In cooperation with the
U.S. ARMY CORPS OF ENGINEERS, CHICAGO DISTRICT

Monitoring and Analysis of Combined Sewer Overflows, Riverside and Evanston, Illinois, 1997-99

By Andrew M. Waite, Nancy J. Hornewer, and Gary P. Johnson

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CONVERSION FACTORS, VERTICAL DATUM, AND ABBREVIATIONS

Multiply	By	Obtain
	Length	
inch (in.)	2.54	centimeter
foot (ft)	0.3048	meter
mile (mi)	1.609	kilometer
	Area	
acre	0.004047	square kilometer
square foot (ft^2)	0.09290	square meter
square mile (mi^2)	2.590	square kilometer
	Volume	
cubic foot (ft^3)	0.02832	cubic meter
	Flow rate	
foot per second (ft/s)	0.3048	meter per second
cubic feet per second (ft^3/s)	0.02832	cubic meters per second
	Mass	
pound, avoirdupois (lb)	0.4536	kilogram

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 level nets of both the United States and Canada, formerly called Sea Level Datum of 1929.

Altitude, as used in this report, refers to distance above or below sea level.

Concentrations of chemical constituents in water are given either in milligrams per liter (mg/L) or micrograms per liter (µg/L).

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ABSTRACT

The U.S. Geological Survey, in cooperation with the U.S. Army Corps of Engineers, collected and analyzed flow data in combined sewer systems in Riverside and Evanston, northeastern Illinois, from March 1997 to December 1999. Continuous 2- and 5-minute stage and velocity data were collected during surcharged and non-surcharged conditions at 12 locations. Mass balances were calculated to determine the volume of water flowing through the tide-gate openings to the Des Plaines River and the North Shore Channel and to determine the volume of water flowing past the sluice gate to the deep tunnel.

The sewer systems consist of circular pipes ranging in diameter from 0.83 feet to 10.0 feet, elliptical siphon pipes, ledges, and tide and sluice gates. Pipes were constructed of either brick and mortar or concrete, and ranged from having smooth surfaces to rough, pitted and crumbling surfaces. One pipe was noticeably affected by water infiltration from saturated ground.

During data analysis, many assumptions were necessary because of the complexity of the flow data and sewer-system configurations. These assumptions included estimating the volume of water entering an interceptor sewer at the “Gage Street pipe” at Riverside, the effect of infiltration on the “brick pipe” at Riverside, and the minimum velocity required for the meter to make an accurate velocity determination. Other factors affecting the analysis of flow data included possible non-instrumented sources of inflow, and backwater conditions in some pipes, which could have caused error in the data analysis. Variations of these assumptions potentially could cause appreciable changes to the final mass-balance calculations.

Mass-balance analysis at Riverside indicated a total inflow volume into chamber 3 of approximately 721,000 cubic feet (ft^3) during April 22-26, 1999. Outflow volume to the Des Plaines River at Riverside through the tide gate was approximately 132,000 ft^3; outflow volume to the deep tunnel through the sluice gate was approximately 267,000 ft^3. The mass-balance analysis at Evanston indicated a total inflow volume into chamber 3 of approximately 5,970,000 ft^3 during April 21-26, 1999. The outflow volume to the North Shore Channel through the tide gates at Evanston was approximately 2,920,000 ft^3; outflow volume to the deep tunnel through the sluice gates was approximately 3,050,000 ft^3.

INTRODUCTION

The U.S. Army Corps of Engineers, Chicago District (Corps), is designing a flood-control reservoir as part of the Chicago Underflow Plan/Tunnel and Reservoir Plan (CUP/TARP) that will provide storage for combined sewage from the Des Plaines and Mainstream tunnel systems (fig. 1). The proposed McCook reservoir is intended to reduce flood damages and minimize the release of untreated combined sewage into local area waterways (U.S. Army Corps of Engineers, 1998). The Des Plaines and Mainstream Tunnel systems (referred to as the deep tunnel) are designed to transport combined sewage to the flood-control reservoir when flows exceed the capacity of the West-Southwest Water Reclamation Plant (referred to as Stickney).

In order to design a cost-effective aeration system for the reservoir, it is necessary to determine the quality and quantity of water expected to enter the reservoir during large rain storms. For this reason, the biochemical oxygen demand (BOD) and other water-quality characteristics of the influent combined sewage for rain storms from 1 to 2 in. and greater are required. The Metropolitan Water Reclamation District of Greater Chicago (MWRDGC) collected water-quality samples at the Riverside and Evanston combined sewer overflow (CSO) locations, the Calumet pumping station, and at the Racine pumping station (fig. 1). To determine the BOD load during these storms, flow data, in addition to water-quality data, are required. The U.S. Geological Survey (USGS), in cooperation with the Corps, monitored and analyzed combined-sewer flow data at Riverside and Evanston, Ill. (fig. 1). The data-collection locations at the Riverside and Evanston combined sewers represent only two of many potential overflow points in the Des Plaines and Mainstream Tunnel systems. The qualitative and quantitative data collected at these two locations will be used to estimate, on a larger scale, the

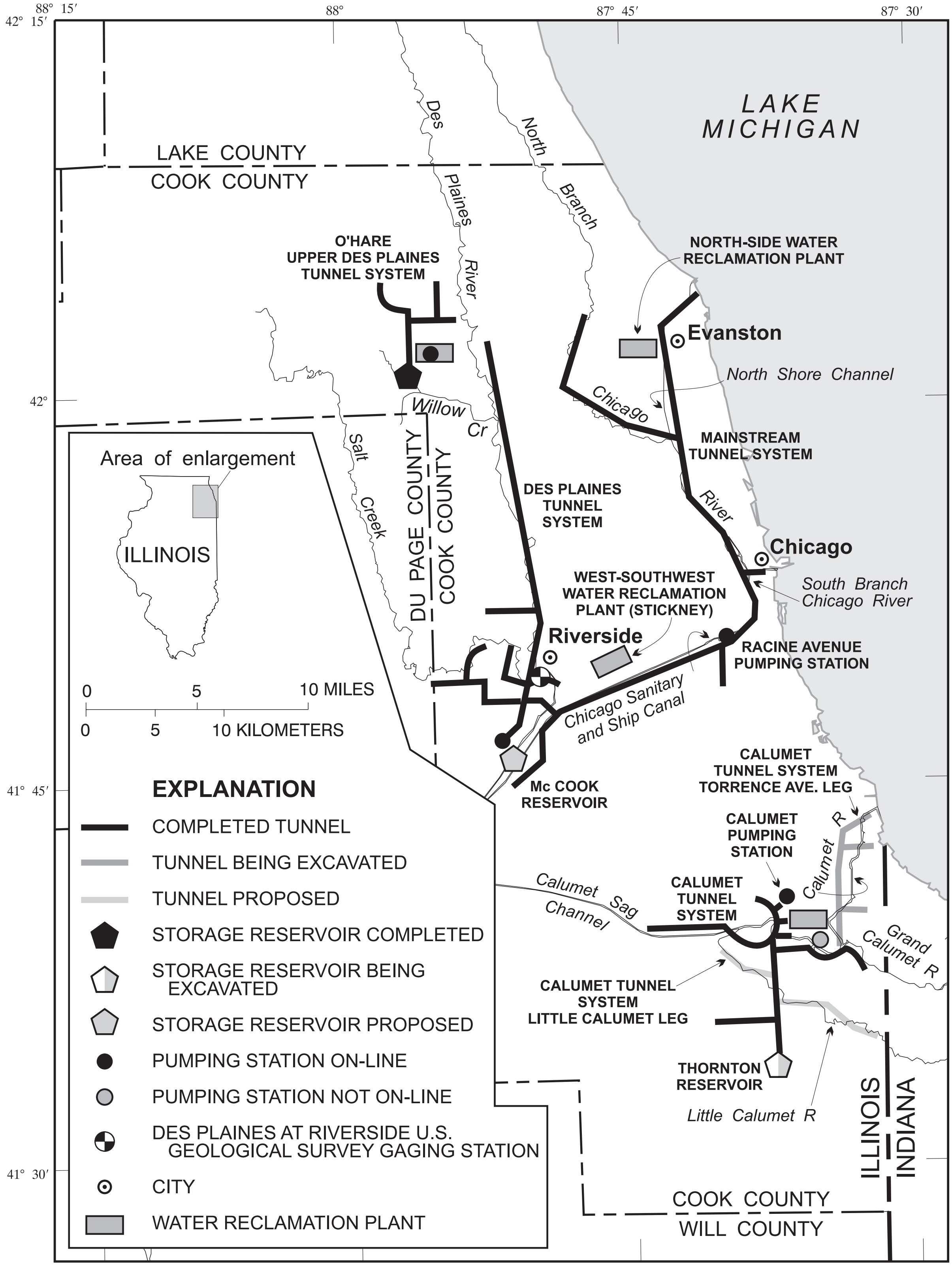

Figure 1. Location of deep-tunnel system and Riverside and Evanston, Ill. (modified from *http://www.mwrdgc.dst.il.us/plants/tarpmap.htm*).

quality and quantity of water that might be expected in the reservoir, and will aid in the design of a reservoir aeration system.

Purpose and Scope

This purpose of this report is to describe the flow data collection and analysis completed as part of the monitoring of combined sewer overflows in Riverside and Evanston, Ill., from 1997 to 1999. This report also describes the reasons for choosing the flow-monitoring locations, the type of equipment used, and the procedures followed in collecting and analyzing the flow data. Flow and rainfall data collected by the USGS and water-quality data collected by the MWRDGC are presented in a CD-ROM included at the back of this report. Water level (stage) and velocity data were collected in 2- and 5-minute intervals.

Physical Setting

The service area for the Des Plaines and Mainstream systems of the TARP consists of 252 mi^2 of the Chicago metropolitan area (U.S. Army Corps of Engineers, 1998). Dry-weather flow, including both domestic and industrial wastewater, stormwater, and inflow and infiltration are transported in these tunnels. The communities of the service area contain approximately 3 million people and are serviced by more than 4,400 mi of combined sewers (U.S. Army Corps of Engineers, 1998).

The Des Plaines tunnel system covers approximately 32 mi^2, which includes part or all of 20 communities. This service area contains a population of approximately 263,000 and mainly consists of residential property. The Mainstream tunnel system covers approximately 220 mi^2, which includes part or all of 21 communities. This service area contains a population of approximately 2.7 million, and mainly consists of residential property with some commercial and industrial areas (U.S. Army Corps of Engineers, 1998).

Acknowledgments

Various individuals and agencies deserve acknowledgment for assistance in this project. The staff of MWRDGC assisted with field operations and provided access to the confined sewer space. Mr. Tony Bednarz, Village of Riverside Fire Department, and Mr. Michael Whalen, City of Evanston Fire Department, offered their department staffs as stand-by rescue teams for USGS personnel as well as performing confined-space rescue training on site. In addition, Mr. William Renaker, Fox Lake Fire Department, and the Illinois Fire Service Institute, provided confined-space rescue training for USGS personnel.

COMBINED SEWER OVERFLOW MONITORING

Methodology

Combined-sewer flows were determined by collecting water level (stage) and velocity data in 2- and 5-minute intervals. Flow generally was calculated using the basic equation

$$Q = AV, \quad (1)$$

where Q is discharge, in cubic feet per second (ft^3/s);
A is the wetted area in the pipe, in square feet (ft^2); and
V is the water velocity, in feet per second (ft/s).

The hydraulic characteristics of the combined sewers were complex because of the pipe configurations, pipe junctions, and chambers. Furthermore, the operation of the sluice gates leading to the deep tunnel caused reverse flows through many of the pipes. Because of the complexity of each sewer system, alternate methods of determining and estimating velocities, and, consequently, flows, were required. For example, velocity estimates were required at times when water was flowing, but sometimes velocities were too slow for the flow meter to measure; also, velocity-magnitude estimates were required when sewer-system turbulence induced unreasonably high velocities.

Generally, a combined sewer system is a gravity-flow sewer that is designed to carry residential, commercial, industrial wastewater, and stormwater runoff (fig. 2). The actual wastewater flow, or dry-weather flow, usually is only a fraction of the stormwater design flow. Dry-weather flow is diverted from the combined sewer to a wastewater-treatment plant through interceptor sewers, which are designed to transport only up to what the wastewater-treatment plant can safely handle (Metcalf & Eddy, Inc., 1991).

Diversion structures are used in combined sewers to control the flow between the combined sewer and the interceptor sewer (Metcalf & Eddy, Inc., 1991). In the case of the monitoring locations discussed in this report, the flow-diversion structures consisted of diversion weirs (fig. 2).

During periods of stormwater runoff, the combined sewer often transports more water than the interceptor sewer can handle. In this case, the water in the combined sewer rises and overflows the weirs and empties into a

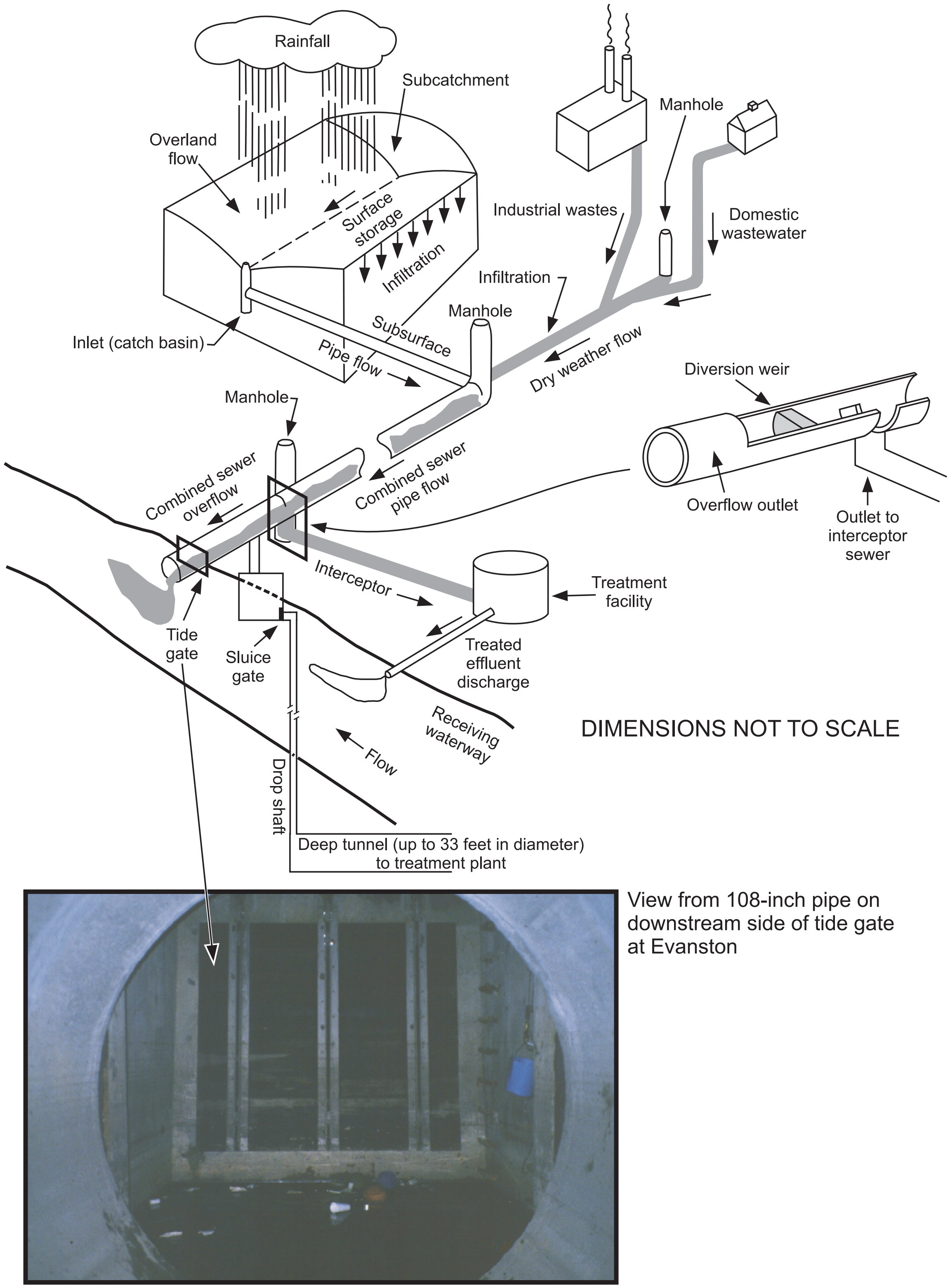

Figure 2. Schematic of a combined sewer system (modified from Metcalf & Eddy, Inc., 1991).

receiving waterway. In order to keep the receiving waterway from backing up into the sewer system, tide gates can be utilized (fig. 2) (Metcalf & Eddy, Inc., 1991). Tide gates generally allow water to flow out of the sewer system when the stage inside the system is higher than the water in the receiving stream.

The MWRDGC's water-quality data collection at Riverside and Evanston began on May 1, 1995. In addition to collecting samples at Riverside and Evanston, the MWRDGC also collected samples at the Calumet pumping station and the Racine pumping station (fig. 1). Water-quality samples were collected with automatic samplers during rain storms when 1 to 2 in. or more of rain fell. Both the sampler intake lines and the program parameters were arranged in such a way that samples automatically would be collected when water began to flow through the tide gates to the receiving streams. During these storms, stages in the sewer systems were expected to rise high enough so that discharges would result to the receiving waterways. Samples were processed and analyzed for BOD, and sometimes for suspended solids and ammonium-N. To determine constituent loadings, or the quantity of constituent per unit volume of water (for example, a BOD load), water volumes also were needed. Originally, water-quality sampling and computer flow modeling together were to be used to indicate the constituent loading. However, because of the hydraulic complexity of the systems at Riverside and Evanston, the Corps deemed it necessary to collect flow data in the combined sewers in addition to the water-quality data. Flow data collection began as early as March 1997 at some locations. In order for the water-quality data to be used to compute constituent loads, flow and water-quality data needed to be collected concurrently at the same locations. These data would be used to compute constituent loads and to calibrate a computer model that could be used to simulate flows and loads for periods prior to and subsequent to flow data collection. The model also may be used to estimate the total quantity and quality of water from all of the possible combined sewer overflow points that may be stored in the proposed McCook reservoir.

Equipment

A typical CSO monitoring installation for this study consisted of an automatic water-quality sampler for collecting samples during periods of high flow and a flow-monitoring device with a water depth and velocity sensor (fig. 3).

Portable long-term flow meters were installed to collect flow data in the combined sewers. Most flow meters installed at both Riverside and Evanston were manufactured by American Sigma, Inc. and are referred to as Sigma meters (fig. 4).

The Sigma meters consist of a data logger in a watertight cylindrical enclosure. This enclosure houses the 6-volt batteries, and all the electronics and circuitry. The data-logger interface allows the Sigma meter to communicate with a modem or portable computer for the purpose of remotely monitoring flow and/or downloading data. A probe that contains a submersible pressure transducer (stage sensor) and an ultrasonic Doppler velocity meter (velocity sensor) is connected to the Sigma meter. The probe is 0.8 in. high, 1.5 in. wide, and 5 in. long. Minimal flow disturbance results from the probe's low profile. The Sigma meter models that were used in this study included the American Sigma 910, to which one probe was connected, and an American Sigma 920 and 930, to which two and three probes were connected, respectively. The multiple-probe Sigma meters were used at locations where more than one stage and velocity measurement were required.

The stage sensor is a diaphragm that deflects under the pressure of the water column above it. Ten transducers capable of measuring stage ranging from 0.018 to 11.5 ft of water, with an accuracy of +/- 0.023 ft (American Sigma, Inc., 1996b). These 10 transducers were located at the "long pipe," "brick pipe," "short pipe," and the "Gage Street pipe" at Riverside, and the "ledge," "new pipe," "outfall pipe," and three probes in the "Lake Street pipe" at Evanston. Pipe and probe locations are described in detail later in the report. Two transducers measured stage ranging from 0.018 to 34.6 ft of water, with an accuracy of +/- 0.07 ft and were located at the "short pipe" and the "floor" at Evanston.

