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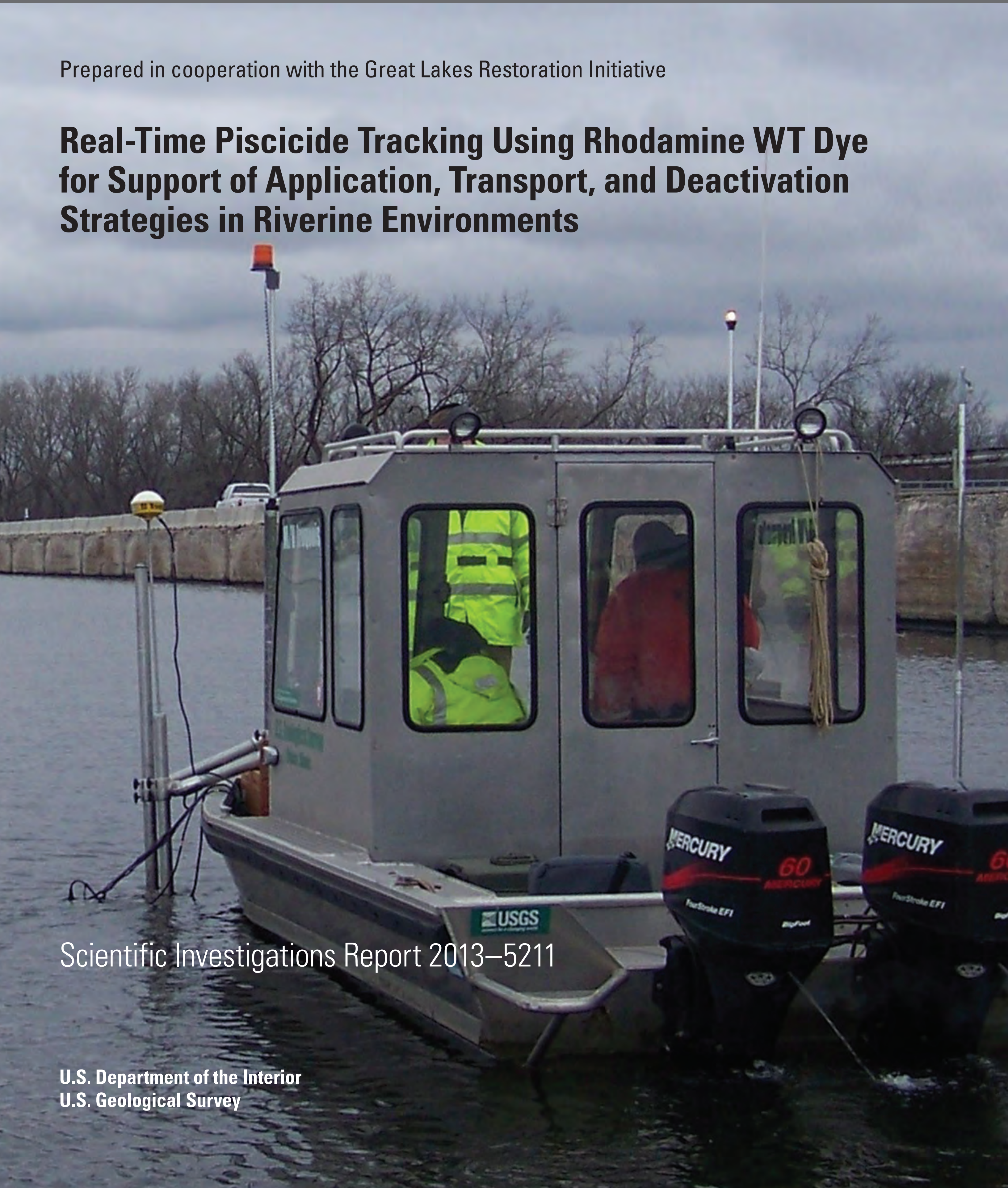

Prepared in cooperation with the Great Lakes Restoration Initiative

Real-Time Piscicide Tracking Using Rhodamine WT Dye for Support of Application, Transport, and Deactivation Strategies in Riverine Environments

Scientific Investigations Report 2013–5211

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

Cover. Photograph of one of the two real-time piscicide/dye tracking vessels used in the 2009 and 2010 rotenone treatments (photograph by J. Duncker, U.S. Geological Survey). The vessel is in the Chicago Sanitary and Ship Canal, with fish collection boats in the background.

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SALLY JEWELL, Secretary

U.S. Geological Survey
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Conversion Factors

Inch/Pound to SI

Multiply	By	To obtain
	Length	
inch (in)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Flow rate	
foot per second (ft/s)	0.3048	meter per second (m/s)
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)

SI to Inch/Pound

Multiply	By	To obtain
	Volume	
milliliter (mL)	0.0338	ounce, fluid (fl. oz)
liter (L)	0.2642	gallon (gal)

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

°F=(1.8×°C)+32

Concentrations of chemical constituents in water are given either in milligrams per liter (mg/L) or in parts per billion (ppb).

Acknowledgments

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Real-Time Piscicide Tracking Using Rhodamine WT Dye for Support of Application, Transport, and Deactivation Strategies in Riverine Environments

By P. Ryan Jackson and Jonathan D. Lageman

Abstract

Piscicide applications in riverine environments are complicated by the advection and dispersion of the piscicide by the flowing water. Proper deactivation of the fish toxin is required outside of the treatment reach to ensure that there is minimal collateral damage to fisheries downstream or in connecting and adjacent water bodies. In urban settings and highly managed waterways, further complications arise from the influence of industrial intakes and outfalls, stormwater outfalls, lock and dam operations, and general unsteady flow conditions. These complications affect the local hydrodynamics and ultimately the transport and fate of the piscicide. This report presents two techniques using Rhodamine WT dye for real-time tracking of a piscicide plume—or any passive contaminant—in rivers and waterways in natural and urban settings. Passive contaminants are those that are present in such low concentration that there is no effect (such as buoyancy) on the fluid dynamics of the receiving water body. These methods, when combined with data logging and archiving, allow for visualization and documentation of the application and deactivation process.

Real-time tracking and documentation of rotenone applications in rivers and urban waterways was accomplished by encasing the rotenone plume in a plume of Rhodamine WT dye and using vessel-mounted submersible fluorometers together with acoustic Doppler current profilers (ADCP) and global positioning system (GPS) receivers to track the dye and map the water currents responsible for advection and dispersion. In this study, two methods were used to track rotenone plumes: (1) simultaneous injection of dye with rotenone and (2) delineation of the upstream and downstream boundaries of the treatment zone with dye. All data were logged and displayed on a shipboard laptop computer, so that survey personnel provided real-time feedback about the extent of the rotenone plume to rotenone application and deactivation personnel. Further, these strategies facilitate adjustment of rotenone application and deactivation strategies in real time if necessary based on the observed advection and dispersion of the rotenone plume.

Two large-scale and complex applications of rotenone in the Chicago Area Waterway System (CAWS) in 2009 and 2010 to combat invasive Asian carp are documented in this report. The application in Chicago Sanitary and Ship Canal (CSSC) in December 2009 involved more than 1,800 gallons of rotenone injected at multiple stations through a 6.2-mile reach of the canal near Lockport, Illinois. The rotenone plume was encased in Rhodamine WT dye so that two survey boats provided real-time feedback to shore personnel regarding the plume extent as it advected downstream. Real-time tracking of the rotenone was essential in this large-scale application because of the multistage injection strategy and the numerous deactivation points required to minimize collateral damage to fisheries in surrounding and receiving water bodies. All timing of application and deactivation operations relied on dye tracking. A second application of rotenone in May 2010 to the Little Calumet River near O'Brien Lock and Dam (Illinois) provided another opportunity for dye-tracking support operations; however, application and deactivation strategies were designed considering zero-flow conditions within the reach of interest. Therefore, dye was injected at the upstream and downstream boundaries of the rotenone application reach and was used to track movement of water in and out of a treatment reach, allowing proper deactivation to occur and avoiding unnecessary damage to fisheries downstream. The data collected during the real-time tracking operations for both applications allowed full documentation of the rotenone treatment for archival purposes and provided information for future applications.

