mean river-gate leakage ranged from 102 ft^3/s on July 13, 1993, to 237 ft^3/s on May 3, 1993. Only two transects were made on May 3 because of time constraints and measurement problems caused by heavy swells from Lake Michigan. The next highest mean river-gate leakage, 148 ft^3/s, was measured on July 15.

Forty-eight ADCP measurements were made in April, May, and July to quantify the leakage through the lake gates. During these measurements, the lake gates were closed as much as possible and the river gates remained open. During the April and May leakage measurements, the south lake gate did not fully close causing the water entering the lock to flow along the inside of the south lake gate before reaching the southern lock wall. This flow pattern caused large eddies to form and move downstream. Leakage through the lake gates in July was measured by opening the gates about 20 in. to simulate the hydraulic conditions prior to the gate repairs. However, because of time constraints and difficulties in adjusting the gates, both lake gates were opened an equal amount allowing lake water to enter the center of the lock and flow parallel to the lock walls. This difference between the July lake-gate measurements and those made earlier in the year may be of significance. It also seems reasonable that this gate configuration provided less resistance to flow and, therefore, more leakage resulted. The mean and standard deviation of all the lake-gate leakage measurements are 919 and 105 ft^3/s, respectively. The mean lake-gate leakage ranged from 835 ft^3/s on April 6, 1993, to 961 ft^3/s on May 10, 1993.

Dye-dilution discharge measurements were made at the Chicago Lock on July 13-15, 1993. For all measurements, dye was injected inside the lock 50 ft west of the lake gate from the lock, and samples were collected inside the lock 50 ft east from the river gate of the lock (500 ft west of the injection point). Injecting and sampling within the lock gives the longest possible dye-mixing length. This also eliminates any dilution or dye loss from mixing with water from the lake or river, as would be possible if the injection or sampling were outside the lock.

Dye was injected with the manifold setup described earlier (see figs. 12-13). Water to mix with the dye was pumped from outside the lock (Lake Michigan water), mixed with the dye, and injected through the manifold located across the center 45 ft of the lock less than 1 ft above the bottom. The injection concentrations and dye-injection rates are listed in table 5. The volumetric pumping rate of water to mix with the dye was 23 gal/min (0.05 ft^3/s) on July 13 and about 45 gal/min (0.11 ft^3/s) on July 14 and 15. This is negligibly small compared to the flow rate measured.

Results of the dye-dilution measurements on July 13 and 14 are not presented in this report. Low pumping rate for the July 13 measurement caused poor vertical mixing of the dye in the lock. During the July 14 measurement, the injection pump stopped partway through the injection. Results from both of these measurements were poor. Only the July 15 dye-dilution measurement met all three criteria for a good measurement: (1) constant-rate injection, (2) adequate vertical and lateral mixing, and (3) adequate serial dilution of the injection solution.

On July 15, the dye was injected from 0900 to 1334 hours. Background samples were collected from 0853 to 0856 hours, and samples for plateau dye concentrations were collected from 1104 to 1337 hours. Samples used for the analysis were collected from 1253 to 1337 hours. Theoretical dye concentrations over time indicate that the dye should have reached a plateau concentration about 180 minutes after the start of dye injection. The mean and depth-weighted average concentrations from each vertical indicate that the mean concentration had reached a

Table 4. Acoustic Doppler current profiler data, April-October 1993

[For each date shown, the mean is in the first row and the standard deviation is in the second row in parentheses ( ); Top, Bottom, Left, and Right are acoustic Doppler current profiler (ADCP) estimated discharges for the respective unmeasured portion of the water column; Middle is measured ADCP discharge]

Date	Start time (hours)	End time (hours)	Number of transects	Discharge (cubic feet per second)						Transect length, in feet	Elapsed time, in seconds	Boat speed, in feet per second	Number of ensembles	Estimated discharge, in percent
				Top	Middle	Bottom	Left	Right	Total					
Chicago Lock at Chicago, Ill. –River-gate leakage														
04-05-93	1345	1835	14	24.3	90.8	6.0	4.8	6.2	132	71	235	0.34	48	30
				(14.3)	(34.2)	(2.5)	(15.8)	(13.4)	(52)	(2)	(91)	(0.12)	(28)	(9)
04-06-93	2035	2100	4	11.5	127.9	5.7	13.1	-15.5	143	69	301	0.23	73	13
				(5.6)	(105.9)	(2.4)	(2.9)	(3.8)	(109)	(7)	(17)	(0.02)	(4)	(5)
05-03-93	1745	1815	2	32.6	168.1	13.1	12.1	10.8	237	80	640	0.13	175	29
				(9.0)	(14.8)	(1.2)	(12.0)	(3.6)	(23)	(11)	(108)	(0.00)	(29)	(0)
05-04-93	0900	1630	22	15.9	87.0	8.7	10.1	9.8	131	65	465	0.14	97	34
				(6.3)	(12.8)	(2.1)	(4.5)	(3.8)	(19)	(3)	(64)	(0.02)	(25)	(6)
05-06-93	1050	1850	18	29.1	70.6	7.5	8.4	7.4	123	62	593	0.11	105	43
				(10.1)	(9.8)	(1.2)	(2.8)	(2.6)	(7)	(4)	(85)	(0.02)	(15)	(7)
07-13-93	1100	1400	10	21.6	68.4	6.3	3.4	1.8	102	65	666	0.11	105	32
				(7.7)	(15.5)	(1.4)	(6.8)	(4.4)	(25)	(3)	(164)	(0.04)	(40)	(9)
07-14-93	1020	1400	14	2.4	104.4	10.8	11.8	13.3	143	77	628	0.12	96	25
				(13.0)	(13.0)	(2.2)	(3.6)	(5.6)	(26)	(11)	(84)	(0.01)	(24)	(12)
07-15-93	1100	1400	11	33.5	87.8	5.9	11.1	9.6	148	69	596	0.13	129	40
				(4.8)	(7.4)	(0.7)	(8.7)	(8.3)	(19)	(10)	(152)	(0.05)	(33)	(11)
Chicago Lock at Chicago, Ill. –Lake-gate leakage														
04-05-93	1210	1245	7	152.1	682.0	46.8	93.6	-62.3	912	71	214	0.37	33	25
				(15.3)	(88.3)	(6.4)	(16.4)	(24.0)	(97)	(2)	(83)	(0.12)	(9)	(4)
04-06-93	1850	2020	10	101.7	654.2	52.3	31.4	-5.0	835	76	298	0.26	73	22
				(25.7)	(145.2)	(13.3)	(45.0)	(43.5)	(152)	(3)	(51)	(0.05)	(12)	(4)
05-10-93	1015	1730	27	120.4	618.1	52.1	77.3	93.3	961	63	338	0.20	74	36
				(28.7)	(51.5)	(9.7)	(5.9)	(18.5)	(40)	(2)	(79)	(0.06)	(25)	(4)
07-12-93	1735	1830	4	157.3	527.6	66.0	130.2	-19.3	862	73	215	0.34	30	37
				(25.2)	(74.0)	(12.1)	(170.5)	(102.3)	(166)	(8)	(26)	(0.02)	(4)	(15)
Chicago River at Lake Shore Drive, Chicago, Ill.														
04-07-93	0830	0830	5	69.0	88.8	7.6	6.5	0.0	172	232	327	0.72	79	52
				(11.2)	(51.7)	(4.4)	(2.7)	(7.3)	(61)	(3)	(47)	(0.12)	(11)	(16)
05-10-93	0615	0700	4	9.7	136.6	16.4	-1.6	6.2	167	194	576	0.34	96	13
				(21.4)	(29.4)	(3.9)	(5.8)	(8.0)	(60)	(1)	(76)	(0.05)	(14)	(22)

