Horizontal and Vertical Acoustic Measurements for the Computation of Discharge in the Chicago River System

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ABSTRACT

In 1900, the city of Chicago completed construction of a canal project that effectively reversed the flow of a portion of the Chicago River to divert wastewater away from the city's water-supply intakes in Lake Michigan. Two additional canals were completed within the Chicago River system by 1930, which resulted in direct diversion from Lake Michigan to the Chicago River system at three lakefront locations. Diversion of Lake Michigan water at Chicago is limited to a mean annual flow of 90.61 cubic meters per second by U.S. Supreme Court decree.

For most of its length, the canal system is cut into bedrock and is approximately 45-76 meters wide. Commercial barge traffic on the canals is appreciable and requires a navigational depth of 4.5-6.1 meters. The primary factor affecting flow in the canal system is the water-surface slope. The Chicago River system has little slope, as little topographic relief is present in the surrounding area. Drainage within the system is managed using three lakefront control structures and one downstream control structure that maintain the water-surface slope for flow in a direction away from the lakefront. At any given time, water in the Chicago River system is a combination of runoff, wastewater effluent, and water from direct diversions at the control structures.

The U.S. Geological Survey measures flow in the Chicago River system at four acoustic velocity meter-gaging stations. Large cross-sectional areas, little slope, and low total discharge (from 0 to 17 cubic meters per second) result in low velocities (from 0.00 to 6.0 centimeters per second). Variable conditions at the upstream and downstream control structures causes highly unsteady flows. Flow also is affected by additional physical factors, such as wind speed, wind direction, contrasting water density, and a high volume of boat traffic. Accurate discharge records are difficult to compute considering these factors. Horizontal and vertical acoustic instruments are utilized to compute discharge records at the gaging stations. An upward-looking acoustic Doppler current profiler is deployed on the channel bottom and a vertical string of temperature probes on one channel wall at one station to help define periods of bi-directional flow related to density currents. Time-series filters have been applied to resolve periods with erroneous spikes in the horizontal line velocity data. Discharge is computed using an index-velocity method that relates measured horizontal line velocities from acoustic velocity meters to mean channel velocity from acoustic Doppler current profiler measurements. An alternative method of computing discharge involves measuring horizontal line velocities at different depths to compute discharge in layers currently is being evaluated. Application of this method may improve the accuracy of the discharge computations during periods of bi-directional flow.

INTRODUCTION

Background: The city of Chicago withdraws its municipal water supply from Lake Michigan. Beginning with the completion of a canal system in 1900, water withdrawn from Lake Michigan has been diverted out of the Lake Michigan Basin and into the Chicago River system to keep wastewater away from the drinking-water intakes located in the lake. Neighboring States opposed to the diversion initiated a series of court battles that resulted in a U.S. Supreme Court decree limiting the state of Illinois to a diversion of 90.61 cubic meters per second.

Since 1984, the U.S. Geological Survey (USGS) has operated and maintained a gaging station on the Chicago River system for the purpose of determining the mean annual flow diversion from Lake Michigan at Chicago. In 1996, three additional stations were installed on the Chicago River system to better define the distribution of flows between the three separate withdrawal points from the lake: the Chicago River, the Calumet River, and the North Shore Channel.

Purpose and Scope: The purpose of this paper is to describe the application of horizontal and vertical acoustic flow measurements in the Chicago River system. These measurements are used to determine the mean annual flow diversion from Lake Michigan.

PHYSICAL SETTING

Prior to 1900, the north and south branches of the Chicago River joined at a location approximately 2.0 km west of the lakefront and flowed into Lake Michigan (Fig. 1). Runoff from large storms would wash the build-up of untreated sewage out into the lake in the vicinity of the drinking-water intakes. This sewage contributed to the spread of diseases related to contaminated drinking water (Hill, 2000). City engineers decided on a plan to breach a low drainage divide between the Lake Michigan Basin and the adjacent Des Plaines River Basin, and divert the water away from the lake. Canal construction continued into the 1920's and resulted in the present post-diversion drainage system (Fig. 1).