The methods presented in this report for real-time tracking and documentation of piscicide applications in riverine environments worked exceptionally well and allowed the multiagency Asian Carp Rapid Response Workgroup to carry out large-scale rotenone applications in urban waterways in an environmentally responsible manner with minimal collateral damage to fisheries outside the treatment reach. Traveltime information extracted from the boat-mounted and fixed-position fluorometers agrees well with empirical predictions from a preliminary dye study (mock rotenone injection) on this system completed in November 2009 on the CSSC and with previously published methods

for estimating traveltimes of the peak, leading edge, and trailing edge of the plume. Although the rotenone application strategy called for zero-flow conditions on the Little Calumet River in 2010, downstream advection of treated water did occur, and dye tracing combined with velocity mapping allowed this advection to be documented and exposed the unique hydrodynamics and mixing within this reach.

The large volumes of data collected during the operations allow documentation and visualization of the rotenone applications, thus providing feedback to planners and archival of the treatments for future reference. The methods developed in this report are directly transferrable to piscicide applications in water bodies in other locations, including rivers, ponds, or lakes, and can be used for real-time tracking of any passive contaminant that may enter a water body.

Introduction

Invasive Asian carp, including the bighead carp (*Hypophthalmichthys nobilis*) and silver carp (*H. molitrix*), are threatening to migrate into the Great Lakes from the Mississippi River Basin via the Chicago Sanitary and Ship Canal (CSSC), a manmade connection between the Mississippi River and Great Lakes watersheds (fig. 1). Impeding their migration is the electric dispersal barrier on the CSSC near Romeoville, Illinois (Ill.). The dispersal barrier, operated by the U.S. Army Corps of Engineers, passes current through the water to generate an electronic fence which prevents passage of fish and other aquatic species between the basins (U.S. Army Corps of Engineers, 2012). The efficacy of the barrier is routinely evaluated by monitoring waters upstream from the barrier for any presence of the invasive Asian carp. Monitoring techniques include netting, electrofishing, and collection of environmental DNA (eDNA) samples (Asian Carp Regional Coordinating Committee Monitoring and Rapid Response Workgroup, 2012). Positive detections of Asian carp at or upstream from the barrier can trigger rapid response actions by a multiagency task force. In addition, barrier-maintenance schedules require the dispersal barriers to be periodically turned off and serviced. Although every effort is made to avoid the use of toxicants in the CSSC and surrounding waterways, preventing the invasion of Asian carps into the Great Lakes has required large-scale applications of the piscicide rotenone to a 6.2-mile (mi) reach of the CSSC during a dispersal barrier maintenance shutdown in 2009 and treatment of a 2.6-mi reach of the Little Calumet River in Illinois during a rapid response action in 2010 (fig. 1).

Piscicides are pesticides that target gill-breathing organisms by inhibiting cellular respiration, making it impossible for fish to use the oxygen absorbed in their blood for respiration (Oberg 1967; Finlayson and others, 2010). A commonly used piscicide, rotenone, is odorless and colorless when applied to water and thoroughly mixed (it is milky white in color during application and prior to mixing). Historically, rotenone has been used primarily in lakes and ponds to eradicate invasive fish species (more than 97 percent of the time it is applied to standing, nonflowing water) and is the most commonly applied piscicide (Finlayson and others, 2000, 2010). Rotenone degrades in the environment but can persist for several days to several months depending on the initial concentration and water temperature (Finlayson and others, 2010). Pond applications can rely on time to deactivate the poison; however, when applied in a riverine environment with flowing water and a designated treatment reach, the toxin must be deactivated downstream from the treatment reach to avoid collateral damage to fisheries downstream. Deactivation can be accomplished by injection of potassium permanganate (or sodium permanganate) within the treated water body. The potassium permanganate deactivates the rotenone through oxidation, a process that requires approximately 30 minutes and takes place within the deactivation zone downstream from the injection point of the potassium permanganate. The application and deactivation of a piscicide in a riverine environment requires precise timing based on knowledge of the transport of the chemical through the system. Such knowledge is difficult to obtain when the chemical being used, such as rotenone, is odorless and colorless in water.

This report focuses on the use of Rhodamine WT dye for real-time monitoring and documentation of piscicide treatments in riverine environments. It is important to note that rotenone and Rhodamine WT may behave differently when applied to water. Rotenone is insoluble in water and is generally mixed with emulsifiers and solvents to allow it to disperse in water. In addition, rotenone degrades rapidly through abiotic (photolytic and hydrolytic) and biological mechanisms and can adsorb to silt, sediment, and algae (Finlayson and others, 2010). In contrast, Rhodamine WT has been extensively used as a tracer in water bodies because of its stability in sunlight and generally low adsorption to sediments. Therefore, when using Rhodamine WT to track rotenone, it is important to acknowledge these differences and understand that whereas the presence of Rhodamine WT dye may indicate the presence of treated water, it may not necessarily indicate the presence of rotenone. Tracking and deactivating all treated water regardless of the rotenone concentration at the point of deactivation is a conservative approach that ensures that the applied piscicide is fully neutralized.

This report presents two successful examples of the use of dye tracing during the large-scale rotenone applications in the CSSC in 2009 and Little Calumet River in 2010. Not only did the use of dye allow real-time monitoring of the piscicide plume to support application and deactivation strategies, but the data collected during the monitoring action provided valuable visualization and documentation of the treatment for any future legal, scientific, and planning uses. In addition, the appendix of this report presents the main results from a mock rotenone injection in the CSSC using Rhodamine WT dye carried out in November 2009 prior to the rotenone treatment in December 2009. This mock injection yielded main-channel traveltime information for planners, helped identify leakage points from the canal, and yielded traveltime information for dye passage through these leakage points, thereby allowing deactivation personnel to plan a strategy to minimize collateral damage.