Table 4. Acoustic Doppler current profiler data, April-October 1993—Continued

Date	Start time (hours)	End time (hours)	Number of transects	Discharge (cubic feet per second) Top	Middle	Bottom	Left	Right	Total	Transect length, in feet	Elapsed time, in seconds	Boat speed, in feet per second	Number of ensembles	Estimated discharge, in percent
Chicago River at Lake Shore Drive, Chicago, Ill.—Continued														
07-14-93	0430	0630	5	126.4	100.9	14.9	-0.4	9.4	251	238	836	0.29	116	63
				(15.9)	(65.8)	(8.6)	(12.5)	(9.6)	(81)	(17)	(167)	(0.04)	(23)	(14)
07-15-93	0425	0610	4	26.4	128.7	17.7	6.5	2.6	182	249	955	0.27	131	30
				(12.6)	(62.8)	(9.2)	(10.8)	(7.0)	(87)	(31)	(269)	(0.05)	(36)	(2)
07-16-93	0455	0530	2	29.7	96.6	7.5	11.5	0.4	145	194	1,237	0.16	284	33
				(25.8)	(9.7)	(0.6)	(2.7)	(6.4)	(32)	(2)	(72)	(0.01)	(1)	(8)
09-20-93	0935	1130	6	59.6	139.1	11.3	18.7	-1.5	227	243	803	0.31	183	40
				(22.1)	(63.9)	(5.6)	(17.7)	(17.1)	(84)	(6)	(146)	(0.07)	(24)	(7)
09-21-93	0810	1010	7	-68.6	257.6	20.4	1.2	-3.1	208	258	832	0.31	190	-31
				(27.3)	(60.6)	(5.1)	(22.6)	(9.8)	(79)	(8)	(120)	(0.04)	(28)	(25)
10-05-93	1400	1425	2	22.2	113.9	8.7	2.7	5.8	153	195	770	0.25	203	26
				(20.4)	(18.7)	(1.5)	(0.9)	(5.6)	(6)	(9)	(10)	(0.02)	(2)	(9)
10-06-93	0800	0915	4	29.1	103.1	8.0	2.9	2.1	145	238	1,050	0.23	276	29
				(7.3)	(34.5)	(2.4)	(4.9)	(1.4)	(45)	(14)	(174)	(0.05)	(45)	(4)
Thomas J. O'Brien Lock and Dam near Burnham, Ill.														
09-14-93	1045	1245	10	1.4	17.0	1.5	4.1	-3.6	20	99	254	0.39	58	-55
				(17.8)	(13.6)	(1.2)	(6.7)	(7.7)	(31)	(9)	(38)	(0.02)	(8)	(358)
09-17-93	0915	1240	10	3.4	14.7	1.4	-0.5	2.3	21	104	958	0.11	218	21
				(5.5)	(7.8)	(0.7)	(5.2)	(3.7)	(10)	(9)	(205)	(0.02)	(47)	(47)
Wilmette Pumping Station at Wilmette, Ill.														
04-06-93	1145	1320	12	20.6	26.9	4.9	-1.4	7.9	59	73	405	0.19	110	54
				(4.8)	(3.4)	(0.6)	(1.3)	(1.6)	(8)	(1)	(81)	(0.04)	(22)	(5)
09-22-93	1520	1610	3	-1.2	8.8	1.6	-4.3	-2.1	3	97	871	0.11	363	71
				(1.1)	(0.9)	(0.2)	(1.8)	(11.1)	(12)	(19)	(224)	(0.01)	(95)	(101)
09-23-93	1200	1300	4	-1.0	-0.2	-2.2	26.3	-16.9	6	89	533	0.21	210	89
				(4.9)	(4.0)	(4.1)	(11.7)	(22.6)	(21)	(20)	(319)	(0.12)	(127)	(14)

Table 5. Concentrations and pumping rates for dye injection at Chicago Lock, July 13-15, 1993
[L, liters; mL, milliliters; min, minutes; mL/min, milliliters per minute]

Date	Volumes of dye and water in injection mixture (L)		Injection concentration (parts per billion)		Volume of mix injected (mL)	Injection time (min)	Injection rate (mL/min)	
	Dye	Water	Mean	Variance			Mean	Variance
July 13	5.4	2.2	1.41×10^8	3.61×10^{12}	3,722	250	14.89	1.64
July 14	5.8	0	2.38×10^8	0	2,247	110	20.43	4.18
July 15	5.0	0	2.38×10^8	0	4,732	276	17.14	5.63

plateau by the time the samples were collected at 1253 hours (fig. 17) and that the dye was fairly well mixed throughout the cross section. The discharge estimated for this dye-dilution measurement is 160 ft^3/s.

Results of quality-assurance samples are listed in tables 6 and 7. Analysis of variance (ANOVA) of normalized concentrations from replicate and split samples indicated that the variance from sampling and analysis was significantly smaller (p less than 0.0001) than the variance across the channel. Concentrations were normalized by dividing by the average of the four depth-averaged concentrations (one from each vertical) from the same sampling transect that the quality-assurance samples were from. These normalized concentrations allowed comparison of samples from days and times with different average dye concentrations in the ANOVA.

Results from blank samples indicated that any contamination was negligibly small compared to the concentration in the river. The mean and standard deviation of the blank samples were 0.06 and 0.09 parts per billion, respectively. In contrast, the mean and standard deviation of the background samples were 0.187 and 0.128, respectively. The two-way Mann-Whitney test (nonparametric t-test) was used to test if the equivalent concentrations of the blank samples were significantly different (α=0.05) from equivalent background concentrations. Results from this test and the observed difference in the means indicated that the equivalent background concentrations were significantly higher than the equivalent concentrations (p equal 0.01) from the blank samples.

Chicago River

The measurements in the Chicago Lock were made to determine the amount of leakage through the lock only. Therefore, the ADCP measurements on the Chicago River were made to determine the total leakage through CRCW into the Chicago River. Most of the Chicago River measurements were made about 20 ft west from the Lake Shore Drive bridge (fig. 2). Several measurements made in April, however, were made at the Columbus Drive bridge and halfway between Columbus Drive and Lake Shore Drive. During the April measurements, the boat was powered across the channel using an outboard or electric trolling motor.

