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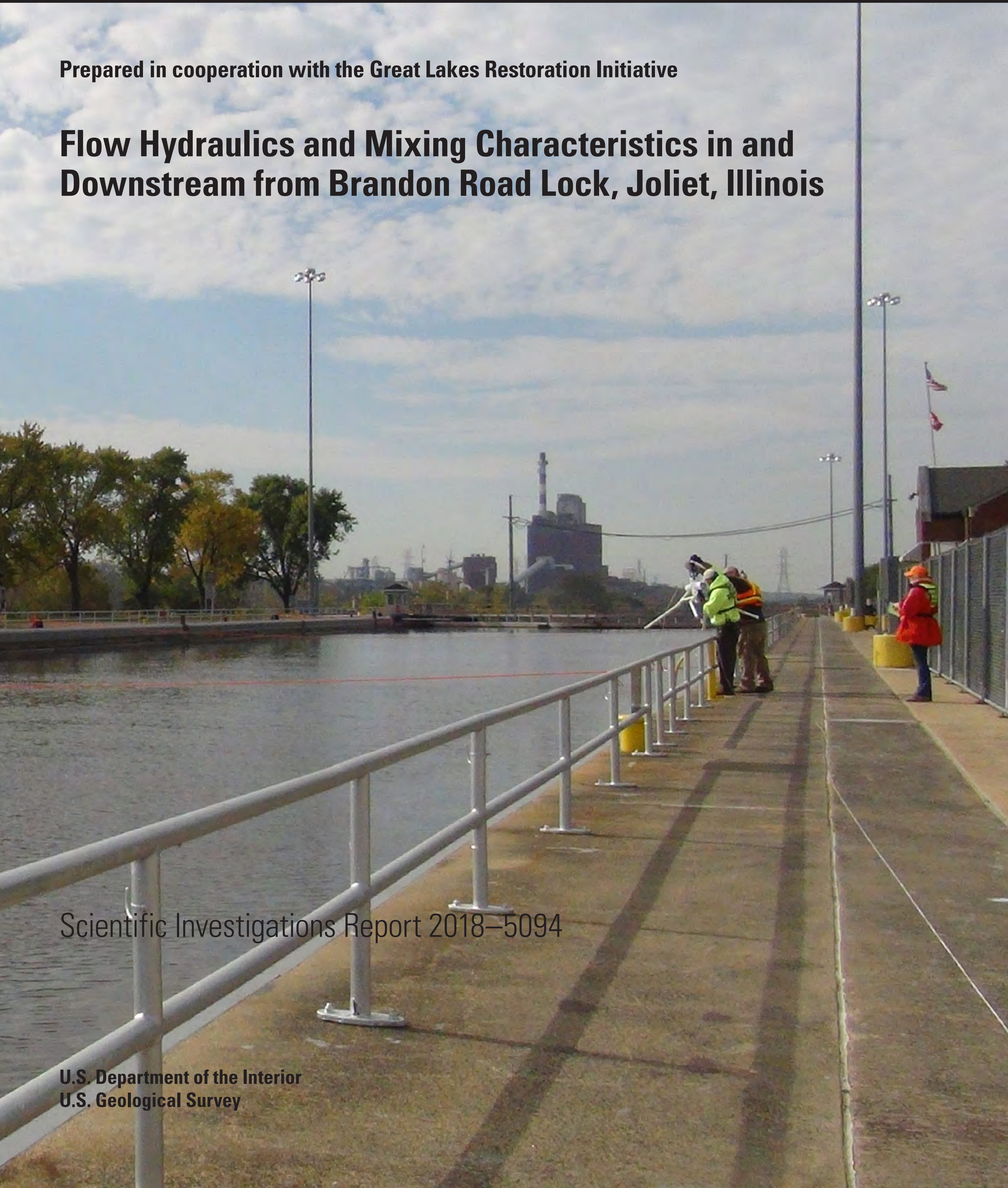
Flow Hydraulics and Mixing Characteristics in and Downstream from Brandon Road Lock, Joliet, Illinois



Scientific Investigations Report 2018–5094

U.S. Department of the Interior
U.S. Geological Survey

Cover. U.S. Geological Survey personnel deploy a submersible fluorometer in Brandon Road Lock during a dye study in October 2015. Photograph by Ayla Ault, U.S. Geological Survey.

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U.S. Geological Survey
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Conversion Factors

International System of Units to U.S. customary units

Multiply	By	To obtain
	Length	
centimeter (cm)	0.3937	inch (in.)
meter (m)	3.281	foot (ft)
kilometer (km)	0.6214	mile (mi)
	Area	
square meter (m^2)	10.76	square foot (ft^2)
square centimeter (cm^2)	0.1550	square inch (ft^2)
square kilometer (km^2)	0.3861	square mile (mi^2)
	Volume	
cubic meter (m^3)	264.2	gallon (gal)
cubic meter (m^3)	0.0002642	million gallons (Mgal)
liter (L)	61.02	cubic inch (in^3)
cubic meter (m^3)	35.31	cubic foot (ft^3)
	Flow rate	
cubic meter per second (m^3/s)	35.31	cubic foot per second (ft^3/s)
	Velocity	
meter per second (m/s)	3.281	foot per second (ft/s)
centimeter per second (cm/s)	32.81	foot per second (ft/s)
kilometer per hour (kph)	0.621	mile per hour (mph)

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as

$$°F = (1.8 \times °C) + 32.$$

Datum

Vertical coordinate information is referenced to the National Geodetic Vertical Datum of 1929 (NGVD 29).

Horizontal coordinate information is referenced to the World Geodetic System of 1984 (WGS 84).

Altitude, as used in this report, refers to distance above the vertical datum.

Supplemental Information

Concentrations of Rhodamine WT dye in water are given in either micrograms per liter (µg/L) or parts per billion (ppb).

Times are specified in 24-hour format in either Central Standard Time (CST) or Central Daylight Time (CDT).

U.S. Geological Survey convention defines the left and right banks of a channel when facing downstream.

Abbreviations

ADCP	acoustic Doppler current profiler
ANS	aquatic nuisance species
ASCII	American standard code for information interchange
BRL	Brandon Road Lock
CAWS	Chicago Area Waterway System
CDT	Central Daylight Time
CST	Central Standard Time
EPA	U.S. Environmental Protection Agency
GLMRIS	Great Lakes and Mississippi River Interbasin Study
GPS	global positioning system
H	water-surface elevation
H_L	head difference
HDPE	high-density polyethylene
IQR	interquartile range
MBES	multibeam echosounder
min	minute
NGVD 29	National Geodetic Vertical Datum of 1929
NWIS	National Water Information System
PVC	polyvinyl chloride
Q_E	estimated discharge
Q_L	net leakage
RTK–GPS	real-time kinematic global positioning system
s	second
USACE	U.S. Army Corps of Engineers
USGS	U.S. Geological Survey
VMT	Velocity Mapping Toolbox
WAAS	Wide Area Augmentation System

Acknowledgments

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Flow Hydraulics and Mixing Characteristics in and Downstream from Brandon Road Lock, Joliet, Illinois

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Abstract

The Brandon Road Lock and Dam on the Des Plaines River near Joliet, Illinois, has been identified for potential implementation of aquatic nuisance species (ANS) control measures. To provide additional information concerning the flow hydraulics and mixing characteristics of the lock and downstream approach channel, the U.S. Geological Survey performed a detailed study of the site between December 2014 and October 2015, which included the collection and analysis of bathymetric, hydrodynamic, and dye tracer data. Synthesis of these data allowed a characterization of the site for future use in feasibility studies of potential ANS control technologies. The results of this study show a highly dynamic system driven primarily by lock operations but influenced by channel characteristics, industrial withdrawals, and meteorological forcing. Lock operation produces rapidly varying flows in the downstream approach channel, including transient oscillations that produce bidirectional flows. When the lock is not in operation, flows in the approach channel are primarily driven by leakage and wind forcing. Uniform concentrations of dissolved constituents in the lock chamber can be achieved by injection of the constituent into the existing lock filling and emptying system; however, valve and gate leakage can inhibit the mixing at the downstream end of the lock and substantially affects the ability to maintain a treated lock chamber at a uniform target concentration at tailwater level. Proper understanding of these hydraulic factors should be accounted for if the lock is to be used to deliver any dissolved constituent or operated in a way to prevent upstream passage of floating ANS. Moreover, extremely variable flow conditions including bidirectional flows and upstream return flows must be considered when implementing any ANS control technologies in the approach channel.

Introduction

Invasive Asian carps (bighead carp [*Hypophthalmichthys nobilis*] and silver carp [*Hypophthalmichthys molitrix*]) are well established in the Mississippi River Basin (Chick and Pegg, 2001) and are threatening to move into the Great Lakes through interbasin connections. There are five interbasin pathways within the Chicago Area Waterway System (CAWS) identified in the U.S. Army Corps of Engineers (USACE) Great Lakes and Mississippi River Interbasin Study (GLMRIS) Report (U.S. Army Corps of Engineers, 2014) and all five of these pathways share a connection point at Brandon Road Lock and Dam. To help prevent the movement of Asian carps and other aquatic nuisance species (ANS) from the Mississippi River Basin to the Great Lakes Basin, ANS control measures have been proposed at Brandon Road Lock and Dam near Joliet, Ill., by the USACE. Unlike other lock and dams downstream on the Illinois Waterway, fish can only pass upstream at Brandon Road Lock and Dam through the lock because the dam is impassible to fish even at the 0.2-percent annual exceedance probability discharge (also referred to as the 500-year flood) (U.S. Army Corps of Engineers, 2017a). The design of deterrent or control technologies that may be considered will require an understanding of the effects of lockages, structures, and other influences that could constrain deployment. If chemical control in the lock is considered then factors such as the mixing, residence time, and dilution downstream must be well characterized. The U.S. Geological Survey (USGS) has collected data that can be used in the design of a system to minimize the movement of ANS above Brandon Road Lock and Dam while preserving the navigation traffic within the river system.

Study Area Description

The Brandon Road Lock and Dam opened in 1933 and is located on the Des Plaines River just south of Joliet, Ill. (fig. 1). Operated by the USACE, Brandon Road Lock and Dam enables navigation of all boat traffic between the lower Des Plaines and Illinois Rivers and the CAWS.

Dam and Lock

The dam is 728.7 meters (m) long and contains 21 Tainter gates, six sluice gates, and 16 pairs of headgates (U.S. Army Corps of Engineers, 2017b). The sluice gates are bulkheaded

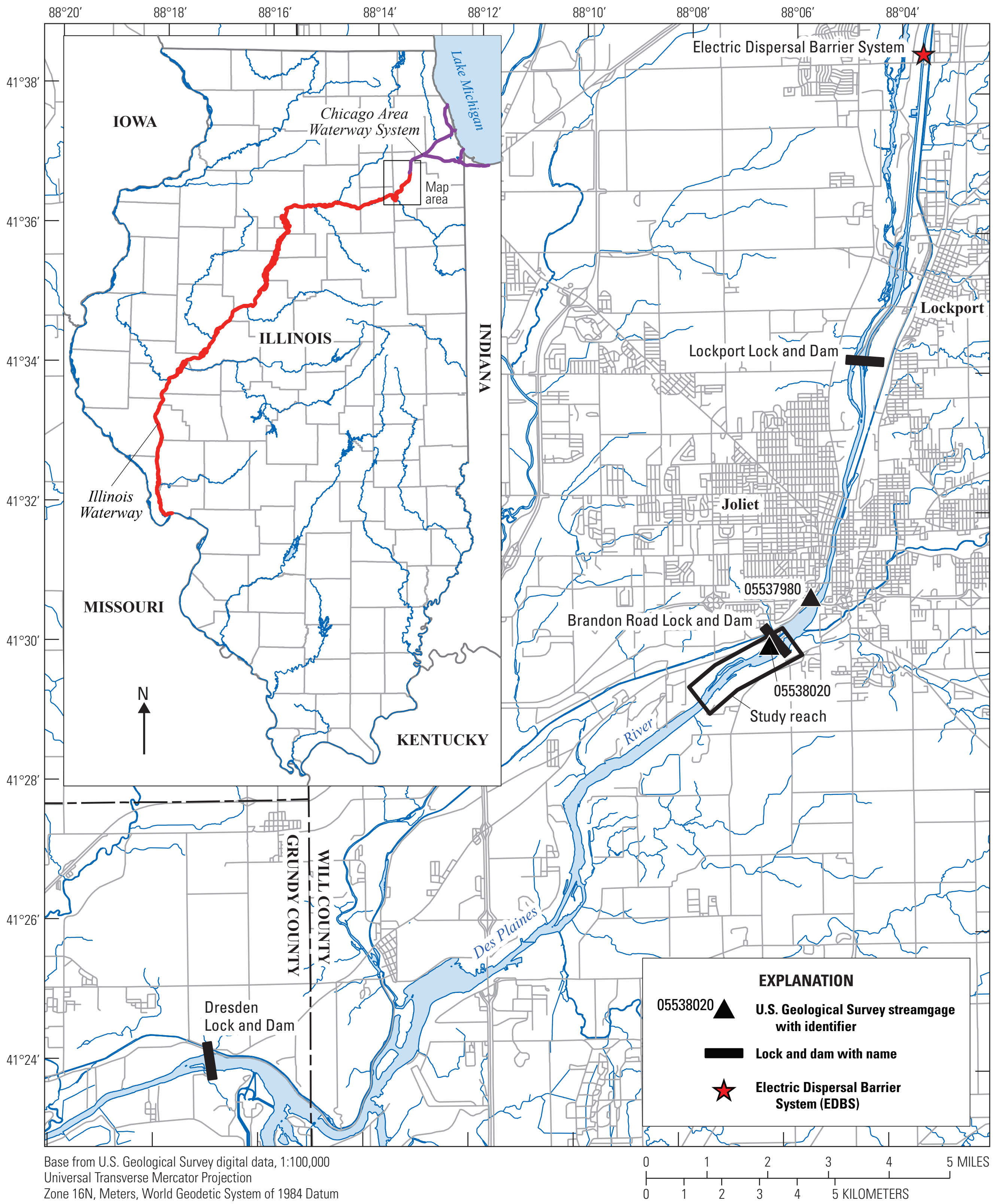


Figure 1. Location of field data collection in and near Brandon Road Lock and Dam near Joliet, Illinois, and other features of interest in the Illinois Waterway.

closed and one-half of the headgates are operational, whereas the other one-half are bulkheaded closed.

The lock chamber is 183 m long, 33.5 m wide, and has a nominal lift height of 10.4 m (U.S. Army Corps of Engineers, 2017b). The chamber releases approximately 71,000 cubic meters of water when emptying for a typical downbound lockage (vessel moving from upstream to downstream through the lock). The lock is gravity-fed using a side-ported filling and emptying system with vertical lift valves. Immediately upstream of the upstream miter gates on each side of the lock chamber, there are filling valves. Likewise, there are emptying valves on the downstream end of the lock immediately downstream of the downstream miter gates. Both upstream and downstream valves are connected to a culvert and side-port system that runs the length of the lock (fig. 2). There are ten 0.9 m by 1.5 m rectangular ports on each of the lock side walls, each located 0.3 m above the lock bottom that allows water to exchange into the lock chamber during filling or emptying (fig. 2).

Under normal operation, the average filling time for the lock is 19 minutes (min), and the average time necessary to empty the lock is 15 min. To change the lock chamber water level, lock operators manually control the opening rates for the left and right wall valves individually. Therefore, each time the lock chamber is filled or emptied, the flow through each culvert can vary slightly. In addition to filling and emptying, the lock can also be “flushed.” During flushing, water is let into the lock through the partially open filling valves and exits the lock through the open downstream miter gates. Flushing is not a typical operation at Brandon Road Lock (BRL) but has been proposed by the USACE as a possible control measure to remove ANS from the lock chamber prior to an upstream lockage (U.S. Army Corps of Engineers, 2014, 2017a).