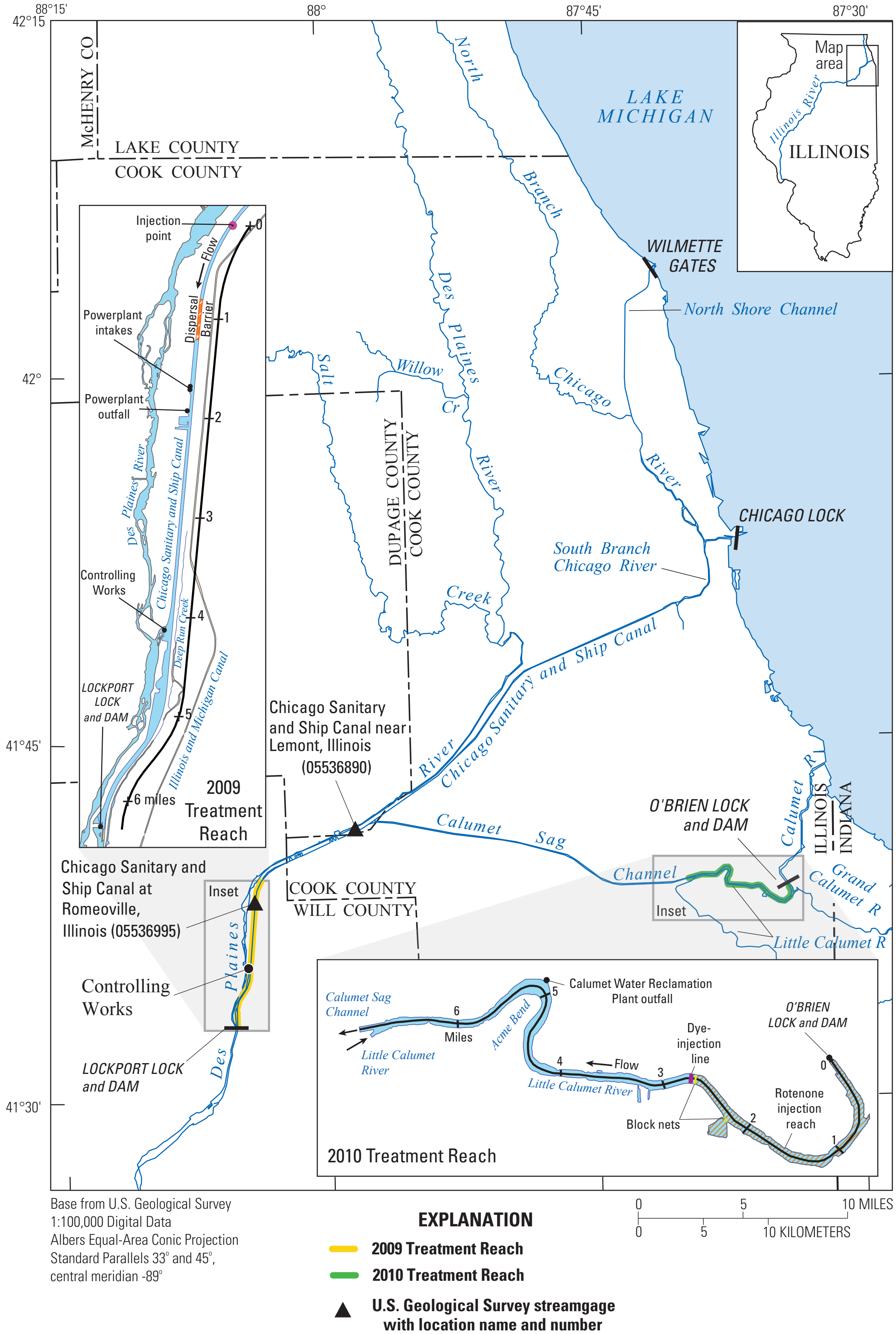


Figure 1. Map of the Chicago Area Waterway System showing the Chicago Sanitary and Ship Canal, Calumet Sag Channel, Little Calumet River, and other waterways in and near Chicago, Illinois. Inset figures show the locations of two large-scale applications of rotenone in 2009 and 2010.

Sites

Large-scale applications of the piscicide rotenone by the multiagency Asian Carp Rapid Response Workgroup in 2009 and 2010 at selected sites in the Chicago Area Waterway System (CAWS) required documentation and real-time monitoring to support application, transport, and deactivation strategies. In 2009, the CSSC between the dispersal barrier and Lockport Lock and Dam was treated during a dispersal-barrier shutdown; in 2010 the Little Calumet River near O'Brien Lock and Dam was treated as a rapid response action. These two sites represent different hydraulic settings with significantly different hydrodynamics; therefore, piscicide application and monitoring differed between the sites. Although these two sites are in an urban environment where river courses are heavily altered from their natural states, the monitoring techniques applied to each site are transferrable to natural rivers.

Chicago Sanitary and Ship Canal, Dispersal Barrier to Lockport Lock and Dam

The 6.2-mi reach starting just upstream from the dispersal barrier and extending to the Lockport Lock and Dam was the site of a large-scale rotenone treatment in December 2009 (fig. 1). In general, the canal is rectangular in cross section with depths of approximately 25 feet (ft) and widths of about 160 ft. However, the channel configuration departs from the rectangular cross section near several slips 1 mi downstream from the dispersal barrier, at the Controlling Works sluice gates 3 mi downstream from the barrier, and in the expansion zone approximately 4 mi downstream from the barrier (fig. 1). Within these sections are side embayments where water velocity is low and depths are shallow in some locations, and widths can reach about 630 ft. At the upstream end of this reach, the canal is excavated into bedrock but transitions to constructed earthen walls with sheet piling, set block, and riprap about 1.5 mi downstream from the dispersal barrier, where the surrounding land elevation drops below canal elevation (Hill, 1896).

The CSSC within this reach is flanked by the Des Plaines River to the west and Illinois and Michigan (I & M) Canal to the east (fig. 1). A local drainage channel called Deep Run Creek parallels the canal between the CSSC and I & M Canal starting about 2 mi downstream from the dispersal barrier and emptying into the CSSC below Lockport Lock and Dam. A distance of as little as 120 ft separates the CSSC from the adjacent waterways, and water-surface elevation differences can be as much as 40 ft between the canal and the surrounding waterways at Lockport Lock and Dam. In addition, the Lockport Controlling Works on the CSSC about 3 mi downstream from the dispersal barrier comprise a series of sluice gates that can spill water directly to the Des Plaines River during floods (fig. 2). At the time of the

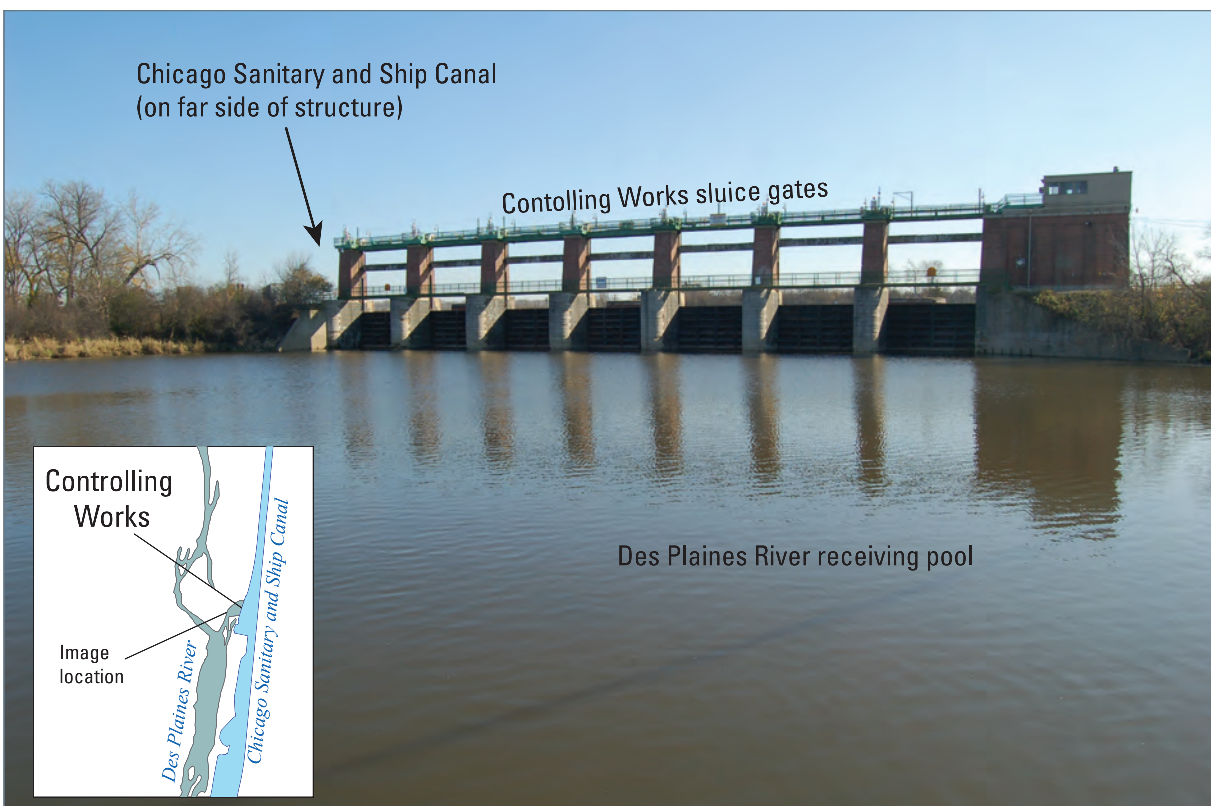


Figure 2. The Des Plaines River side of the Lockport Controlling Works on the Chicago Sanitary and Ship Canal, near Lockport, Illinois (photograph by R. Jackson, U.S. Geological Survey). Inset figure shows image location.