Thirty-nine ADCP measurements were made on the Chicago River in April, July, September, and October 1993 (table 4). The mean and standard deviation of all Chicago River measurements are 192 and 73 ft^3/s, respectively. The highest mean leakage measured was 251 ft^3/s on July 14, and the lowest mean leakage measured was 145 ft^3/s on July 16 and October 6, 1993.

Thomas J. O'Brien Lock and Dam

The leakage through O'Brien is considerably less than at CRCW. While there is noticeable leakage between the sector gates and gate seals in the lock, leakage through the four sluice gates is not visually apparent. Attempts to measure leakage through the sluice gates in September were unsuccessful. Any leakage through the sluice gates was too small to be accurately measured with the ADCP.

Four leakage measurements were made at O'Brien in April 1993. The measurements were made about 100 ft upstream from the lock (Lake Michigan side). An outboard motor was used to power the boat across the Calumet River for each of the four measurements. Because the leakage through the lock and sluice gates was so small and the boat velocity was much larger than the water velocity, accurate measurements were not possible. Therefore, the results of these measurements are not shown in table 4.

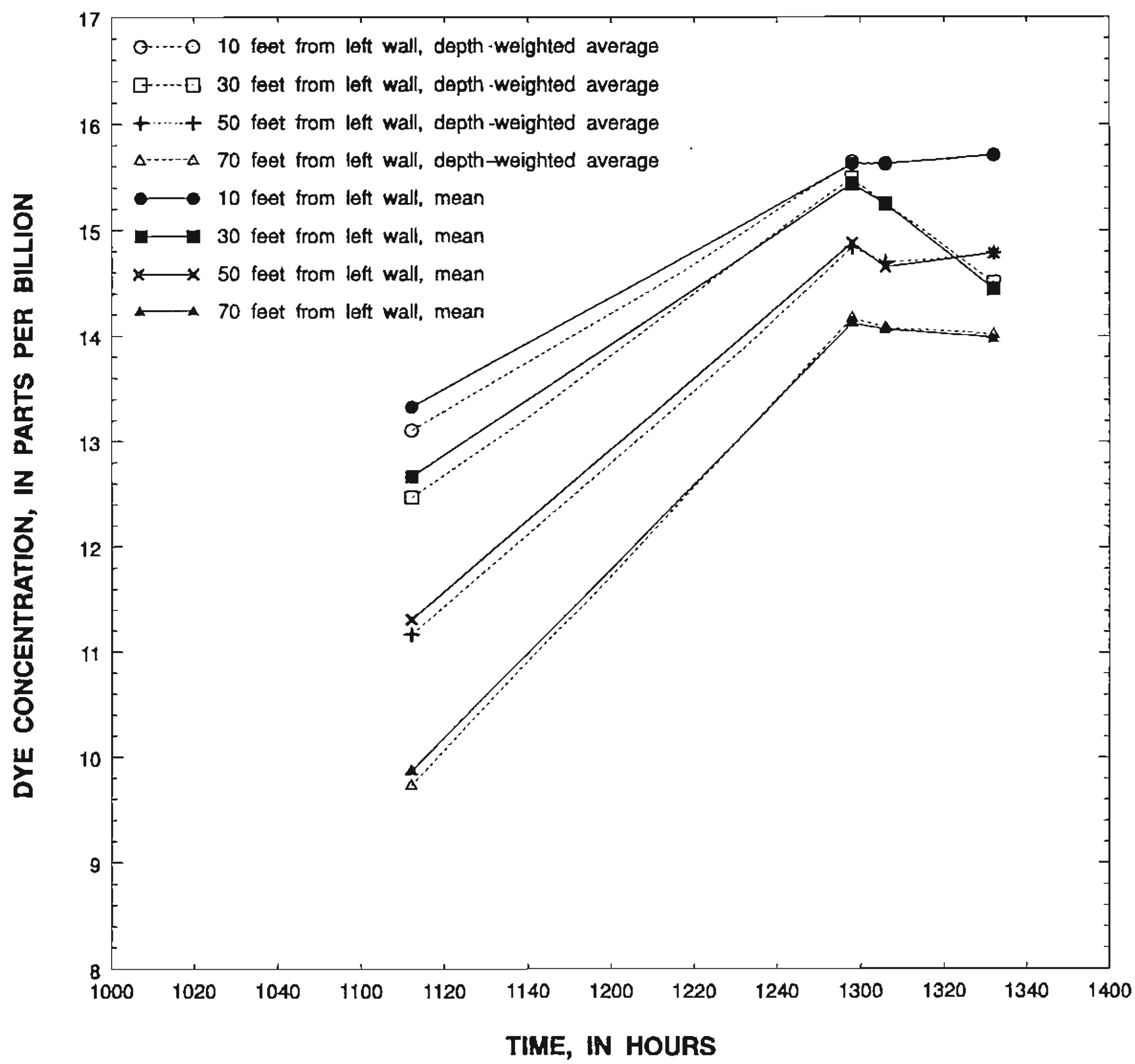


Figure 17. Mean and depth-weighted average concentrations from each vertical sampled at Chicago Lock, July 15, 1993.

Table 6. Results of replicate and split samples collected at Chicago Lock, July 1993

[ft, feet; ppb, parts per billion; calibration number refers to table 2; concentrations were normalized by dividing by the average of the depth-averaged concentrations for all four verticals from the transect that the sample was taken]

Sample number	Sample date	Sample time (hours)	Distance from left edge of lock (ft)	Depth (ft)	Sample type	Calibration number	Fluorometer reading	Mean concentration in transect (ppb)	Equivalent dye concentration (ppb)	Normalized concentration
25	July 13	1138	50	12	Sample	1	2.2	3.24	2.96	0.911
26	July 13	1139	50	12	Replicate of 25	1	2.6	3.24	3.46	1.066
27	July 13	1140	50	12	Replicate of 25	1	2.3	3.24	3.05	.952
39	July 13	1227	30	12	Sample	1	2.1	3.83	2.79	.729
40	July 13	1227	30	12	Replicate of 39	1	2.0	3.83	2.72	.710
48	July 13	1232	70	18	Sample	1	4.5	3.83	6.06	1.582
49	July 13	1233	70	18	Replicate of 49	1	4.0	3.83	5.37	1.402
59	July 13	1311	10	6	Sample	2	1.9	3.66	2.43	.665
60	July 13	1311	10	6	Split of 59	2	1.8	3.66	2.29	.628
61	July 13	1312	10	6	Replicate of 59	2	1.7	3.66	2.16	.590
62	July 13	1312	10	6	Split of 61	2	1.7	3.66	2.18	.598
136	July 15	1256	50	12	Sample	5	9.9	15.02	15.01	.999
147	July 15	1256	50	12	Split of 136	5	10.0	15.02	15.16	1.009
151	July 15	1259	30	18	Sample	5	10.5	15.02	15.95	1.062
152	July 15	1259	30	18	Split of 151	5	10.5	15.02	15.95	1.062
153	July 15	1301	10	6	Sample	5	10.0	15.02	15.21	1.012
154	July 15	1301	10	6	Replicate of 153	5	10.0	15.02	15.21	1.013