The velocity sensor operates according to the Doppler-shift principle. The probe transmits an ultrasonic acoustic signal (1 MHz) into the water column and waits for a return signal bounced off reflectors or particulate matter. The return signal is received back at the probe with a different, or shifted, frequency. The magnitude of the frequency shift is proportional to the magnitude of the velocity, and the direction of the frequency shift is proportional to the direction of the velocity (Michael Simpson, U.S. Geological Survey, written commun., 1999). The velocity sensor measures the average velocity, as opposed to discrete velocities, in the water column. The Sigma meter can measure velocities ranging from –5.0 ft/s to 20.0 ft/s with an accuracy of +/- 2 percent (American Sigma, Inc., 1996b). Negative velocities

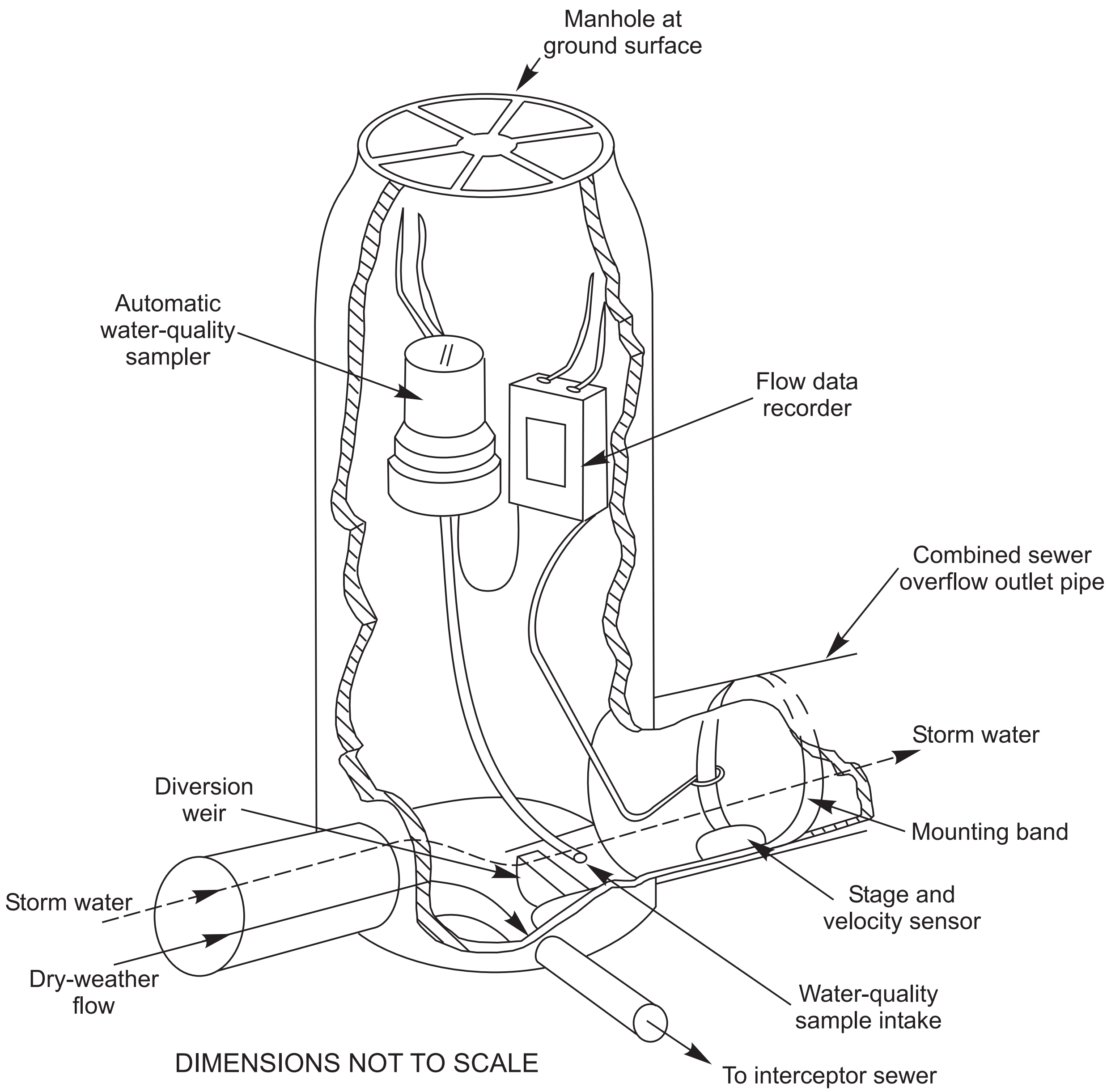

Figure 3. Schematic of a combined sewer overflow flow monitoring and water-quality sampling installation (modified from Metcalf & Eddy, Inc., 1991).

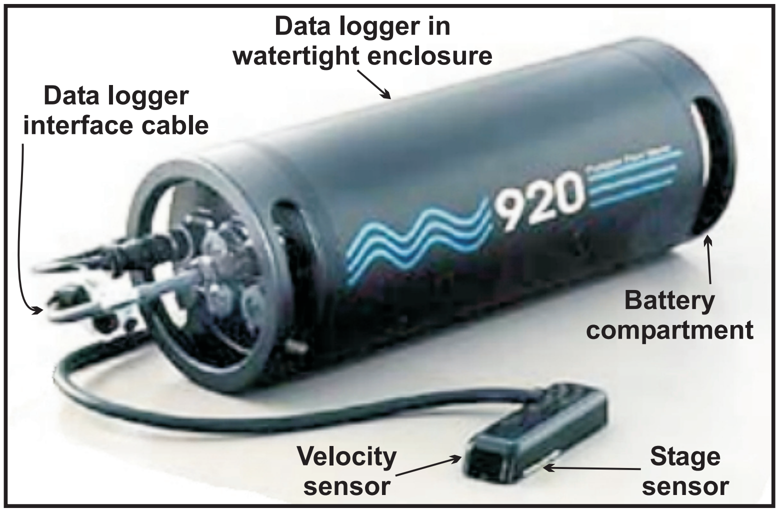

Figure 4. American Sigma 920 Long-Term Flow Monitor data logger and probe used to measure flow in combined sewers during this study (modified from *http://www.americansigma.com/920.htm*).

result if reverse flow occurs. The minimum velocity required for "good" velocity measurement is approximately from 0.20 to 0.30 ft/s (Joe Prell, American Sigma, Inc., oral commun., 1999). If the water is clear and has few reflectors, or if the water is pooled, allowing the particulate matter to settle out, or if the velocity is below the detection limit of the meter (from 0.20 to 0.30 ft/s), a zero velocity may be recorded.

The Sigma meters were programmed to record stage and velocity every 5 minutes, regardless of the depth of water over the probe. The Sigma meters were capable of recording battery voltages; however, in an effort to maximize the amount of available data-logger memory, battery voltages were not recorded. The 5-minute recording interval was chosen because stages in the sewers can quickly change from dry-pipe to full-pipe conditions in a matter of minutes. It is likely that with a longer data-recording interval (for example, 15 minutes), the data resolution to account for abrupt changes in stage and velocity would not have been adequate to determine flow rates.

Selection for the placement of the probe is critical for proper operation of the velocity sensor. To obtain the most accurate velocity measurement possible, various items need to be considered. For example, turbulence induced by obstructions, vertical drops, pipe bends, and elbows can cause poor velocity measurements. Ideally, if the probe is mounted in a pipe near an outfall, or is near a vertical drop, it should be located at least 10 times the maximum expected water level away from the disturbance (American Sigma, Inc., 1996b). If the probe is located in a pipe with surcharged or backwater conditions such that the pipe would become full, then the probe should be mounted at least 10 pipe diameters upstream from the end of the pipe or any flow disturbance.

In general, a series of stainless-steel straps and ring-style bands were used to mount the probes to the pipes (fig. 5). The probe was mounted near the end of the strap with the cable fastened to the strap with duct tape to avoid accumulating debris. The strap, which only spanned a portion of the pipe circumference, then was bolted to the wall of the pipe, with the probe placed at the bottom of the pipe. In certain cases, the strap and probe assembly was rotated and mounted slightly higher on the wall of the pipe to keep the probe from fouling by accumulating debris.

Ring-style stainless-steel bands were used in pipes of small diameter, generally 28 in. or less. In the case of the stainless-steel band, the probe would be mounted on the band and the cable again would be duct taped to the band. The assembly would be inserted into the pipe and expanded with an expanding clamp or scissor jack, causing the band to snugly adhere to the pipe.

In addition to the techniques described above, other techniques sometimes were required for probe installation. For example, at the "Lake Street pipe" the probes were mounted on the flange of an I-beam and lowered

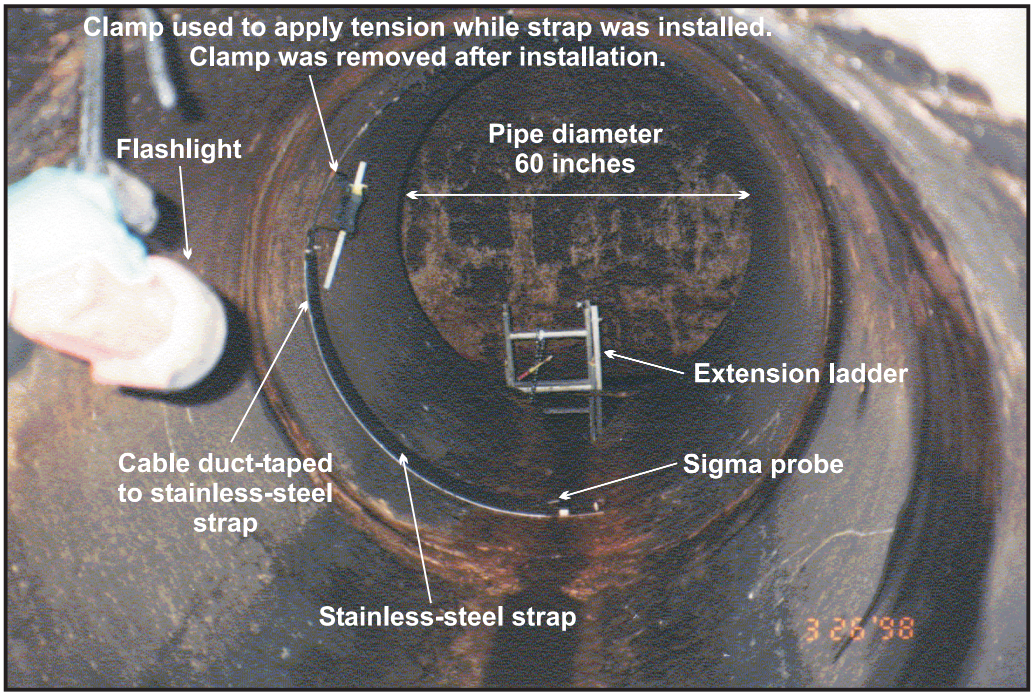

Figure 5. Sigma probe installation in 60-inch "short pipe" at Riverside, Ill.

into the water (fig. 6). This mounting was done because the pipe surface was pitted, broken, and crumbling. Also, the water at this location was too deep for a stainless-steel band installation.

Each I-beam was approximately 14 in. tall, 10 in. wide, and 31 in. long, and weighed about 175 pounds. The weight of the I-beams generally prevented their movement during high-flow conditions. Because more than one probe was located in the same pipe, each probe was mounted on a separate I-beam, and the I-beams were offset. Offsetting the I-beams ensured that no interference resulted with the velocity signal during velocity measurements.

After May 5, 1998, the water routing downstream of the probes at the "Lake Street pipe" was altered, which caused the stages in this pipe to drop approximately 1.70 ft. In this condition, the I-beams could no longer be used to mount and secure the probes. The I-beam flange, and, consequently, the probe, often was out of the water. An alternative to this installation was mounting and securing the probes with C-channels (fig. 7). Again the probes were mounted on small stainless-steel plates and were then mounted on the web of three different C-channels. Each C-channel was approximately 4 in. tall, 12 in. wide, and 48 in. long, and weighed about 180 pounds. The weight of the C-channels generally prevented their movement during high-flow conditions. The C-channels also were anchored to the bottom of the pipe. This helped prevent their movement during high-flow conditions.

In addition to the 8 Sigma meters with 12 probes, one Unidata Starflow Ultrasonic Doppler Instrument (referred to as the Starflow meter) was used for measuring flow. The Starflow meter (fig. 8) consists of a probe with a stage sensor, velocity sensor, and internal thermistor. Interface cables connected to the probe are accessible through an environmental enclosure. The probe dimensions are 1.0 in. high, 2.5 in. wide and 9.5 in. long.

The Starflow meter operates in the same manner as the Sigma meter. The stage sensor is a diaphragm that deflects under the pressure of the water column above it. The transducer can measure stage ranging from 0.0 to 16.4 ft of water, with an accuracy of +/- 0.01 ft (Unidata, 1995). The velocity sensor in the probe operates according to the Doppler-shift principle. The velocity sensor measures the average velocity, as opposed to discrete velocities, in the water column. The Starflow meter can measure velocities ranging from -14.7 ft/s to 14.7 ft/s, with an accuracy of +/- 2 percent, although the

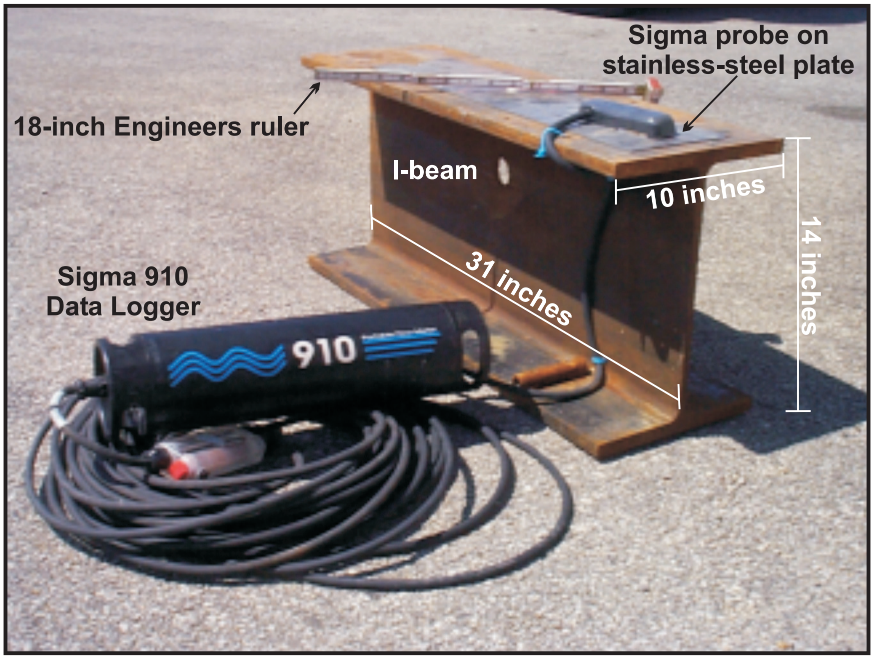

Figure 6. Sigma 910 meter with probe mounted on I-beam.

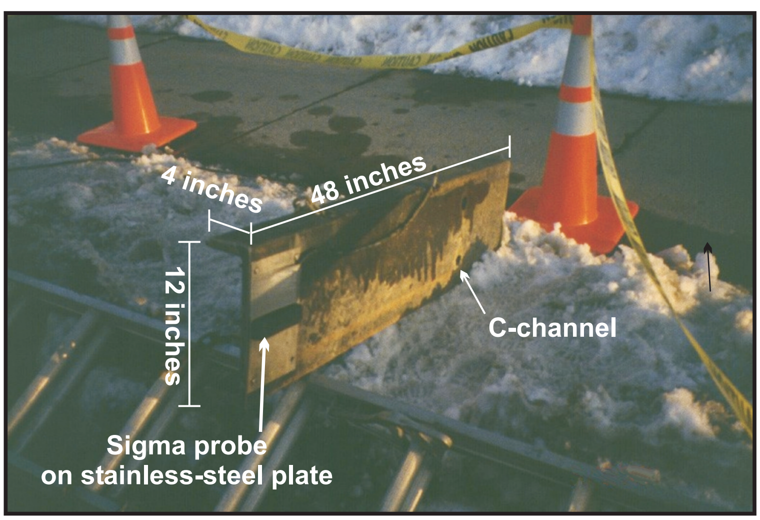

Figure 7. Sigma probe mounted on C-channel.

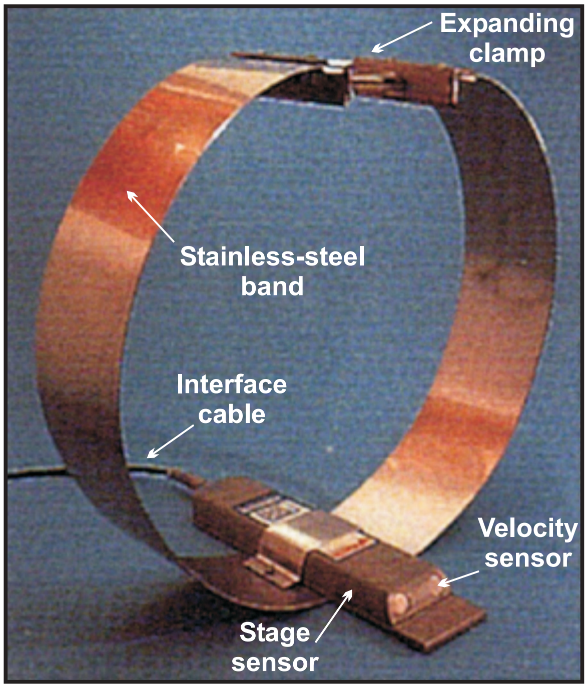

Figure 8. Starflow Ultrasonic Doppler Meter mounted on a 3-inch wide stainless-steel band with an expanding clamp (modified from *http://unidata.com.au/car/6705.htm*).

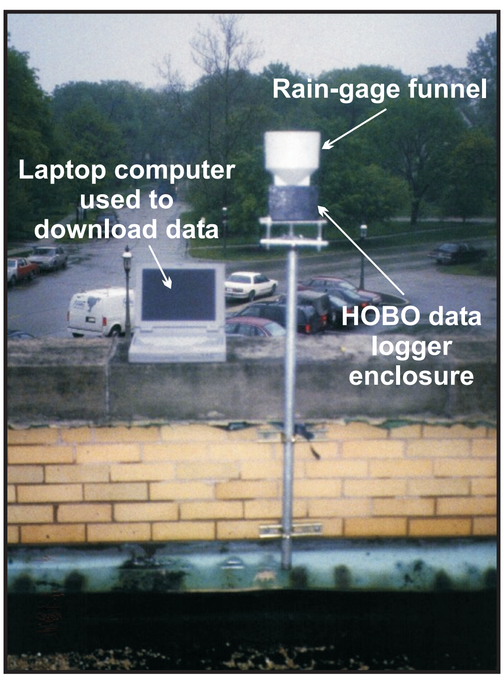

Figure 9. Rain-O-Matic rain gage mounted on Village of Riverside Fire Department building, Riverside, Ill.

minimum velocity required for the Starflow meter to make a "good" velocity measurement is approximately 0.07 ft/s (Unidata, 1995). Negative velocities result if reverse flow occurs.

For the Starflow meter to collect representative velocity data, an adequate amount of reflectors or particulate matter must be in the water. If the water is very clear or has few reflectors, or if the water is pooled, allowing the reflectors to settle out, an accurate velocity measurement cannot be made. In these cases, the Starflow meter reports the last "good" velocity measurement as the present velocity.

The Starflow meter was programmed to operate using an event-based logging sequence. The Starflow meter was inactive and did not log any data until water was sensed over the probe. Once the probe detected water, data logging began; when water was no longer detected over the probe, logging was discontinued. The Starflow meter was programmed to record stage, velocity, water temperature and battery voltage at 2-minute intervals. Filling the logger memory was not a concern because the logger only was collecting data when water was detected over the probe.

In addition to the Sigma and Starflow flow meters, a Rain-O-Matic rain gage (fig. 9) was installed on the roof of the Village of Riverside Fire Department building. The fire department building is approximately 0.3 mi northwest of Olmstead Street, where the "long pipe," "brick pipe" and "short pipe" probes were located. The rainfall data collected with this rain gage will be useful for relating the quantity of rain that fell in the watershed to the amount of water that flowed through the sewer system.

The rain gage contains a 6.25-in. funnel, which drains into a spoon that tips when full. Each 0.01 in. of precipitation causes the spoon to tip. Because the rain gage does not have the capability to log and store data, a HOBO contact-closure event data logger also was installed with the rain gage.

Operation and Maintenance

Operation and maintenance of the Sigma and Starflow meters required site visits on a monthly basis. Because of the composition of combined sewage, the probes were prone to fouling from debris accumulation and grease/oil film development. If the leading edge of a probe became sufficiently fouled, the velocity signal strength would be adversely affected and a zero velocity would be recorded. For this reason, the probes needed to be cleaned once per month. Additionally, the data logger in the Sigma meter was used in "wrap" memory mode. In this mode, when the memory becomes full, the newest readings overwrite the oldest readings (American Sigma, Inc., 1996a). Because of the large volume of data collected, the Sigma 910 memory became full after approximately 32 days of continuous operation. Therefore, data needed to be retrieved monthly. Finally, because of the frequent measurement and logging interval of 5 minutes, the Sigma meters required monthly battery replacement.