rotenone treatment in 2009, the gates had visible leaks when closed that spilled CSSC water to the Des Plaines River. Additional leaks through the earthen walls of the canal were present within the lower 2 mi upstream from Lockport Lock and Dam and spilled into both the Des Plaines River (fig. 3) and Deep Run Creek (fig. 4).

A coal-fired powerplant operated by Midwest Generation is approximately 1 mi downstream from the dispersal barrier. This powerplant uses CSSC water for cooling purposes during electricity production and withdraws approximately 1,700 to 1,900 cubic feet per second (ft^3/s) at its intakes. The water is discharged about 1,000 ft downstream at a slightly higher temperature (about 5 degrees Celsius) (fig. 1). This withdrawal was active during the rotenone treatment in 2009 and represents withdrawal of about 70 percent of the discharge in the canal during normal operations. This withdrawal creates a low-velocity dead zone within the canal between the intakes and the outfall, and it presented a significant challenge to rotenone application and transport. The canal is highly regulated and was maintained at approximately 2,400 ft^3/s during the duration of the rotenone treatment by the Lockport Powerhouse adjacent to Lockport Lock. The Lockport Lock was closed for the duration of the treatment, and the approximately 300 ft^3/s of known leakage through the lock gates was accounted for when setting the flow rate in the canal. Although the flow was relatively steady during the treatment, perturbations elsewhere on the system due to lockages, withdrawals and discharges, and vessel traffic are capable of causing flow variability within this reach (see Jackson and others, 2012). Only the lower 6.5 mi of canal was closed to vessels, and the remainder of the CAWS was fully operational during the treatment.

Little Calumet River Downstream from O'Brien Lock and Dam

The 6.8-mi reach of the Little Calumet River between O'Brien Lock and Dam and the Calumet Sag Channel (fig.1) was the site of a rapid-response-action rotenone treatment in 2010. Although only approximately 2.6 mi of the Little Calumet River downstream from O'Brien Lock and Dam was treated with rotenone, the larger 6.8-mi reach (fig. 1) was exposed to rotenone-treated water as a result of the treatment. This reach of the Little Calumet River has a relatively natural channel

Figure 3. Photograph of the western embankment of the Chicago Sanitary and Ship Canal (CSSC) near Lockport Powerhouse, with channel formed by leakage from the CSSC and the Des Plaines River in the background (photograph by R. Jackson, U.S. Geological Survey). Inset figures show one of four V-notch weirs installed to measure leakage discharge (photograph by J. Duncker, U.S. Geological Survey) and image location.

Figure 4. Deep Run Creek and the Chicago Sanitary and Ship Canal (CSSC) near Lockport Lock and Dam, with seepage from the CSSC evident from steam pockets in the earthen embankment (photograph by R. Jackson, U.S. Geological Survey). Inset figure shows image location.

geometry compared to the CSSC. The cross section of the river is trapezoidal, with vertical walls only near structures. Maximum depths are at the center of the channel and are generally about 16 ft at typical pool elevations. Several embayments are within the treatment reach, approximately 2.2 and 3.2 mi downstream from O'Brien Lock and Dam. Depth of the largest embayment at 2.2 mi is as great as 13 ft, whereas depths of the two small slips at 3.2 mi are generally less than 6 ft. Except in the vicinity of structures, the banks and bed of the Little Calumet River in this reach are earthen and generally composed of fine sediments and sand. Several marinas line the left bank within the 1-mi reach downstream from O'Brien Lock and Dam.

Historically, the Little Calumet River joined the Grand Calumet River and drained to Lake Michigan, but the opening of the Calumet Sag Channel in 1922 and O'Brien Lock and Dam in 1960 reversed the flow and allowed the Little Calumet, Grand Calumet, and Calumet Rivers to drain to the Calumet Sag Channel and eventually the CSSC. Flow in this reach is generally induced by lockages through O'Brien Lock and Dam or by opening of the sluice gates at the dam to allow Calumet River and Lake Michigan water into the Little Calumet River.

A variable but constant inflow occurs at the outfall of the Calumet Water Reclamation Facility on the outer bank of Acme Bend (fig. 1). The low head across O'Brien Lock and Dam combined with little to no inflow from the Grand Calumet River during dry weather make the outfall from the Calumet Water Reclamation Facility a primary inflow to this reach, with inflows in May 2010 of the same order of magnitude as typical discretionary diversion of Lake Michigan water through O'Brien Dam (300–600 ft^3/s). However, during the rotenone treatment in May 2010, the sluice gates at O'Brien Lock were closed. With no flow through the sluice gates at O'Brien Lock and Dam, the reach between the dam and Acme Bend is generally stagnant but can exhibit flow variability, with periodic bidirectional flows driven, in part, by wind forcing and fluctuations in discharge propagating from the CSSC. During wet weather, the Little Calumet River at the confluence with the Calumet Sag Channel can contribute more than 5,000 ft^3/s, causing backwater effects in the study reach (unless O'Brien Lock and Dam open to backflow to Lake Michigan, which has occurred in extreme floods). Johnson and others (2012) present a thorough history of streamgaging in this reach and describe the complex hydraulics in the area of O'Brien Lock and Dam.

Methods of Tracking Piscicide Applications by Using Rhodamine WT

This section describes the instrumentation, techniques, and equipment required for real-time tracking of piscicide by using Rhodamine WT dye and fluorometry. Although the number of instruments used, their placement, and their configuration differ between the two applications discussed in this report, the general technique and protocol remains consistent between the studies and can be transferred to tracking of other piscicides or passive contaminants in general. This section is broken down into four subsections: (1) a discussion of the rotenone application strategies, (2) a discussion of the Rhodamine WT injection strategies for the two different rotenone treatments, (3) a description of instrumentation and techniques for real-time tracking, and (4) a discussion of the use of fixed instrumentation deployments for documentation purposes.

Rotenone Application Strategies

Rotenone applications were carried out by a multiagency task force led primarily by the Illinois Department of Natural Resources. The details of the application methods are beyond the scope of this report, but the general strategy for each treatment is summarized in this section. Both treatments targeted the maximum allowable rotenone concentration of 250 parts per billion (ppb) and an exposure period of at least 8 hours, in accordance with the recommendations of Chapman and others (2003), to ensure a complete kill of silver and bighead carps.