Downstream Channel and Spillway

The areas downstream from the lock and dam structures are shown in figure 3. Below the downstream miter gates of the lock chamber is the constructed part of the approach channel, with reinforced concrete walls. The right bank guidewall of this section of the approach channel is referred to as the “long wall” and is 212 m long. Barges are commonly tied up along the long wall when necessary as part of normal operations for entering or exiting the lock chamber. An 85-m guidewall on the left bank (referred to as the “short wall”) protects the Brandon Road drawbridge piers. The channel width in this walled section near the lock chamber is 33.5 m. The approach channel widens to 70 m downstream from the left bank wall. Immediately downstream from the lock entry, the approach channel (fig. 3) to the lock is 79 m wide with sloping banks. The approach channel geometry is roughly parabolic, with a thalweg depth of 4.3 m.

The spillway receives the flow over the dam and is not part of the navigable channel. The spillway joins the navigable Des Plaines River channel approximately 700 m downstream from the downstream lock miter gates. After the confluence with the spillway, the channel widens to approximately 150 m. There are two powerplants downstream from the confluence that draw water from the river—one on the north side of the river (right bank) and one on the south side of the river (left bank).

Purpose and Scope

The purpose of this report is to describe the data collection and analysis of the flow hydraulics and mixing characteristics at Brandon Road Lock and Dam. These data can be used to aid in the development and evaluation of ANS control technologies proposed at this location. This report is structured around providing answers to the following questions driving the research on control technologies at Brandon Road Lock and Dam:

1. What are the flow hydraulics of the lock and downstream channel reach when the lock is filling, emptying, flushing, and when lock gates and valves are all closed?
2. Does the Brandon Road Lock filling process mix dissolved constituents to a uniform concentration throughout the lock?
3. What is the fate of dissolved constituents downstream when the lock is being emptied or flushed and when water is not being released to the downstream channel?

Methods of Data Collection and Data Analysis

This section describes the methods used to collect and analyze the bathymetric, water-surface elevation, velocity, discharge, and dye concentration data presented in this report. The data collected have been published, along with metadata or references describing the methods used, through ScienceBase or the USGS National Water Information System (NWIS) and are available as USGS data releases (Boldt and Martin, 2017; Engel, 2016; Engel and Bosch, 2017; Engel and Krahulik, 2016; Jackson, 2016a,b,c; Jackson and Engel, 2016). Both fixed-site and mobile sensor platforms were used to capture the temporal and spatial variation in the dye and velocity distributions.

Bathymetry

Bathymetric survey data of the Brandon Road Dam spillway were collected on May 27 and May 28, 2015, using Trimble® Real-Time Kinematic Global Positioning System (RTK–GPS) equipment (Engel and Krahulik, 2016). In wadeable sections, a global positioning system (GPS) rover was

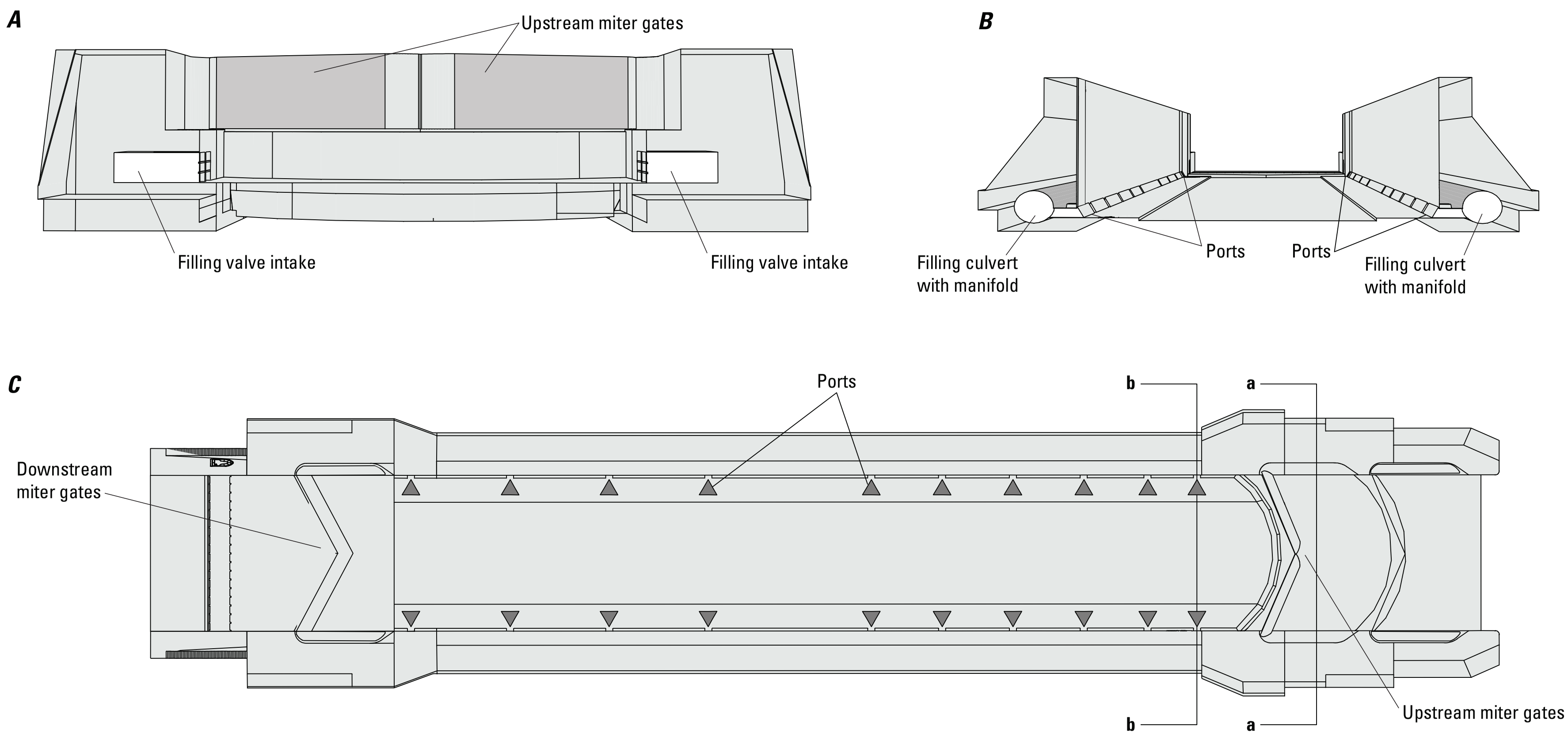


Figure 2. Schematic of the lock chamber. *A*, Section view of the filling valves looking downstream toward the miter gates. *B*, Section view of the side-ported filling and emptying system looking downstream from the upstream lock gates. *C*, Plan view of the ports and miter gates. Modified from K. Sunderman, unpub. data, 2015.

Figure 3. Brandon Road Lock and Dam, spillway, lock approach channel, and Des Plaines River downstream from the lock with powerplant intakes and outfalls.

deployed. In sections unable to be waded, a range pole was fix-mounted to a jon boat, and a boat-mounted acoustic Doppler current profiler (ADCP) was used to collect the depth data. The RTK–GPS survey points of the water-surface elevations were used to convert ADCP-measured depths into bed elevations. An In-Situ Level Troll® placed in the spillway pool collected 1-min water-surface elevation data throughout the 2-day survey. These data were used to verify that a flat-pool assumption was reasonable for the conversion of the ADCP data to bed elevations given the measurement precision of the ADCP. Bathymetric survey data of the lock approach channel were collected on February 13–14, 2017, using a multibeam echosounder (MBES) (Boldt and Martin, 2017).

Water-Surface Elevation in the Lock Chamber

Water-surface elevation in the lock chamber was monitored with an In-Situ Level Troll® between December 2014 and October 2015 (Jackson and Engel, 2016; Engel and Bosch, 2017). The instrument was deployed in conduit inside a ladder well on the right wall of the lock chamber and was calibrated to the water-surface elevation readings (headwater elevation) made by the USACE (U.S. Army Corps of Engineers, 2018). Water-surface elevation measurements were sampled at a 1-min frequency throughout the study.

Using the change in water-surface elevation in the lock chamber over time and the lock chamber geometry, an estimated discharge to the approach channel was computed. Inherent assumptions in computation of estimated discharge using this method include the following: (1) the approximate surface area of the lock is 6,975 plus or minus (±) 20 square meters (m^2) for water-surface elevation above 158.70 m National Geodetic Vertical Datum of 1929 (NGVD 29) and 6,882±20 m^2 for water-surface elevation below 158.70 m NGVD 29; (2) the discharge during lock flushing is 34.6±3.7 cubic meters per second (m^3/s) (as measured in December 2014; Engel and

Bosch, 2017); (3) the net leakage rate through the lock is a function of head difference and can be described by an empirical relation derived from periods of prolonged leakage; (4) the water surface in the lock chamber is uniform; and (5) the accuracy of the pressure sensor is ±0.011 m and the resolution is ±0.0011 m (manufacturer's specifications). Net leakage is defined as leakage into the lock from the upstream pool minus leakage out of the lock to the downstream pool. The primary sources of uncertainty for this method are the accuracy of the pressure sensor and fluctuations in the water level. For an accuracy of 0.011 m, a lock surface area of 6,975 m^2, and a sampling interval of 60 seconds (s), the uncertainty in estimated discharge due to the pressure sensor accuracy is approximately 2.6 m^3/s. The standard deviation of the water-surface elevation during periods when the lock was held at the headwater elevation for extended periods (at least 1 hour) is approximately 0.02 m. The uncertainty in estimated discharge due to these fluctuations is approximately 4.7 m^3/s. Conservatively combining these two primary sources of uncertainty and rounding up produces an estimate of the total uncertainty in estimated discharge of approximately 8 m^3/s.

Several steps are required to compute discharge to the approach channel from volumetric changes in the lock chamber. First, a 7-min moving average was applied to the 1-min water-surface elevation data to remove noise and minor fluctuations owing to waves, seiches, or other disturbances of the water surface (the mode 1 seiche period is about 30 s). Next, the time rate of change of water level in the lock chamber was computed (dH / dt , where *H* is the water-surface elevation in the chamber and *t* is time). Multiplying dH / dt by the lock chamber surface area yielded a time series of the change in volume (*V*) of water in the lock chamber (dV / dt). A negative value of dV / dt indicates discharge of water from the chamber to the approach channel downstream, and a positive value indicates filling of the lock chamber from water upstream (all positive values of dV / dt were subsequently set to zero because approach channel water is not used to fill the lock). The estimated discharge (Q_E) to the approach channel was computed as $Q_E = -dV / dt$.

Although this method works well for rapidly changing water levels in the lock chamber, it can produce noisy results for near-constant or slowly varying water levels and fails to capture net leakage through the lock chamber when the lock operators hold the chamber at the headwater or tailwater elevation by leaving one set of valves open. To overcome these issues, an empirical relation between net leakage (Q_L) and head difference (H_L) was developed using data from periods when leakage caused the water level to drop in the chamber (all gates and valves closed, lock chamber initially full). A total of 835 observations meeting these criteria were fit with a power law producing the relation

$$Q_L = 0.0245 H_L^{2.2782} \quad (1)$$

(coefficient of determination [R^2] = 0.97; standard error = 0.15 m^3/s),

where $H_L = H - 153.75$. A constant tailwater elevation of 153.75 m NGVD 29 was used because the range of tailwater elevation is small (about 0.3 m) compared to the head difference (approximately 10.4 m) during dry weather (U.S. Geological Survey, 2017a). During periods with only leakage (gates closes, valves closed), the predicted net leakage (Q_L was used in place of $-dV / dt$ to estimate discharge. For the remaining periods in which the lock was operational (filling, emptying, holding at headwater level), the predicted net leakage Q_L was added to the estimated discharge from the lock chamber Q_E. This correction captures the leakage through the lock that is not measured by the pressure sensor. It should be noted that this method predicts zero discharge when the lock is at tailwater level (despite leakage through the upstream gates) and it cannot predict negative discharge in the approach channel.

Velocity and Discharge

Velocity data were collected in the lock chamber, in the approach channel, and in the downstream channel with Teledyne RD Instruments Rio Grande® ADCPs that were connected to GPS receivers for georeferencing. Submeter positional accuracy was achieved by using the Wide Area Augmentation System (WAAS) signal for differential correction. Specific configurations of the ADCP were dependent on the vessel deployment and survey date (table 1). To ensure accurate headings, each ADCP internal compass was calibrated and evaluated prior to data collection. In the lock chamber measurements, and for Vessel 1 during the October 2015 experiment, the ADCP was paired with a Hemisphere V102® Compass GPS, which reported independent headings that are not affected by hard and soft iron effects. For surveys using Vessel 1 and Vessel 2, 1,200-kilohertz ADCPs were mounted to the starboard (Vessel 1) and port (Vessel 2) forward sides with the GPS antenna mounted directly above the ADCP on a 5-centimeter diameter aluminum pipe. Velocity data from the ADCP were collected by using the WinRiver II software (Teledyne RD Instruments, 2014). The ADCPs were run continuously during the surveys, allowing survey boats to not only measure and document discharge in the canal but also provide mapping of the velocity distribution in the study reach.

The ADCPs were used to collect water velocities throughout the water column at a sample rate of about 0.8 hertz. Each sample, termed an ensemble, contains depth cells (or bins) that range in size depending on the ADCP configuration (table 1). Velocity data nearest to the probe were excluded to eliminate contamination of the velocity measurements from the draft of the probe and ringing of the transducer heads (blanking distance) (Mueller and others, 2007). Velocity data near the channel bed (6 percent of the flow depth for Teledyne RD Instruments Rio Grande® ADCPs) were also discarded to eliminate ADCP cells contaminated by side-lobe interference.

Table 1. Configurations of acoustic Doppler current profilers used throughout data collection.

[GPS, global positioning system; cm, centimeter; water mode: 1=dynamic flow conditions, 12=dynamic flow conditions shallow water; bottom track mode: 5=default condition setting]

Date	Frequency, in hertz	Vessel	Survey locations	GPS used	Cell size, in cm	Transducer depth, in cm	Magnetic variance, in degrees	Water mode	Bottom track mode
12/10/2014	600	Tethered boat	Lock chamber	Hemisphere V102	50	7.6	–3.35	1	5
5/27/2015	1200	Vessel 3	Spillway channel	Trimble GA510/ DSM 232	25	30	–3.34	12	5
10/19/2015	1200	Vessel 1	Approach and downstream	Hemisphere A100	25	18.3	–3.47	12	5
10/20/2015	1200	Vessel 2	Approach and downstream	Hemisphere A100	10	25.9	–3.47	12	5
10/20/2015	1200	Vessel 1	Approach and downstream	Hemisphere V102	25	17.7	–3.47	12	5
10/21/2015	1200	Vessel 2	Approach and downstream	Hemisphere A100	10	28.3	–3.47	12	5

In the downstream channel, ADCP velocity data were collected and quality assured using the WinRiver II software. Resulting measurements were exported into an American Standard Code for Information Interchange (ASCII) format and processed using the Velocity Mapping Toolbox (VMT), a Matlab-based program for visualizing and exporting moving-boat ADCP data (Parsons and others, 2013). The VMT was used to produce depth-averaged velocities over the measured portion of the water column. The resulting velocity magnitudes and directions allowed assessment of general circulation patterns.

In December 2014, velocities were measured with an ADCP within the lock chamber to attempt to quantify the hydrodynamics of the flow during a typical lock filling operation (table 1) (Engel and Bosch, 2017). The ADCP was pulled along approximately the lock centerline for the duration of the lock filling sequence, approximately 19 min. The ADCP measurement started near the upstream miter gates, where the ADCP was then pulled downstream to near the downstream miter gates, and then pulled back upstream toward the upstream miter gates. This procedure was repeated twice during the lock filling period, producing four individual transects of the lock centerline. The water-surface elevation was monitored at a 1-min frequency within the lock chamber as described previously.

The in-lock velocity data were collected and initially reviewed with the WinRiver II software and processed with the VMT to produce plots of the vertical component of velocity occurring along a centerline transect of the lock during the filling operation. Owing to the highly turbulent and nonhomogeneous flow characteristics present during lock filling, additional quality assurance steps were required to ensure invalid data were excluded from analysis. These steps included censoring all measured velocities by the processed error velocities reported by WinRiver II and the VMT. Error velocity was computed for each cell as the difference between the ADCP measured vertical velocity measured by opposing beam pairs scaled by the variance in the horizontal velocity for that cell (Teledyne RD Instruments, 2007). Using these error velocities, data were censored based on a median interquartile range (IQR) approach. The IQR of the processed error velocities was computed. Error velocities less than the 25th percentile of error velocity minus 1.5 times the IQR and error velocities greater than the 75th percentile of error velocity plus 1.5 times the IQR were marked invalid. Using this method, all processed velocities where error velocities were marked invalid were excluded from the dataset (Engel and Bosch, 2017).