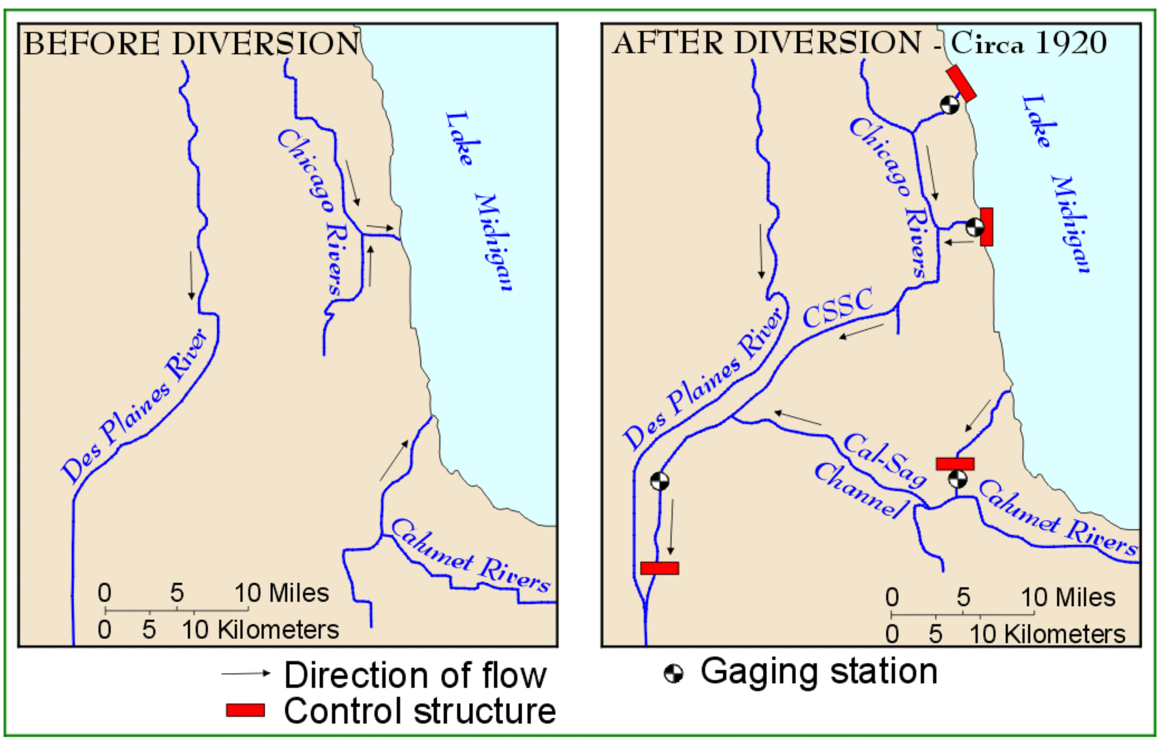

Fig. 1. The Chicago River system before and after construction of diversion projects.

The Chicago River system currently consists of a combination of natural and excavated channels in the upper reaches of the basin and a man-made canal system that is cut into bedrock in the middle and lower portions of the basin. The basin has little topographic relief (approximately 10-20 meters). The entire system includes almost 200 kilometers (km) of channels and canals. The bed slope for the excavated canals is in the range of .00004 (3.8 cm/km). The slope of the water-surface primarily controls flow within the Chicago River system. The water-surface slope is controlled at three lakefront locations where water is diverted directly from the lake through control structures and by a control structure at the lower end of the system at Lockport (Fig. 1). Commercial barge traffic is appreciable and requires a navigational depth of 4.5-6.1 meters.

Low bed-slope and relatively large channel cross-sections produce hydraulic conditions in which low velocities are common. Variable control structures at the upstream and downstream ends of the system result in extremely unsteady, low-velocity flow conditions. Diurnal effects of wastewater discharged at three locations within the system contribute additional complexity to the task of making accurate flow measurements. All of these factors combine to produce a hydrologic setting that can only be measured with acoustic methodology.