2009 Chicago Sanitary and Ship Canal Rotenone Application Strategy

The application strategy used in the 2009 rotenone application in the CSSC required a steady discharge in the canal of 2,400 ft^3/s. This discharge was maintained by the control operations at the Lockport Powerhouse and Lockport Lock and Dam. Lockport Lock was closed for the entire duration of the application. To treat the entire 5.3-mi reach of the CSSC from the dispersal barrier to Lockport Lock and Dam, rotenone was injected approximately 1 mi upstream from the dispersal barrier by using a perforated cross-channel pipe suspended at approximately the middle of the water column (fig. 5). Approximately 1,400 gallons (gal) of 5 percent liquid rotenone formulation (Prentox® Prenfish™ Toxicant) was injected continuously over a nearly 9-hour period. The target rotenone concentration in the CSSC was 250 ppb. As the rotenone plume advected downstream, four bank-staged booster injections of rotenone were delivered to the main plume by using underwater perforated pipe in order to increase the concentration. Booster stations were spaced approximately 1 mi apart over the first 4 mi of the treatment reach, and each injected approximately 110 gal of 5 percent liquid rotenone formulation (Prentox® Prenfish™ Toxicant). In addition, side embayments and barge slips (dead zones cutoff from the main flow in the channel) were treated by manual injection of rotenone 5 percent liquid rotenone formulation (Prentox® Prenfish™ Toxicant) from moving boats as the main rotenone plume passed each of the dead zones.

Deactivation of the piscicide was primarily completed just downstream from Lockport Lock and Dam by using potassium permanganate at a target concentration of 9 ppm. Deactivation of the treated slips and dead zones was carried out by manual injection of potassium permanganate from moving boats. Finally, known leakage points were treated by using potassium permanganate drip systems (where the leakage formed channels, fig. 6) or by neutralizing the receiving water body (Deep Run Creek, for example).

2010 Little Calumet River Rotenone Application Strategy

The application strategy used in the 2010 Little Calumet River rotenone application required a zero-net-discharge condition. Unlike the 2009 treatment of the CSSC, the Little Calumet River treatment was carried out much like a treatment in a lake or pond and did not rely on advection of the piscicide. O'Brien Lock and Dam was closed for the duration of the application. A 2.6-mi reach starting downstream from O'Brien Lock and Dam was designated as the treatment reach (fig. 1). Large block nets were deployed across the channel at the downstream end of the treatment reach, in the Grand Calumet River, and across the mouth of the large embayment about 2.2 mi downstream from O'Brien Lock to keep fish from exiting the treatment reach (figs.1 and 7). Numerous boats equipped with motor-mounted Venturi pumps delivered approximately 2,180 gal of 5 percent emulsifiable rotenone (Prentox® Prenfish™ Toxicant) to the treatment reach by using their propeller wash to drive the mixing (fig. 7). The target concentration of rotenone was 250 ppb, as determined by Chapman and others (2003).

Deactivation of the treated water using 40 percent sodium permanganate solution (Carusol C) took place continuously at the downstream side of the block net from the time the injection started through the full treatment duration (4 days) to ensure that any water that exited the treatment reach was fully deactivated (fig. 7). After approximately 4 days, boats equipped with sodium permanganate were deployed in the treatment reach and manually deactivated all the treated water from 1 mi downstream from O'Brien Lock and dam to the block net. Owing to concerns by boat owners at marinas immediately downstream from O'Brien Lock and Dam that the sodium permanganate might stain their boats, the water in a 1-mi reach of the Little Calumet River just downstream from O'Brien Lock and Dam was flushed downstream before deactivation. The sluice gates at the lock were opened to provide a discharge of approximately 3,300 ft^3/s, and the treated water was flushed downstream from the marinas, where it was deactivated.

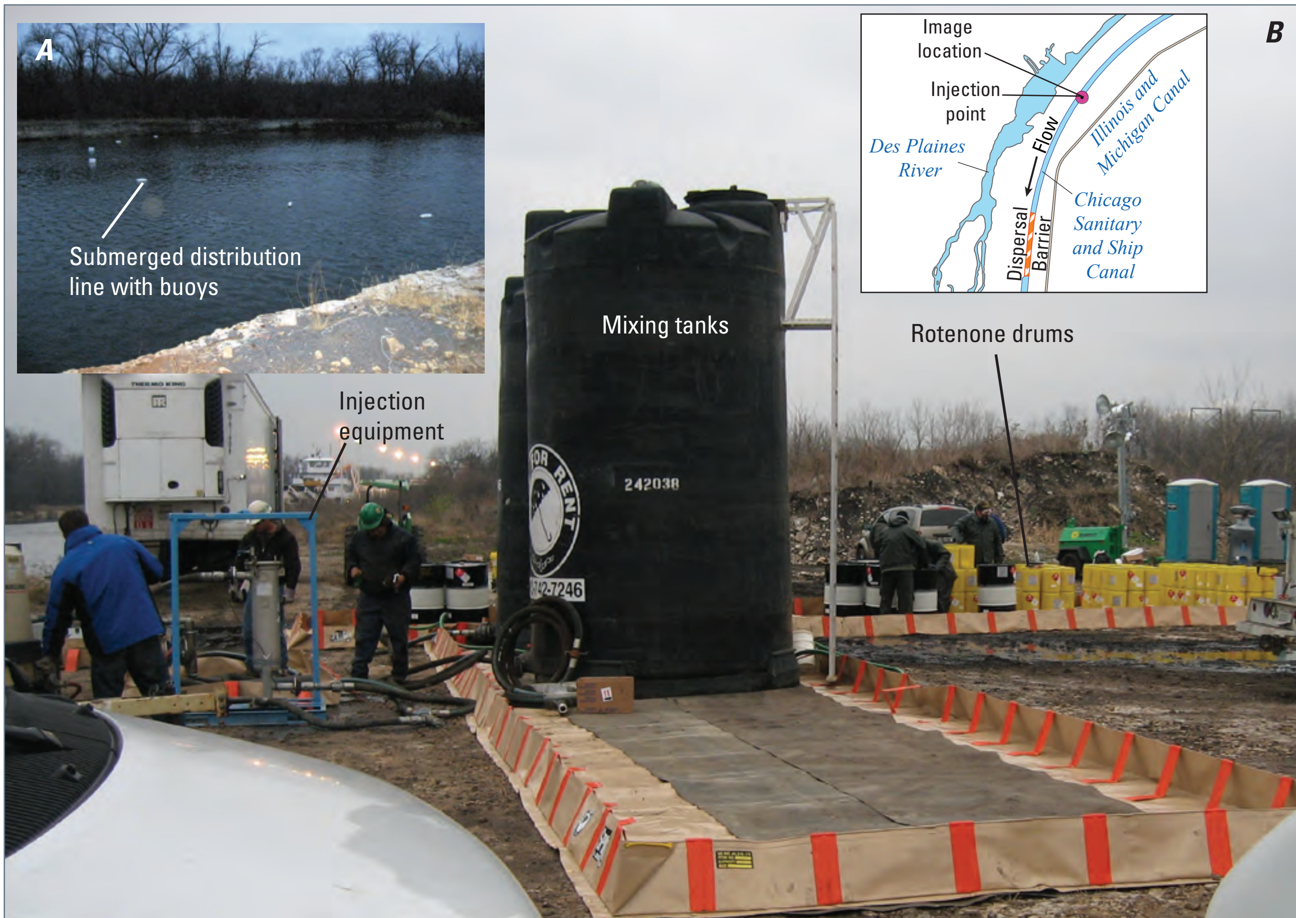
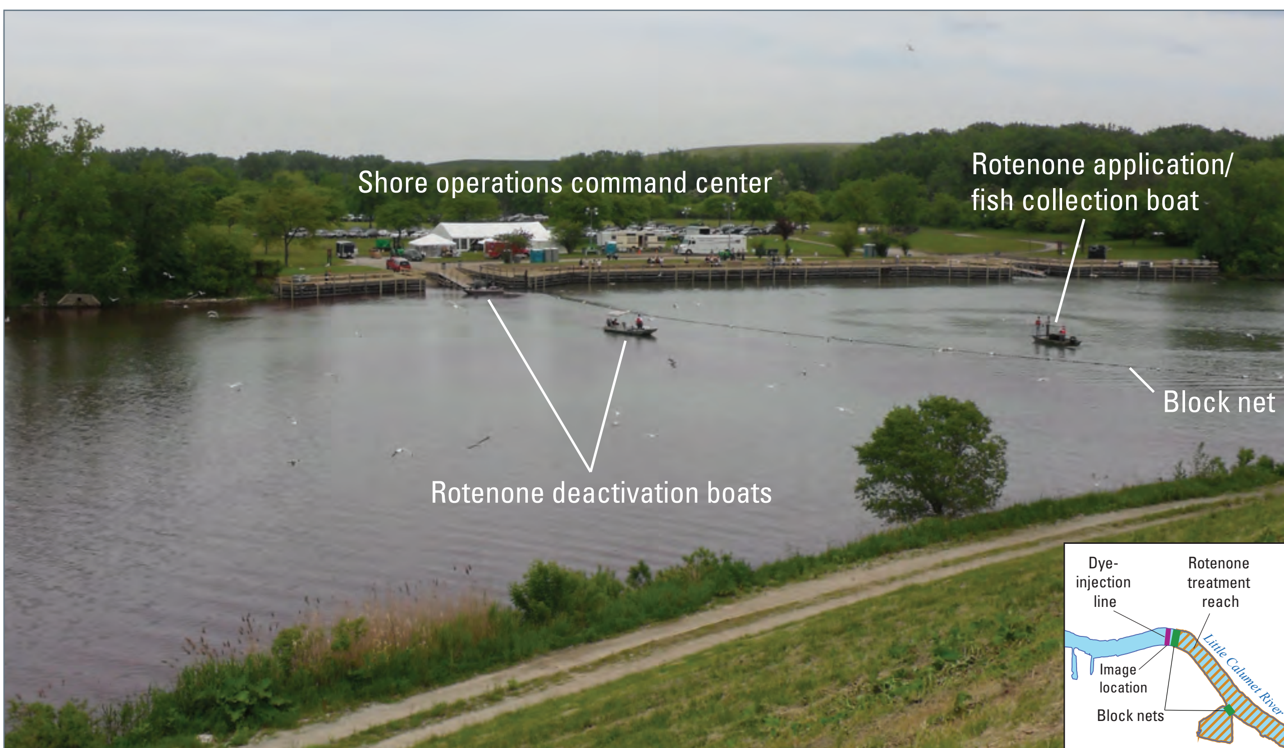