Discharge was measured in the Des Plaines River from approximately river kilometer 460 to kilometer 457 on October 19–21, 2015, using ADCPs (table 1; Engel, 2016). Data were georeferenced with differential GPS receivers with submeter accuracy.

The ADCP data were collected and initially reviewed in the WinRiver II software. Final review of discharge measurements was completed using the QRev discharge computation and review software (Mueller, 2016). The QRev software includes a large suite of quality assurance checks for ADCP discharge measurements and provides an estimate of measurement uncertainty based on a series of empirical and statistical error propagation approaches. These uncertainty estimates, expressed at the 95th percentile level, were used to present upper and lower discharge bounds for measured discharges in the study area. In cases where discharge measurements were made in the same region and using the same site characteristics, but on different days, the measurement uncertainty (ΔT) was combined using a root-mean squares approach (Taylor, 1982):

$$\Delta T = \sqrt{(\Delta a)^2 + (\Delta b)^2} \qquad (2)$$

where Δa and Δb are the uncertainty estimates for each *independent* discharge measurement.

In August 2015, a USGS streamgage was established in the approach channel approximately 360 m downstream from the lock chamber (05538020, Des Plaines River in Lock Channel at Rockdale, Ill.; fig. 3). In addition to continuously monitoring stage, this streamgage was established to collect near real-time, continuous velocity data across the approach channel using a horizontal acoustic Doppler velocity meter (U.S. Geological Survey, 2017a). The USGS NWIS database provides digital access to the stage and velocity data from this streamgage along with numerous associated discharge measurements (U.S. Geological Survey, 2017a).

Dye Tracer

A tracer, Rhodamine WT dye, was injected into the lock chamber during lock filling and tracked downstream from the lock to quantify the fate and transport of lock water and any dissolved constituents therein. The dye tracer is highly miscible in water, passive (does not affect the density of the water), and conservative.

To examine the fate and transport of dye injected into the lock chamber as it was released downstream through the emptying valves, a two-pronged data collection effort was used in the approach channel: (1) deployment of fixed fluorometers downstream from the lock to measure time series of dye concentration at fixed points, and (2) real-time tracking of dye using moving boat measurement platforms. The combination of time series of dye concentration at fixed locations and mobile dye tracking allowed characterization of the temporal and spatial variation in the dye plume.

Dye Injection

To determine if the lock chamber filling system can effectively mix passive dissolved constituents into the lock chamber, Rhodamine WT dye was injected into the two filling valve intake wells in equal measure while the lock chamber was filled using standard operating procedures (Perry Jones, U.S. Army Corps of Engineers, oral commun., 2015). To ensure dye was delivered to all filling ports, the injection of dye commenced once turbulence (boils) could be seen throughout the lock chamber, indicating that fill water had reached the downstream end of the lock. A supplemental time-lapse video of the dye study can be found online (Engel, 2015). At each of the two filling valve wells, a simple dye injection system was used consisting of a funnel inserted into the safety grating covering the access well, 2 liters (L) of Rhodamine WT dye in a 20-percent solution, and two 5-gallon buckets filled with rinse water (fig. 4). On October 20, 2015, at 10:24 Central Daylight Time (CDT) the dye (4 L total) was poured into the two intake wells on either side of the lock and the dye containers and funnels were immediately rinsed into the wells to ensure all dye was injected into the lock chamber fill water. The injection of the dye (including rinsing) took approximately 6 min and ended at 10:30 CDT on October 20, 2015. The volume of dye injected was computed using a target in-lock concentration of 10 parts per billion (ppb) and the estimated volume of the lock chamber at the headwater elevation.

In-Situ Measurements of Dye Concentration

Turner Designs® C3 submersible fluorometers were used for in-situ measurements of Rhodamine WT dye concentration in the lock chamber and throughout the study reach. Apart from the lock chamber measurements, which included vertical profiles of dye concentration, all in-situ measurements were made within the top 1.2 m of the water column. The locations of the fixed-site deployments and the stations for vertical profiling in the lock chamber are shown in figure 5 and provided in tables 2 and 3.

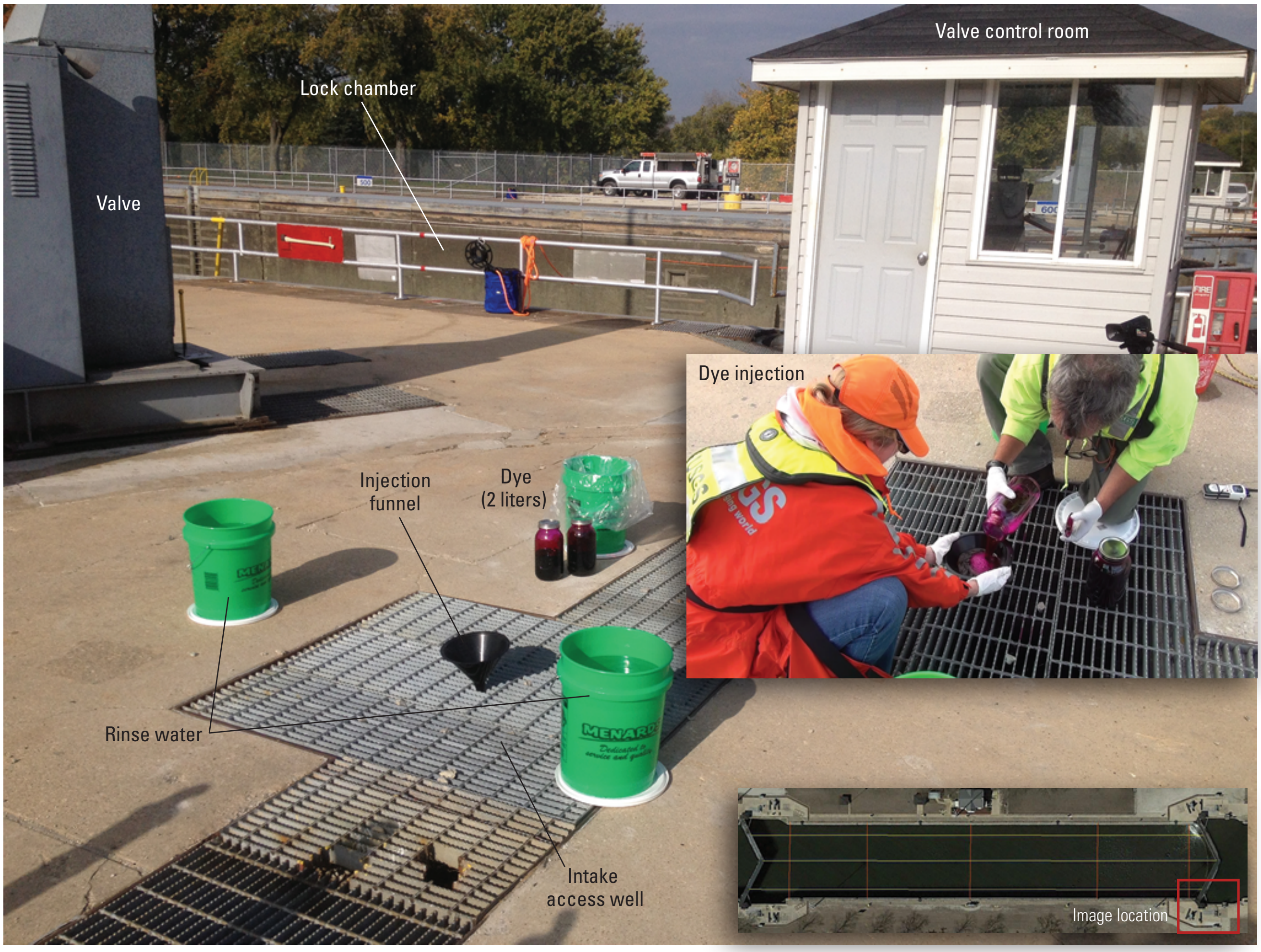
All fluorometers used in this study were calibrated using prepared standards and a two-point calibration (table 2). Site water was used for the final dilution of the standards from a 100-ppb standard made with deionized water. Use of water from each deployment site ensures that background fluorescence in the water is accounted for in the calibration and results in instruments that measure relative fluorescence rather than absolute fluorescence. The sampling rate of the instruments varied depending on whether the instrument was deployed on a mobile platform (1 s) or a fixed platform (30 s) (table 2). Internal logging was enabled on all instruments and instrument clocks were synchronized before deployment.

Measurements of Dye Concentration in the Lock Chamber

The dye distribution within the lock chamber was measured using a submersible fluorometer (FL1; table 2) mounted in a custom-made polyvinyl chloride (PVC) frame (nicknamed the “bottom lander”) that kept the instrument from touching the sediment on the bottom of the lock chamber (fig. 6*A*). The use of the bottom lander was necessary because the optical fluorometer can be fouled by sediment if the sensors come in contact with the bed. In addition, turbidity can affect background fluorescence and the use of the bottom lander minimizes disturbance of the bed near the instrument during profiling.

Vertical profiles of the dye concentration in the lock were repeatedly measured at 15 stations in the lock chamber (fig. 5*B*; table 3; Jackson, 2016a). Positioning of the profiler at each station and lowering the profiler through the water column was achieved using a system of five pre-marked taglines (1 at each of the 5 transects in the lock) and a rope and pulley system that attached to each tagline and to the profiler. This system allowed access to all the stations in the lock chamber without requiring a boat in the water (which could create additional mixing in the lock).

Profiling of dye concentration in the lock required three people—two people to handle the positioning lines and one person to raise and lower the profiler. Once the profiler was positioned at a station, the profiler was lowered by



Background photograph by J. Duncker, U.S. Geological Survey (USGS).
Upper inset photograph by A. Ault, USGS.
Lower inset image from Google, Landsat/Copernicus.

Figure 4. Dye injection into south intake well upstream from the filling valve, Brandon Road Lock and Dam, Joliet, Illinois. An identical setup was used at the north intake well.

Table 2. Submersible fluorometers used in the study and their associated deployment locations and configurations.

[ID, identification number; WGS 84, World Geodetic System of 1984]

Fluorometer ID (fig. 5*A*)	Serial number	Deployment type	Latitude, in degrees (WGS 84)	Longitude, in degrees (WGS 84)	Depth, in meters	Sampling rate, in seconds	Calibration standards, in parts per billion
FL1	2300164	Mobile (profiler)	variable	variable	variable	1	0, 50
FL2	2300166	Fixed	41.500290	−88.106867	1.2	30	0, 10
FL3	2300174	Fixed	41.500705	−88.107464	0.5	30	0, 10
FL4	2300294	Fixed	41.498394	−88.109684	1.2	30	0, 10
FL5	2300175	Fixed	41.498965	−88.110277	0.5	30	0, 10
FL6	2300295	Fixed	41.497865	−88.112724	0.5	30	0, 10
FL7	2300165	Mobile (vessel 1)	variable	variable	0.5	1	0, 10
FL8	2300150	Mobile (vessel 2)	variable	variable	0.5	1	0, 10

Base imagery from Google, Landsat/Copernicus

Figure 5. Aerial photographs of study area. *A*, Study area with deployment locations of fixed fluorometers downstream from the lock. *B*, Study area with sampling stations within the lock chamber.

Table 3. Coordinates of vertical profiling stations in the Brandon Road lock chamber.

[WGS 84, World Geodetic System of 1984]

Station (fig. 5*B*)	Latitude, in degrees (WGS 84)	Longitude, in degrees (WGS 84)
1A	41.503969	–88.102282
1B	41.503891	–88.102190
1C	41.503804	–88.102090
2A	41.503723	–88.102657
2B	41.503644	–88.102565
2C	41.503557	–88.102466
3A	41.503382	–88.103178
3B	41.503302	–88.103086
3C	41.503215	–88.102987
4A	41.503104	–88.103602
4B	41.503025	–88.103510
4C	41.502939	–88.103409
5A	41.502896	–88.103919
5B	41.502816	–88.103828
5C	41.502729	–88.103728

hand through the water column at a rate of approximately 0.14 meter per second (m/s) until the bottom lander touched the lock chamber floor. The profiler was then retrieved and moved to the next station. At each station, a note keeper recorded the exact time (to the second) the profiler started each descent, the time it reached the bottom, and the time it surfaced. The note keeper's watch was synchronized with the fluorometer data logger clock prior to deployment.

As a backup for instrument failure or errant fluorometer readings, a grab sample was collected at stations 1A, 2A, 3A, 4A, and 5A (fig. 5*B*) for each set of profiles using opaque brown 125-milliliter (mL) high-density polyethylene (HDPE) plastic bottles. The sample bottle was attached to the bottom lander (fig. 6*A*) and filled as the profiler was lowered into the water. The samples were labeled with date, time, and station number and stored for later analysis (if necessary); however, the profiling fluorometer generally performed well and these samples were not analyzed and will not be discussed further in this report.

To correct for leakage-induced dilution in the lock chamber during a set of measurements (profiles at each of the 15 stations in the lock), a dilution correction factor was computed for each profile in the set and applied to the measured dye concentrations for that profile. This simple volumetric correction factor is the ratio of the volume of water in the lock at the time each profile is measured and the volume of water in the lock at the start of each measurement set. For the first set of profiles in which the lock was held at the headwater elevation, the change in volume was computed using the estimated net leakage rate for a full lock and the elapsed time since the start of the profile set. This method assumes instantaneous mixing of leakage water throughout the volume of the lock chamber. It should be noted that this method does not correct for dilution due to leakage between measurement sets.

Fixed Fluorometers Downstream from the Lock Chamber

To document the travel time of the dye plume throughout the study reach, five submersible fluorometers were deployed at fixed locations downstream from the lock spanning the full length of the study reach (fig. 5*A*; table 2; Jackson, 2016b). Turner Designs C3 submersible fluorometers with battery packs and shade covers were deployed at each location (fig. 6*B*; table 2). The fluorometers were deployed on October 20, 2015, between 8:28 and 9:04 CDT to allow at least an hour of data collection of background concentrations before the dye was injected into the lock. The fluorometers were either suspended from nylon lines near middle depth in the water column at the deployment location (fig. 6*B*, FL2), mounted to cinderblocks and placed deep enough to ensure the sensors would stay submerged (fig. 6*B*, FL3, FL5, FL6), or mounted to existing USGS streamgaging instrumentation (fig. 6*B*, FL4; USGS streamgage 05538020 auxiliary acoustic Doppler velocity meter). Prior to each reading, the fluorometer was programmed to run the wiper, cleaning the optical sensors. All fixed fluorometers were equipped with turbidity and temperature sensors. The fixed fluorometers were recovered between 11:23 and 11:35 CDT on October 21, 2015.