Table 7. Results of analysis of blank samples collected at Chicago Lock, July 1993
[ft, feet; ppb, parts per billion; calibration number refers to table 2; dashes indicate no data]

Sample number	Sample date	Sample time (hours)	Distance from left edge of lock (ft)	Depth (ft)	Calibration number	Fluorometer reading	Equivalent dye concentration (ppb)
456	July 14	--	--	--	1	0.2	-0.010
457	July 14	--	--	--	1	.2	-.010
93	July 14	1149	10	0	3	.3	.070
106	July 14	1251	80	0	3	.25	.027
146	July 14	1347	80	0	3	.2	.002
175	July 15	1334	--	--	5	.19	.227
179	July 15	1338	--	--	5	.15	.141

Measurements of the leakage through the lock at O'Brien were made with the ADCP on September 14 and 17, 1993. ADCP measurements were made in the lock about 200 ft away from the downstream sector gates with the windlass assembly to power the boat across the lock. The traverse times across the lock for measurements made on September 14 averaged 254 seconds. These times were considerably faster than traverse times for the measurements made on September 17 because of a malfunction in the windlass. The mean and standard deviation of ADCP measurements made on September 14, 1993, are 20 and 31 ft^3/s, respectively. The mean and standard deviation of ADCP measurements made on September 17, 1993, are 21 and 10 ft^3/s, respectively.

Wilmette Pumping Station

Most of the leakage at Wilmette is through the pump bays in the pumphouse. Little leakage through the sluice gate has been observed. As previously mentioned, in July 1993, MWRD removed the pumps and sealed the pump bays at Wilmette. Prior to the sealing of the pump bays, the leakage through the bays was readily apparent. After the sealing, little or no leakage could be observed.

Three sets of leakage measurements were made at Wilmette with the ADCP: one set on April 6, 1993, and the others on September 22-23, 1993. A tagline was used to pull the boat across the North Shore Channel at Wilmette during the April 1993 measurements. The September 1993 measurements were made with the windlass assembly to power the boat across the channel. A total of 19 transects were made at Wilmette, 12 of which were made on April 6, 1993. The mean and standard deviation of the April 6 ADCP measurements are 59 and 8 ft^3/s, respectively. Leakage during the September measurements was so small that these ADCP measurements are questionable. It is likely that the leakage is less than 15 ft^3/s at Wilmette.

Accuracy of Measurements

The accuracy of the measurements made with the Broadband ADCP cannot be calculated in a rigorous statistical manner at the present time. Although sources of error for narrowband ADCP's have been identified and discussed by a number of investigators, including Simpson and Oltmann (1993), little work has been done to document the errors of Broadband ADCP's.

Uncertainty in ADCP measurements may be both random and systematic. Random errors can be reduced by data averaging; systematic errors cannot be reduced. Random errors may be caused by side-lobe interference, self-noise, or errors in the signal-processing algorithm used in the ADCP (M.R. Simpson, U.S. Geological Survey, written commun., 1993). Theoretical equations for describing the random uncertainty of the Broadband ADCP have not yet been released by the manufacturer. Systematic ADCP errors have been reduced with the introduction of the Broadband ADCP's used in this study because of wider bandwidth in the acoustic signals and a better signal-processing algorithm (M.R. Simpson, U.S. Geological Survey, written commun., 1993). The most significant systematic errors are because of potential misalignment in the beam angles and pitch and roll offsets. The manufacturer has instituted procedures that minimize potential for error in transducer alignment and provides a rigorous test of each ADCP prior to delivery (J. R. Marsden, RD Instruments, oral commun., 1993). Therefore, systematic errors are believed to be less than 3 percent.

Generally, the accuracy of the discharges measured using the ADCP tended to improve with time. Most of this increase in accuracy can be attributed to improvement in measurement technique over time. For the measurements made in April and May 1993, average boat velocities tended to be higher and the number of ensembles lower than those for measurements made in July-October 1993. This is particularly noticeable for measurements made in the Chicago River (see table 4).

The accuracy of the measured ADCP discharges also is reflected in the standard deviations of measured discharges and the sample sizes shown in table 4. The standard deviation of the Chicago River measurements tended to be higher than the standard deviation of measurements elsewhere. This, however, is not only an estimate of measurement uncertainty, but it also may be an indication of the natural variability in flow. At such low velocities, the potential for oscillations in flow and velocity is considerable, particularly at sites such as the Chicago River.

The percentage of the total ADCP discharge that is estimated, including the top and bottom of the water column and the two edges, is also shown in table 4. The percentage estimate shown in table 4 was computed by (1) summing the unmeasured (estimated) discharge (top, bottom, left, and right discharge) and dividing by the total discharge and (2) computing the mean for each transect. The percentage of the discharge estimated (not measured by the ADCP) ranged from -55 percent for O'Brien measurements to 89 percent for Wilmette measurements. For most measurements, however, the discharge estimated with the ADCP ranged from 30 to 40 percent. If the percentage of the discharge estimated is negative, it indicates that one or more of the estimated discharges were negative. For example, on September 21, 1993, a strong wind was blowing from west to east at CRCW. This caused bi-directional flow, with the top layer flowing upstream (eastward) and the rest of the water column flowing downstream (westward). The top discharge shown in table 4 is negative and, therefore, the percentage of discharge estimated is -31 percent.

The effect of the techniques for extrapolating the velocity profile measured by the ADCP was evaluated with sensitivity analysis. The extrapolation technique and the value of the exponent were varied for selected ADCP measurements. The exponent was allowed to vary between 0.11 (1/9) and 0.20 (1/5), representing a range of exponents suggested by various investigators, and the resulting discharge was computed. Results of this sensitivity analysis indicate that the measured discharges are relatively insensitive to changes in the exponent. Figure 18 shows the results of the sensitivity analysis for several transects at CRCW.

The error in the dye-dilution discharges was estimated using a first-order analysis (Ang and Tang, 1975, p. 199) to estimate the effect of error in each measured factor on the error in the calculated discharge assuming that the factors are independent. The equation used to determine the error is

$$S^2(\hat{Q}) = \left(\frac{\partial(\hat{Q})}{\partial(i)}\right)^2 S^2(i) + \left(\frac{\partial(\hat{Q})}{\partial(C_i)}\right)^2 S^2(C_i) + \left(\frac{\partial(\hat{Q})}{\partial(C_s)}\right)^2 S^2(C_s), \quad (6)$$

where

$S^2(\bullet)$ is the variance of the term in parentheses,

$\hat{Q}$ is the estimated discharge, and

$\partial(\hat{Q})/\partial(\bullet)$ is the partial derivative of the discharge with respect to the term •.