Figure 5. (Above) The primary rotenone injection staging area on the bank of the Chicago Sanitary and Ship Canal near Romeoville, Illinois (photograph by J. Lageman, U.S. Geological Survey). Inset figures show the channel with the submerged cross-channel distribution pipe (photograph by C. Ostheimer, U.S. Geological Survey) and the image location.

Figure 6. (Top right) Potassium permanganate drip system treating leakage from the Chicago Sanitary and Ship Canal to the Des Plaines River near the Controlling Works (photograph by J. Duncker, U.S. Geological Survey). The color of the leakage is due to the addition of potassium permanganate during deactivation. Inset figure shows image location.

Figure 7. (Bottom right) Photograph of the Little Calumet River 2.6 miles downstream from O'Brien Lock and Dam with the cross-channel block net and rotenone application and deactivation boats (photograph by R. Jackson, U.S. Geological Survey). Inset figure shows image location.


Potassium permanganate drip system
Neutralized leakage from the canal
Controlling Works
Image location
Des Plaines River
Chicago Sanitary and Ship Canal


Shore operations command center
Rotenone application/ fish collection boat
Block net
Rotenone deactivation boats
Dye-injection line
Rotenone treatment reach
Image location
Block nets
Little Calumet River

Rhodamine WT Dye Application Strategies

Rhodamine delivery and tracking strategies were adapted to the rotenone application strategies described above. In both cases, the goal of the Rhodamine WT dye application was to fully delineate the rotenone plume by using dye to ensure that the boundaries of the rotenone plume would be detectible in real time through fluorometric measurements of dye concentration. Although driven by the same goal, the strategies employed to the 2009 and 2010 applications are significantly different. Each dye application and tracking strategy is described in this section.

2009 Chicago Sanitary and Ship Canal Rhodamine WT Dye Application Strategy

To ensure that the entire rotenone plume was encased within a detectible dye plume in the CSSC, a continuous injection of dye was delivered to the canal immediately downstream from the primary rotenone injection site (fig. 8). Delivery of dye started 10 minutes prior to the start of the rotenone injection and ran continuously for the entire duration (nearly 9 hours) of the rotenone injection, ceasing 10 minutes after the rotenone injection stopped. Starting the dye injection prior to the rotenone injection and extending the injection after the rotenone injection had ceased created a buffer zone around the rotenone plume and ensured that the presence of rotenone-treated water correlated with the detection of dye.

A 20 percent concentration solution of Rhodamine WT was delivered to the canal at a flow rate of 177.3 milliliters (mL) per minute by using a fluid metering pump assembly (FMI Model PM6013, PN: 911-30-0500-9) with redundant, calibrated pumps (fig. 8*B*) just downstream of the rotenone injection point (fig. 8*C*). The pumps were calibrated by using a stopwatch and graduated cylinder. Adjustments between calibration trials were made until the desired flow rate for each pump was achieved. The pumps were plumbed in parallel so that in the event of a pump malfunction during the injection, the second pump could continue with the same pumping rate. The dye was delivered from the left bank of the canal by using PVC conduit to support the 3/8-inch (in.) acrylic injection tubing extending the injection point away from the bank (approximately 15 ft) (fig. 8*A*).