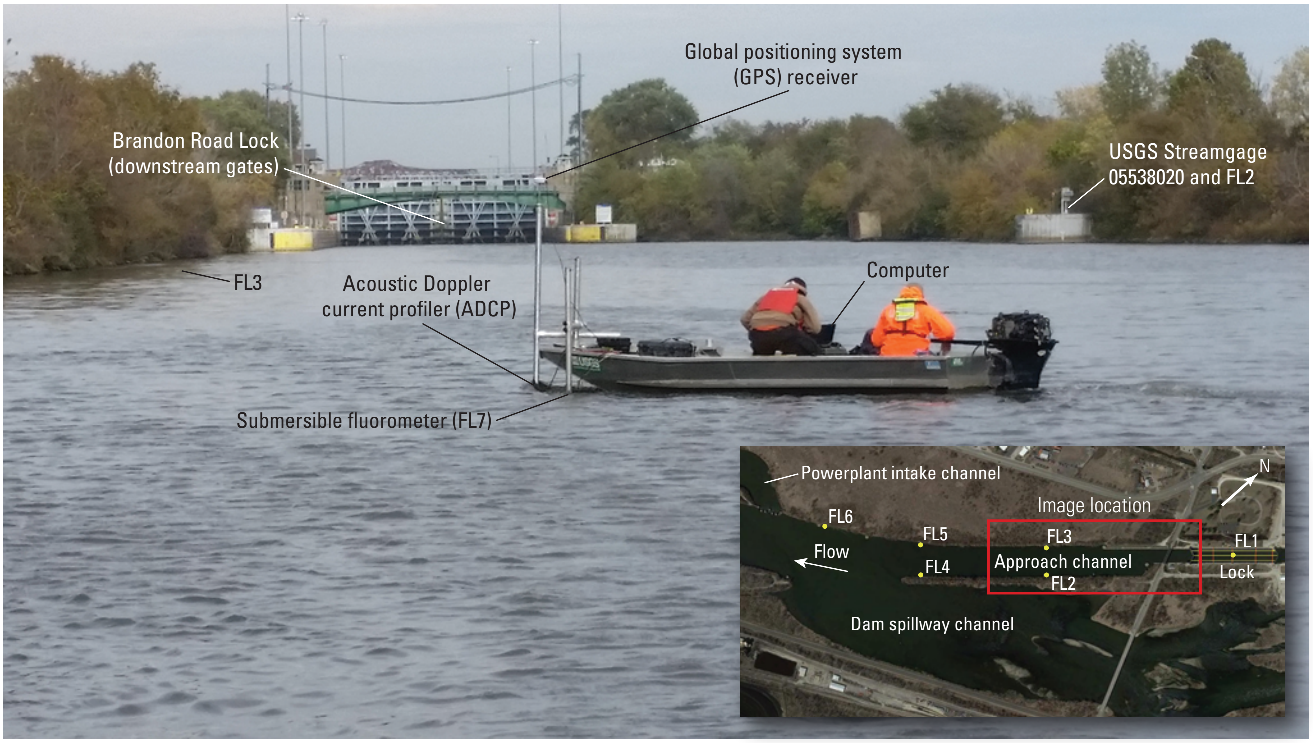
Mobile Fluorometers Downstream from the Lock Chamber

Real-time tracking of Rhodamine WT dye requires accurate positional information for georeferencing of the data, a low-noise and properly calibrated fluorometer mounted on a mobile sampling platform such as a boat, and real-time data display and logging capabilities onboard the survey vessel. Such a system allows the hydrographer to locate the leading and trailing edges of a dye plume and adapt the survey domain accordingly. Two survey vessels (Vessel 1 and Vessel 2) were equipped with submersible fluorometers, GPS receivers, and ADCPs to enable real-time dye tracking (fig. 7). The setup of the GPS and ADCP systems was described in the "Velocity and Discharge" section. The purpose of using two vessels was to allow one boat to act as a rover and move throughout the survey reach, mapping the full extent of the dye plume, while the second boat measured discharge and dye concentration within the approach channel and at key locations within the study reach. To capture the full extent of the plume, including the cross-stream variability in concentration, the rover boat typically used serpentine survey methods (bank-to-bank "zig-zags" as the vessel transited the study reach). During periods of quiescent flow in the approach channel, both boats were used to map the dye plume.

Positional data were acquired using the same differential GPS receiver used for the ADCP (table 1). Positional data were logged in using the Tera Term software (Tera Term Open Source Project, 2018) running on a laptop personal computer

Photographs by J. Lageman, U.S. Geological Survey

Figure 6. Annotated photos of equipment deployments. *A*, Profiling submersible fluorometer used to measure dye distribution in the lock (FL1). *B*, Fixed and mobile submersible fluorometers ready for deployment.



Background photograph by F. Engel, U.S. Geological Survey
Inset map imagery from Google, Landsat/Copernicus

Figure 7. Annotated photograph showing survey boat equipped with the mobile sensor package in the approach channel downstream from Brandon Road Lock. U.S. Geological Survey (USGS) streamgage 05538020 (Des Plaines River in Lock Channel at Rockdale, Illinois) and the deployment locations of FL2 and FL3 are also shown.

and each sample was time stamped with the computer clock time, which was synchronized to all the fluorometers and the note keeper's watch. The GPS antenna was placed atop masts directly above the ADCP (within 0.5 m of the fluorometer) and high enough off the water surface to avoid multipath errors caused by the boat cabin or hull (fig. 7). The GPS was programmed to sample five times per second.

In addition to internal logging, the submersible fluorometer provided real-time data to the user by way of an RS232 connection. The data from the fluorometer were displayed and logged in the Tera Term software with time stamping enabled. With the GPS data and the fluorometer data timestamped using the computer clock, assigning positions to the fluorometer data was achieved using a simple script that interpolates position (latitude and longitude) for each 1-s sample from the fluorometer. The georeferenced mobile fluorometer data are available online (Jackson, 2016c).

Flow Hydraulics and Mixing Characteristics

This section is organized by the questions driving this research as presented in the "Purpose and Scope" subsection of the "Introduction" section. This section begins with a discussion of the observed flow hydraulics of the lock chamber and approach channel as related to lock operations. Using the underlying flow hydraulics characterization of the system as a backdrop, the mixing and transport characteristics of the lock chamber and approach channel are discussed through presentation of dye tracer data obtained in this study. The efficacy of the flushing-lock scenario is also discussed.

Flow Hydraulics

Flow hydraulics described in this section include water-surface elevation, discharge, and velocity. The discharge and velocity distributions within the approach channel downstream from BRL are highly dependent on lock operations. More specifically, the water released from the lock (intentionally or through leakage) directly affects the hydrodynamics in the approach channel. This section presents findings with regard to characterization of the hydrodynamics within and downstream from BRL under typical and atypical lock operations.

Water-Surface Elevation

Although lock operations records are kept by the USACE, the 1-min water-surface elevation data recorded in the lock chamber provide a detailed record of lock operations throughout the study. A subset of this dataset for the period of the dye study (Jackson and Engel, 2016) is shown in figure 8*A*, and table 4 contains the times of key operations at BRL on October 20, 2015.

The record of water-surface elevation in the BRL chamber reveals much about the integrity of the lock, the variability of the flow in the approach channel, and the effect of variability in lock operation on the peak discharge in the approach channel during lock emptying. Lock integrity can be evaluated in terms of net leakage. As seen in figure 8, when the lock is full, negative net leakage causes the water-surface elevation to drop in the lock. The net leakage rate decreases with decreasing head difference. When the lock is empty, positive net leakage causes the lock to fill. At some water-surface elevations between 156 and 158 m, the net leakage through the lock is balanced (leakage in equals leakage out) and the water-surface elevation should remain constant. For the period of record shown in figure 8, the maximum discharge to the approach channel owing to leakage is approximately 5.1 m^3/s and occurs when the lock is full (at headwater elevation).

Discharge to the approach channel estimated from the water-surface elevation changes in BRL varies considerably owing to lock operations. Emptying of the full lock releases flood pulses into the approach channel that increase discharge from approximately 5.1 m^3/s (leakage through closed gates) to a mean discharge of approximately 120 m^3/s. The operation of the valves during emptying, the vessels in the lock, and the headwater and tailwater levels all likely introduce variability into the maximum discharge of the flood pulse in the approach channel. The full lock was emptied 10 times during the 51-hour period shown in figure 8 and the resulting estimated peak discharge in the approach channel ranged from 87.5 to 129 m^3/s with a mean of 120 m^3/s and a standard deviation of 13.0 m^3/s. Peak discharge estimated from the water-surface elevation in the lock (108.8 m^3/s) compares well with measured discharge (105.4 m^3/s) for the one full-lock emptying event starting at 12:26 CDT on October 20, 2015 (3.2 percent difference; fig. 8*C*), but measured discharge shows greater variability than estimated discharge at low flows when the lock is idle and only leakage is present. Measured discharge will be discussed in more detail later in this section.

Emptying of a partially full lock introduces even more variability in discharge and can produce peak discharges in the approach channel that are equal to or greater than peaks produced by emptying a full lock. This finding indicates that operation of the emptying valves by the lock operator and the differences in valve operation when the lock is occupied by a vessel as compared to not occupied can substantially affect the peak discharge in the approach channel.

Flow Characteristics in Downstream Channel Regions

Measured discharge in the approach channel when no lock operation is underway and downstream gates and emptying valves are closed helps to validate the estimated leakage discharge based on water-surface elevation data. The average discharge measured in the approach channel when the lock was not being operated on October 19 and 20, 2015, was 6.5±1.6 m^3/s (fig. 9, table 5, region 1). Differences between the measured discharge and the estimated leakage in the approach channel could arise from factors including (1) wind driven surface currents, (2) interaction of the approach channel with the downstream channel, (3) instrument noise, and (4) travel time of the flood pulse.

Dam operations pass incoming flow in the Des Plaines River upstream from Brandon Road Lock and Dam through the dam spillway Tainter gates during nonflood conditions. During the dye study, no changes to gate settings were made (Brandon Road Lock staff, U.S. Army Corps of Engineers, written commun., October 2015). It was not possible to directly measure discharge across the entrance of the spillway channel because shallow depths restricted boat access. Thus, flow for the spillway (fig. 9, table 5, region 2) is taken as the combined daily mean discharge of 55.6 m^3/s reported by USGS streamgage 05537980 Des Plaines River at Route 53 at Joliet, Ill., (fig. 1; U.S. Geological Survey, 2017b) for October 19 and 20, 2015. When the lock is not being operated, the approach channel is quiescent, with the main driver of flow hydraulics being wind, and a small amount of leakage through the lock downstream miter gates and (or) emptying valves (6.5±1.6 m^3/s).

Although no operations were occurring at the lock, the north powerplant was observed to be withdrawing approximately 44.1±10.6 m^3/s from the Des Plaines River, as measured across the cooling water supply channel entrance (fig. 9, region 4). This demand for flow into the intake caused most of the spillway flow to be directed into Intake channel 1, and is in part why the approach channel measured discharge is approximately the same as the lock leakage (table 5). The approach channel is “cut off” from the main channel when the lock is not discharging flow (other than leakage) and the powerplant is withdrawing cooling water, which, as will be discussed below, has implications for the fate and transport of dissolved constituents in the approach channel.

Water withdrawal from Intake channel 2 was approximately 15.5±3.9 m^3/s as measured across the entrance to the water supply channel (fig. 9, region 5). Measurement of the South outfall discharge was not possible, as the channel was too shallow to safely navigate a boat across the outfall. Downstream from both powerplant outfalls, the discharge in the channel was 39.1±11.0 m^3/s (fig. 9, region 6). The differences in total water budget between the downstream channel and the upstream spillway, approach, and intake channels (−11.4±15.3 m^3/s) are caused by a combination of wind-induced flow into the region that lies between the north cooling water entrance and exit and by measurement uncertainty. In particular, the difference between the entrance and exit for the north powerplant channels accounts for −12.6 m^3/s (table 5).

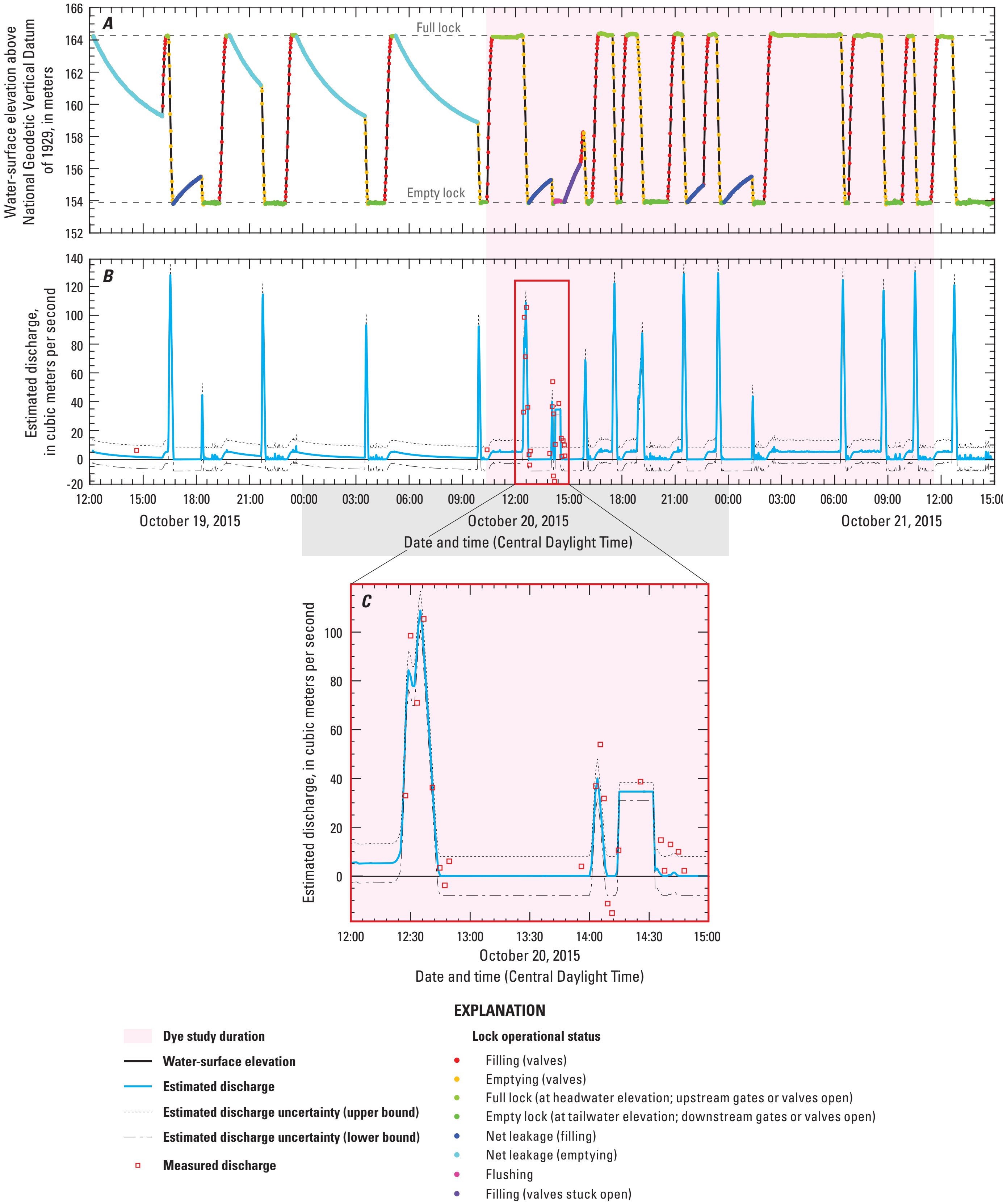


Figure 8. Time series of *A*, water-surface elevation in the lock chamber; *B*, estimated discharge in the approach channel downstream from the lock; and *C*, enlarged view of estimated discharge for 3-hour period on October 20, 2015. Lock operations, discharge measurements in the approach channel, and the period of the dye study are shown for reference.

Table 4. Times of key operations at Brandon Road Lock on October 20, 2015.

[Elapsed time, the time from the beginning of the dye injection; --, not applicable; lock chamber profiling sets shaded in gray]

Time (Central Daylight Time)	Elapsed time, in hours	Operation
5:15	--	Lock chamber full (at headwater elevation).
5:16	--	Lock chamber begins draining due to leakage.
9:50	--	Emptying valves opening, emptying partially filled lock in preparation for study.
10:00	--	Begin navigational closure of lock to marine traffic.
10:05	--	Lock at tailwater elevation, all valves closed.
10:22	--	Opening filling valves, begin filling lock chamber.
10:24	0.00	Start dye injection.
10:30	0.10	End dye injection.
10:43	0.32	Lock chamber at headwater elevation (filling valves mistakenly left open).
10:43	0.32	Start lock profiling set number 1 (at station 1A).
11:55	1.52	End lock profiling set number 1 (at station 5C).
12:26	2.03	Opening emptying valve (right only due to problems with left valve).
12:31	2.12	Opening emptying valve (left valve opened to 1.83 meters).
12:34	2.17	Left emptying valve opened fully.
12:43	2.32	Lock at tailwater elevation, valves closed, gates closed (leakage into lock from upstream).
12:50	2.43	Start lock profiling set number 2 (at station 1A).
13:40	3.27	End lock profiling set number 2 (at station 5C).
14:00	3.60	Opening emptying valves to empty lock of volume filled by leakage.
14:06	3.70	Downstream gates opening.
14:08	3.73	Downstream gates fully open, all valves closed, lock at tailwater elevation.
14:15	3.85	Opening filling valves to 25-percent opening[1] to begin flushing procedure (starting with left valve).
14:32	4.13	Flushing procedure ended, left filling valve closed, right filling valve stuck open at about 5 centimeter opening.
14:43	4.32	Downstream gates closed, lock at tailwater elevation, begins filling due to leakage into chamber.
14:50	4.43	Start lock profiling set number 3 (at station 5A).
15:31	5.12	End lock profiling set number 3 (at station 1C).
15:32	5.13	Filling valves opening to partially fill lock (necessary to remove pressure from stuck valve and allow it to close).
15:48	5.40	Filling valves closed fully.
15:49	5.42	Opening emptying valves to empty partially filled lock chamber.
16:03	5.65	Lock at tailwater elevation.
16:04	5.67	End navigational lock closure, resuming normal operations.