The variance of the injection rate was determined from the samples of volume remaining in the dye container at different times. The variance of the injection concentration was determined from analysis of multiple samples of the injection solution. For days that raw dye was injected, the variance in injection concentration was set to zero. The variance in the sampled concentration was determined from the average concentration from each vertical sampled.

The error analysis describes the variance in the estimated discharge for the conditions measured. The sensitivity of the estimated discharge to each term varies as the injection rate, injected concentration, and sampled concentration vary. The variance, expressed as the standard deviation of the estimated discharge on July 15 and computed using equation 6, is 23 ft^3/s. This is a conservative estimate of the variance because

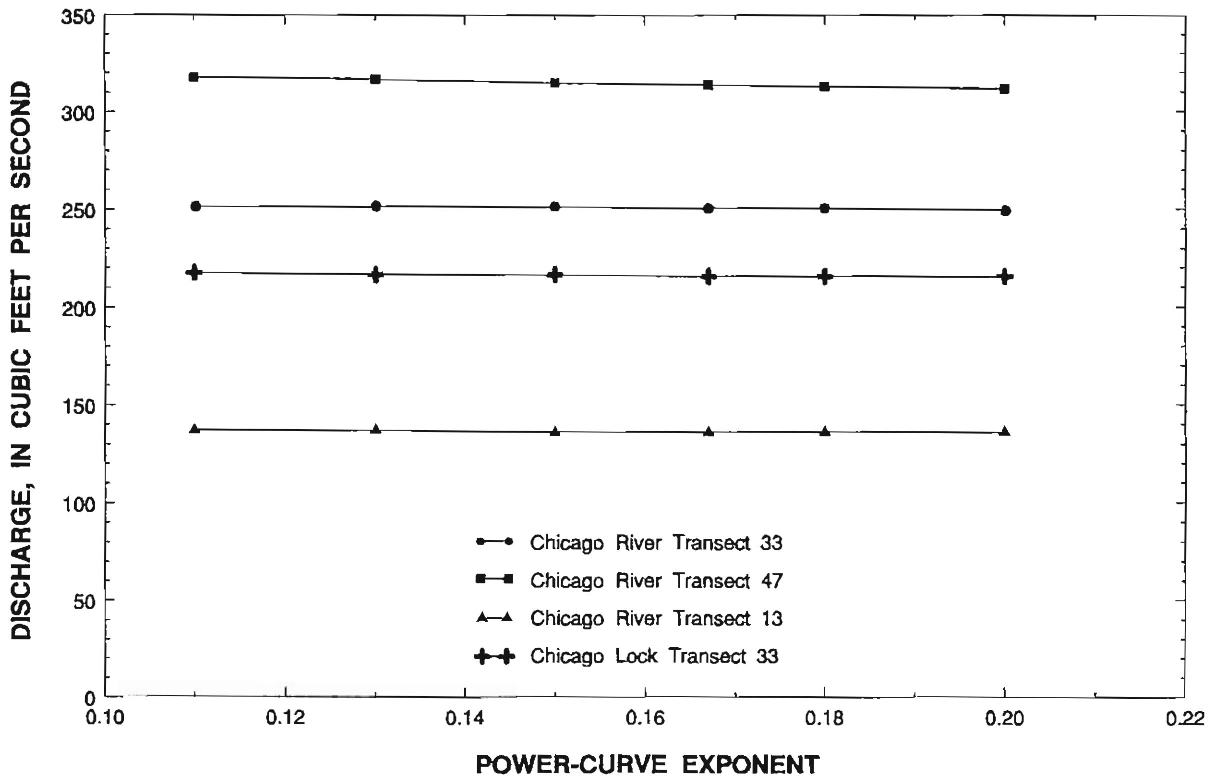


Figure 18. Sensitivity of acoustic Doppler current profiler discharge to changes in the power velocity-distribution law exponent.

it was computed using the variance of the point-sample data rather than the variance of the cross-section averages for the injection rate, injected concentration, and sampled concentration.

The dye-dilution measurements were made because ADCP's have not previously been used to measure such low discharges. Comparison of discharges estimated by dye dilution with those measured with the ADCP show that on July 15, 1993, the dye-dilution estimate of discharge was within 8 percent (12 ft^3/s) of the ADCP-measured discharge. The difference between the two discharges is less than the standard deviation of the dye-dilution discharge estimate.

FUTURE WORK

Study results indicate that the ADCP and dye-dilution leakages should be used with caution. Measurements described in this report give an indication of the order of magnitude of the leakage through each control structure, rather than precise values of leakage. Use of these leakage values to develop a method for predicting leakage at CRCW, O'Brien, and Wilmette for a range of stage differences is not recommended at this time. Estimates of leakage may be more sensitive to factors other than the stage difference at the control structure. For example, the gates at Chicago Lock did not always close to exactly the same position with each use. The effective gate opening is likely to have a much larger effect on the leakage than the head differences normally observed for Lake Michigan and the Chicago River.

The measurement results indicate that additional leakage measurements are needed at each of these locations if more accurate values are desired and if those values are to be used for estimating leakage. Specifically, it is desirable to obtain leakage measurements for a complete range of head conditions at each control structure. The accuracy of the measured leakage may also be improved by increasing the number of transects. Most measurements made in the Chicago River consisted of only 3-5 transects, for example. Alternative techniques for measuring discharge at the Chicago River, such as a Neil-Brown acoustic velocity meter, might be explored. Use of an alternative technique for measuring discharge in the Chicago River would provide greater confidence in the ADCP measurements at this location and improve the possibility of developing a means to estimate leakage.

Dye-dilution measurements can also be done for O'Brien. A continuous injection over a long time period (1 week) should allow for more reliable estimates of leakage at both of these locations. This can be achieved without requiring that the lock be closed to river traffic.

SUMMARY AND CONCLUSIONS

Measurements of leakage were made at three control structures near Chicago, Ill., using acoustic Doppler current profilers (ADCP's) and dye-dilution techniques. The leakage results from the seepage of Lake Michigan water through sea walls and through and around lock gates and sluice gates. The water leaking through each of these structures forms part of the diversion of Lake Michigan water by the State of Illinois. The amount of the Lake Michigan diversion is regulated by U.S. Supreme Court decree.

Leakage measurements were made at the Chicago River Controlling Works (CRCW) (including both the Chicago Lock and the Chicago River), Thomas J. O'Brien Lock and Dam (O'Brien), and Wilmette Pumping Station (Wilmette) in April, May, July, September, and October 1993 using an ADCP. ADCP's are used to measure vertical profiles (ensembles) of water velocities from a moving boat. Water velocities are measured by transmitting short, phase-encoded acoustic pulses along four narrow beams at a known frequency. The ADCP detects and processes the echoes reflected from successive volumes along the beams and determines the time-lag and difference in frequency (frequency shift). The time-lag change and frequency shift between transmitted and reflected sound is proportional to the relative velocity between the ADCP and the suspended material in the water column. The ADCP cannot profile near the water surface, near the channel bottom, near vertical walls, or in water less than 5 ft deep. Velocities near the surface were assumed to be constant and equal to the shallowest water velocity measured by the ADCP. Velocities near the bottom were estimated using an approximation of the 1/6 power velocity-distribution law. Velocities in the unmeasured edges of a channel were estimated using the average velocity of ensembles near each edge.