Because access to the pipes was required for operation and maintenance of the meters, and because each of these pipes was considered a permit-required confined space, permits were filled out before every entry into the sewer. All confined space protocols were followed according to American Industrial Hygiene Association (1995). In addition, personal protective clothing was worn, including multiple layers of gloves, Tyvec suits, and chest waders.

ANALYSIS OF COMBINED SEWER OVERFLOW DATA AT RIVERSIDE, ILLINOIS

Description of Study Area

The Village of Riverside, Ill., has a population of approximately 8,800 (http://www.pe.net/~rks-now/ilcountyriverside.htm#statistics) and is located along the Des Plaines River, approximately 11 mi west of Chicago, Ill. (fig. 1). The combined sewer system where data were collected (fig. 1) services a total area of 305 acres (0.48 mi^2) (Darren Olson, Christopher B. Burke Engineering, Ltd., written commun., 2000), and is predominantly residential.

Two Sigma meters with four probes were installed in the Riverside sewer system at the "Gage Street pipe," "long pipe," "brick pipe," and the "short pipe" (fig. 10). The Starflow meter was used to monitor the "outfall pipe." Elevations of each of these pipes and probe locations are relative to the USGS datum at the gaging station on the Des Plaines River at Riverside, (figs. 11 and 12) and were determined using a laser level. The meters were set such that a stage of 0.00 ft indicated dry-pipe conditions.

The "Gage Street pipe" is a 48.5-in. diameter brick pipe with a drainage area of approximately 210 acres (0.33 mi^2) (Darren Olson, Christopher B. Burke Engineering, Ltd., written commun., 2000). Dry-weather flow is diverted by a diversion weir (fig. 10) to an interceptor sewer and is conveyed to Stickney. During periods of stormwater flow, the stage in the "Gage Street pipe" can exceed the height of the diversion weir just downstream of the interceptor sewer. In this case, water overflows the weir and enters chamber 1 (fig. 10) near the entrance to the "long pipe." Overflow water can take two possible paths from this chamber. The first path is through the "long pipe." The bottom of the "long pipe" in chamber 1 is nearly the same elevation as the chamber floor; therefore, when water enters chamber 1 it immediately begins to flow through this pipe towards chamber 2 (fig. 10). If the stage in chamber 1 rises sufficiently because of backwater conditions (described later), it also may flow through a rectangular tide gate (3.75 ft by 4.25 ft) in chamber 1 (second path) to the Des Plaines River. This tide gate has a switch-closure alarm that is activated when the gate opens. The alarm is relayed to Stickney and signals the sluice-gate operator to open the sluice gate (described later).

Between chamber 1 and 2, a small, unmonitored, 10-in. diameter connecting sewer (fig. 10) may contribute water to the "long pipe" during periods of stormwater flow. This combined flow is monitored in the 54-in. diameter smooth concrete "long pipe" (fig. 10), upstream of chamber 2.

A 27.5-in. diameter "brick pipe" combined sewer (fig. 10), with a drainage area of approximately 83 acres (0.13 mi^2) (Darren Olson, Christopher B. Burke Engineering, Ltd., written commun., 2000) also can contribute stormwater flow into chamber 2. Dry-weather flow is diverted by a diversion weir to an interceptor sewer, as in the "Gage Street pipe." When stormwater overflows the diversion weir, it flows through the "brick pipe" into chamber 2. The probe in the "brick pipe" was mounted approximately half the distance between the diversion weir and chamber 2 (fig. 10).

From chamber 2, there are two possible flow paths and the first is through the "short pipe" (60-in. diameter, mildly pitted concrete pipe) (fig. 10) and into chamber 3. An 18-in. diameter sewer pipe with a drainage area of approximately 12 acres (0.02 mi^2) (Darren Olson, Christopher B. Burke Engineering, Ltd., written commun., 2000) enters near the top of chamber 3 and was

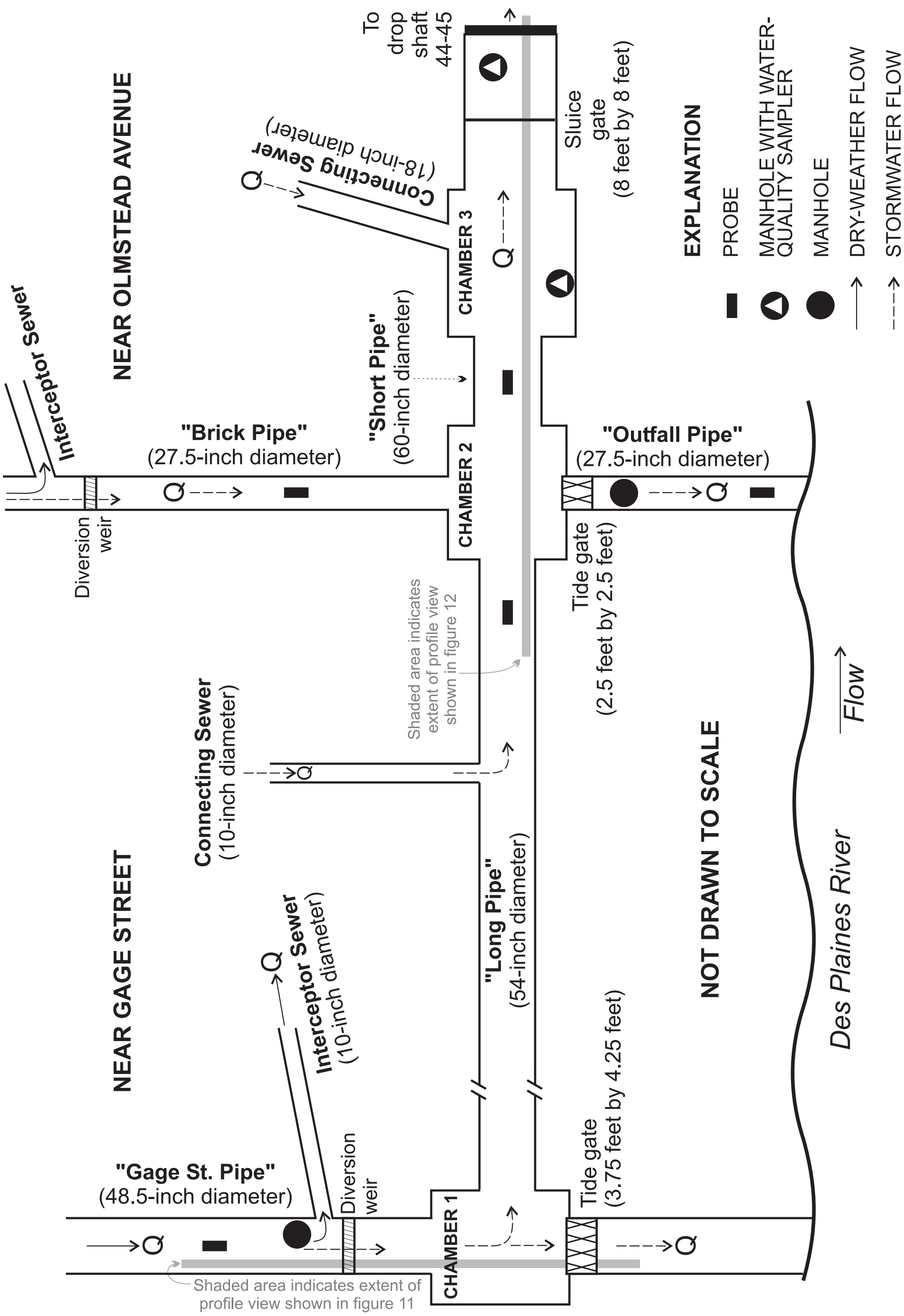

Figure 10. Schematic (plan) of sewer system used in measuring combined sewer overflows at Riverside, Ill.

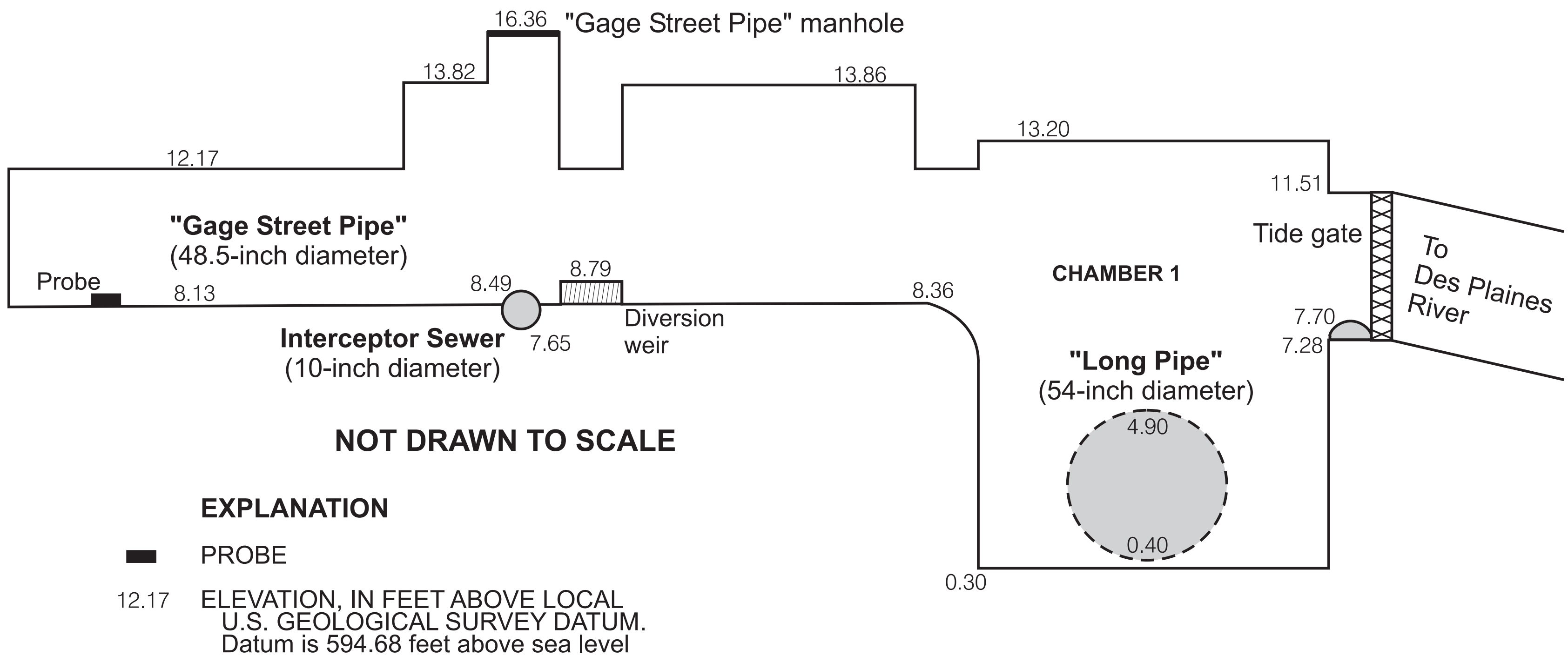

Figure 11. Schematic (profile) of sewer system near Gage Street, Riverside, Ill.

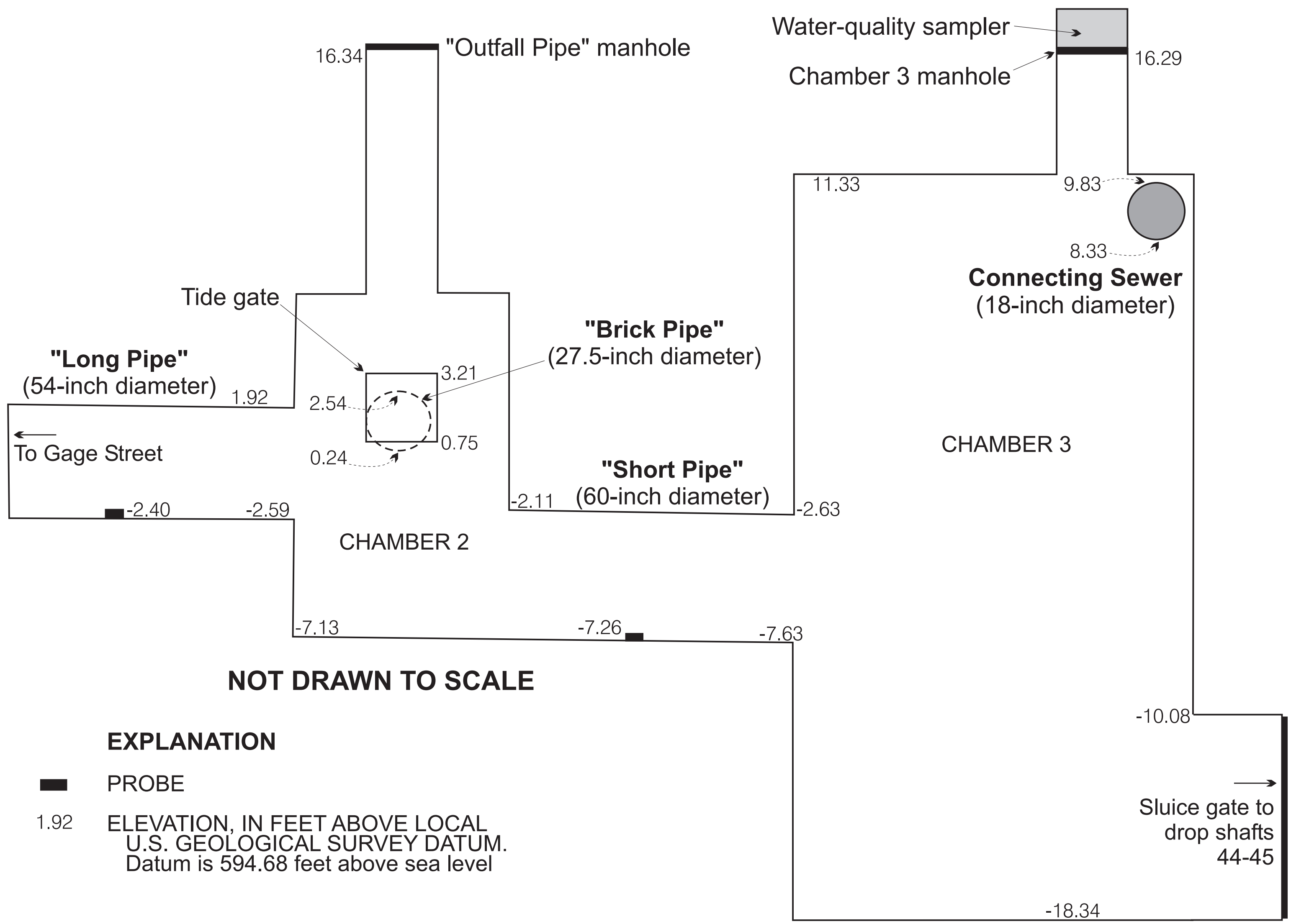

Figure 12. Schematic (profile) of sewer system near Olmstead Avenue, Riverside, Ill.

not instrumented. Therefore, the flow contribution into chamber 3 is unknown. The second path is through the 2.5-ft square tide gate, through the "outfall pipe," and into the Des Plaines River. Water that enters chamber 3 is diverted by a single 8-ft by 8-ft sluice gate that is fully closed during dry-weather periods. When the sluice gate is closed, a backwater condition can result, allowing the stage in chamber 3 to increase rapidly and cause reverse flow through the "short pipe." In the event of reverse flows, the stage in chamber 2 can increase to the point that water starts to flow in reverse directions through both the "long pipe" and "brick pipe." If the stage continues to increase, water also may discharge to the Des Plaines River through a 2.5-ft by 2.5-ft tide gate near Olmstead Ave. in chamber 2. This tide gate has a switch-closure alarm that is activated when the gate opens. The alarm is relayed to Stickney and signals the operator to open the sluice gate. If the backwater condition persists, water can back up through the "long pipe" into chamber 1 and discharge through the tide gate in chamber 1 to the Des Plaines River, as described previously.

If the tide gate in chamber 2 opens, water empties into the "outfall pipe" (fig. 10). This 27.5-in. diameter brick pipe discharges directly to the Des Plaines River. This pipe is instrumented with the Starflow meter, which begins recording data once it senses water over the probe. When the tide gates in both chamber 2 and/or chamber 1 open, personnel at Stickney usually open the sluice gate leading to the deep tunnel. Once the sluice gate is opened, the water in the sewer system flows through the open sluice gate and drops approximately 235 ft through a vertical shaft to the deep tunnel (fig. 13). Opening the sluice gate causes the stage in the sewer system to decrease and causes the water to stop discharging to the Des Plaines River.

The deep tunnel (up to 33 ft in diameter) conveys the CSO to Stickney to be treated and released. In addition to conveying water to Stickney, the deep tunnel also can store excess stormwater if Stickney is utilized to full capacity. Storage in the deep tunnel will continue until the treatment facility is capable of treating and releasing the stormwater. If Stickney is over capacity and all or most of the deep tunnel is used for storage, the sluice gates may be closed to keep any additional stormwater from entering the drop shaft and deep tunnel, which reduces the chance of hydraulic surging (Patrick Connolly, Metropolitan Water Reclamation District of Greater Chicago, written commun., 2000). During the periods when the sluice gates are closed, the stormwater collects in the sewer system upstream of the sluice gate until a sufficient level is reached to again cause the tide gate in chamber 2 (and possibly in chamber 1) to open and discharge to the Des Plaines River.

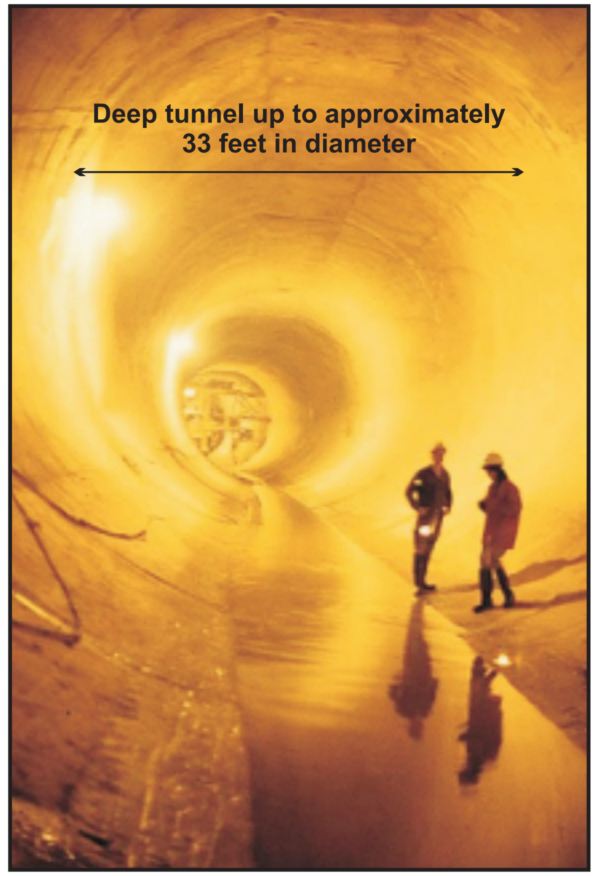

Figure 13. The deep tunnel that transports combined sewer overflow water to the West-Southwest Water Reclamation Plant (Stickney)(modified from *http://www.mwrdgc.dst.il.us/plants/tarp.htm*).

Storm Volumes

A detailed description is given below of the assumptions and methods used to analyze the flow data during the storm of April 22-26, 1999, at Riverside beginning at the "Gage Street pipe" in downstream order toward the sluice gate. The measured flow and calculated volumes are affected greatly by limitations of the flow meters and the numerous associated assumptions and unknown factors. Generally, the same assumptions and methods were used for the quantification of other storm volumes. Differences in assumptions made in the analysis of the April 1999 storm and other storms are given at the end of this section.

All of the dry-weather flow at the "Gage Street pipe" is diverted into an interceptor sewer by means of a diversion weir downstream of the probe (fig. 14). Because no flow-monitoring equipment was installed in the interceptor sewer in the "Gage Street pipe," it was necessary to estimate the quantity of water diverted by the weir in order to compute the volume of water that overflowed the weir during rain storms.