[1]The U.S. Army Corp of Engineers used 25-percent valve opening as the upper limit for flushing because that is the largest opening that still allows safe closure of the valves (Toby Hunemuller, U.S. Army Corp of Engineers, written commun., January 2018).

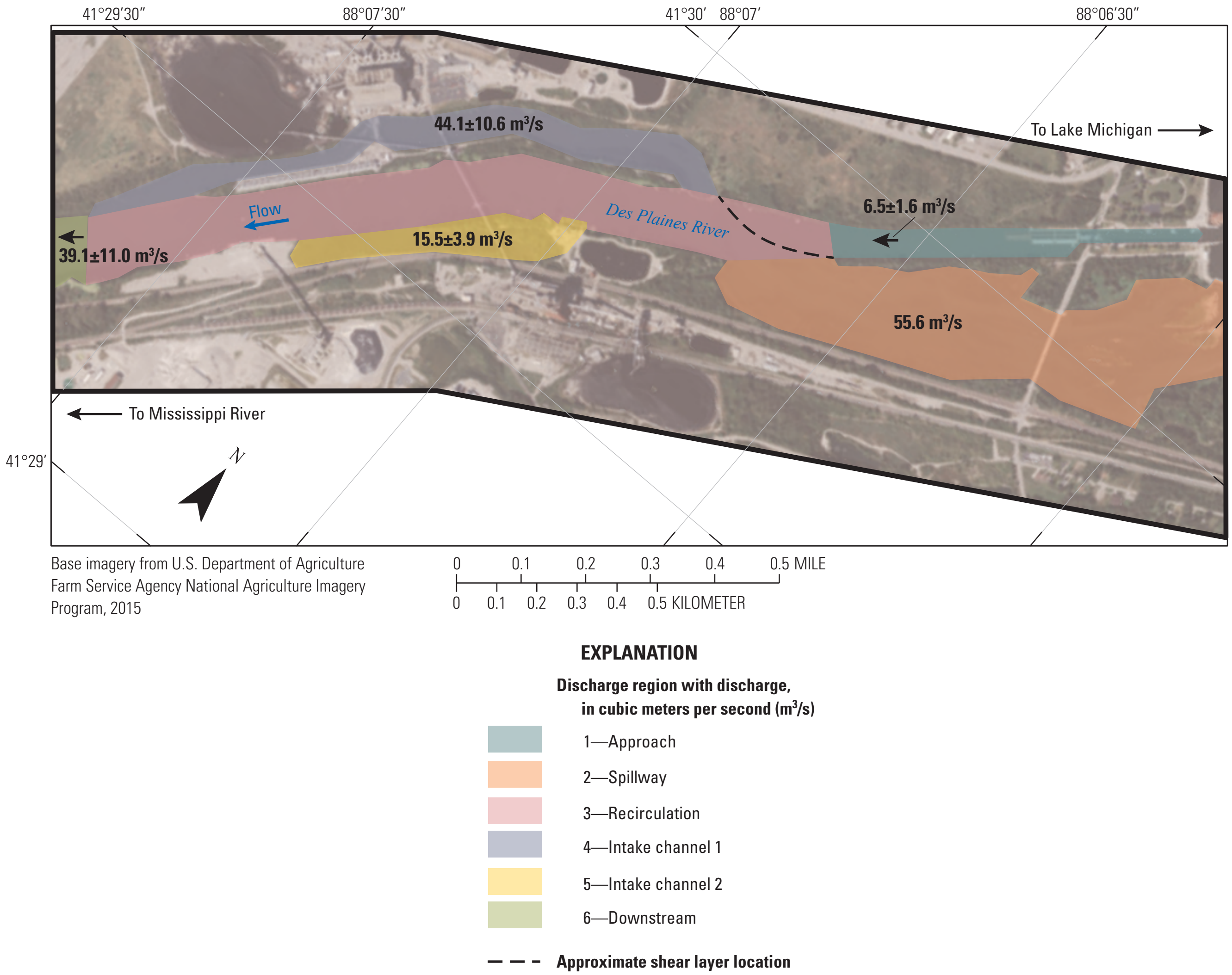


Figure 9. Average measured and estimated discharges for various regions in the Des Plaines River downstream from Brandon Road Lock and Dam when no lock operation was underway during the October 19–20, 2015, dye study.

Table 5. Average discharges measured on October 19 and 20, 2015, in the Des Plaines River downstream of Brandon Road Lock and Dam while no operations were occurring at the lock.

[ID, region identification number shown in fig. 9; --, not applicable]

ID (fig. 9)	Measurement location	Average discharge for both days, in cubic meters per second	Combined expanded 95-percent uncertainty, in cubic meters per second
1	In the approach channel at streamgage (05538020)	6.5	1.6
2	Across the Brandon Road Spillway (as indicated by streamgage 05537980)	55.6	--
4	Across the entrance of the north powerplant cooling water supply channel	44.1	10.6
5	Across the entrance of the south powerplant cooling water supply channel	15.5	3.9
--	Across the exit of the north powerplant cooling water supply channel	31.5	8.6
6	Downstream from both supply channels	39.1	11.0

Although measurement uncertainty is present, the quality of measurements still allows for some interpretation of the water budget within the downstream channel reach. The information in figure 9 and table 5 shows that in the absence of lock discharge, the powerplant cooling water intake captures upwards of 95 percent of the total discharge from the spillway and lock leakage. This condition means that the recirculation region (fig. 9, region 3) is largely stagnant or even flowing upstream depending on wind direction and magnitude, a finding which was observed by the Vessel 1 crew during the dye study (Engel, 2016).

Discharge in the approach channel varied considerably depending on the state of the lock valves, gates, and lock chamber head. Discharge was nearly continuously measured in the approach channel (fig. 9, region 1) during the dye study period, and for several lock states on October 20, 2015 (tables 4 and 6). While the dye was injected in the lock chamber, the downstream gates and emptying valves were closed and a discharge of 6.8±1.0 m^3/s was measured in the approach. At 12:26 CDT the lock emptying procedure began, which consisted of opening the emptying valves in stages to pass water from the lock chamber into the approach channel (table 4). The discharge measured in the approach channel during the lock emptying procedure was dynamic and hydraulically unsteady. About 1 min after the valves started opening, an increase in discharge to 32.8±2.6 m^3/s was observed at 12:27:20 CDT (measurement 19 midpoint time, table 6). The emptying valves were fully open by 12:34 CDT and discharge quickly rose to a peak of 105.4±16.3 m^3/s at 12:36:42 CDT, only to fall to just 3.4±0.3 m^3/s by 12:44:46 CDT. The

Table 6. Discharges measured in the Brandon Road approach channel (Des Plaines River in Lock Channel at Rockdale, Illinois; streamgage 05538020) on October 20, 2015, for various lock states.

[Shading indicates approximate lock emptying (light gray) and flushing (dark gray) operations times. Times represent the midpoint of the measurement period. Refer to table 4 for further lock activity logs. USGS, U.S. Geological Survey; NWIS, National Water Information System; Elapsed time, the time from the beginning of the dye injection; --, not applicable]

USGS NWIS measurement number	Lock state	Measurement time (Central Daylight Time)	Elapsed time, in hours	Measured discharge, in cubic meters per second	Estimated uncertainty expressed in discharge, in cubic meters per second
18	Chamber filling, not discharging	10:23:22	0.00	6.8	1.0
19	Emptying valves opening	12:27:20	2.05	32.8	2.6
20	Emptying valves opening	12:30:04	2.10	98.4	62.2
21	--	12:33:13	2.15	71.1	5.7
22	--	12:36:42	2.20	105.4	16.3
23	Emptying valves open	12:41:14	2.28	36.3	2.9
24	--	12:44:46	2.33	3.4	0.3
25	--	12:47:12	2.38	−3.8	0.3
26	Emptying valves closed	12:49:41	2.42	5.9	0.5
27	Chamber near tailwater elevation, not discharging	13:56:04	3.53	4.0	1.2
28	Emptying valves open	14:03:24	3.65	36.7	2.9
29	Downstream gates open, emptying valves closed, filling valves opening	14:05:17	3.68	53.7	4.3
30	--	14:07:07	3.72	31.7	2.5
31	--	14:09:00	3.75	−11.4	0.9
32	Filling valves open 25 percent	14:11:14	3.78	−15.1	1.2
33	--	14:14:28	3.83	10.5	3.1
34	--	14:25:35	4.02	38.6	5.1
35	Filling valves closing	14:35:46	4.18	14.6	1.2
36	--	14:37:49	4.22	2.0	0.2
37	Filling valves closed (right valve stuck partially open)	14:40:46	4.27	12.9	10.6
38	Downstream gates closing	14:44:45	4.33	9.9	5.5
39	Downstream gates closed, emptying valves closed	14:47:47	4.38	2.3	0.2

emptying valves were fully closed by 12:43 CDT (table 4) and at 12:47:12 CDT, the net discharge in the approach channel at the streamgage (05538020) was upstream (−3.8±0.3 m^3/s).

From 12:43 to 14:00 CDT, the downstream gates and emptying valves were closed. During this time the discharge in the approach varied between 4.0 and 5.9 m^3/s (table 6). At approximately 14:00 CDT, the emptying valves were opened to lower the lock chamber head to the tailwater elevation (leakage had partially filled the lock), causing discharge to rise to 53.7±4.3 m^3/s during a span of about 5 min (table 6, measurements 28 and 29). The downstream gates were opened at 14:06 CDT, and the filling valves were opened to 25 percent of total opening by 14:15 CDT—this was the start of the 17-minute flushing operation. During this time, the discharge in the approach varied substantially. At 14:07:07 CDT, a discharge of 31.7±2.5 m^3/s was measured, but within 2 min, the net discharge was upstream (−11.4±0.9 m^3/s) and upstream (negative) discharge continued until 14:14:28 CDT (10.5±3.1 m^3/s). Approximately 11 min later, the transient oscillation in net flow from downstream to upstream had subsided, and discharge was measured at 38.6±5.1 m^3/s. The lock operators attempted to close the filling valves at 14:32 CDT; however, the right valve malfunctioned and would not fully close (it remained open about 5 centimeters; table 4). Because of this malfunction, the discharge in the approach dropped to a little less than one-half the full flushing discharge to 14.6±1.2 m^3/s. While the lock operators attempted to close the right filling valve, the discharge fluctuated in the approach channel until the downstream gates were closed at 14:43 CDT (table 6, measurements 36–39).

A complex picture of the discharge fluctuations under various lock states has been described. By synthesizing these results, along with the discharge measured throughout the study reach during periods of no lock activity, several key findings emerge:

1. When the lock was not active (downstream gates and emptying valves are closed), the water in the approach channel was essentially quiescent with a small (less than 7 m^3/s) net downstream flow owing to leakage through the lock. Almost all the observed flow at points downstream from the approach channel was dictated by the spillway flow being passed from upstream as observed at streamgage 05537980.

2. When the lock was not active, as much as 95 percent of the spillway flow was directed into two powerplant intake channels (fig. 9, regions 4 and 5), leaving a largely stagnant recirculation zone (region 3) between the intakes and outfalls of the powerplants on both banks.

3. When the lock chamber was discharging into the approach channel, the observed discharge in the approach was highly unsteady and dynamic. Peak discharge in the approach was highly variable and depended on lock conditions and operation.

4. During a typical lock emptying procedure (emptying valves opened, lock chamber initially full), the discharge in the approach quickly increased to as much as 105.4 m^3/s, but approximately 10 min thereafter a net-upstream return flow was observed toward the end of the falling limb of the hydrograph. This transient oscillation was likely caused by the gravitational adjustment of the water level between the approach channel and the spillway (fig. 9, regions 1 and 2) combined with the recovery of a shear layer at the end of the approach where spillway flow was directed into Intake channel 1 (region 4). As the shear layer recovers, a pulse of returning flow moves upstream toward the downstream lock gates. This oscillation dampens in time as the system regains equilibrium.

5. During the atypical lock flushing procedure (filling valves open 25 percent, downstream gates open), the discharge in the approach was highly variable as the system attempted to achieve equilibrium in the new configuration. The flushing flow interacted with the shear layer at the end of the approach channel to produce transient oscillations of the discharge in the approach as some return flow interacted with the flow exiting the lock chamber. The 17-min flushing procedure was not long enough for the system to fully equilibrate to this condition.

6. Although the estimated discharge, computed using the lock water-surface elevation and area (fig. 8), predicted the peak discharge of the emptying procedure well, this computation could not account for any return flow effects (minimum discharge in fig. 8 is 0 m^3/s).

Velocity in the Approach Channel/Spillway during Empty and Flushing

Velocities were nearly continuously measured at the USGS 05538020 streamgage during dye injection, lock emptying, and lock flushing procedures (fig. 10). Comparing observed differences in flow velocities between each condition helps place the results of the dye concentration fate and transport into the context of the hydrodynamics occurring in the lock approach channel. Patterns of flow velocities differ considerably depending on what lock gate and valve settings are in place for a particular scenario.

Velocity in the approach channel prior to the lock gates or emptying valves being opened and while dye was injected into the lock chamber is shown in figure 10*A*. These data constitute the temporally and spatially averaged velocities from a total of 58 individual ADCP transects measured from 10:20 to 12:16 CDT on October 20, 2015. In general, streamwise velocities are on the order of 5 centimeters per second (cm/s) or less throughout the cross-section. The depth-averaged

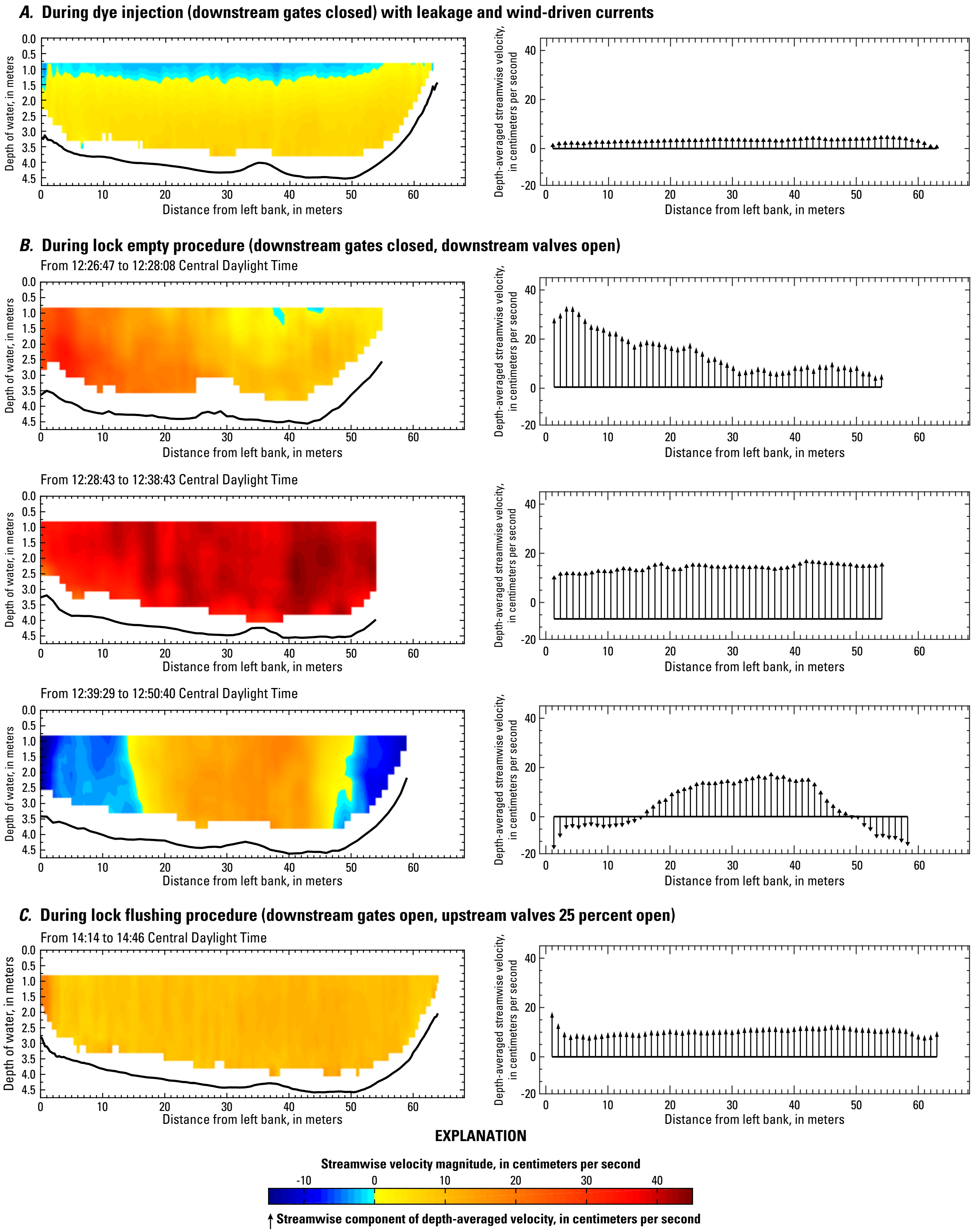


Figure 10. Contours of spatially and temporally averaged streamwise velocity magnitudes (left) and depth-averaged streamwise velocity vectors (right) for the Brandon Road Lock approach channel during *A*, dye injection into the lock chamber; *B*, a typical lock emptying procedure; and *C*, a lock flushing procedure.

streamwise component of velocity indicates a mean flow in the downstream direction (positive velocities) throughout the cross-section; however, streamwise velocities from the water surface to approximately 1.25 m depth are negative, indicating that flow in this layer is directed upstream toward the lock gates. This upstream current in the near-surface layer was caused by wind, which for the entire period of the dye experiment was blowing south-southwest at around 12 to 16 kilometers per hour (kph) (Weather Underground, 2017). Wind effects cause quiescent flow conditions with only leakage from the lock contributing to downstream flow, and an upstream blowing wind contributing to an upstream flow near the water surface. This bidirectional flow could have major implications for the fate and transport of dye and (or) dissolved constituents in the approach channel.