Dye-dilution measurements of leakage were made at the Chicago Lock in July 1993 to evaluate the discharges measured using the ADCP. Dye-dilution methods to measure discharge are based on a mass-balance calculation for the flow. Most applications of dye-dilution methods to measure discharge are for highly turbulent flows where mixing is not a problem. In the application used in the study and described in this report, an injection manifold was designed for mixing of the dye in the flow because leakages were too small for adequate mixing.

A total of 221 discharge measurements were made with the ADCP. The greatest mean leakage measured for the lake gate at Chicago Lock was 961 ft^3/s. However, because the river gate is normally closed, the leakage through that gate is a better estimate of the normal leakage through the Chicago Lock. The mean and standard deviation of leakage measured by the ADCP for the Chicago Lock river gate were 133 and 38 ft^3/s, respectively. The mean and standard deviation of ADCP leakage measurements at CRCW were 192 and 73 ft^3/s, respectively. River-gate leakage accounted for more than half of the total leakage measured at CRCW. The mean and standard deviation of leakage measured at O'Brien on September 17, 1993, were 21 and 10 ft^3/s, respectively. Leakage measurements at O'Brien on September 14, 1993, were less accurate; the mean and standard deviation were 20 and 31 ft^3/s, respectively. The mean and standard deviation of April 1993 leakages measured at Wilmette using the ADCP were 59 and 8 ft^3/s, respectively. After the Metropolitan Water Reclamation District of Greater Chicago sealed the pump bays at Wilmette in July 1993, the leakage dropped to less than 15 ft^3/s in September 1993.

Discharges were estimated by dye dilution at Chicago Lock on July 13-15, 1993. The measurements made on July 13-14 did not meet the criteria for a good dye-dilution measurement and, therefore, were not used for further analysis. On July 15, the leakage through the Chicago Lock river gates was estimated by dye dilution to be 160 ft^3/s or within 8 percent of the ADCP-measured discharge.

The sensitivity of ADCP-measured discharges to changes in the power velocity-distribution law exponent was evaluated. The exponent was varied from 0.11 (1/9) to 0.20 (1/5) for a number of transects near CRCW. Results indicate that for the leakages being measured, discharges are insensitive to the changes in the exponent.

ADCP measurements made in April and May 1993 are less accurate than those made in July, September, and October 1993. The improved accuracy obtained for measurements after May 1993 is primarily due to improvements in ADCP measuring techniques. Results of the measurements reported here should be used with caution and should probably not be used to estimate leakage based only on stage differences at the three control structures. Although the results of the ADCP measurements are, in general, acceptable, improvements in measurement methods can be made. Alternative methods for measuring discharge at the Chicago River, such as the use of an acoustic velocity meter, might provide more reliable leakage information at this location. Similarly, dye-dilution measurements could be made at O'Brien and Wilmette if more reliable estimates of leakage are necessary.

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APPENDIXES

APPENDIX 1. SUMMARY OF FLUOROMETER CALIBRATIONS, JULY 15-16, 1993

[ppb, parts per billion]

Date	Time (hours)	Standard concentration (ppb)	Fluo-rometer scale	Fluo-rometer reading
		Calibration 4		
July 15	0925	0.5	3	0.63
July 15	0927	1	3	1.23
July 15	0929	5	10	4.30
July 15	0930	20	30	15.0
July 15	0932	25	30	18.5
July 15	0934	50.	100	40
July 15	0935	100	100	78
		Calibration 5		
July 16	0906	.5	3	.55
July 16	0907	1	3	1
July 16	0909	5	10	3.7
July 16	0911	20	30	13.
July 16	0913	25	30	15.5
July 16	0915	50	100	34
July 16	0917	100	100	68
		Calibration 5.5		
July 16	1057	1	3	.90
July 16	1059	5	10	3.5
July 16	1100	20	30	12.5
July 16	1102	25	30	15.5
July 16	1103	50	100	33
July 16	1105	100	100	64

APPENDIX 2. SUMMARY OF ALL DYE SAMPLES COLLECTED FROM THE CHICAGO LOCK, BOTH GATES SHUT, JULY 15, 1993

[ft, feet; ppb, parts per billion; ±, plus or minus; <, less than; calibration number refers to table 5; shaded lines indicate background samples; the suffix 's' on the sample number indicates a split sample; dashes indicate no data]

Sample number	Sample date	Sample time (hours)	Distance from left edge of water (ft)	Sample depth (ft)	Analysis date	Analysis time (hours)	Fluo-rometer readings	Calibration number	Dye concen-tration (ppb)	95-percent confidence interval for dye concen-tration (ppb)
113	July 15	0853	70	12	July 15	0910	±0.35	4	0.38	±0.01
114	July 15	0854	50	12	July 15	0912	±.40	4	.45	±.01
115	July 15	0855	30	12	July 15	0914	±.32	4	.34	±.01
116	July 15	0856	10	12	July 15	0916	±.30	4	.32	±.01
117	July 15	1104	70	6	July 16	0920	7.00	5	10.56	±.33
118	July 15	1105	70	12	July 16	0922	7.00	5	10.56	±.33
119	July 15	1108	70	18	July 16	0923	5.60	5	8.49	±.26
120	July 15	1110	50	6	July 16	0925	9.10	5	13.68	±.42
121	July 15	1111	50	12	July 16	0926	7.70	5	11.61	±.36
122	July 15	1112	50	18	July 16	0927	5.70	5	8.64	±.27
123	July 15	1114	30	6	July 16	0929	9.70	5	14.59	±.45
124	July 15	1115	30	12	July 16	0931	8.90	5	13.41	±.41
125	July 15	1116	30	18	July 16	0933	6.60	5	9.99	±.31
126	July 15	1117	10	6	July 16	0935	9.50	5	14.32	±.44
127	July 15	1118	10	12	July 16	0936	9.60	5	14.47	±.45
128	July 15	1119	10	18	July 16	0938	7.40	5	11.20	±.34
129	July 15	1211	40	6	July 16	0940	11.00	5	16.58	±.51
130	July 15	1213	40	12	July 16	0943	11.00	5	16.60	±.51
131	July 15	1214	40	18	July 16	0944	10.00	5	15.11	±.47
132	July 15	1253	70	6	July 16	0946	9.10	5	13.77	±.42
133	July 15	1254	70	12	July 16	0947	9.20	5	13.92	±.43
134	July 15	1254	70	18	July 16	0950	9.70	5	14.69	±.45
135	July 15	1255	50	6	July 16	0953	10.00	5	15.15	±.47
136	July 15	1256	50	12	July 16	0955	9.90	5	15.01	±.46
147	July 15	1256	50	12	July 16	0954	10.00	5	15.15	±.47
148	July 15	1257	50	18	July 16	0958	9.50	5	14.42	±.44
149	July 15	1258	30	6	July 16	1000	10.00	5	15.18	±.47
150	July 15	1258	30	12	July 16	1001	10.00	5	15.19	±.47
151	July 15	1259	30	18	July 16	1002	10.50	5	15.95	±.49
152	July 15	1259	30	18	July 16	1003	10.50	5	15.95	±.49
153	July 15	1301	10	6	July 16	1005	10.00	5	15.21	±.47
154	July 15	1301	10	6	July 16	1006	10.00	5	15.21	±.47
155	July 15	1302	10	12	July 16	1008	10.30	5	15.68	±.48
156	July 15	1302	10	18	July 16	1011	10.50	5	15.99	±.49
157	July 15	1304	30	6	July 16	1013	10.00	5	15.24	±.47
158	July 15	1304	30	12	July 16	1014	10.00	5	15.25	±.47
159	July 15	1305	30	18	July 16	1015	10.00	5	15.25	±.47
160	July 15	1307	50	6	July 16	1016	9.70	5	14.80	±.45
161	July 15	1307	50	12	July 16	1018	9.40	5	14.35	±.44
162	July 15	1308	50	18	July 16	1020	9.70	5	14.82	±.45