To estimate the flow into the interceptor sewer from the "Gage Street pipe," three small stage rises were analyzed. The magnitude of these rises was such that the depth of the water approached, but did not exceed, the height of the weir (0.85 ft). This result was confirmed in that no water was detected at the "long pipe" probe during these periods. This condition indicates that all the flow in the "Gage Street pipe" was diverted into the interceptor sewer. It was determined that a maximum average discharge of 3.75 ft^3/s was flowing through the "Gage Street pipe" during these periods, and, consequently, through the interceptor sewer. Therefore, it was assumed that any flow rate in the "Gage Street pipe" that exceeded 3.75 ft^3/s overflowed the weir. This flow rate could be an over- or underestimate, depending on the flow conditions downstream in the interceptor sewer. If backwater conditions were present, caused by the submerged interceptor sewer outlet, it is possible that the sewer would accept less than 3.75 ft^3/s of stormwater. This condition indicates that during a storm more water could overflow the weir than estimated. However, if the interceptor sewer allowed for free-orifice flow, meaning that the interceptor outlet was a free outfall and not submerged, it is possible that more than 3.75 ft^3/s was flowing through the interceptor. This condition indicates that during a storm less water than estimated could overflow the weir.

When water overflows the weir, it should be detected at the "long pipe" probe in the form of a stage and velocity increase within 5 to 10 minutes. This method of estimating the overflow provided reliable results, as water was detected at the "long pipe" at nearly the same time that the flow in the "Gage Street pipe" exceeded 3.75 ft^3/s (fig. 15). A calculated volume of 357,009 ft^3 overflowed the "Gage Street" weir during the April 1999 storm.

When the "long pipe" probe detected increased amounts of water on April 23, the stage and velocity increased rapidly. This water then combined with the water from the "brick pipe" in chamber 2 and flowed through the "short pipe" into chamber 3. After chamber 3 filled, reverse flow, measured as a negative velocity, occurred through the "short pipe" and then through the "brick pipe" and "long pipe." The first negative velocity at the "long pipe" occurred at 12:50 am (00:50, 24-hour time) on April 23 at a stage of approximately 3.65 ft. This negative velocity appears reasonable, because chamber 3 likely filled and caused water to back up throughout the sewer system. At 01:35 and 01:40 on April 23, the stage indicated that the 54-in. "long pipe" was surcharged, meaning that the static pressure of the water above the probe was greater than the pipe diameter. However, the stage did not exceed 9.58 ft, at which point backwater from the "long pipe" would have caused the stage in chamber 1 to reach the bottom of the

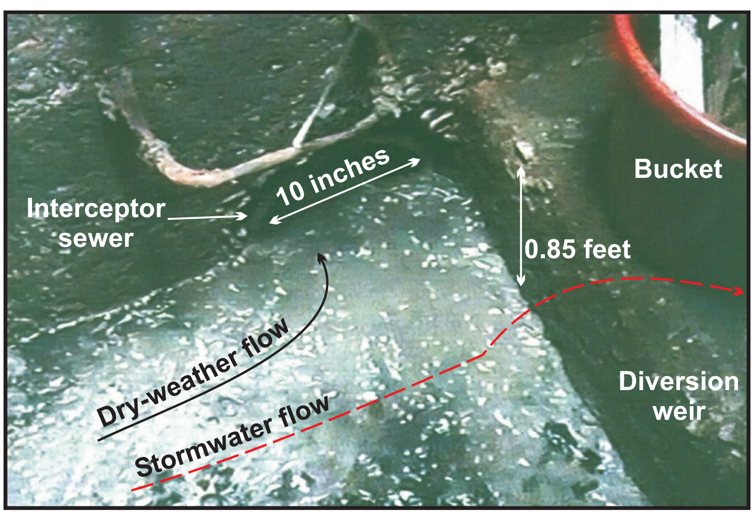

Figure 14. Interceptor sewer and diversion weir in the "Gage Street pipe," Riverside, Ill.

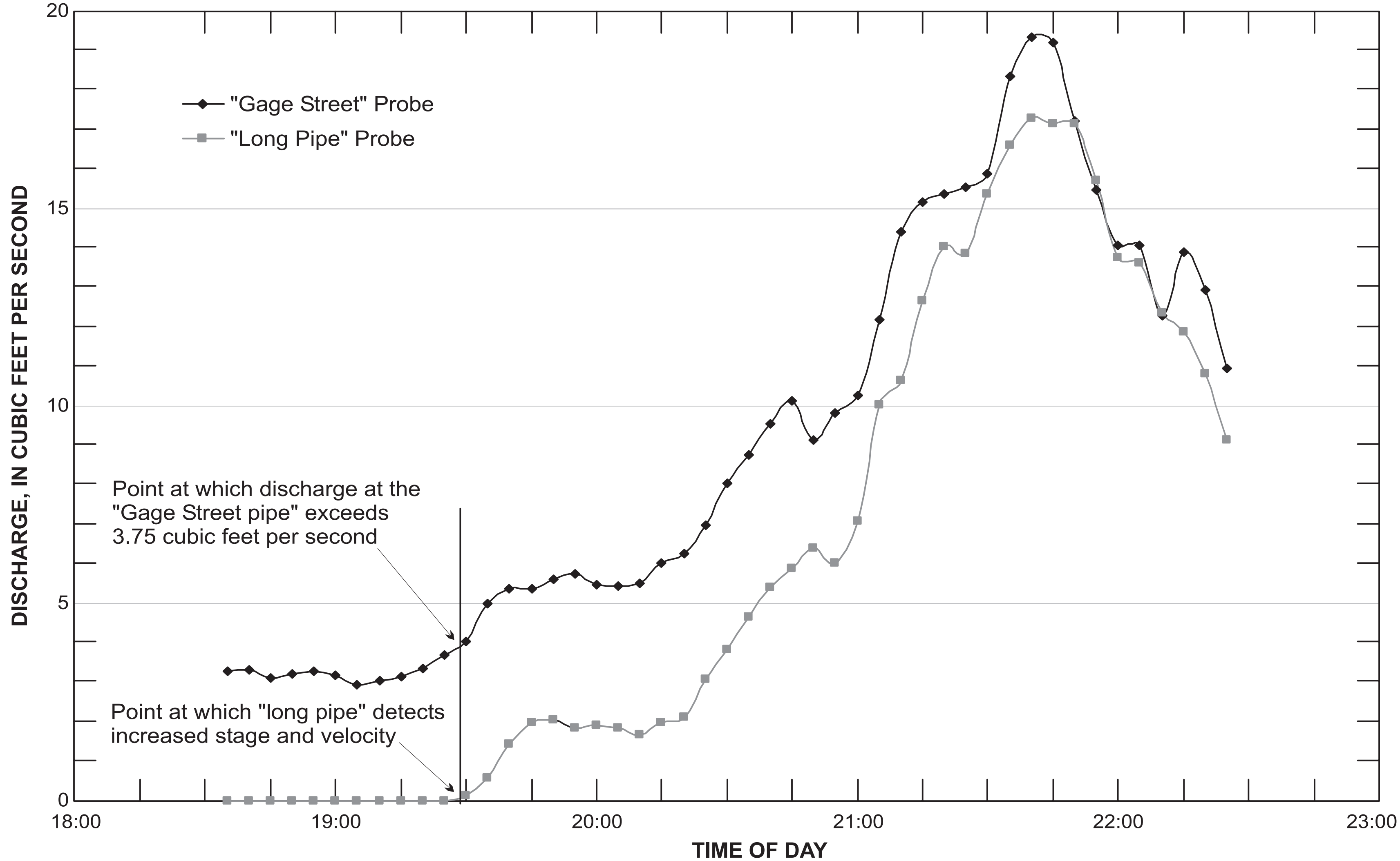

Figure 15. Discharge at the “Gage Street pipe” and the “long pipe,” Riverside, Ill., April 22, 1999.

tide gate in chamber 1, potentially allowing for discharge to the Des Plaines River. During this surcharged period, two large consecutive negative velocities in the “long pipe” were recorded (-7.07 and -5.28 ft/s) resulting in large negative flow rates (-112 and -84 ft^3/s, respectively). Because more water was being added to the sewer system during this period, it was likely that turbulence resulted throughout the entire sewer system, potentially causing exaggerated negative velocity magnitudes. These negative velocities indicate that the entire pipe cross section was traveling in a reverse direction from 5 to 7 ft/s. This result is unlikely. It is more likely that the water was turbulent in the vicinity of the probe and that negative velocities resulted but at a lower magnitude than recorded. However, because it was impossible to verify flows during high-flow conditions, the recorded velocity data were accepted and used in the flow analysis. The stages and the velocities in the “long pipe” recorded during the April 1999 storm are shown in figure 16.

Beginning at 10:55 on April 23, velocities in the “long pipe” were “noisy,” indicating that the data had “random and persistent disturbances that reduced the clarity or quality of [the] signal” (Riverside Publishing Company, 1988) and fluctuated between 0.00 and approximately –0.50 ft/s (fig. 16). These negative velocities probably are erroneous, because they were not confirmed by velocities in the “short pipe” or the “brick pipe” (0 ft/s) measured during this period. In general, because these velocities in the “long pipe” are noisy, they normally would be considered zero because no flow likely was detected. However, when the stage is changing, it is obvious that water is being added to or removed from the sewer system. If the velocity is noisy, or more realistically zero during a period of rising or falling stage, it is apparent that water is moving in the sewer system. However, no velocity was detected by the Sigma meter. This result probably is because the actual velocity is lower than the minimum meter detection limit (from 0.20 to 0.30 ft/s). During periods when the velocity was lower than the detection limit and the stage was rising, velocities were changed to zero. This change was done because during any stage increase, it was impossible to determine whether the velocities should be positive or negative, because of more water entering the system, or because of backwater or turbulent conditions. Alternately, during periods when the velocity was lower than the detection limit, and if the stage was decreasing, water was discharging from the system, most likely through the sluice gate. In general, the velocities were changed to one-half the average minimum velocity detection limit of the Sigma meter (0.125 ft/s). This change was done because it was assumed that water was flowing through the sluice gate, but slowly enough to be undetected by the Sigma meter. One-half the average minimum detectable velocity commonly is used when computing flow that is below the detection limit for these types of meters (Jennifer Miller, U.S. Army Corps of Engineers, oral commun., 2000).

From 10:55 to 11:35 on April 23, velocities in the “long pipe” were noisy and changed to zero because the stage was still rising (fig. 16). From 11:40 on April 23 to 03:15 on April 24, the stage was decreasing and these velocities were changed to 0.125 ft/s. It is likely that water was released slowly through the sluice gate to the deep tunnel. From 03:20 on April 24 to 08:55 on April 26, the noisy and zero velocities were changed to zero because the stage primarily remained constant, indicating that the sluice gate was closed, and only very minor seepage may have resulted.

Stage decreased rapidly at the “long pipe” from 09:00 to 09:05 on April 26. The corresponding measured positive velocities indicated that the sluice gate was opened, allowing all the water to flow in a positive direction out through the sluice gate and to the deep tunnel. A calculated volume of 647,714 ft^3 flowed through the “long pipe” during the April 1999 storm period (table 1).

Water in the “brick pipe” empties into chamber 2. Although the “brick pipe” stage plot for the April 1999 storm is similar to the “long pipe” stage plot, the velocity plots are different. On March 17, 1999, the “brick pipe” probe stage sensor was found to be faulty. The sensor was replaced and moved approximately 4 ft downstream of the original location on April 14, 1999. At the new location, a small opening near the top of the pipe allowed infiltration into the pipe, ranging from small drips during dry weather, to more substantial trickling when the surrounding ground was saturated. In addition, throughout the length of the “brick pipe,” approximately 0.10 ft of pooled water was present because of its variable slope. The infiltration from the top of the “brick pipe” dripped into the pooled water in the vicinity of the probe, and caused the velocity sensor to record this irregular dripping water as noisy positive and negative velocities. This problem was detected and the probe was moved another 2 ft downstream in the pipe on June 25, 1999. No further problems resulted. The velocity data before and after the probe was relocated on June 25 are shown in figure 17.

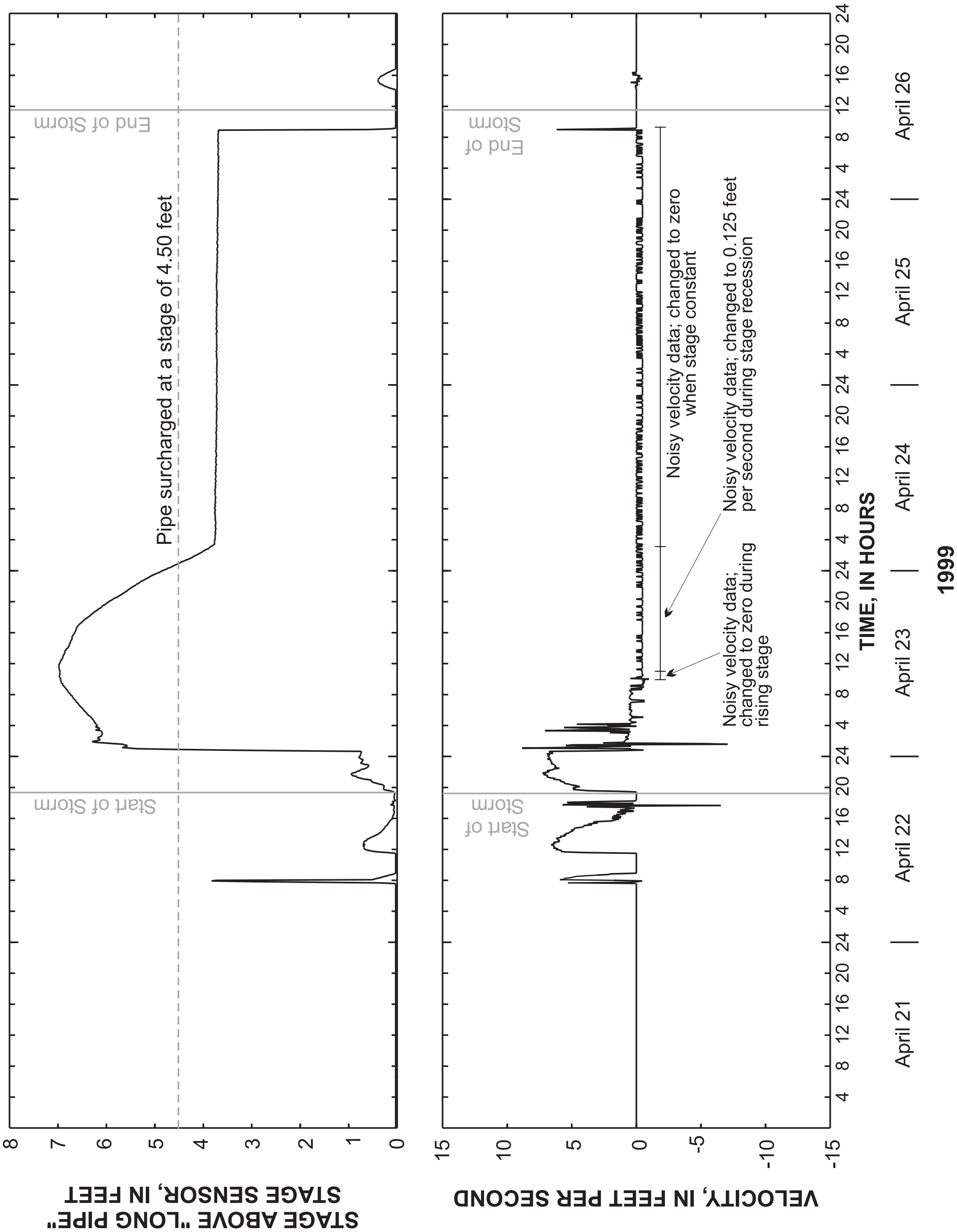

Figure 16. Stage and velocity at the "long pipe," Riverside, Ill., April 21-26, 1999.

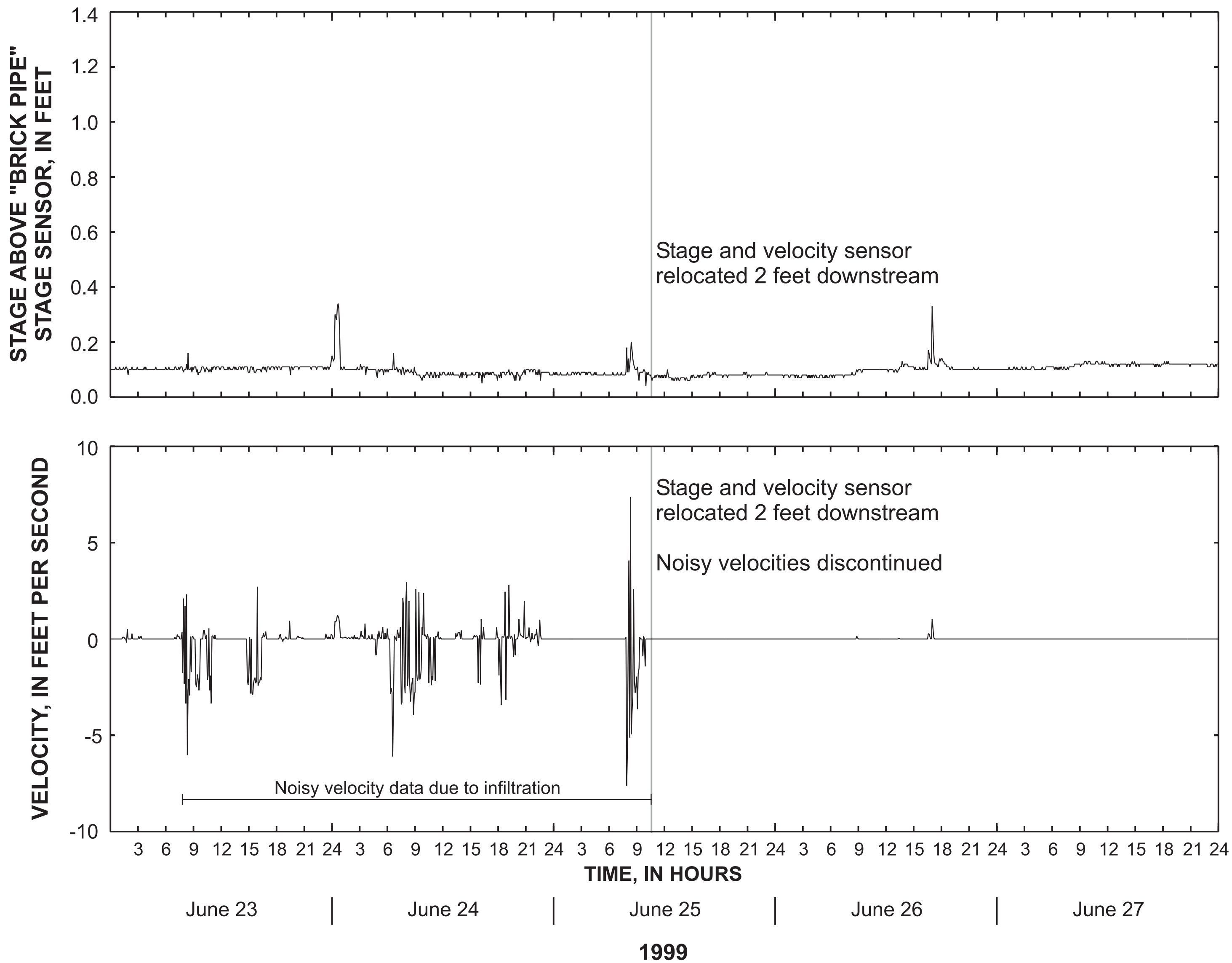

Figure 17. Stage and velocity at the “brick pipe,” Riverside, Ill., June 23-27, 1999.

During the period when the velocities in the "brick pipe" were affected by infiltration, two large storms occurred in April 1999 and June 1999. A plot of the stage and velocity data for the "brick pipe" during the April 1999 storm is shown in figure 18.

During the large stage rise on April 23, the velocity in the "brick pipe" was positive, as expected when the water flows toward the sluice gate. From 10:55 to 11:35 on April 23, the zero velocities were not changed, because it was unknown whether the stage rise was caused by water entering the system in a positive or negative (reverse flow) direction.

As the flow through the "brick pipe" increased, the water combined with water from the "long pipe" in chamber 2 and flowed through the "short pipe" into chamber 3. Because the sluice gate was closed, the water filled chamber 3 and flowed back through the "short pipe," and then through the "long pipe" and "brick pipe." As the "brick pipe" surcharged, the velocities fluctuated between small positive and negative values, indicating turbulent conditions in the sewer system. During the stage rise, the velocity data indicated a period of both zero, and small positive velocities (0.30 ft/s), similar to velocities from the "long pipe." However, near the beginning of the stage recession on April 23, the velocities consistently were negative, which is an unrealistic result. Also, during the period when the stage was constant, throughout the latter half of the storm, the velocities fluctuated between positive and negative values, and then became mostly negative throughout the end of the storm. These velocities most likely are erroneous. As mentioned earlier, errors probably were caused by infiltration near the probe. If these data were correct, reverse flow resulted in the "brick pipe" during most of the storm, which also is unlikely.