The flow velocities in the approach channel during the lock emptying procedure differ greatly from the velocities measured for an idle lock (fig. 10*B*). Velocities from a total of 10 individual ADCP transects surveyed from 12:26 to 12:50 CDT on October 20, 2015, are presented for the lock emptying condition and are divided into three time periods to highlight the dynamic nature of the flow hydraulics. The first period from 12:26:47 to 12:28:08 CDT shows the initial increase in flow from the emptying valves being opened. Streamwise velocities were greatest along the left bank and approached nearly 35 cm/s. A small region of upstream directed surface flow was still observed at about 40 m from the left bank; however, this region of upstream velocity was small enough that the depth-averaged velocity vectors were all directed entirely downstream. The differences in flow magnitudes between the left and right bank observed during this time were in part an artifact of the sampling method. A single boat transect that started on the right bank and ended on the left bank was used to compute the velocities displayed in this period (fig. 10*B*); the flow magnitudes were increasing rapidly even as the boat crossed the channel, leading to the appearance of the highest velocities near the left bank.

The second period from 12:28:43 to 12:38:43 CDT includes temporally and spatially averaged velocities from a total of 5 individual ADCP transects, and was where the largest velocities in the approach channel were observed as the discharge from the emptying valves peaked (see table 6). The minimum velocity in the channel was 23 cm/s, and velocity peaked at 43 cm/s near the right bank at a depth below the water surface of about 2 m. Although the peak velocity occurred below the surface, in general velocities do not vary greatly over depth throughout the cross-section. These observations are consistent with a highly turbulent flow condition in which strong vertical mixing of streamwise momentum exists (Nezu and Nakagawa, 1993).

The last period from 12:39:29 to 12:50:40 CDT includes temporally and spatially averaged velocities from a total of 4 individual ADCP transects, and illustrates the return flow phenomenon described in the section “Flow Characteristics in Downstream Channel Regions.” The overall magnitudes of streamwise velocities were reduced compared to the two previous periods, with a depth-averaged peak of 15.8 cm/s; however, along both banks, a region of upstream flow was observed, with streamwise velocity magnitudes approaching 10 cm/s in the upstream direction. The rapidly changing velocity patterns observed during the lock empty procedure corroborate similar results seen in the variation of discharge in the approach (table 6), and have implications for the distribution and fate of the dye slug released by the lock, as will be discussed in later sections.

The flow velocities in the approach channel during the lock flushing procedure differ greatly from the lock injection and lock emptying procedures (fig. 10*C*). Velocities from a total of 17 individual ADCP transects surveyed from 14:14 to 14:46 CDT are presented for conditions during the lock flushing procedure. Streamwise velocity magnitudes averaged approximately 10 cm/s with a maximum of 19.6 cm/s occurring near the left bank. Similar to the lock emptying condition, velocities are very consistent throughout the full depth for the flushing procedure. No mixing layers or recirculation zones were observed, and the entirety of the measured flow is in the downstream direction. Apart from the left-most 2 m of the cross-section, the depth-averaged velocities are nearly uniform across the channel width. It is important to note that the velocity distribution in figure 10*C* is the result of data averaged over about 30 min and does not capture the variability in discharge measured during this period (table 6).

From comparing the streamwise velocity magnitudes and the depth-averaged velocity vectors for each flow condition, some distinguishable characteristics can be elucidated:

1. With quiescent lock conditions, flow in the approach channel can be bidirectional and consists of the interaction between a small amount of leakage-generated flow and wind-driven flows.

2. The flow in the approach channel seems to be vertically uniform for the emptying and flushing flows within the measured portion of the water column.

3. Velocities changed rapidly during the lock empty procedure and scaled with the measured discharge (table 6).

4. In the last 10 min of the lock emptying procedure, strong upstream directed flow was observed along both channel banks and was likely caused by transient oscillations of flow created by system equilibration and the recovery of the shear layer present at the downstream end of the approach channel.

These observations indicate that while the lock is discharging water, dye or dissolved constituents will likely be well mixed vertically in the approach channel; however, there may develop regions of differing concentrations where recirculation zones are present. Moreover, when no lock operation is underway, mixing in the approach channel may be dominated by wind-driven flows, rather than energy gradient or water-surface slope processes.

Velocity in the Lock during Filling

The lock chamber has 10 ports on each side (fig. 2) that release water upstream from the lock into the chamber when the filling valves are opened. The flow is driven by head differences between the lock chamber and the pool upstream. The ports are symmetrical, such that each port on one side of the lock has a corresponding port on the opposite lock side. As the filling valves are opened, water rapidly exits the ports on each side of the lock chamber, creating high-velocity jets of fluid near the bottom of the lock. These jets collide near the bottom of the lock, and upwell to the water surface creating a dynamic, turbulent, and three-dimensional flow in the lock chamber.

It is important to acknowledge that a filling lock chamber is a very challenging environment for hydroacoustic measurements. The flow characteristics violate the assumption of flow homogeneity inherit to ADCP processing algorithms, which state that velocities measured by diverging beams should be characteristic of the velocity field directly below the ADCP sensor. Moreover, air entrainment into the intakes results in bubbles and further decays the amount of valid ADCP velocity results. Despite these limitations, these data discussed below, after careful review and quality assurance practices, still present reasonable and expected circulation patterns in the lock chamber that are useful for understanding and interpreting the general mixing characteristics of the lock.

During the start of the lock filling operation, the upwelling flow was sufficiently turbulent and fast enough that no valid ADCP measurements could be made, and thus for the region about 102 to 200 m upstream from the downstream miter gates, there are no velocities shown (fig. 11*A*). Once the lock water elevation reached a depth of approximately 10 m, the velocity field became measurable with an ADCP. For the first 6 min of the filling operation, vertical velocity magnitudes were on the order of 20–30 cm/s or greater (fig. 11*A*). Most of the flow was directed upward toward the water surface, as indicated by warm colors (yellows through reds), with the exception of the upstream-most extent of valid velocities occurring from about 92 to 100 m from the downstream miter gates (fig. 11*A*). In this region, flow was downwelling toward the bottom of the lock and observed vertical velocities were between −20 and −30 cm/s. The downstream distance between the lock ports is greatest in this region where the downwelling flow was observed. This region of downwelling is approximately halfway between the adjacent ports where there is convergence of water from the two adjacent upwelling cells and, by continuity, water is forced down and away from the surface.

As the lock continued to fill, vertical velocity magnitudes remained above 10 cm/s in a large portion of the measured area (fig. 11*B*). Most of the flow, as measured along the lock centerline, was still directed upward throughout the lock chamber; however, more regions of downwelling flow were observed than in figure 11*A*. Several regions of lower velocity magnitude flow are differentiable as the depth of the lock rises to about 13 m. There were two such regions near the downstream miter gates at approximately 38–42 m and 82–94 m, respectively, where some downwelling flow was observed. Like in figure 11*A*, the downwelling occurred in the regions between lock ports.

As the lock depth increased above 14 m, the flow velocity magnitudes also decreased and much more downwelling flow was observed along the lock centerline (fig. 11*C*). Additionally, more of the ADCP data were marked valid as the turbulence associated with the high-velocity jets of water coming from the ports began to subside. The velocity magnitudes were higher near the upstream end of the lock, where the measurement first started, and gradually decreased as the ADCP was transited downstream. A region of downwelling flow over the entire flow depth was observed near the downstream miter gates, from about 10 to 28 m.

In the last 4 min of the filling operation, the water velocities continued to decrease and a more regular “banding” pattern of upwelling and downwelling flow was observed (fig. 11*D*). In general, velocity magnitudes were ±2 cm/s throughout the lock in this time period with occasional pockets of higher velocity flow. Because the velocity measurements occurred only along the lock centerline, upwelling flow was expected to dominate the measurement, especially early in time, when the lock depth was relatively shallow compared to later in time when the lock depth approached its maximum. To satisfy continuity, downwelling must have taken place along the walls. As the depth increased, the sampling volume of the ADCP also increased and more of the flow near the walls was captured in the measurement, resulting in more balanced upwelling and downwelling being observed.

From these data and the analysis, a few general observations can be made about the characteristics of the flow in the lock chamber during a typical filling operation:

1. Because the lock ports on each wall are directly opposite of each other and are located near the bottom of the lock, filling operations create high-velocity water that creates jets along the bottom of the lock, which collide near the center of the lock (where the ADCP was measuring) and produce strong upwelling along the lock centerline and corresponding downwelling along the lock walls.

2. At least within the observed lock centerline, the vertical velocities are positive (upward directed) throughout most of the lock chamber. This finding correlates well with the position of upwelling jets caused by the opposing lock port jets colliding at the lock bottom and upwelling.

3. As the lock continues to fill, the difference in water elevation between the lock chamber and the upstream pool decreases, producing lower velocity magnitudes in the lock chamber.

4. As the velocities decrease and the jet flow dissipates, a more balanced vertical “banding,” with upwelling and downwelling flows more or less covering the same cross-sectional area, is observed throughout the lock centerline.

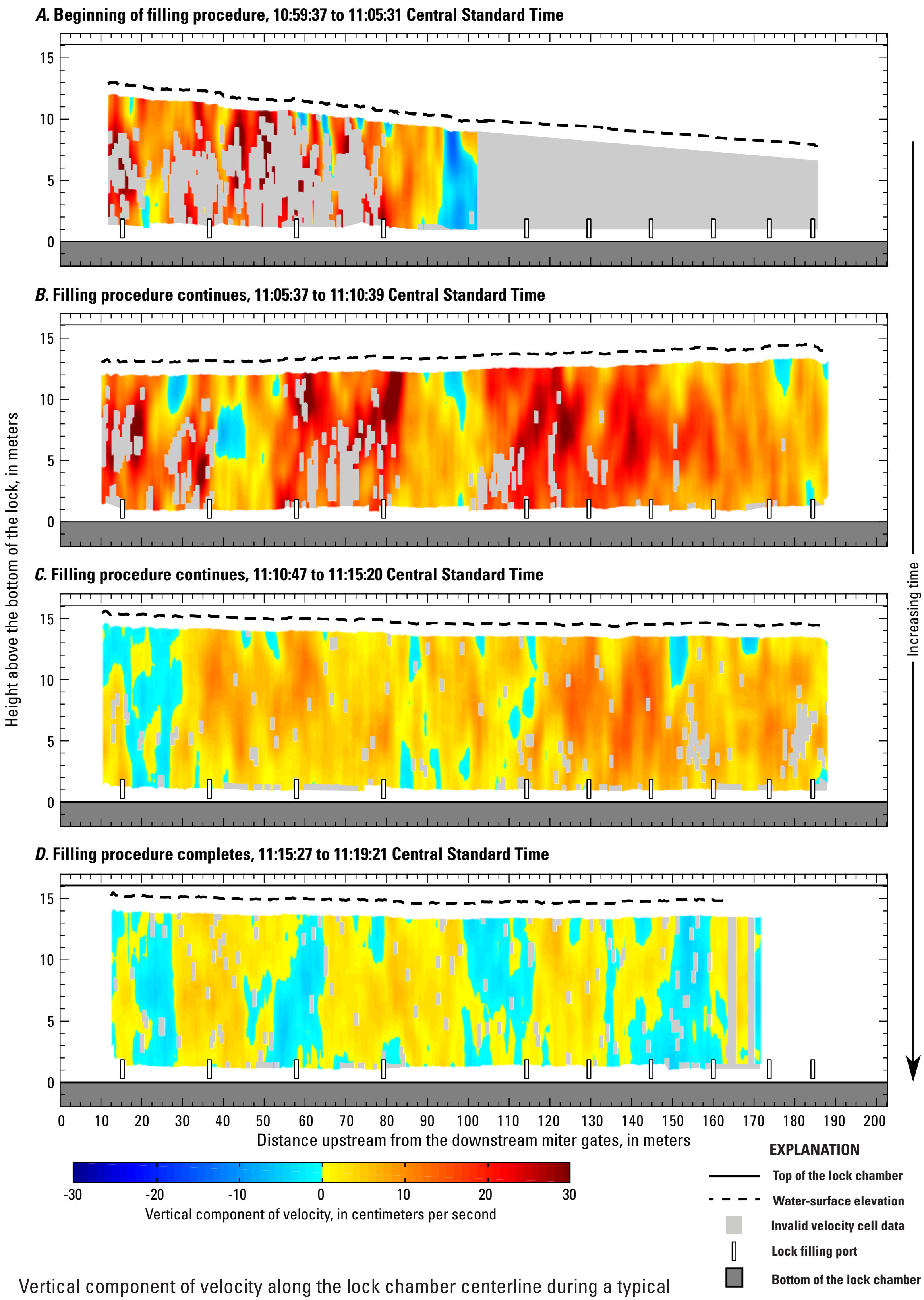


Figure 11. Vertical component of velocity along the lock chamber centerline during a typical lock filling procedure. Shown are velocities on December 10, 2014, during the following periods: *A*, 10:59:37 to 11:05:31 Central Standard Time (CST); *B*, 11:05:37 to 11:10:39 CST; *C*, 11:10:47 to 11:15:20 CST; and *D*, 11:15:27 to 11:19:21 CST. The bottom of the lock chamber is at an elevation of 149.27 meters above the National Geodetic Vertical Datum of 1929. Positive vertical components of velocity are directed toward the water surface.

The observed hydrodynamics of the flow in the filling lock chamber along the centerline indicate the lock ports create a favorable environment for highly turbulent mixing at the beginning of the filling operation. As the lock continues to fill, although turbulence is reduced, large scale patterns of upwelling and downwelling likely aid in the distribution of dissolved constituents throughout the lock. The head difference and filling time of the BRL chamber are sufficiently large to allow full-depth circulation cells to form. Early in the filling operation (approximately 3 min after the valves are open), the full water column turns over approximately every 40 s (10 m depth, 25 cm/s vertical velocity). As the depth increases and the vertical velocity decreases, the overturn timescale increases. Approximately 9 min into the filling operation, the water column overturns roughly every 140 s (14 m depth, 10 cm/s vertical velocity). By the end of the filling procedure, the overturning timescale is approximately 12.5 min (15 m depth, 2 cm/s vertical velocity), which indicates that constituents introduced to the inflow early in the filling process are much more likely to mix over the depth of the lock compared to those introduced late in the filling process.