APPENDIX 2. SUMMARY OF ALL DYE SAMPLES COLLECTED FROM THE CHICAGO LOCK, BOTH GATES SHUT, JULY 15, 1993—Continued

Sample number	Sample date	Sample time (hours)	Distance from left edge of water (ft)	Sample depth (ft)	Analysis date	Analysis time (hours)	Fluorometer readings	Calibration number	Dye concentration (ppb)	95-percent confidence interval for dye concentration (ppb)
163	July 15	1309	70	6	July 16	1021	9.00	5	13.75	±0 .42
164	July 15	1310	70	12	July 16	1023	9.20	5	14.07	± .43
165	July 15	1311	70	18	July 16	1025	9.40	5	14.38	± .44
166	July 15	1327	70	6	July 16	1027	8.90	5	13.62	± .41
167	July 15	1328	70	12	July 16	1029	9.10	5	13.94	± .42
168	July 15	1329	70	18	July 16	1032	9.40	5	14.41	± .44
169	July 15	1330	50	6	July 16	1034	9.70	5	14.88	± .45
170	July 15	1330	50	12	July 16	1036	9.60	5	14.74	± .45
171	July 15	1331	50	18	July 16	1037	9.60	5	14.74	± .45
172	July 15	1333	30	6	July 16	1038	9.60	5	14.74	± .45
173	July 15	1333	30	12	July 16	1041	9.10	5	13.99	± .42
174	July 15	1334	30	18	July 16	1043	9.50	5	14.61	± .44
176	July 15	1336	10	6	July 16	1045	10.20	5	15.70	± .47
177	July 15	1337	10	12	July 16	1048	10.20	5	15.72	± .47

APPENDIX 3. REVIEW OF U.S. GEOLOGICAL SURVEY DATA COLLECTED IN THE CHICAGO AREA USING AN ACOUSTIC DOPPLER CURRENT PROFILER

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Review of U.S. Geological Survey Data collected in the Chicago area using an Acoustic Doppler Current Profiler.

Discharge measurements at several sites in the Chicago area were collected by the U.S. Geological Survey between May and October 1993. The data were acquired using a Acoustic Doppler Current Profiler (ADCP). The sites are on the Chicago River and in or near control structures that allow water to pass from Lake Michigan into the Chicago River. Of particular interest for this review are those measurements collected when all sluice gates and/or locks were in their closed positions.

In the following, an overall review of the general quality of the data is given and some specific measurements are examined in detail. The emphasis is on determining the accuracy of the data relative to the expected performance of the instrument and the technique used to compute the discharge.

An ADCP measures a vertical profile of the horizontal velocity of the water. The velocity is determined in a number of discrete bins known as 'depth cells' (see Figure 1). The ADCP also measures its own velocity relative to the bottom of the channel. This velocity is then subtracted from the water's velocity relative to the ADCP to determine the velocity of the water relative to the earth. The total discharge through the section of the water actually measured by the ADCP is the time integral of the cross product of the ADCP's velocity and the water's velocity. This computation is done using software supplied with the ADCP.

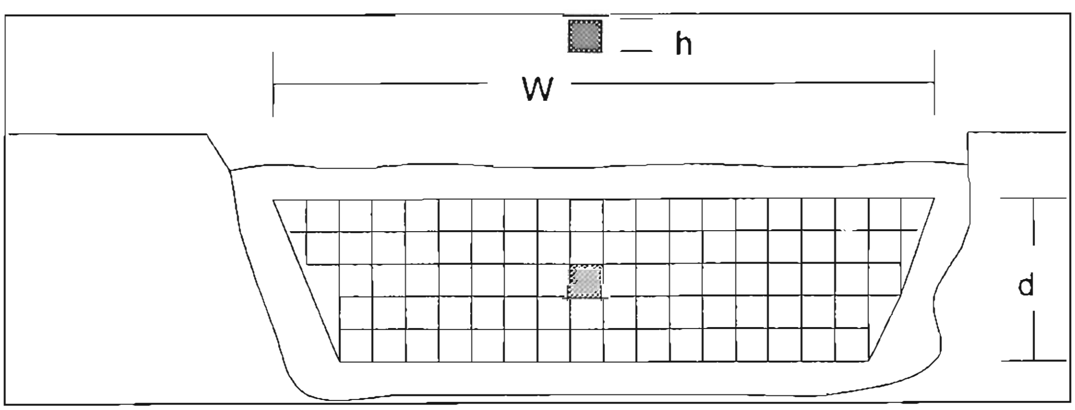

Figure 1
Channel section actually measured with an ADCP

It is important to note that the ADCP does not measure the entire water column. There are layers on the top and bottom that are not measured; likewise for the edges. The discharge in these unmeasured sections is extrapolated from the data actually acquired with the ADCP. The user has some control over the method of extrapolation.

The error of a discharge measurement has a number of possible sources. The prominent contributions are:

- the ADCP's inherent measurement errors
- extrapolation of the unmeasured discharge
- temporal fluctuations in flow

For the ADCP used in these measurements, it can be shown that the instrument's contribution to error in the discharge calculated for the section directly measured by the ADCP is given by

$$\Delta Q_{ADCP} = \sigma_v \sqrt{Whdv_b t}$$

where v_b is the average velocity of the boat,
σ_v is the single ping standard deviation of the ADCP,
t is the time for an individual ping.