Many of the negative velocities in the "brick pipe" measured during the storm probably are not correct. First, the measured velocities were not *all* negative, indicating considerable turbulence in the sewer system. Negative velocities were not confirmed by velocities measured in other pipes. Second, because the diversion weir upstream of the "brick pipe" probe was 0.85 ft high, it is unlikely that the water in the "brick pipe" (at an average depth of 0.95 ft) was flowing in a reverse direction at an average velocity of 1.50 ft/s. Additionally, the rainfall data collected from the rain gage on the Village of Riverside Fire Department building indicate that most of the rainfall ended at about 02:00 on April 23. During the period from 03:30 April 24 to 08:50 on April 26, when the stage primarily was constant and the velocity primarily was negative, no water was contributed by overflow at the "Gage Street" weir (fig. 19).

Therefore, the only water that possibly could be added to the system, allowing for reverse flow in the "brick pipe,"was seepage through the tide gate in chamber 2 because of the high stage of the Des Plaines River, and the two non-instrumented sources of inflow, including the 10-in. diameter inflow pipe upstream of the "long pipe" probe and the 18-in. diameter pipe in chamber 3. It is unlikely that any of these sources of inflow contributed much water because the 12-acre (0.02 mi^2) drainage area for the 18-in. diameter pipe only was approximately 4 percent of the total drainage area of 305 acres (0.48 mi^2) for the entire system. Also, no substantial negative velocity was measured with the Starflow meter in the "outfall pipe." Finally, velocity plots of data in the "brick pipe" indicate that prior to April 1999, velocities were noisy and similar to those in the "long pipe,"whereas during most of April and June 1999, the negative velocities appeared largely overexaggerated. It only was during the period when the probe was affected by infiltration from April 1999 to June 1999 that velocities appeared noisy during large stage rises.

From 11:40 on April 23 to 03:25 on April 24, the stage was decreasing. The velocities in the "brick pipe" were changed to 0.125 ft/s, as it was assumed that water slowly was released through the sluice gate to the deep tunnel. From 03:30 on April 24 to 08:50 on April 26, the velocities were changed to zero, because the stage basically remained constant. This constant stage indicates that the sluice gate was closed, and only very minor seepage may have been occurring.

As the stage in the "brick pipe" rapidly decreased at the end of the storm because the sluice gate opened, two unlikely negative velocities were recorded. If the probe is in still water, an internal gain adjustment is boosted automatically in an effort to allow the probe to detect very small movements in the water (Joe Prell, American Sigma, Inc., oral commun., 1999). The Sigma meter might record the initial turbulence as the correct velocity because the gain is boosted. This condition resulted during this stage recession. When the sluice gate was opened, some turbulence probably was induced in the sewer system, which caused the Sigma meter to record a negative velocity rather than a positive velocity. This negative velocity also supports the assumption that the water in the "brick pipe" was pooled, and not flowing in a reverse direction (negative flow) throughout the storm, as described earlier. As the velocities during the stage recession were very likely to have been positive as the water flowed toward the sluice gate, they were changed to positive values for the purpose of data analysis.
A calculated volume of 72,726 ft^3 flowed through the "brick pipe" during the April 1999 storm period (table 1).

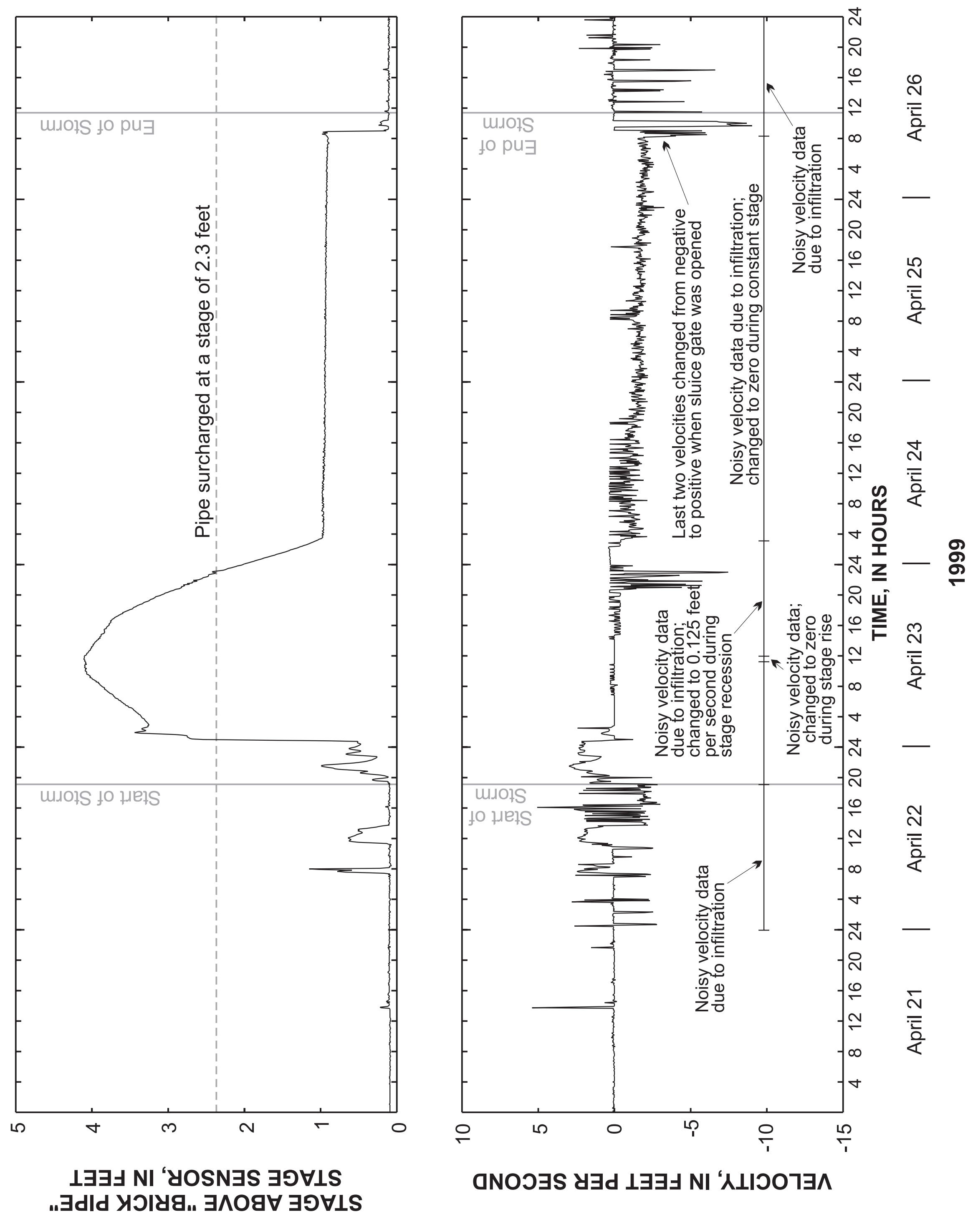

Figure 18. Stage and velocity at the "brick pipe," Riverside, Ill., April 21-26, 1999.

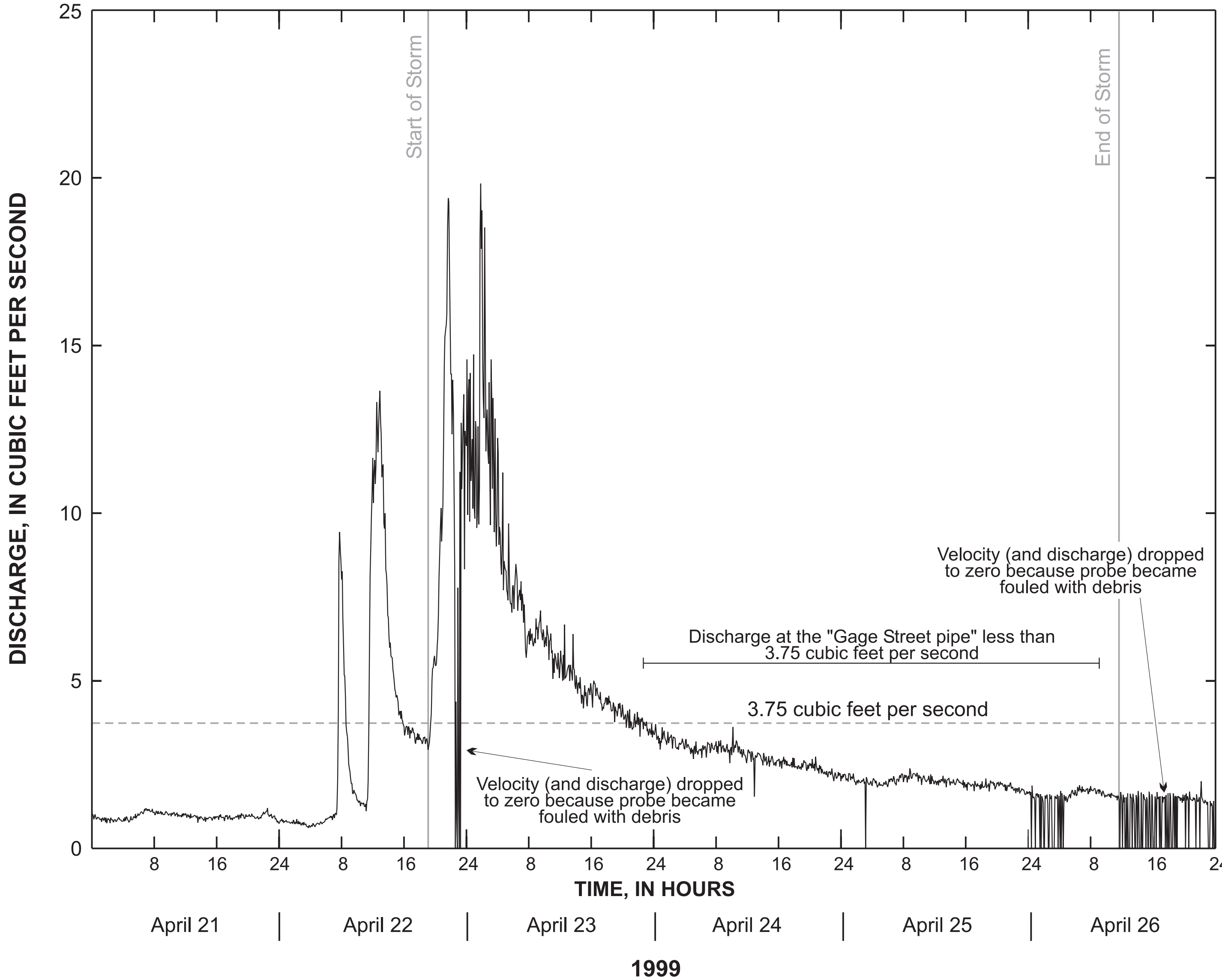

Figure 19. Discharge at the “Gage Street pipe,” Riverside, Ill., April 21-26, 1999.

Water in chamber 2 flows through the “short pipe” to chamber 3. A plot of the stage and velocity data for the “short pipe” during the April 1999 storm is shown in figure 20.

This 60-in. diameter pipe was surcharged for the majority of the April 1999 storm. This stage plot closely resembles plots of the “long pipe” and “brick pipe.” The velocities near the beginning of the storm are positive during the stage rise, as expected. Once chamber 3 filled, water backed up into the “short pipe” and the rest of the sewer system; however, no negative flows were detected in the “short pipe,” unlike in the other pipes. Data indicate that at 00:40 on April 23, the stage in the “short pipe” rose more than 6.0 ft in a 5-minute period, and more than 8 ft in a 10-minute period. During this rapid stage rise, it is possible that negative velocities occurred between recorded velocity values. Five minutes after the pipe became surcharged, the water stopped flowing, as indicated by the zero velocities. From 00:50 to 11:40 on April 23, no changes were made to the velocities. Velocities primarily were zero, because the stage was rising. During this time, it was impossible to determine whether the velocities are positive, because more water was added to the system, or negative, because of backwater or turbulence. From 11:45 on April 23 to 03:35 on April 24, the stage was decreasing and the velocity was changed to 0.125 ft/s. The water probably was released slowly through the sluice gate to the deep tunnel. From 03:40 on April 24 to 08:55 on April 26, recorded velocities of 0.00 ft/s remained unchanged, because the stage basically remained constant. These results indicate that the sluice gate was closed, and only very minor seepage may have been occurring.

At the end of the storm, from 08:55 to 09:10 on April 26, the stage decreased rapidly and positive velocities were recorded. Positive velocities indicate that the sluice gate was opened, allowing all the water in the sewer system to flow in a positive direction through the gate and to the deep tunnel. A calculated volume of 267,106 ft^3 flowed through the “short pipe” during the April 1999 storm period (table 1).

When the stage in chamber 2 rises sufficiently, water can flow out of the sewer system through a tide gate to the “outfall pipe” to the Des Plaines River, and should be detected by the Starflow meter. When the Des Plaines River stage exceeds approximately 4.70 ft above the datum at the USGS gaging station on the Des Plaines River at Riverside, river water can flow from the river into the “outfall pipe” and over the Starflow meter (fig. 21).

Table 1. *Flow mass balance for chamber 2 in the combined sewer system at Riverside, Ill., April 22-26, 1999*

Flow into chamber 2	Volume (cubic feet)
Long pipe:	647,714
Brick pipe (drainage area of 83 acres):	72,726
Total:	720,440
Flow out of chamber 2	
Short pipe (to the sluice gage):	267,106
Outfall pipe (to the Des Plaines River):	131,686
Total:	321,648
Difference (Total in - Total out):	321,648

During the April 1999 storm, the stage in the “outfall pipe” rose smoothly and steadily, whereas the velocity remained nearly zero (fig. 22) because the rise in stage recorded by the Starflow meter actually was a reflection of the rise in stage of the Des Plaines River. The first time that an appreciable positive velocity was detected by the Starflow meter was at 23:04 on April 22, while large negative velocities were detected at 23:48. These velocities resulted because of the turbulence of the river water inside the pipe, rather than water discharging through the tide gate, because the stage inside the sewer was not high enough to cause a gate opening. The difference in elevation between the “long pipe” probe and the bottom of the tide gate in chamber 2 is 3.15 ft; therefore, the “long pipe” stage must exceed 3.15 ft for the tide gate in chamber 2 to potentially open.

Identical velocities were recorded by the Starflow meter for extended time periods because good velocity readings could not be made consistently due to the lack of reflectors in the pooled water. During these periods, the Starflow meter reported the last “good” velocity measurement as the present velocity. For the purpose of data analysis, it was assumed that if any repeated velocities were present, they were not valid and not used in the data analysis. A calculated volume of 131,686 ft^3 flowed through the “outfall pipe” during the April 1999 storm period (table 1).

To verify the analytical methods used in data analysis, a flow mass balance was calculated for chamber 2. The two inflows into this chamber are the “long pipe” and the “brick pipe,” whereas the two outflows are the “short pipe” and the “outfall pipe.” The volume of water calculated in the “Gage Street pipe” was not used in the mass balance; instead, this volume was used to verify the volume calculated in the “long pipe.” Also, the quantity of water measured through the “short pipe” is the same as what flowed through the sluice gate to the deep tunnel. Mass-balance results for chamber 2 are given in

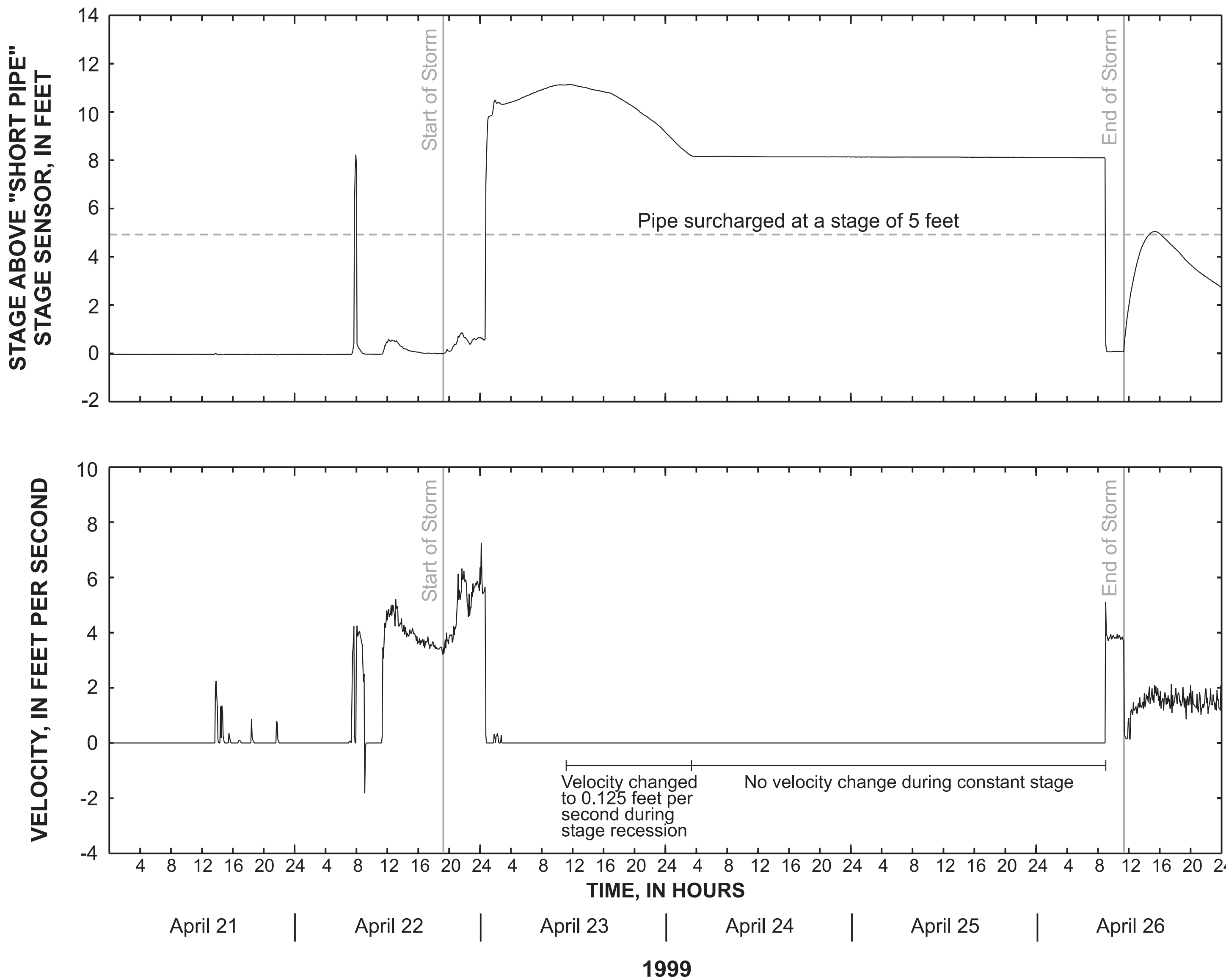

Figure 20. Stage and velocity at the "short pipe," Riverside, Ill., April 21-26, 1999.