Mixing Characteristics in the Lock

The dye tracer was used to determine the mixing characteristics of the lock chamber. The distribution of dye in the lock chamber was evaluated for three lock states: (1) a full lock immediately after injection during the fill; (2) an empty lock where the downstream gates remain closed, and (3) an empty lock after a 17-min post flushing procedure.

Full Lock Immediately after Tracer Injection during Filling

One guiding question for this research was whether or not the existing BRL filling system is capable of mixing dissolved constituents added to the filling water to a uniform concentration throughout the lock chamber. Apart from cross-section 5 at the downstream end of the lock, dye concentrations within the lock chamber after filling were within 6 percent of the target concentration of 10 ppb and were generally uniform over the depth, width, and length of the lock chamber (fig. 12; table 7). The spatial uniformity of the dye distribution within the lock chamber at cross-sections 1 through 4 is consistent with the highly turbulent flows and strong vertical circulation measured during filling (fig. 11).

Cross-section 5, nearest the downstream lock gates, showed substantially more variation in dye concentration than elsewhere in the lock (fig. 12; table 7). Although station 5A on the north side of the lock had a nearly uniform concentration over the depth and was slightly higher than the target concentration (8.7 percent), station 5B showed a decrease in concentration with depth below an elevation of 155 m NGVD 29 from just above 10 ppb to 4.91 ppb near the bottom of the lock. Moreover, station 5C had a nearly uniform profile of concentration over the depth but was substantially lower (22.2 percent) than the target concentration of 10 ppb. The variability in dye concentration at cross-section 5 is likely due to the following factors: (1) dye leaked out of the lock during filling and (2) cross-section 5 was measured last and may have been diluted by net leakage through the lock. Immediately after completing the dye injection at 10:31 CDT on October 20, 2015, crews on a mobile survey vessel downstream from the lock measured dye concentrations of more than 15 ppb along the south (short) wall of the approach channel about 10 to 20 m downstream from the lock gates on the left bank. This measurement indicates that some high concentration dye (greater than 15 ppb) bypassed the lock chamber and leaked directly into the approach channel downstream from the lock on the south wall. The location of the leakage plume is consistent with the outfall from the south emptying (left) valve and indicates that this valve may have been leaking during the study. At the time of this study, this valve was due for maintenance and was operational, but in a limited capacity (Brandon Road lock staff, U.S. Army Corps of Engineers, oral commun., October 2015). Dye injected into the culvert system likely leaked out of this valve instead of entering the lock chamber near station 5C, causing dye concentrations at this station to fall below the target concentration.

After filling, the lock operator accidentally left the filling valves open, allowing water from upstream into the lock at a rate of approximately 5.1 m^3/s (net leakage estimate for a full lock). This flow of freshwater into the lock kept the lock at the headwater level, but allowed some dilution of the dye in the lock. Although the concentrations presented in figure 12 have been corrected for the dilution during each measurement time period (see the “Methods of Data Collection and Data Analysis” section), the correction assumes the instantaneous mixing of the “fresh” water throughout the lock. The low concentrations within 5 m of the lock bottom at station 5B may indicate that the leakage had a preferential path from the intakes through the culvert system to the downstream end of the lock. It is possible that during the 79 min between the end of the fill and the profile at station 5B, the preferential leakage to the downstream end of the lock diluted the concentration near the lock bottom at cross-section 5.

Despite the leakage issues that likely caused concentrations at stations 5B and 5C to fall below the target concentration, the culvert-and-ports filling system for BRL was capable of uniformly mixing a passive tracer throughout most of the lock chamber. If the leakage was minimized through maintenance of the south emptying (left) valve and repair or replacement of the gate seals, it is likely that uniform mixing throughout the entire lock chamber could be achieved. This finding indicates that the culvert-and-ports lock filling system is a viable option for distribution of dissolved constituents into the lock chamber.

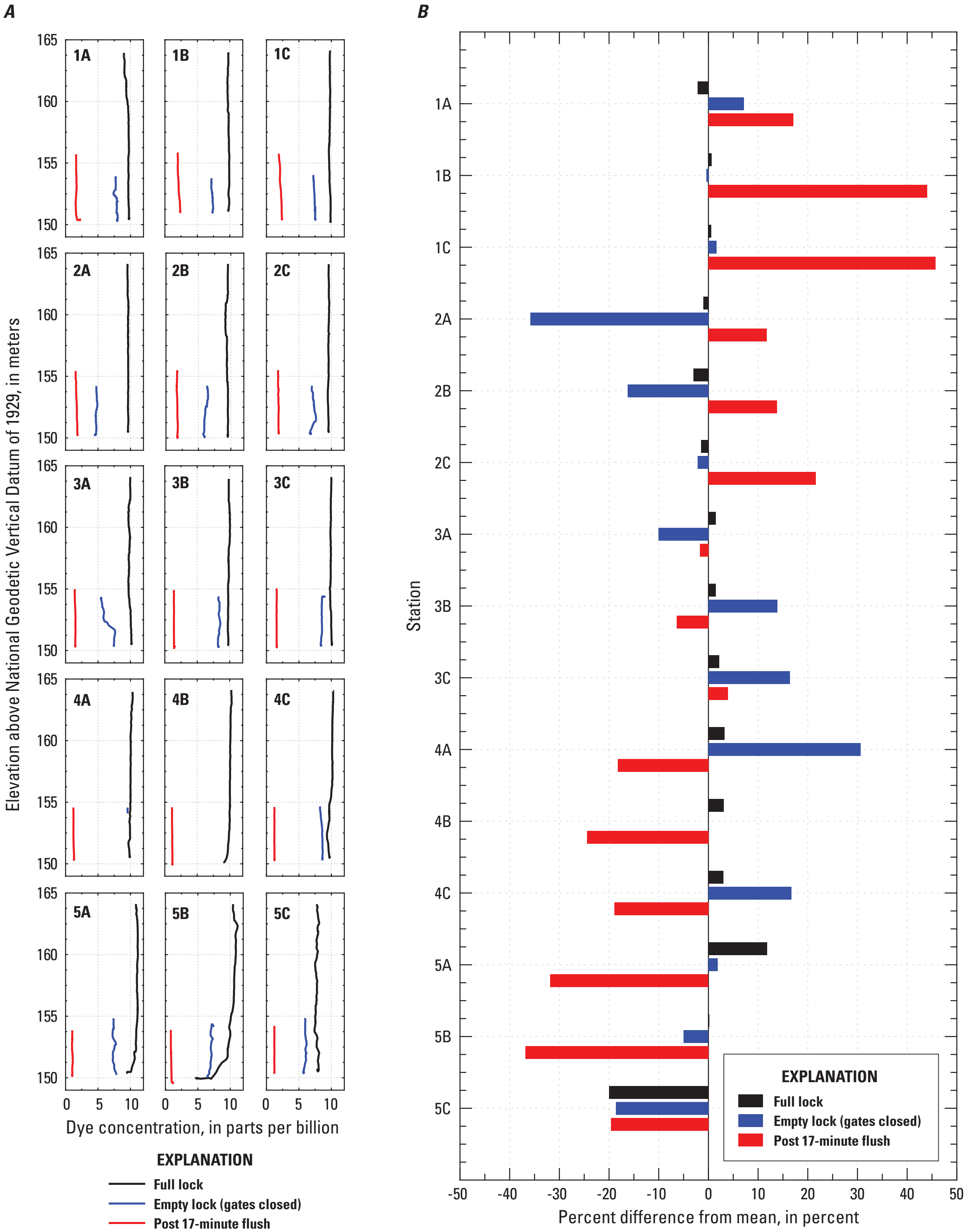


Figure 12. Dye concentration in the Brandon Road Lock chamber. *A*, vertical profiles of dye concentration at each station. *B*, the percent difference at each station from mean concentration in the lock chamber. Station locations are shown in figure 5*B*.

Table 7. Mean dye concentration and percent difference from the target concentration at 15 stations in the Brandon Road lock chamber.

[ppb, parts per billion; -- no data]

Station (fig. 5*B*)	Target concentration, in ppb	After lock fill		After lock empty (downstream gates closed)		After flushing	
		Mean concentration of vertical profile, in ppb	Percent difference of mean concentration from target concentration	Mean concentration of vertical profile, in ppb	Percent difference of mean concentration from target concentration	Mean concentration of vertical profile, in ppb	Percent difference of mean concentration from target concentration
1A	10	9.51	–4.9	7.84	–21.6	1.77	–82.3
1B	10	9.79	–2.1	7.29	–27.1	2.18	–78.2
1C	10	9.78	–2.2	7.44	–25.6	2.21	–77.9
2A	10	9.62	–3.8	4.70	–53.0	1.69	–83.1
2B	10	9.43	–5.7	6.13	–38.7	1.72	–82.8
2C	10	9.58	–4.2	7.16	–28.4	1.84	–81.6
3A	10	9.87	–1.3	6.58	–34.2	1.49	–85.1
3B	10	9.87	–1.3	8.33	–16.7	1.42	–85.8
3C	10	9.94	–0.6	8.52	–14.8	1.57	–84.3
4A	10	10.04	0.4	9.56	–4.4	1.24	–87.6
4B	10	10.02	0.2	--	--	1.14	–88.6
4C	10	10.02	0.2	8.54	–14.6	1.23	–87.7
5A	10	10.87	8.7	7.46	–25.4	1.03	–89.7
5B	10	9.74	–2.6	6.95	–30.5	0.96	–90.4
5C	10	7.78	–22.2	5.95	–40.5	1.22	–87.8
Mean	10	9.72	–2.8	7.32	–26.8	1.51	–84.9

Empty Lock with the Downstream Gates Closed

Emptying a lock full of water with a nearly uniform dye concentration near 10 ppb and leaving the downstream gates closed should leave the lock at the tailwater elevation, but still with in-lock dye concentrations near 10 ppb; however, this experiment at BRL produced very different results. After emptying the lock and correcting for leakage dilution during the time period required to complete profile set 2 (51 min; see the “Methods of Data Collection and Data Analysis” section), the dye concentrations within the lock chamber were well below the target concentration of 10 ppb (fig. 12; table 7). Mean dye concentrations computed at each station ranged from 4.70 to 9.56 ppb with a mean concentration for the entire lock chamber of 7.32 ppb. These concentrations are between 4.4 and 53 percent lower than the target concentration of 10 ppb (table 7). To dilute the empty lock chamber at a tailwater elevation of 154 m NGVD 29 from a mean concentration of 9.72 ppb (the mean concentration of the full lock chamber) to a mean concentration of 7.32 ppb requires approximately 11,200 m^3 of freshwater (based on lock geometry). This dilution must have occurred during the 55 min between the end of the first set of profiles (lock full) and the beginning of the second set (lock empty; table 4). The total Q_L computed using equation 1 for this 55-min period is 11,300 m^3; therefore, the net leakage computed using equation 1 can account for the dilution observed in the lock chamber between the profile sets.

In addition to the dilution of dye concentration at all stations within the lock chamber, the emptying of the lock resulted in nonuniform distributions of dye throughout the lock chamber. Although the full lock had uniform dye concentration throughout the lock except at cross-section 5 near the downstream gates, the empty lock shows considerable differences between concentrations in the same cross-section as well as between cross-sections (fig. 12). The greatest variability is seen in stations 2, 3, and 4 (A–C). Compared to the mean concentration for the entire lock chamber, cross-section 2 had as much as 36 percent lower concentrations, whereas cross-section 4 had as much as 31 percent higher concentrations. Cross-section 3 had 10 percent lower concentrations at station 3A (north side) and 16 percent higher concentrations than average at station 3C (south side). In addition, stations 2C and 3A showed variation of concentration with depth (fig. 12).

The dilution owing to leakage is substantial. Target concentrations of dissolved constituents may be achieved by adding the constituent to the fill water; however, the net leakage through the lock chamber during filling, during the emptying of the lock, and during the period the lock is at tailwater level (the time it takes for a vessel to enter the lock, for example) can dilute the constituent to concentrations well below the target concentration. Addressing and minimizing leakage is important to maintain target concentrations within the empty lock chamber.

Post Flushing Procedure

Understanding the hydrodynamics, mixing, and transport characteristics within the lock chamber during a flushing procedure was necessary to evaluate the efficacy of such a procedure for removal of floating ANS from the lock chamber. Following a 17-min flushing procedure of the lock chamber in which the downstream gates were open and the filling valves were 25 percent open, the dye concentration in the lock decreased about 80 percent, from a mean concentration of 7.32 ppb to 1.51 ppb (table 7). The 17-min flush provided a sufficient volume of water to replace the dye-treated water in the empty lock chamber, and the distribution of the filling ports along the length of the lock chamber created large circulation cells and intense mixing but did not provide effective flushing of the water from the lock. The upstream one-half of the lock had approximately 13 percent less dilution after flushing compared to the downstream one-half of the lock (fig. 12; table 7). Qualitative observations of floating debris that remained trapped in the upstream portion of the lock during flushing provide further evidence of incomplete flushing of the lock (Engel, 2015). These findings indicate that the water and floating or weak-swimming ANS may be trapped in the upstream portion of the lock during flushing. One potential alternative to produce more effective flushing of the lock would require the deactivation of all but the most upstream set of filling ports, allowing the water to enter at the upstream end of the lock and create a unidirectional flow downstream and out of the lock. With no individual valves on the ports in the current lock, this would require retrofitting of the lock culvert-and-port filling system.

Fate of Constituents Downstream from the Lock

With the volume of the approach channel approximately three times the volume of the water released from the lock during a lockage, water from the lock and any dissolved constituents move downstream through the approach channel in pulses (fig. 13). A single lockage does not contain enough water to replace the water in the approach channel and the quiescent nature of the approach channel when the lock is idle limits the primary mixing to periods when lock water is released. However, the transient oscillations in flow in the approach channel following lockages (see section "Velocity in the Approach Channel/Spillway during Empty and Flushing") and periodic flow reversals, especially along the banks of the approach channel, provide some mixing and transport of "fresh" (undyed) water upstream (figs. 13 and 14).

A good example of the effect of the transient oscillation on transport in the approach channel is shown in figure 13 at FL2 and FL3 during the period after the lock was emptied and before the flushing commenced (period labeled "fig. 14*B*" in fig. 13). After the lock was emptied, the leading edge of the dye plume reached FL2 and FL3, with five-times higher concentration at FL2 (fig. 13, point *a*); however, once the lock was empty, the discharge to the approach channel dropped to near zero and the transient oscillation in the pool initiated upstream transport in the approach channel, pushed the dye back toward the lock, and decreased the dye concentration at FL2 from 5 ppb to 2 ppb (fig. 13, point *b*). At an elapsed time of approximately 2.7 hours after the start of the dye injection, the transient oscillation changed the flow direction back to downstream in the approach channel and concentrations at FL2 and FL3 increased to about 5 ppb (fig. 13, point *c*) before dropping again during the next 30 min.

The flushing of the lock chamber pushed the center of mass of the dye plume from the downstream gates of the lock chamber to FL2 and FL3 in the approach channel (about 360 m; fig. 13, point *d* and fig. 14*C*). The flushing procedure also pushed the leading edge of the dye plume out of the approach channel and into the confluence with the spillway channel. Mixing at the shear layer between the approach channel and the spillway channel further diluted the leading edge of the dye plume and only small concentrations of about 0.1 ppb were detected at FL6 (fig. 13, point *e*). Another good example of the transient oscillation-induced transport is the dramatic drop of the concentration at FL4 at an elapsed time of 5 hours (fig. 13, point *f*). This drop was caused by the upstream flow of lower concentration water past FL4 as the pool oscillated after being disturbed by the flushing procedure.

When the partially filled lock was emptied at an elapsed time of about 5.4 hours, the dye plume underwent another rapid downstream advection, pushing the centroid past FL2 and FL3 and closer to FL4 and FL5 (fig. 13, point *g*). This rapid advection of the plume also pushed higher concentrations of dye into the shear layer at the downstream end of the approach channel, causing a rapid rise in the concentration at FL6. The idle lock that followed allowed mixing at the shear layer to quickly dilute the dye leaving the approach channel, causing concentrations to drop at FL5 and FL6 (fig. 13, point *h*). During this period, FL4 remained at a high concentration (5.5 ppb).