The expected error in the top layer extrapolation (extrapolating the uppermost depth cell velocity to the surface, known as constant extrapolation) is given by

$$\Delta Q_{top} = \sigma_v l \sqrt{Wv_b t}$$

where l is the thickness of the extrapolated layer.

The error predicted for one side's discharge extrapolation is given by

$$\Delta Q_{side} = \sigma_v \frac{.707 L d_m}{2} \sqrt{\frac{h}{d w_p}}$$

where d_m is the actual depth of the vertical section nearest the shore
w_p is the number of pings in the vertical section.

Note that the section referred to above may have comprise many individual pings or ensembles of pings averaged together. The total side extrapolation error will include the error from both sides of the channel. The .707 factor may change depending on the geometry of the channel banks.

The three equations above allow the total measurement error to be estimated. There are other less significant errors; these will be ignored for the following discussion.

Case Study: Chicago River at Lake Shore Drive

As an example to analyze, consider the measurement on 9/21/93 in file RIV1043R.000. The approximate parameters for this run are

W	72 meters	L_1	2.5 meters
d	6 meters	L_2	5.0 meters
v_b	0.1 meters/sec	d_{m1}	3.5 meters
v_w	0.015 meters/sec	d_{m2}	5.0 meters
h	0.25 meters	t	1.0 sec
σ_v	0.10 meters/sec.	l	1.5 meters
w_p	5 pings		

The 0.707 factor used to estimate edge discharge was changed to 0.91 for this channel

From these parameters, the various components of the measurement error are estimated to be

$$\Delta Q_{ADCP} = 0.33 \text{ m}^3/\text{s} = 12 \text{ cfs}$$
$$\Delta Q_{top} = 0.40 \text{ m}^3/\text{s} = 14 \text{ cfs}$$
$$\Delta Q_{side1} = 0.07 \text{ m}^3/\text{s} = 2.5 \text{ cfs}$$
$$\Delta Q_{side2} = 0.15 \text{ m}^3/\text{s} = 5.1 \text{ cfs}$$

In addition to these errors, the other errors not accounted for in detail here (such as turbulence or temporal variations in the flow) will be, in aggregate, on the order of the top layer error. This gives a total estimated error of roughly 48 cfs for this measurement.

A total of 7 discharge measurements were made at this site on 9/21/93 under similar conditions. For those seven measurements, the calculated standard deviation is 67 cfs. This is in fair agreement with the error predicted above. The slightly higher than estimated error may be due to a shear in the vertical velocity profile that was present during these runs. The top few feet were flowing east while the underlying water was flowing west. This shear condition will add an error term that is not accounted for above.

With this one exception, the data from these measurements are consistent with the error that should be expected for the flow conditions present. The overall quality of the data is quite good. The ADCP data itself exhibits good backscatter strength (for a good signal to noise ratio) and nearly ideal correlation (one of the ADCP's measures of the quality of the data). There are no BIT (built in test) errors in the data, so that based on the self test routines that occur on every ping the instrument appears to be functioning correctly.

Overview of the data at all three sites

Chicago River at Lake Shore Drive

Only data collected with the lock gates and sluice gates all closed are considered here. In particular the data from 9/20, 9/21, 10/5 and 10/6, 1993 are examined. For all four sets of data, the average flow velocity, and river cross section are similar. Based on the ADCP's indicators of data quality, the raw data are all valid. The average discharge (except for the edges) is 210 ± 85, 220 ± 70, 145 ± 10, and 140 ± 44 cfs for the three days respectively. And for each set of data, the edge distances and hence the edge contributions will be about the same. From the case study above, we know the edge discharge is about 10 cfs. The final values, which include edge discharge, given in Table 4 of the body of the report (Oberg and Schmidt, 1994) are reasonable and accurate values.

Thomas O'Brien Lock and Dam

Measurements of leakage through the lock were collected on two days, 9/14 and 9/17, 1993. On 9/14, the time taken to cross the channel was typically 3 to 4 minutes. while on 9/17, the time was between 15 and 20 minutes. The longer data acquisition times on 9/17 yielded much better quality data. Neglecting the edge areas, the discharge results were 19.5 ± 21.7 cfs and 22.1 ± 7.4 cfs on 9/14 and 9/17 respectively. Using the earlier formula for the error contributions, we predict an error of 2.7 cfs from the ADCP, and a top layer error of 4.0 cfs, for a total of 6.7 cfs from those sources for the data of 9/17. This is in excellent agreement with the actual data. For the data of 9/14, the same errors are 5.9 cfs and 8.9 cfs for a total of 14.8 cfs, also consistent with the actual results.

Data files OBR1093R.000 and OBR1099R.000 we examined in detail. All quality indications from the ADCP were good, and the instrument registered no self test errors. Using the average measured velocity and the edge distances for the runs of 9/17, the total edge discharge is 2.5 cfs. So, the total average leakage through the O'Brien Lock is roughly 24 ± 7.5 cfs on 9/17/93.

Wilmette Pumping Station at Wilmette, IL.

Again, only data collected with all gates closed is analyzed. For the data collected on 9/22/93, the flow was organized but very slow, with an average velocity of 0.023 ft/sec. The average discharge (without the edges) is 8.3 ± 1.3 cfs. This is consistent with a predicted error of 1.5 cfs for the channel parameters. With edge estimates, the flow is 9.0 ± 1.5 cfs. For the data collected on 9/23/93, the dominant flow feature is an eddy structure that fills the volume measured. The discharge measured with the ADCP is 3.1 ± 1.1 cfs. However, for this case, the edge estimates may dominate the total flow: this is because the highest velocities are at the edges of the flow rather than in the middle. An average velocity cannot be used to extrapolate the flow in these regions.

The data from files WLM1004R.000 and WLM1028R.000 were examined in detail. All the data were within acceptable limits by all criteria that the ADCP makes available. The speed of the boat was sufficiently slow to keep the measurement technique effects from dominating the data.

This site is the most difficult of the three because of its shallow depth and the very low water velocity. The data collected on 9/22/93 are the more reliable of the two data sets because the flow was more uniform without the large scale circulation evident in the data of 9/23/93.

Summary

All of the data that were reviewed appear to be of high quality. The ADCP had sufficient signal, the pulse-to-pulse correlation coefficient was within acceptable bounds, and the ADCP reported no BIT errors during the data sets reviewed in detail.

The statistical error of the data is in good agreement with theoretically predicted statistical error for the channel geometry and flow velocities involved at the three sites (when the edge discharge estimates are neglected).

An important parameter in achieving these results was the extremely slow boat speeds that were used on many of the measurement runs. The average boat speed was 2 cm/sec for many of these channel transects. This allowed a sufficiently large number of individual data points to be gathered to bring the statistical errors down low enough so as not to dominate the very low velocities encountered at these sites. These discharge measurements are the lowest values ever achieved with such good statistical reproducibility.

References

Oberg, K. A. and Schmidt, A. R., *Measurements of Leakage from Lake Michigan through Three Control Structures near Chicago, Illinois, April - October, 1993* (1994).

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