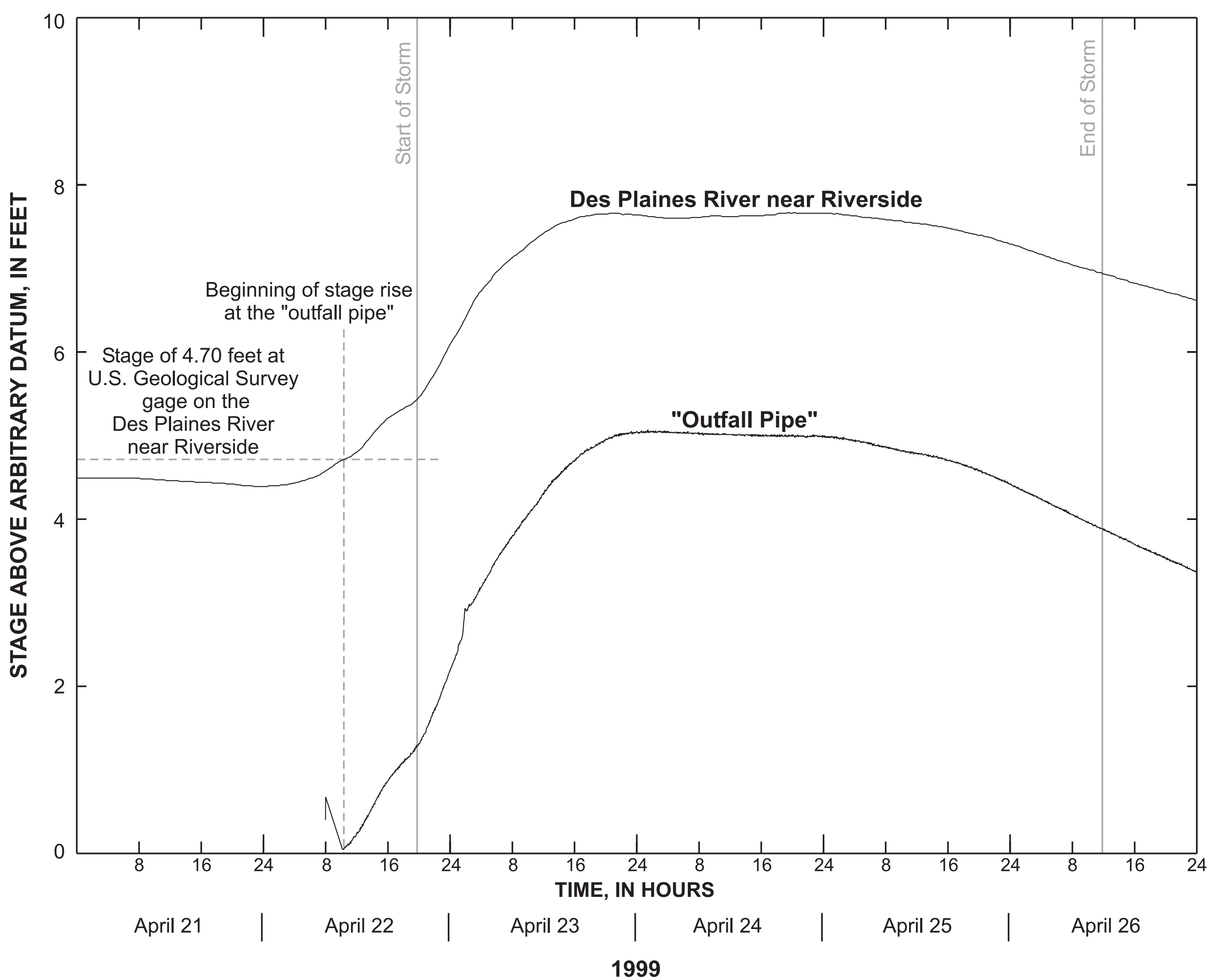

Figure 21. Stages at the “outfall pipe” and the Des Plaines River, Riverside, Ill., April 21-26, 1999.

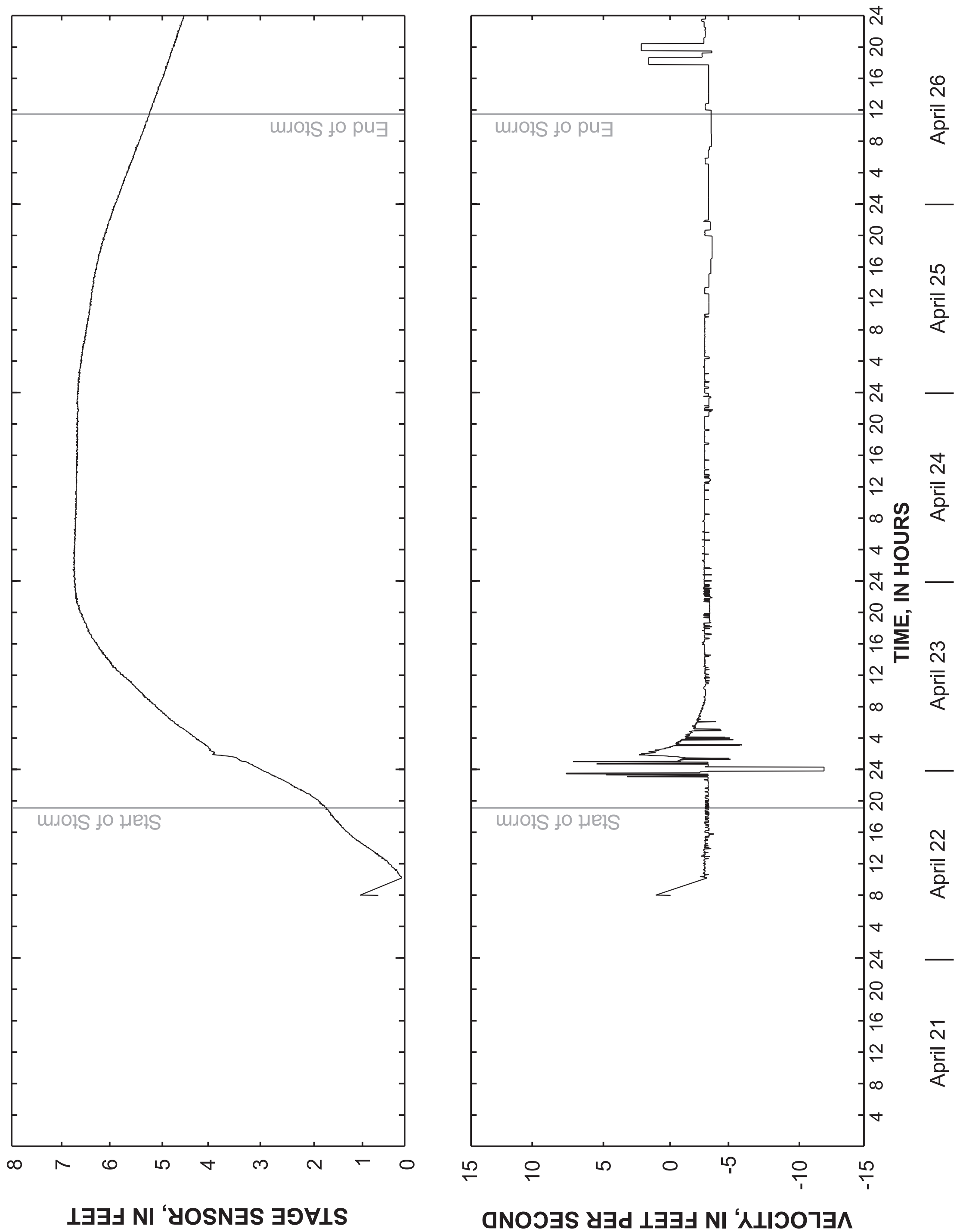

Figure 22. Stage and velocity at the "outfall pipe," Riverside, Ill., April 21-26, 1999.

table 1. The total calculated inflow to chamber 2 from the "long pipe" and the "brick pipe" was 720,440 ft^3 (table 1). The total calculated outflow in the "short pipe" (to the sluice gate) and the "outfall pipe" (to the Des Plaines River) was 398,792 ft^3.

Generally, the same assumptions and methods were used in the analysis of the June and December 1999 storms. However, some variations were required and are described below. During the June 1999 storm, the Starflow meter was not operating properly and no flow data were recorded. To determine the flow through the "outfall pipe," a storm on July 19, 1998, was investigated as the Starflow meter was operating properly. It was important that during the July 19, 1998, storm the Des Plaines River stage measured at the USGS gage on the Des Plaines River at Riverside was low enough that no water was backed up into the "outfall pipe" and no river water was present on the downstream side of the tide gate. This condition was similar to the June 1999 storm. A relation between the "long pipe" stage and the "outfall pipe" discharge was established (fig. 23); then the discharges for the July 19, 1998, storm were related to the "long pipe" stage during the June 1999 storm to determine the total outflow to the Des Plaines River.

Finally, during the December 1999 storm, the volume of water that reportedly overflowed the "Gage Street" weir exceeded the volume of water detected at the "long pipe" probe. Because the "long pipe" probe detects water from the "Gage Street" overflow, along with the water from the 10-in. diameter inflow pipe upstream of the "long pipe" probe, the water volume through the "long pipe" should be equal to or greater than the volume that overflows the "Gage Street" weir. During this storm, four large negative velocities were measured in the "long pipe" during the rise on December 4, 1999, accounting for a considerable volume of water supposedly flowing in the reverse direction (nearly 94,000 ft^3). Although negative velocities during this period are realistic, the magnitude of these velocities appears unreasonably large. It was assumed that there was sufficient turbulence near the probe to cause the large negative velocities. For the purpose of data analysis, these velocities were reduced to one-tenth their original magnitude so that the quantity of water detected at the "long pipe" probe was greater than the quantity that overflowed the weir at "Gage Street."

ANALYSIS OF COMBINED SEWER OVERFLOW DATA AT EVANSTON, ILLINOIS

Description of Study Area

The city of Evanston is a suburb of Chicago, Ill., has a population of about 73,200 (*http://www.pe.net/~rksnow/ilcountyevanston.htm#statistics*), and primarily most of the city is located between the North Shore Channel and Lake Michigan (fig. 1). The combined sewer system where data were collected as part of this study services an area of 2,313 acres (3.61 mi^2) that is predominantly residential and commercial. Six flow meters with nine probes were installed in the Evanston sewer system at the following USGS named pipes: the "Lake Street pipe" (three probes), "siphon pipe," "new pipe," "short pipe," chamber 3 "floor," chamber 3 "ledge," and "outfall pipe" (fig. 24). Elevations of each of these pipes and probe locations are relative to an arbitrary datum (figs. 25 and 26) and were determined using a laser level. The meters were set such that a stage of 0.00 ft indicated dry-pipe conditions.

The "Lake Street pipe" is a 120-in. generally circular pipe with a flat bottom. The pipe is rough concrete and has a drainage area of 1,738 acres (2.72 mi^2) (Darren Olson, Christopher B. Burke Engineering, Ltd., written commun., 2000). Dry-weather flow is diverted by a diversion weir (fig. 2) to an interceptor sewer ("siphon pipe") and is conveyed to the North-Side Water Reclamation Plant (fig. 1). The elliptical "siphon pipe" is located just upstream of the "Lake Street pipe" overflow weir and allows for a maximum water depth of 3.87 ft before surcharging. During stormwater flow periods, the stage in the "Lake Street pipe" can exceed the height of the weir just downstream of the "siphon pipe" and overflow into chamber 3 (fig. 24). There are three possible paths for the overflow water in this chamber. The first path includes two 8-ft by 8-ft sluice gates that divert the water from chamber 3 and convey the water to the deep tunnel. During dry-weather flow periods, one sluice gate is open approximately 5 percent (approximately 5 in.) and the other gate is closed (Pat Connolly, Metropolitan Water Reclamation District of Greater Chicago, written commun., 2000). Although one sluice gate is partially open, water can collect in chamber 3 more rapidly than it can flow through the partially open gate. The second path is taken when the stage in chamber 3 rises sufficiently, causing reverse flow through the "short pipe" and "new pipe." The third path is taken when the system becomes surcharged and water flows through tide gate and into the North Shore Channel.

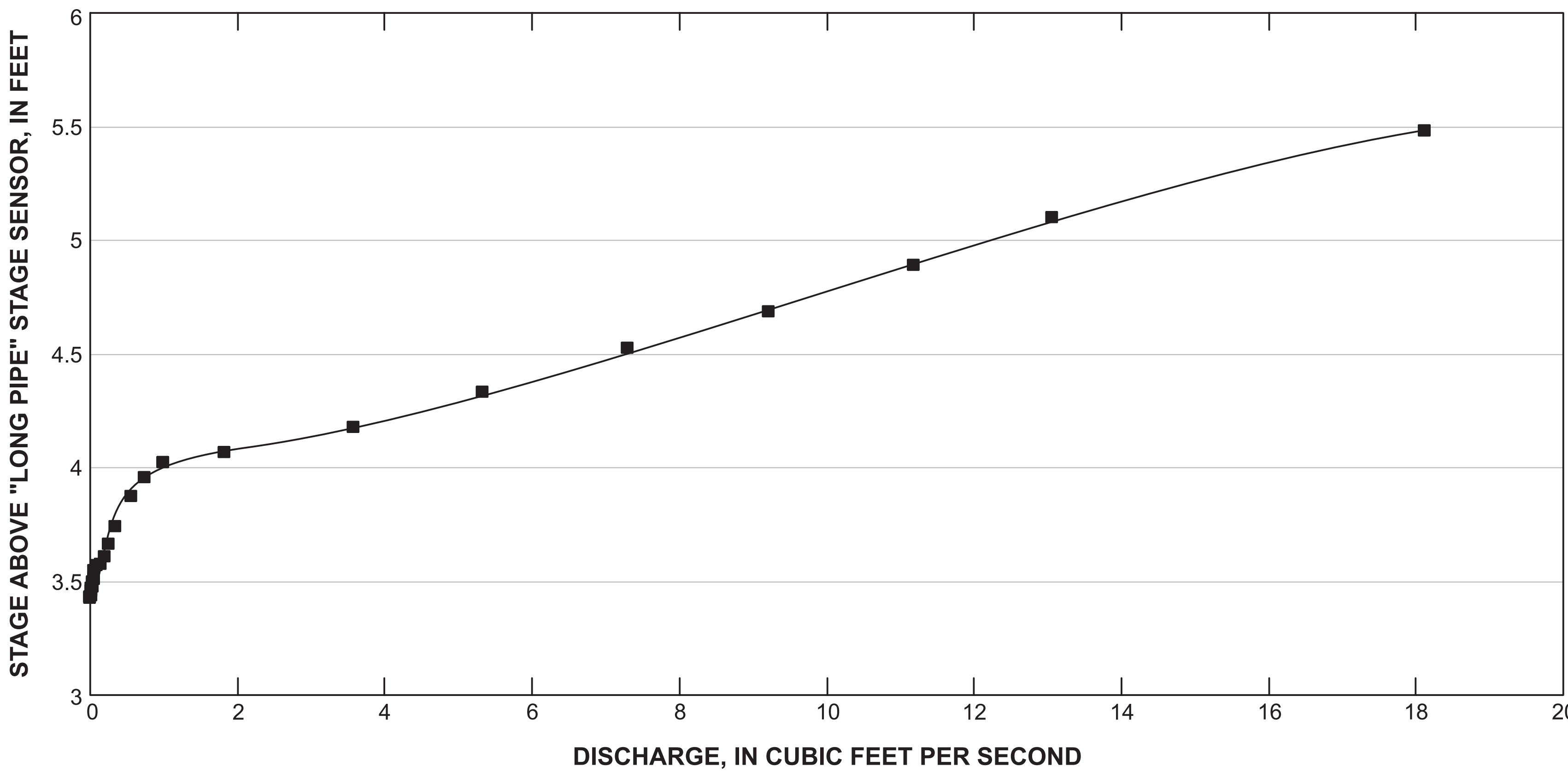

Figure 23. Stage at the “long pipe” and discharge at the “outfall pipe” during the storm of July 19, 1998, Riverside, Ill.

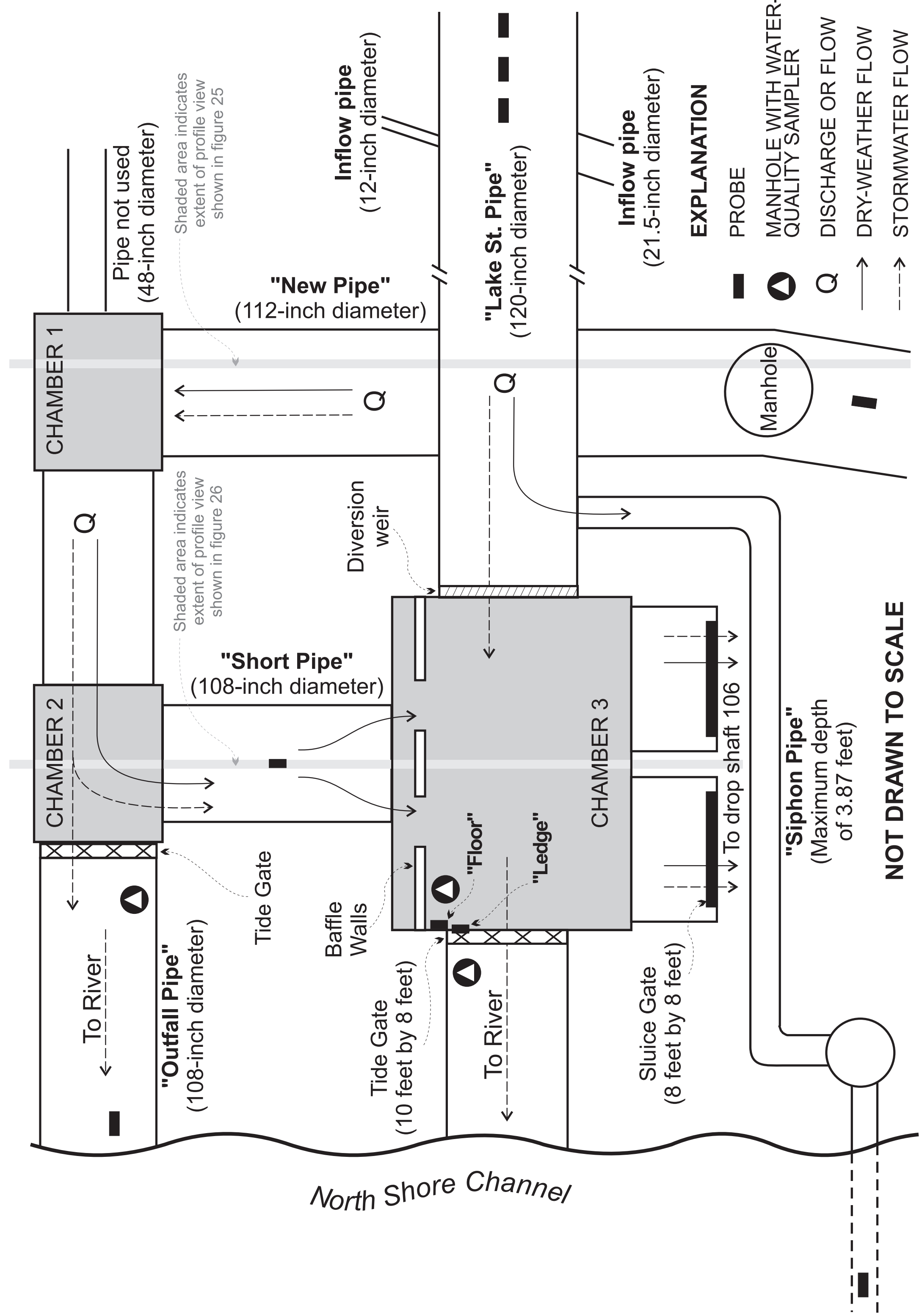

Figure 24. Schematic (plan) view of sewer system used in measuring combined sewer overflows at Evanston, Ill.

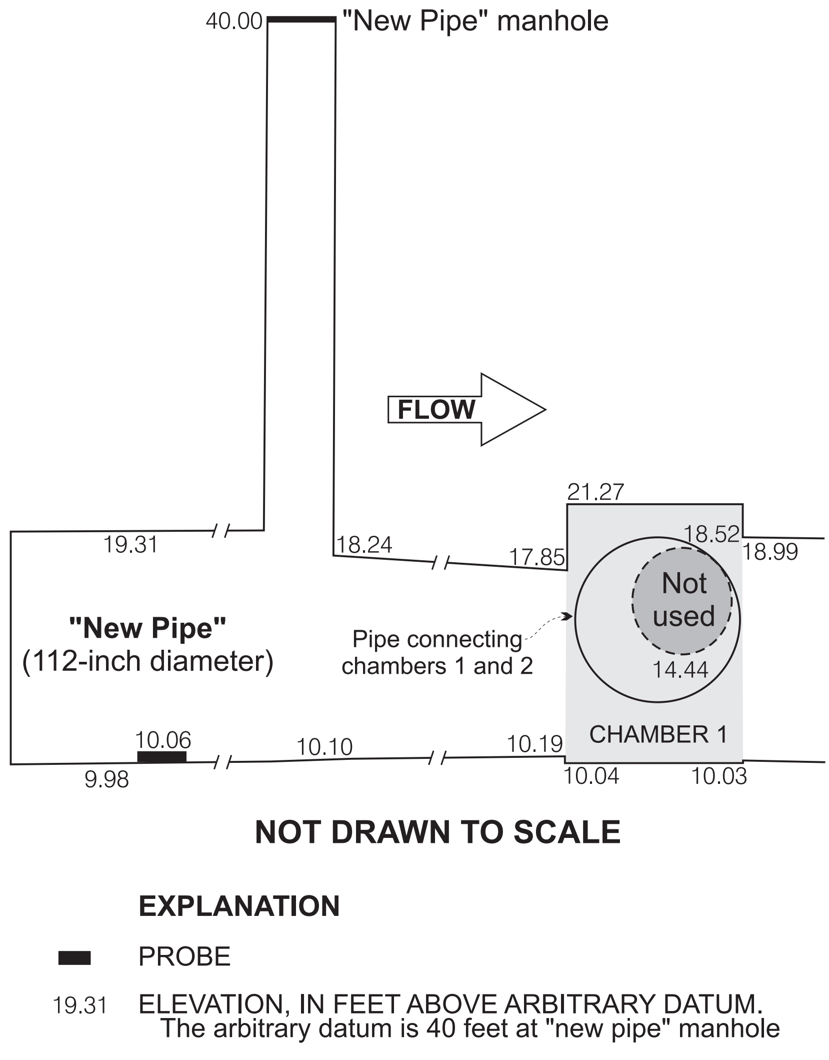

Figure 25. Schematic (profile) of sewer system at Evanston, Ill.