Chicago Sanitary and Ship Canal at Romeoville

In 1984, the USGS installed a multi-path acoustic velocity meter (AVM) 8.4 kilometers above the control structure at the lower end of the system at Romeoville, Illinois. Higher discharges and velocities are present in the lower reaches of the system, but extremely unsteady flow conditions result in these reaches because of frequent lockages and changes in turbine settings at a hydroelectric station. This reach is cut into bedrock with vertical walls and depths typically range from 6 to 8 meters. Multiple upward-looking ADCP's and horizontal ADCP's have been deployed in this reach at various times to investigate horizontal and vertical flow variation in the cross-section. In a comparison with a four-path AVM (Oberg and Duncker, 1999), the ADCP results indicated that depth-averaging the data from the vertical profiler better determines the mean channel velocity than the horizontal profiler in this site.

Chicago River at Columbus Drive at Chicago

In response to the need for more detailed information on direct diversions, three additional AVM stations were installed in 1996 at locations near each of the lakefront control structures. Each of these sites can be characterized by low velocity (+/- 0.06 meter per second) conditions consisting of small discharges (0-17 cubic meters per second) through a relatively large (418 square meters) cross section. In the Chicago River at Columbus Drive, the low velocity, density currents present on a seasonal basis further complicate unsteady flow conditions. Discharge measurements using an ADCP first revealed bi-directional flow where the lower half of the water column was moving in a direction opposite the upper half of the water column. Continuous monitoring of the vertical velocity profile using an upward-looking ADCP at this site has defined the persistence and magnitude of the density currents. This monitoring will be important in managing the water quality in the Chicago River. Further investigation has revealed that the density currents form when water with a high percentage of wastewater effluent from the North Branch of the Chicago River meets colder, less dense, water from Lake Michigan. The seasonal aspect of the density current formation is a function of winter periods when diversions through control structures are reduced and water temperatures result in density contrasts.

DISCHARGE COMPUTATION

Velocity and stage data are collected at 5-minute increments at each site to capture the unsteady flow characteristics. Bathymetric surveys are used to develop stage-area ratings. Discharge is computed with an index-velocity method. Acoustic Doppler current profiler discharge measurements are used to define an index-velocity rating. This rating relates the velocity measured by the acoustic instrument to the mean channel velocity Periods when density currents form and bi-directional flow develops can cause problems with the acoustic signal of the AVM's. During these periods, mixing water temperatures along the path length of the acoustic signal may cause ray bending. Under these conditions, the AVM does not measure accurate velocity data. Alternative methods of computing discharge have been used and continue to be evaluated at this time. Depth-averaging the velocity data from the vertical profilers has provided a good indication of the mean channel velocity at some sites (Oberg and Duncker, 1999). Index-velocity ratings between the depth-averaged velocity from the vertical profiler and the mean channel velocity as defined by ADCP discharge measurements currently are being evaluated. However, indexing the depth-averaged velocity data is not appropriate at all sites because of horizontal variation in velocity across the channel.

FUTURE WORK

Data from horizontal and vertical acoustic profilers continues to define the complex flow conditions in the Chicago River system. Alternate methods for computing discharge using a combination of horizontal and vertical profilers are being evaluated. Increasing the accuracy of discharge computations, especially during periods when density currents are present, should lead to more accurate assessment of the overall diversion and better management of the Chicago River system. The velocity and discharge data collected from the Columbus Drive station (Fig. 1) also are being used to calibrate a three-dimensional hydraulic model to further investigate density currents. Currently, providing telemetry for near real-time data acquisition to a vertical profiler is being implemented. Near real-time access to the velocity data from the profiler will provide information that can be used in managing the water quality in the Chicago River system.

CONCLUSIONS

Horizontal and vertical acoustic profilers are providing data that define the complex, low-velocity flow found in the Chicago River system. The knowledge gained from the analysis of the acoustic flow data and continued improvement in instrumentation should lead to more accurate measurement of flow within this system and better management of the diverted water.

REFERENCES

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