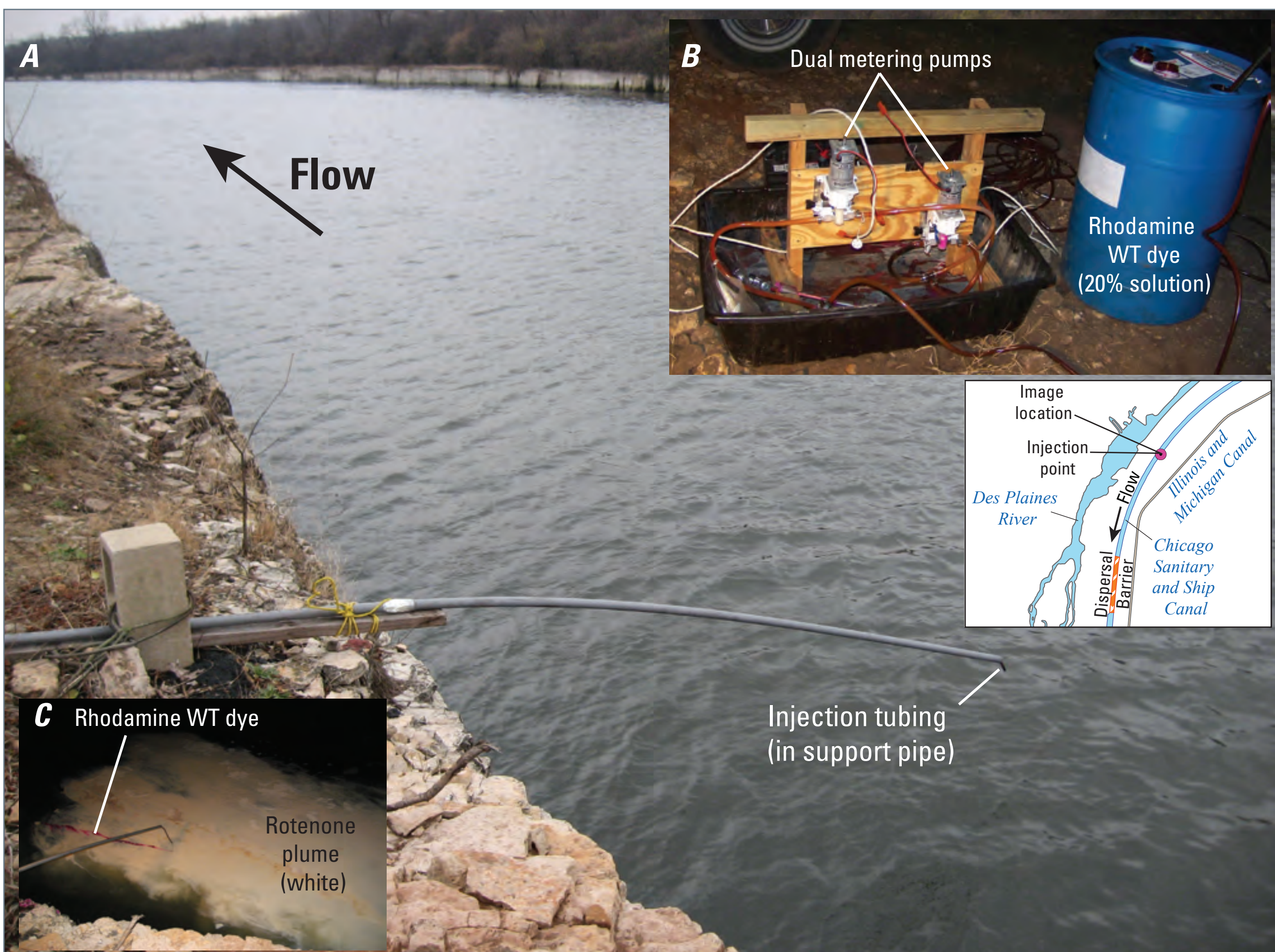


Figure 8. The Rhodamine WT injection system installed on left bank of the Chicago Sanitary and Ship Canal near Romeoville, Illinois: *A*, View looking downstream prior to injection. *B*, Injection pump system. *C*, View of the rotenone plume with streak of dye during the injection (prior to mixing) (photographs by J. Lageman, U.S. Geological Survey). Inset figure shows image location.

The dye injection point was approximately 100 ft downstream from the rotenone injection site (41.657160 degrees north latitude, 88.053611 degrees west longitude). The dye injection started at 19:51 on December 2, 2009, and ceased at 04:47 on December 3, 2009 (duration of 8.933 hours). A total of approximately 25.09 gal (95.03 liters (L)) of Rhodamine WT dye was injected. The volume of dye and injection rate was determined from the target discharge in the canal and a peak concentration at downstream sites of 10 ppb (in accordance with Kilpatrick and Wilson, 1989).

2010 Little Calumet River Rhodamine WT Application Strategy

A zero-net-discharge condition in the Little Calumet River due to closure of the O'Brien Lock and Dam and negligible flow from the Grand Calumet River allowed for a different dye application strategy. Instead of mixing dye with rotenone throughout the entire treatment reach, a stripe of Rhodamine WT dye was injected approximately 400 ft downstream from the treatment reach and block net (41.649664 degrees north latitude, 87.592853 degrees west longitude) (fig. 1). The upstream side of the treatment reach was blocked by O'Brien Dam, so no dye was required (initially) at the upstream end. Any rotenone leaving the treatment reach due to a downstream discharge would be preceded by the dye, so the dye delineated the boundary between treated water and untreated water (fig. 9).

The dye was injected by using a simple gravity-feed injection system comprising a 60-L carboy filled with approximately 3.2 gal (12 L) of Rhodamine WT dye in a 20 percent solution and a weighted hose suspended about 5 ft below the water surface perched on the bow of a 19-ft survey vessel (fig. 10). The dye was diluted with approximately 10.5 gal (40 L) of river water prior to injection. The injection of the dye began at 12:39 on May 20, 2010, and ended at 13:45 on May 20, 2010. The injection vessel completed bank-to-bank transects at a 470-ft-wide cross section approximately 400 ft downstream from the block nets during the injection period.

A second dye injection was performed 13:40 on May 24, 2010, at the sluice gates of O'Brien Lock and Dam to mark the upstream edge of the rotenone-treated water as the upper 1 mi of the treated reach was flushed downstream for deactivation. Approximately 0.6 gal (2.3 L) of Rhodamine WT dye in 20 percent solution was added as a slug injection to the inflow from the sluice gates as they opened (fig. 11). The dye quickly mixed with the turbulence of the inflow and delineated the upstream end of the treated water. The volume of dye injected was computed by requiring a peak concentration at 1 mi downstream from O'Brien Lock and Dam of 2.5 ppb at a projected discharge of 4,000 ft^3/s (see Kilpatrick and Wilson, 1989). The injection consisted of simply pouring the small volume of dye by hand into the sluice gate inflow from the catwalk above the gates.

Figure 9. The Little Calumet River just downstream from the block net with a visible dye streak, mass of untreated and undyed water, and mass of treated and deactivated water (photograph by R. Jackson, U.S. Geological Survey). Inset figure shows image location.