At an elapsed time of about 5.7 hours, the lock resumed normal operations and the dye plume progressively moved downstream out of the approach channel with each lockage. By 10 hours after the dye injection, all the fluorometers in the study reach measured concentrations less than 0.5 ppb (fig. 13, point *i*). It should be noted that FL4 maintained a higher concentration compared to the other fluorometers until an elapsed time of about 15 hours, which is likely due to the location of FL4 relative to the shear layer. FL4 is the closest fluorometer to the stagnation zone of the confluence. Dye can be trapped in the approach channel near this point and dilute slowly over time owing to the weak mixing associated with the low-velocity water in the stagnation zone.

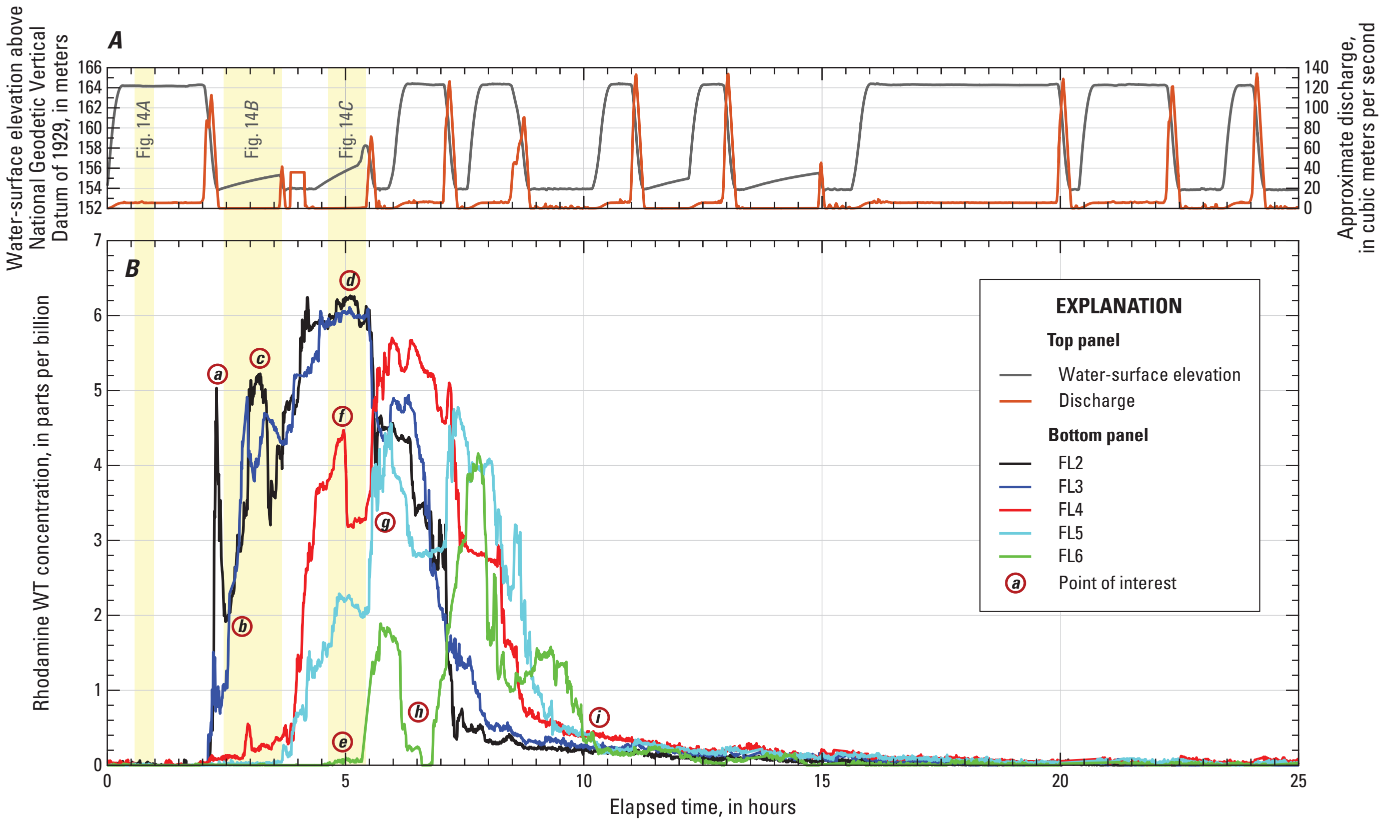


Figure 13. Time series of dye concentration measured by the fixed fluorometers downstream from Brandon Road Lock. *A*, the water-surface elevation in the lock chamber and the approximate discharge from the lock into the approach channel from figure 8. *B*, time series of dye concentration. The elapsed time is measured from the start of the dye injection at 10:24 Central Daylight Time on October 20, 2015. The data collection time periods corresponding to the contour plots in figure 14, and points of interest (discussed in text) are shown for reference.

Implications for Aquatic Nuisance Species Control

The Brandon Road Lock and Dam on the Des Plaines River near Joliet, Illinois, has been identified for potential implementation of ANS control measures. Future feasibility studies of ANS control technology implementation at Brandon Road Lock and Dam need to consider the complex hydrodynamics present in the lock chamber, in the downstream approach channel, and within the Des Plaines River immediately downstream from the lock where powerplants have a substantial effect on main channel flows. Proper understanding of these hydraulic factors should be considered if the lock is to be used to deliver any dissolved constituent or operated in a way to prevent upstream passage of floating ANS. Moreover, any ANS control technologies that target the approach channel for implementation must be capable of operating effectively under extremely variable flow conditions including bidirectional flows and upstream return flows. Although improvements can be made to the lock chamber to reduce leakage or improve flushing, the complex hydrodynamics downstream from the lock chamber are a result of many factors that cannot be so easily solved.

For ANS control technologies that are designed to treat the lock during every fill operation, each subsequent lockage would add additional dissolved constituent to the approach channel; therefore, it is theoretically possible to maintain an increasing streamwise gradient in concentration from the downstream end of the approach channel to a maximum in the lock chamber, provided leakage dilution issues could be addressed through maintenance of seals and such a system would allow the lock to function normally and would not hinder vessel traffic. The streamwise gradient in constituent concentration spanning the entire length of the approach channel and peaking in the lock chamber may discourage upstream migrating ANS from entering the approach channel or lock chamber (assuming the constituent used is effective at repelling the target ANS).

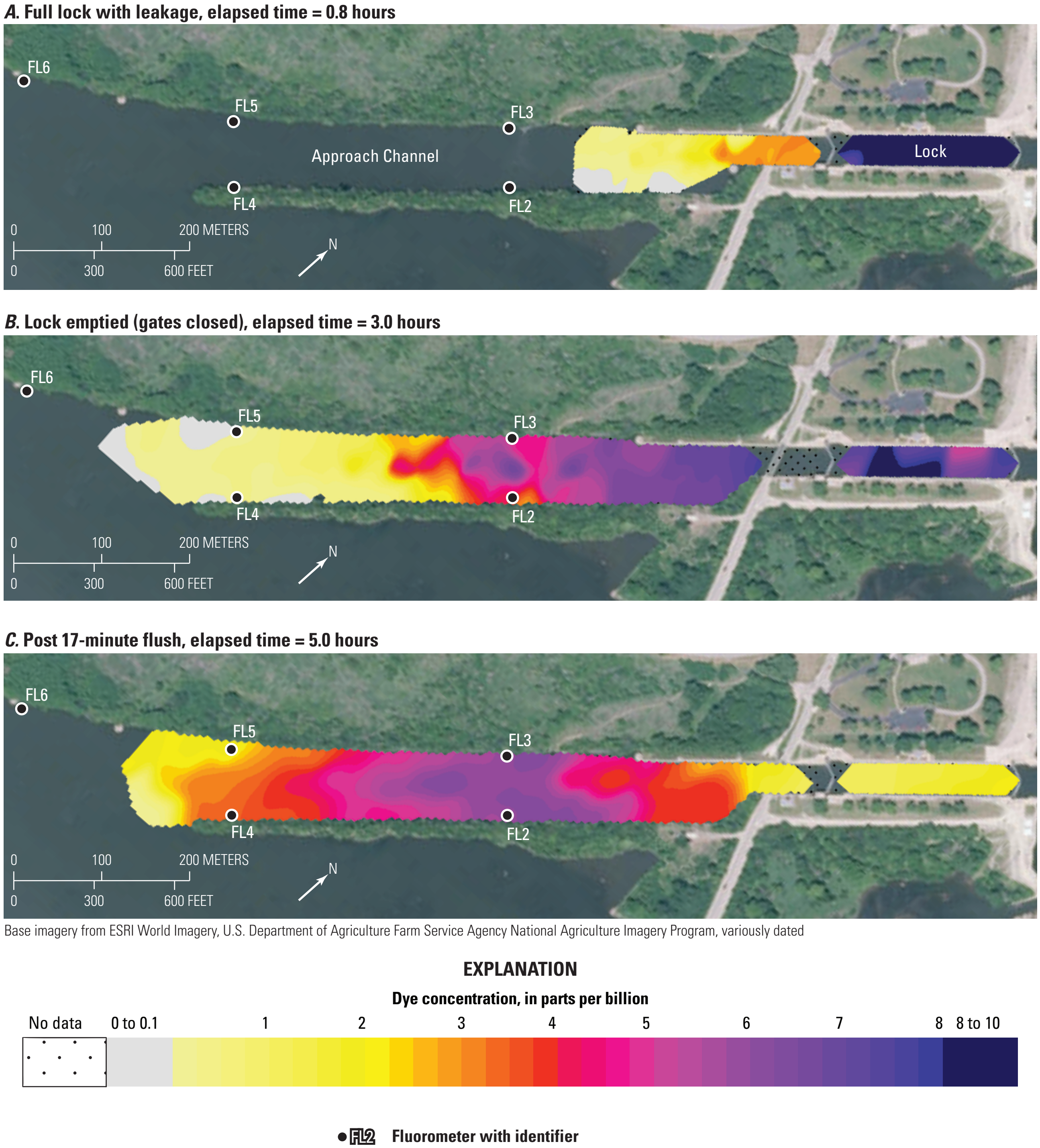


Figure 14. Evolution of the dye plume in the approach channel downstream from Brandon Road Lock. The data used to develop these contour plots downstream from the lock were collected on October 20, 2015, during the following periods: *A*, 11:00 to 12:21 Central Daylight Time (CDT); *B*, 12:50 to 14:02 CDT; and *C*, 15:01 to 15:50 CDT. The elapsed time represents the mean time for each survey and is measured from the start of the dye injection at 10:24 CDT on October 20, 2015. The contours in the lock are developed from the vertically averaged mean concentrations at each profiling station (table 7).

Summary and Conclusions

The Brandon Road Lock and Dam on the Des Plaines River in Illinois has been identified for potential implementation of aquatic nuisance species (ANS) control technologies. To provide additional information concerning the flow hydraulics and mixing characteristics of the lock and downstream approach channel, the U.S. Geological Survey performed a detailed study of the site between December 2014 and October 2015. This study included the collection and analysis of bathymetric, hydrodynamic, and dye tracer data. Synthesis of these data allowed a characterization of the site for future use in feasibility studies of potential ANS control technologies.

The highly turbulent flows and strong vertical circulation produced by the existing side-ported filling system at the Brandon Road Lock (BRL) is sufficient to uniformly mix dissolved constituents added to the fill water throughout the lock chamber. Apart from the downstream end of the lock, dye concentrations within the lock chamber after filling were within 6 percent of the target concentration and were generally uniform over the depth, width, and length of the lock; however, dilution due to leakage can substantially affect the ability to achieve and maintain a target concentration and uniform distribution of a dissolved constituent in the lock chamber through the lockage cycle. Effects of leakage are most pronounced when the lock is at or near tailwater level. If the leakage was minimized through maintenance of the south emptying valve and repair or replacement of the gate seals, it is likely that uniform mixing throughout the entire lock chamber could be achieved and target concentrations maintained in the chamber throughout the lockage cycle.

Flushing of the lock chamber using the existing infrastructure has been proposed as a possible option to remove floating ANS from the lock and prevent upstream transport. During this atypical lock flushing operation (filling valves open 25 percent, downstream gates open, 17-minute flushing period), flow in the lock chamber is not unidirectional, but rather hydrodynamically complex and consisting of a series of large circulation cells created by convergence of high-velocity jets from the filling ports. Flushing produces intense mixing in the lock chamber that is capable of rapidly diluting the mean concentration of dissolved constituents in the chamber by approximately 80 percent. However, flushing was determined to be about 13 percent less effective in the upstream one-half of the lock compared to the downstream one-half of the lock. This finding indicates that the water and floating or weak-swimming ANS may be trapped in the upstream portion of the lock during flushing, which was confirmed with qualitative observations of floating debris during flushing. More effective flushing of the lock requires a unidirectional flow downstream and out of the lock. Retrofitting the filling system to allow the deactivation of all but the most upstream set of filling ports is one potential way to achieve such a flow.

Hydrodynamics and discharge in the approach channel are highly variable in both space and time and are heavily dependent on lock operations. When the lock is idle and the downstream gates and emptying valves are closed, flows in the approach channel are generally slow and variable and are mainly driven by wind and (or) leakage from the lock. Emptying of the full lock releases flood pulses into the approach channel that cause the discharge and the velocity distribution to vary rapidly in time. The manual operation of the valves during emptying, the vessels in the lock, and the headwater and tailwater levels introduce variability into the maximum discharge of the flood pulse in the approach channel. The perturbation of the system caused by the emptying of the lock produces a transient oscillation in the approach channel. Approximately 10 minutes after the peak of the flood pulse and near the end of the falling limb of the hydrograph, a net-upstream return flow is observed in the approach channel. This transient pulse dampens in time owing to both frictional and gravitational forces. The highly variable, bidirectional flows observed in the approach channel have substantial implications for ANS control technologies deployed in the approach channel that may rely on steady or unidirectional flows. Such technologies must, at a minimum, be able to maintain their efficacy over the range of flows observed in this study.

The fate of dissolved constituents added to the water in the lock chamber and released to the approach channel downstream when the lock empties is dependent on subsequent lock operations. As the lock empties, it discharges a volume of treated water approximately one-third the volume to the approach channel. Dye distributions indicate dissolved constituents will form a concentration gradient in the approach channel with the concentration steadily increasing from the downstream entrance to the approach channel to a maximum within the lock chamber; however, pockets of variable concentrations may develop where recirculation zones are present and return flows owing to transient oscillations can create periodic temporal variations in concentration that are greatest along both banks. Without subsequent lock operations, the concentration gradient developed in the quiescent approach channel likely would persist with a slow decrease in concentration due to net leakage through the lock and mixing across the shear layer (assuming passive, nonreactive constituents). For ANS control technologies that are designed to treat the lock during every fill operation, each subsequent lockage would add additional dissolved constituent to the approach channel; therefore, it is theoretically possible to maintain an increasing streamwise gradient in concentration from the downstream end of the approach channel to a maximum in the lock chamber, provided leakage dilution issues could be addressed through maintenance of seals and such a system would allow the lock to function normally and would not hinder vessel traffic. The streamwise gradient in constituent concentration spanning the entire length of the approach channel and peaking in the lock chamber may discourage upstream migrating ANS from entering the approach channel or lock chamber (assuming the constituent used is effective at repelling the target ANS).

Future feasibility studies of ANS control technology implementation at Brandon Road Lock and Dam need to consider the complex hydrodynamics present in the lock chamber, in the downstream approach channel, and within the Des Plaines River immediately downstream from the lock where powerplants have a substantial effect on main channel flows. Proper understanding of these hydraulic factors should be considered if the lock is to be used to deliver any dissolved constituent or operated in a way to prevent upstream passage of floating ANS. Moreover, any ANS control technologies that target the approach channel for implementation must be capable of operating effectively under extremely variable flow conditions including bidirectional flows and upstream return flows. Although improvements can be made to the lock chamber to reduce leakage or improve flushing, the complex hydrodynamics downstream from the lock chamber are a result of many factors that cannot be so easily solved.

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