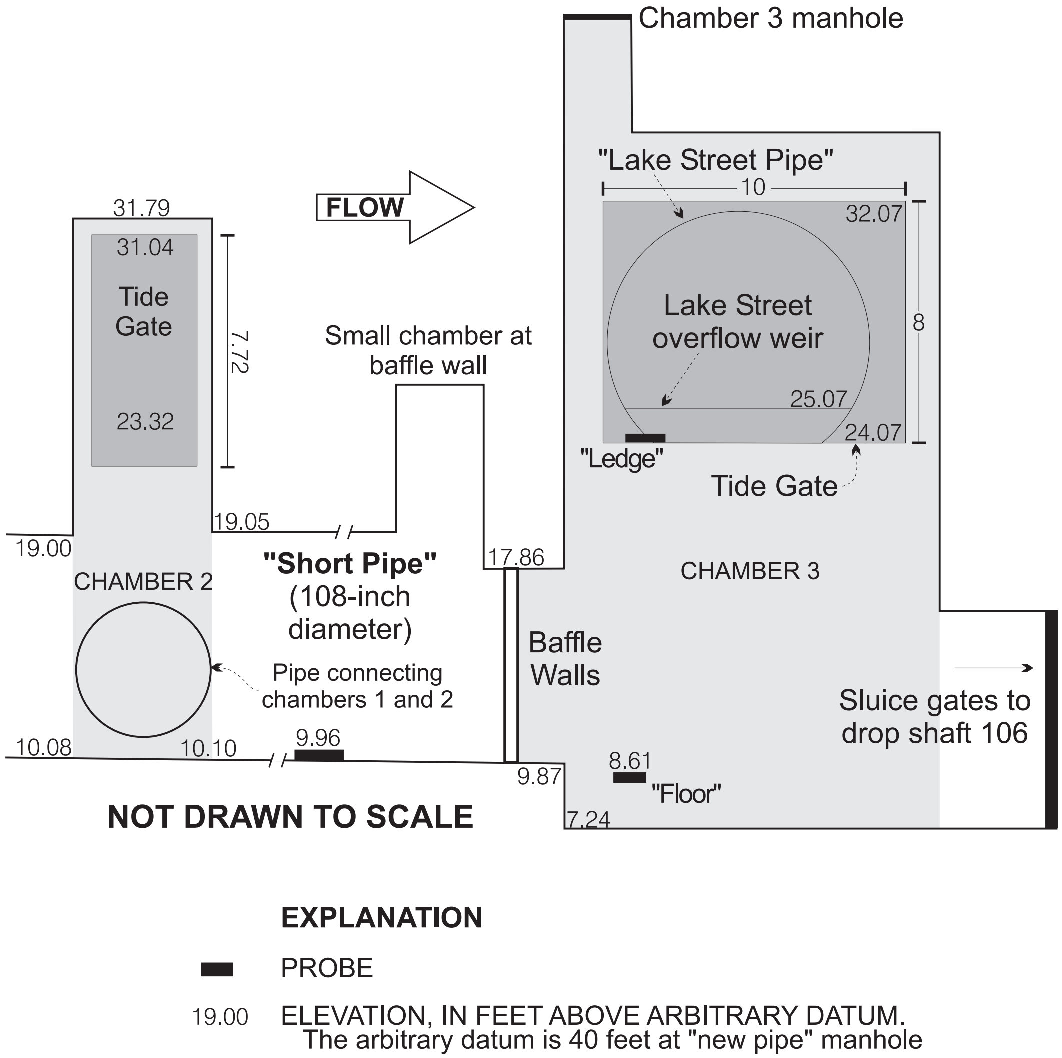

Figure 26. Schematic (profile) of sewer system at Evanston, Ill.

The “new pipe” is a 112-in., smooth, concrete, storm-relief sewer (fig. 24) with a drainage area of 575.4 acres (0.90 mi^2) (Darren Olson, Christopher B. Burke Engineering, Ltd., written commun., 2000). The “new pipe” conveys stormwater and provides storage for water that backs up from chamber 3. Water flowing past the “new pipe” probe in a positive direction enters chamber 1 and flows through a pipe into chamber 2. The water then flows from chamber 2 through the “short pipe” and enters chamber 3. A 48-in. diameter concrete pipe enters into chamber 1, but does not contribute water to the sewer system (Nancy Hornewer, U.S. Geological Survey, oral commun., Jan. 2000). This pipe can provide storage during periods of storm-water flow.

The “short pipe” is a 108-in., smooth, concrete sewer (fig. 24) that conveys stormwater from the “new pipe,” through two baffle walls, which help diminish velocities, over a 2.63-ft vertical drop, and finally to chamber 3. The “short pipe” also provides storage for water that backs up from chamber 3.

When overflow from the “Lake Street pipe” and water from the “short pipe” enters chamber 3, it is soon detected by the “floor” probe (fig. 24), which is located 1.33 ft above the chamber floor and near the 2.63-ft vertical drop. Because of extensive turbulence in chamber 3, velocities could not be accurately measured here and, thus, the floor probe only was used to measure stage.

If the stage in chamber 3 exceeds the 2.63-ft drop at the baffle walls, reverse flow can occur through the “short” and “new pipe.” As the stage rises, water can enter the 48-in. diameter pipe that will provide storage until the water can be released. If severe backwater conditions are present in the “short pipe,” it can cause chamber 2 (containing a tide gate) (fig. 24) to fill with water.

The “outfall pipe” is a 108-in., smooth, concrete overflow sewer (fig. 24) located downstream of the tide gate in chamber 2. If the stage in chamber 2 is high enough so that the tide gate opens, the water flows through the gate and into the “outfall pipe,” and finally to the North Shore Channel. This tide gate has a switch-closure alarm that is activated when the gate opens. The alarm is relayed to Stickney and signals the sluice-gate operator to open the sluice gate(s).

If the stage is high enough in chamber 3, a tide gate that is located near the top of chamber 3 (fig. 24) can open. A probe is located on the ledge (referred to as the “ledge” probe) just upstream of the tide gate. This tide gate also has a switch-closure alarm that is activated when the gate opens, signaling the operator to open the sluice gate(s). If the stage is high enough so that the tide gate opens in chamber 3, the water flows through the gate opening and into an unmonitored outfall, and finally to the North Shore Channel.

Once the sluice gates are opened, the water in the chambers flows through the open sluice gates (fig. 24) and drops approximately 179 ft through a vertical shaft to the deep tunnel (fig. 13). Opening the sluice gates stops water from discharging to the North Shore Channel.

Storm Volumes

A detailed description is given below of the assumptions and methods used in data analysis during the storm of April 21-26, 1999, at Evanston, beginning at the “Lake Street pipe” in downstream order toward the sluice gates (fig. 24). The measured flow and calculated volumes are greatly affected by limitations of the flow meters, and the numerous assumptions made in analysis and unknown factors not considered. As with the analysis at Riverside, generally the same assumptions and methods were used for quantification of other 1999 storms.

Three Sigma probes were installed in the “Lake Street pipe” because they were prone to fouling from debris accumulation and grease/oil film development. The probes were mounted on C-channels and located in line, resulting in the most fouling at the most upstream probe. Therefore, the velocities measured at this probe often were recorded as zero. However, the two downstream probes weren’t as prone to fouling. Of the two downstream probes, one was a standard stage/velocity probe, and the other was a Keppler stage/velocity probe. The Keppler probe functions best in clear water because the velocity sensor in a Keppler probe has “larger crystals and, therefore, a greater beam/return signal sensitivity to reflectors in the water” (Joe Prell, American Sigma, Inc., oral commun., 1999). Because of the Keppler probe’s greater sensitivity to particles in the water, the recorded velocities can be higher than the actual values if the probe is used in water containing high quantities of particulate matter, including combined sewage. The manufacturer stated that when the velocity between the standard and the Keppler probe differed substantially, the standard probe likely would indicate a more representative average velocity (Joe Prell, American Sigma, Inc., oral commun., 1999).

For the purposes of data analysis in the “Lake Street pipe,” the data from the two downstream probes were used. Because the Keppler probe sometimes reported higher velocities than those reported by the standard probe, data from the standard probe were used if the instantaneous velocities measured by the two probes differed by more than 0.50 ft/s. If the instantaneous velocities differed by less than 0.50 ft/s, the two velocities were averaged.

Two additional inflow pipes, 21.5- and 12-in. diameter, respectively, connect to the “Lake Street pipe” on opposite sides (fig. 24) downstream of the Sigma probes, and were, therefore, not measured. On October 5, 1999, during dry-weather conditions, discharge measurements were made in an attempt to quantify the flow entering the “Lake Street pipe” through these pipes. Although the instantaneous flow rates were very low (less than 0.10 ft^3/s), it was assumed that flows could be substantially higher during stormwater flow periods. Therefore, 0.50 ft^3/s was added to each instantaneous measurement made in the “Lake Street pipe” during the 1999 storms. During the April 1999 storm, this 0.50 ft^3/s represented a total volume of 186,300 ft^3. A calculated volume of 12,372,224 ft^3 flowed through the “Lake Street pipe” during the April 1999 storm period (table 2).

Table 2. *Flow mass balance for chamber 3 in the combined sewer system at Evanston, Ill., April 21-26, 1999*

Flow into chamber 2	Volume (cubic feet)
Lake Street Pipe (drainage area of 1,738 acres):	12,372,224
Siphon Pipe (water withdrawn from Lake Street Pipe):	7,277,579
New Pipe (drainage area of 575 acres):	850,309
Total:	5,944,954
Flow out of chamber 2	
Outfall Pipe (to the North Shore Channel):	1,651,312
Ledge (to the North Shore Channel):	1,267,903
Total:	2,919,215
Volume to sluice gages and deep tunnel (Total in - Total out):	3,025,739

All the dry-weather flow from the “Lake Street pipe” is diverted by a diversion weir (fig. 2), through the “siphon pipe” interceptor sewer and conveyed to the North-Side Water Reclamation Plant. The time-of-travel for water from the “Lake Street pipe” to the “siphon pipe” probe was examined using the timing of four stage peaks at both locations. However, no direct correlation between the stage peaks at the “Lake Street pipe” and the “siphon pipe” were found. For this reason, no time correction was made for time-of-travel between the two pipes.

Throughout the April 1999 storm, the data collected at the “siphon pipe” generally indicated large stage rises along with consistent positive velocities (fig. 27). Between 23:05 and 23:15 on April 22, however, the stage dropped more than 7.0 ft in 10 minutes, whereas the velocity increased from approximately 1.0 ft/s to over 3.0 ft/s. This large change in stage and velocity probably is attributable to a sudden release of water to the treatment plant. Between 00:45 and 00:55 on April 23, a period of zero velocities was recorded. Zero velocity could have been recorded if the leading edge of the probe was fouled, not allowing for the velocity signal to be emitted, although this condition is unlikely. Zero velocities also could have resulted if the water actually stopped moving because the treatment plant was at, or over, capacity. From 03:10 to 03:55 on April 23, a second period of zero and negative velocities again was recorded. Again, zero velocities could have been caused by fouling of the upstream side of the probe; however, because negative velocities also were recorded, it is more likely that the treatment plant reached capacity and could not handle any additional inflow. Thus, backwater conditions and eventually turbulence or reversed flow resulted. These negative velocities were measured during a very large stage rise (more than 8.0 ft), which also indicates the treatment plant may have reached capacity and could not accept additional inflow. During this period of zero and negative velocities at the “siphon pipe,” velocity at the “Lake Street pipe” dropped from nearly 3.0 ft/s to less than 1.0 ft/s while the stage increased, indicating that the “siphon pipe” was not accepting more water from the “Lake Street pipe.” Thus, the water overflowed the weir and entered chamber 3, which quickly filled. This second period of both zero and negative velocities in the “siphon pipe,” from 03:10 to 03:55 on April 23, verifies the results during the first period from 00:45 to 00:55 on April 23. Because of this condition, the “siphon pipe” data were accepted for the analysis. A calculated volume of 7,277,579 ft^3 flowed through the “siphon pipe” during the April 1999 storm period (table 2).

The volume of water overflowing the diversion weir at the “Lake Street pipe” was calculated by subtracting the total volume through the “siphon pipe” from the “Lake Street pipe.” It was assumed that any instantaneous volume of water in the “Lake Street pipe” that exceeded that of the “siphon pipe” overflowed the weir and entered chamber 3. A calculated volume of 5,094,645 ft^3 overflowed the weir and entered chamber 3.

Chamber 3 receives “Lake Street pipe” overflow as well as water from the “new pipe” conveyed by the “short pipe.” Because of limitations with the location of the “short pipe” probe, explained below, the data from the “new pipe” were used in the analysis. The “short pipe” probe was located in a 108-in. diameter pipe (approximately 25 ft long). Downstream of the “short pipe” were velocity-diminishing baffle walls and a

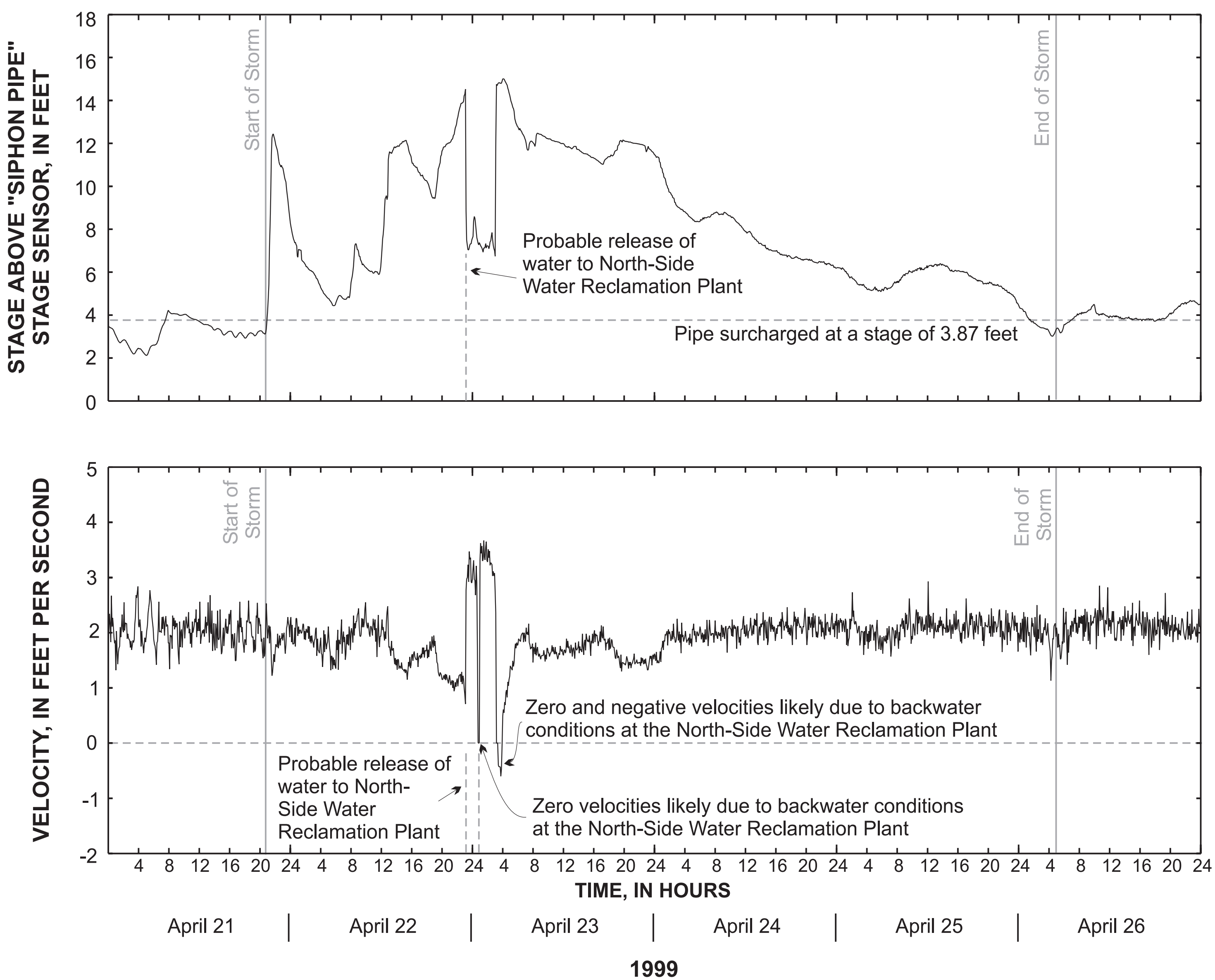

Figure 27. Stage and velocity at the “siphon pipe,” Evanston, Ill., April 21-26, 1999.

2.63 ft vertical drop leading into chamber 3. The probe was mounted near the middle of the "short pipe" approximately 15 ft from the 2.63-ft drop (fig. 26). Because this pipe becomes surcharged, it would have been ideal to locate the probe at least 10 pipe diameters upstream from the vertical drop, but this was not possible because the length of the "short pipe" was less than the required 10 pipe diameters. Flow was affected by the vertical drop (which could cause drawdown), but also by the velocity-diminishing baffle walls (which would cause turbulence). Although the data from the "short pipe" probe were not used for flow or volume calculation, the stage data were used for comparison to determine stages inside and outside the sewer system, indicating when the tide gates in chambers 2 and 3 may have opened.

In contrast, the "new pipe" probe was located in a 112-in., smooth, concrete, storm-relief pipe that receives stormwater flows as well as provides storage for backwater from chamber 3. Just downstream of the "new pipe" probe is a small bend at the manhole access (fig. 24), which possibly could have induced some turbulence; however, because the bend was small, the flow was unlikely to be substantially affected. In addition, chamber 1 was downstream of the "new pipe" probe, and could have caused some disturbance; however, because this chamber is much farther away than the sources of turbulence at the "short pipe," "new pipe" data were deemed more reliable. There were no apparent flow disturbances or sources of turbulence upstream of the probe.

Three distinct, large stage rises are indicated in the "new pipe" (fig. 28) during April 21-26, 1999. The water-level rises were due to stormwater from upstream sources and backwater from chamber 3. As the stage increased near the beginning of each rise, a positive velocity was measured. Positive velocities indicate that storm water was conveyed to the "new pipe" from upstream sources. Shortly after each rise began, the velocities became negative. Negative velocities indicate that water filled chamber 3 to the point that water backflowed through the "short pipe" and the "new pipe." During the peak of each rise, the stage became relatively steady and the velocities became zero. This resulted because water that entered chamber 3 from "Lake Street pipe" overflow was released through the tide gates in chambers 2 and 3, before an additional stage increase could be realized at the "new pipe." During the latter part of the stage recession, generally on April 25-26, velocities fluctuated between zero and small positive values (an average of about 0.4-0.5 ft/s). Zero velocities were recorded probably because the water velocity was below the detection limit of the meter. Because the stage was changing, it is evident that water was moving through the sewer system. Therefore, when a zero velocity was recorded, it was changed to 0.125 ft/s.

During normal dry-weather operation, one 8-ft by 8-ft sluice gate in chamber 3 is open approximately 5 percent (approximately 5 in). When a tide-gate alarm is received at Stickney, one or both of the sluice gates are opened between 10 and 20 percent (approximately 10 to 20 in); however, exact gate openings are unknown. When the stage began to decrease in the "new pipe" during each of these three rises in April, not only was water flowing through the tide gates in chamber 2 and 3, but the sluice gate was partially open. During the stage recessions, the water was flowing through the partially opened sluice gate to the deep tunnel, although positive velocities were not detected at the "new pipe" probe; instead, zero velocities were recorded. During the recession of April 21-22, the stage in the "new pipe" dropped approximately 13 ft before a positive velocity again was detected (1.81 ft/s). During this period, velocity was not detected by the Sigma meter because the velocity in the "new pipe" was lower than the Sigma meter's detection limit of 0.20 to 0.30 ft/s. During the periods when the velocity was lower than the detection limit, the velocities were not changed if the stage was rising. In these cases, it was impossible to determine whether the velocities should have been positive because more water was being added to the sewer system; or negative, which would have resulted because of backwater or turbulence. Alternately, during these same periods when the velocity was below the detection limit, if the stage was decreasing, it is evident that water was being removed from the system through the tide gate in chambers 2 and 3, and also through sluice-gate openings. During these periods, the velocities were changed to 0.125 ft/s, as described in the "Storm Volumes" section for Riverside. A calculated volume of 850,309 ft^3 flowed through the "new pipe" during the April 1999 storm period (table 2).

Although the "floor" probe was installed to verify stage peaks detected at the "ledge" probe and elsewhere, the "short pipe" stage was used for this verification instead because values at the "short pipe" more closely verified values recorded at the "ledge probe." When the stage in chamber 3 rises higher than the 2.63-ft vertical drop, flow can reverse and cause chamber 2 to fill. The tide gate in chamber 2 then can open and water can flow through the gate opening to the "outfall pipe," which is located downstream of this tide gate, and finally into the North Shore Channel (fig. 1). Alternately, when the North Shore Channel stage rises, water can flow from the river into the "outfall pipe," but the tide gate theore-

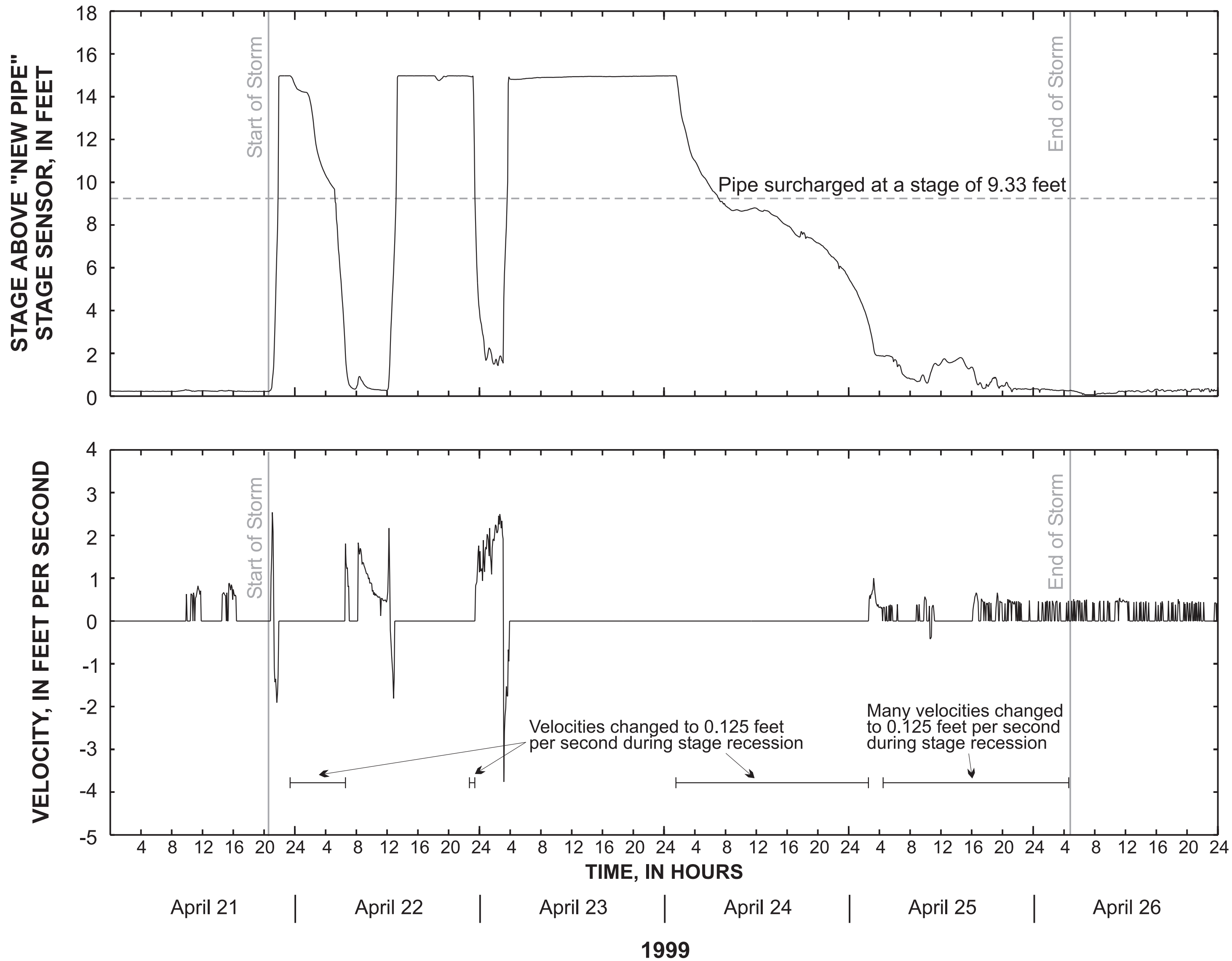

Figure 28. Stage and velocity at the “new pipe,” Evanston, Ill., April 21-26, 1999.

tically prevents flow into the sewer system. A plot of the "outfall" stage and velocity data for the April 1999 storm is presented in figure 29.

The stage in the "outfall pipe" rose smoothly because the North Shore Channel was high enough to back up into the pipe. The rise in stage is a reflection of the rise in stage of the North Shore Channel, which is the reason for the nearly zero velocity measured early on April 21. During three distinct periods (from 21:55 on April 21 to 01:55 on April 22; from 13:20 to 18:00 on April 22; and from 19:25 to 23:05 on April 22) positive velocities were detected in the "outfall pipe" because of the tide-gate openings. In addition to these periods of consistent positive velocities, smaller magnitude, inconsistent positive velocities were recorded but were not used for data analysis because they were assumed to be affected by turbulence from the North Shore Channel. The stage on the upstream side of the tide gate from the CSO was compared to the stage on the downstream side of the tide gate from the North Shore Channel. During the periods of inconsistent positive velocities, because stage was higher at the North Shore Channel than in the sewer system, it was decided not to include these velocities in the data analysis, based on the assumption that the gate was not open. Finally, flow might have occurred from the North Shore Channel around the edges of the tide gate in chamber 2 and into the sewer system during periods when the North Shore Channel stage was high when compared to the stage in the sewer system. This condition resulted at the tide gate in chamber 3 (described later), and because both tide gates are at approximately the same elevation, the assumption that reverse flow could have resulted through the tide gate in chamber 2 is valid. A calculated volume of approximately 1,651,312 ft^3 flowed through the "outfall pipe" during the April 1999 storm period (table 2).

If the stage rises in chamber 3, water can exceed the height of the "ledge" at the tide gate in chamber 3 and be detected by the "ledge" probe. A plot of the "ledge" probe stage and velocity data is presented in figure 30.

During the first appreciable stage and velocity rise from 21:55 on April 21 to 00:50 on April 22, velocities mostly were positive, indicating flow out through the tide gate. However, at 22:20, 22:25, and 22:55 on April 21, negative velocities were detected, indicating turbulence near the probe probably caused by the tide gate closing momentarily. The second appreciable stage rise indicated the same trend with consecutive positive velocities and one negative velocity at 13:55 on April 22, indicating turbulence near the probe. For the purpose of data analysis, the negative velocities during these two periods were changed to zero, because water probably was not flowing back through the gate. After the second period of flow through the gate, the water inside the sewer decreased and remained high enough that the water still was over the "ledge" and on the gate, but not high enough to open the gate. During this period, velocity values were both positive and negative, indicating turbulence on and near the "ledge." This portion of the data was not included in the analysis, because water probably did not flow through the gate opening during this period. The third appreciable stage rise was accompanied by a large velocity rise, indicating that water once again flowed through the gate. However, following this rise, at 23:10 on April 22, the stage in the sewer decreased below the level of the tide gate. However, because the North Shore Channel stage was high enough to submerge part of the tide gate, water from the North Shore Channel began to seep around the edges of the gate causing reverse flow into the sewer system. This condition can be seen from 23:10 on April 22 to 03:40 on April 23; from 00:30 to 10:00 on April 24; from 15:00 to 16:55 on April 24.

The flow calculated from the "ledge" probe data was affected by turbulence because of the probe location. According to the manufacturer's specifications, the probe should be located at least 10 times the maximum expected depth away from any flow obstruction; however, the location of the "ledge" probe did not permit this installation. Additionally, turbulence at the "ledge" probe was induced when water overflowed the "Lake Street" weir, directly toward the "ledge" probe. A calculated volume of 1,267,903 ft^3 flowed over the "ledge" during the April 1999 storm period (table 2).

Because no probe directly measured the water flowing to the sluice gates, as in the "short pipe" at Riverside, the volume of water through the sluice gates at Evanston was calculated based on a mass balance in chamber 3. The inflows into chamber 3 include the water overflowing the "Lake Street" weir, the "new pipe," conveyed by the "short pipe," and seepage around the tide gates. The outflows are the "outfall pipe," the "ledge" gate and the sluice gates. Mass-balance results for chamber 3 are given in table 2. The total inflow to chamber 3 from the "Lake Street pipe" overflow and the "new pipe" was 5,944,954 ft^3, whereas the total outflow through the tide gates to the North Shore Channel was 2,919,215 ft^3. The remainder of the volume was 3,025,739 ft^3 and flowed through the sluice gates to the deep tunnel (table 2).

Similar assumptions and analytical methods generally were used during the June 1999 and December 1999 storms as used with the April 1999 storm. How-

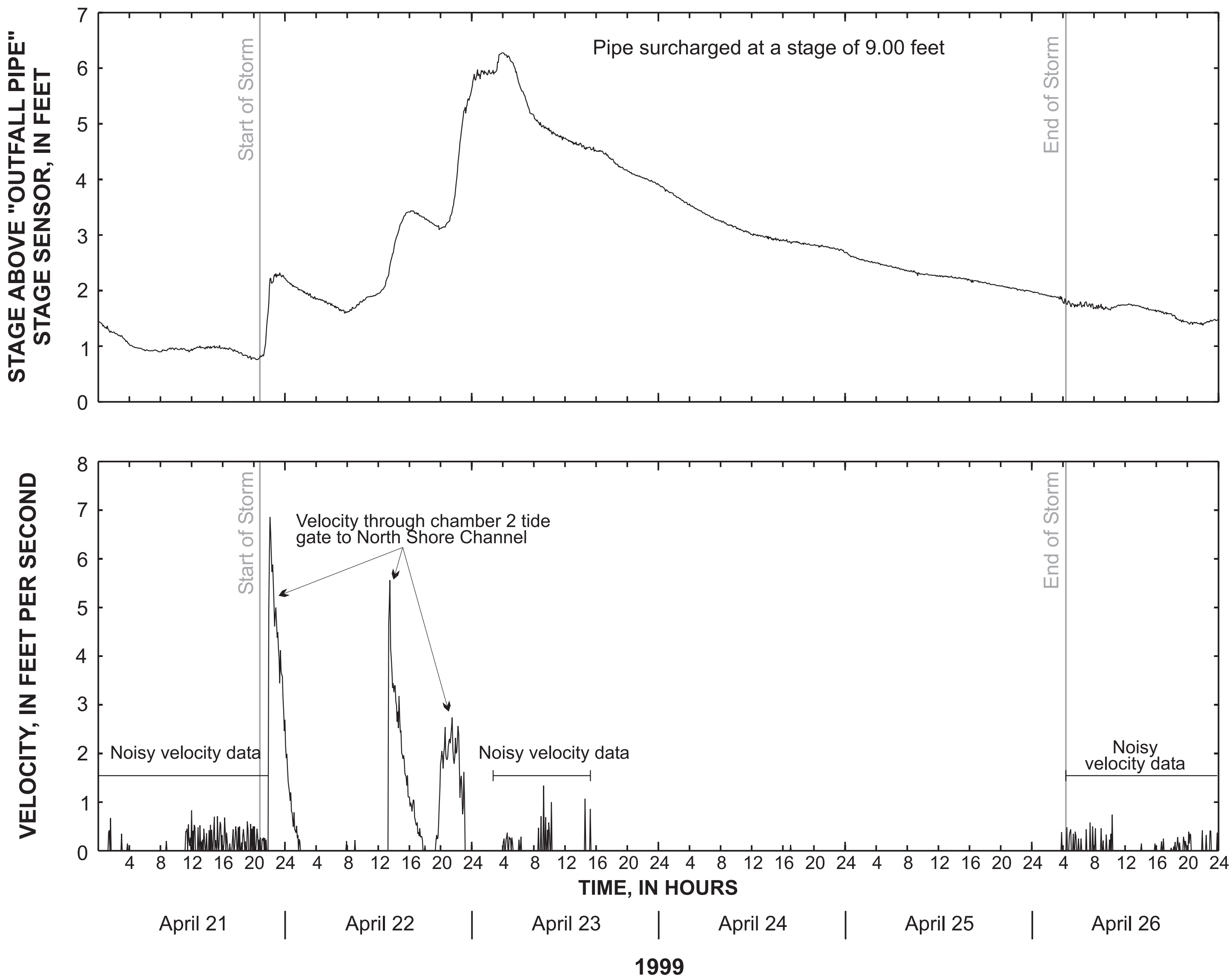

Figure 29. Stage and velocity at the “outfall pipe,” Evanston, Ill., April 21-26, 1999.

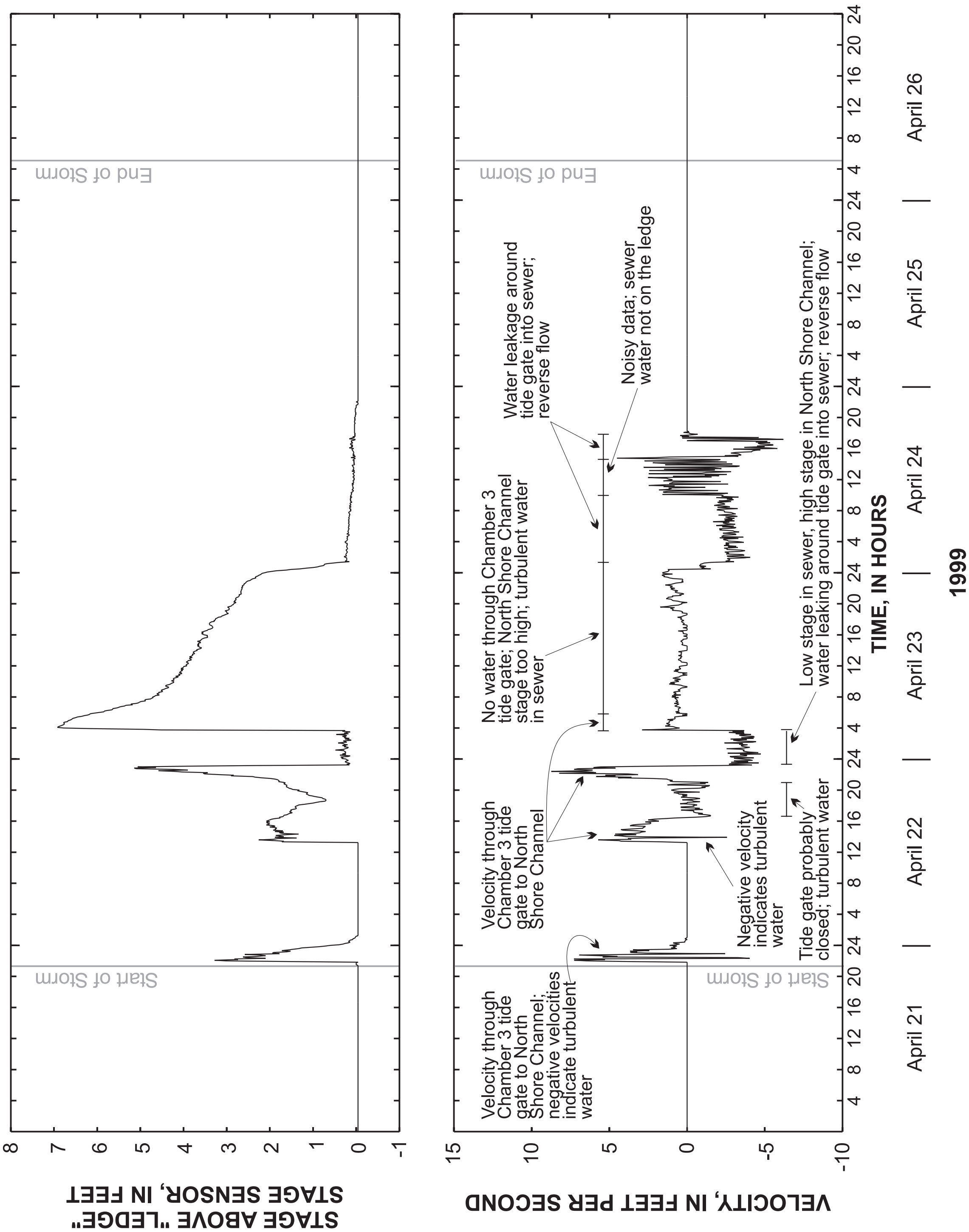

Figure 30. Stage and velocity at the "ledge," Evanston, Ill., April 21-26, 1999.

ever, one minor variation in flow analysis at the "new pipe" was required. On August 10, 1999, the probe in the "new pipe" was moved about 3 ft upstream and up along the side of the pipe to keep it from being buried by debris. The adjusted probe elevation was 1.09 ft above the bottom of the pipe. Therefore, during the start and end of the December 1999 storm, water was not detected by the probe until it reached a depth of 1.09 ft. The amount of water that flowed past the probe at the beginning of the storm was estimated by examining six other storms and taking the average volume of water flowing past the probe before the stage reached 1.09 ft. It was estimated that the total volume of water undetected by the probe during the rising stage was approximately 0.60 percent (approximately 1,802 ft^3) of the entire storm volume (317,291 ft^3).

SUMMARY

The U.S. Geological Survey, in cooperation with the U.S. Army Corps of Engineers, collected and analyzed flow data in combined sewer systems in Riverside and Evanston, Ill., during 1997-99. Water-quality data were collected by the Metropolitan Water Reclamation District of Greater Chicago (MWRDGC) at Evanston, Riverside, the Calumet pumping station, and the Racine pumping station from May 1, 1995, to December 9, 1999. This study was done in an effort to provide data and analysis that can be used in the design of a flood-control reservoir as part of the Chicago Underflow Plan/Tunnel and Reservoir Plan.

The sewer systems consist of circular pipes ranging in diameter from 0.83 ft to 10.0 ft; elliptical siphon pipes; ledges; and tide and sluice gates. Stage and velocity data were collected at 12 locations at Riverside and Evanston, Ill., from March 1997 to December 1999 using American Sigma ultrasonic flow meters and a Starflow ultrasonic Doppler instrument. The instrument probes were mounted on stainless-steel straps, stainless-steel bands, I-beams, and C-channels. Operation and maintenance of the meters required monthly site visits. Some probes were prone to fouling from debris accumulation and grease/oil film development. Flow mass balances were performed for the sewer systems at Riverside and Evanston to determine the quantity of water flowing through the sluice-gate openings to the deep tunnel and to determine the quantity of water flowing through tide-gate openings to receiving waterways.

Because of the complexity of the flow data and data-collection locations at both the Riverside and Evanston locations, various assumptions were required. In six pipes, during periods when the stage was decreasing, if the velocity of the water was below the minimum detection limit of the Sigma meters (from 0.20 to 0.30 ft/s), then one-half of the average minimum detection velocity (0.125 ft/s) was applied in the analysis. In addition, unquantified volumes of water may have seeped around the edges of the tide gates and into the sewer system from the receiving waterways, as indicated at one site in Evanston. It is unknown what effect this volume would have on the final volume calculation results. The diversion from the "Gage Street pipe" into the interceptor sewer at Riverside was not measured and, therefore, was estimated. One probe at Riverside was affected by infiltration, which caused measurement of erroneous velocity data during much of the April 1999 and June 1999 storms. Velocity corrections were made throughout these periods.

The mass balance at Riverside for the storm during April 22-26, 1999, indicated a total inflow into chamber 2 of 720,440 ft^3, whereas the outflow to the Des Plaines River was 131,686 ft^3 and the outflow through the sluice gate to the deep tunnel was 267,106 ft^3. The mass balance at Evanston for the storm during April 21-26, 1999, indicated a total inflow into chamber 3 of 5,944,954 ft^3, whereas the outflow to the North Shore Channel was 2,919,215 ft^3 and the outflow through the sluice gates to the deep tunnel was calculated to be 3,025,739 ft^3.

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