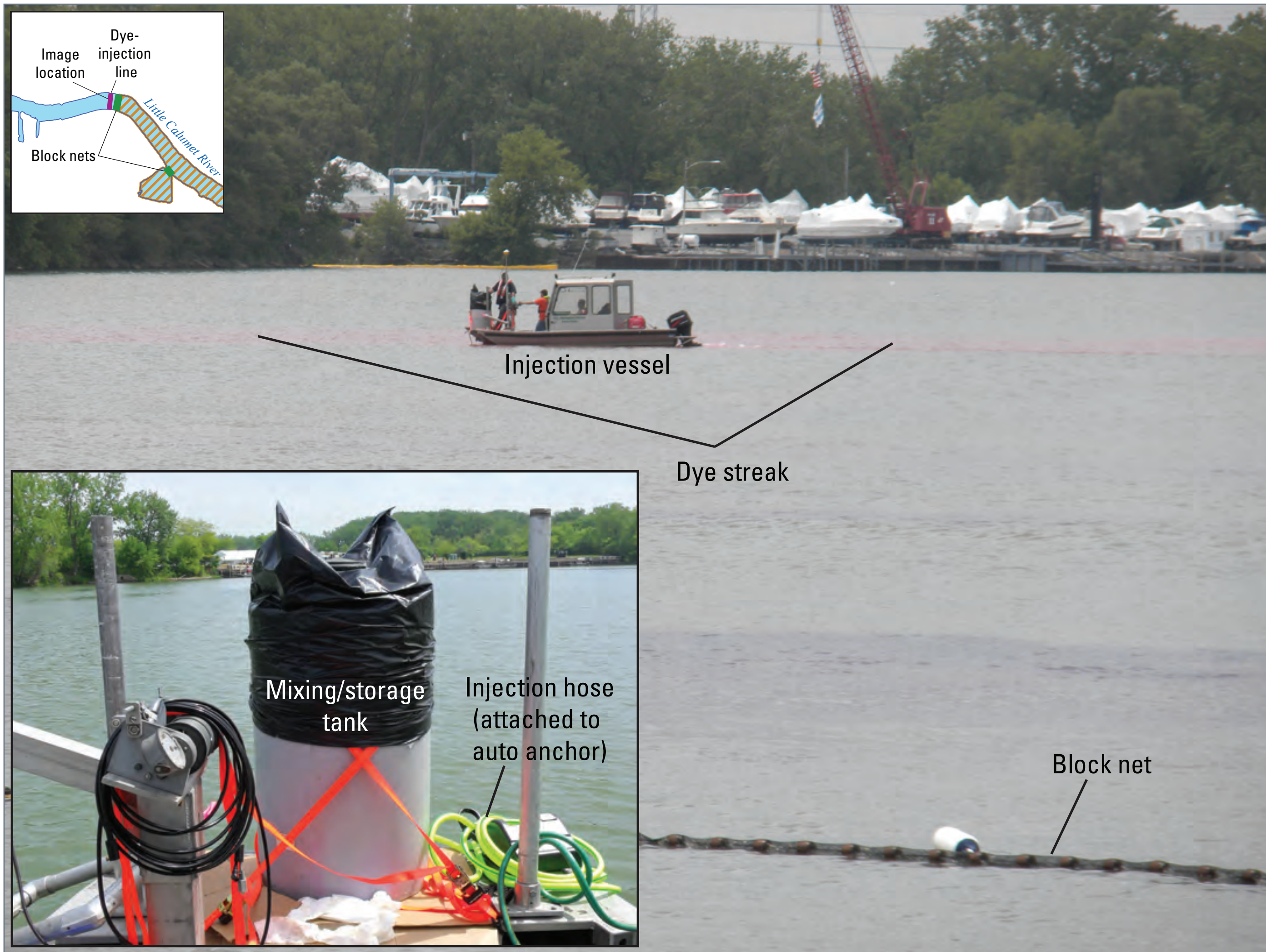


Figure 10. The Rhodamine WT injection system used on the Little Calumet River in May 2009 (photograph by D. Yeskis, U.S. Geological Survey; inset photograph by R. Jackson, U.S. Geological Survey). Inset figure shows image location.

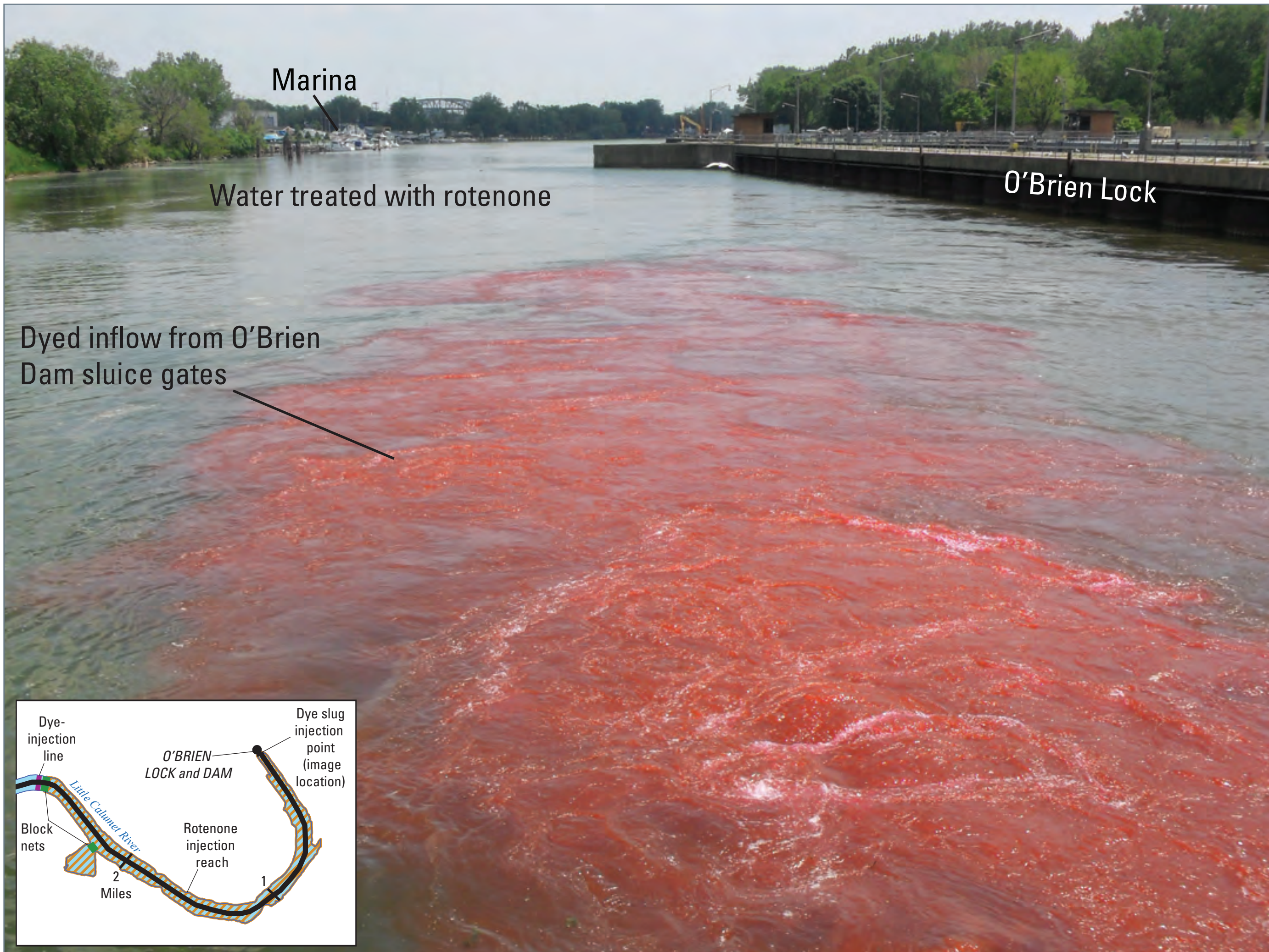


Figure 11. The Rhodamine WT injection slug mixing in the sluice-gate inflow to the Little Calumet River downstream from O'Brien Dam on May 24, 2010 (photograph by R. Jackson, U.S. Geological Survey). Inset figure shows image location.

Real-Time Tracking

Real-time tracking of piscicide by using Rhodamine WT dye and fluorometry 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 relay these positions to application and deactivation personnel. Misidentification of the plume or the inability to accurately delineate the plume boundary because of high background fluorescence, low dye concentrations, or noisy fluorometry data will significantly affect the success of this method and may result in unintended collateral damage to downstream fisheries. The systems and instruments used in real-time tracking should be tested prior to use and backup instruments and grab samples should be available throughout the application in case the real-time fluorometry fails.

Survey Techniques

In both surveys in 2009 and 2010, two survey vessels were equipped with submersible flouorometers, differential global positioning system (GPS) receivers, and acoustic Doppler current profilers (ADCP) to enable real-time dye and piscicide tracking (fig. 12). The purpose of using two vessels is 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 remains at fixed positions to monitor for the arrival of the leading or trailing edges of the dye plume. The fixed positions are important points in the water body in which booster rotenone injections must be made (to increase the plume concentration) or deactivation operations are staged (known leakage points and the end of the treatment reach). Once the fixed position boat detects the edge of the dye plume, it is repositioned to the next downstream fixed position. The fixed-position boat is also responsible for making discharge measurements at each fixed position to monitor any variation in the flow. Discharge information and dye-plume detections were relayed via radio to onshore operations personnel, along with estimated time of arrival of the piscicide at the next station downstream (computed by using the mean velocity from the ADCP discharge measurement).

The rover vessel was responsible for mapping the dye/piscicide plume over the full extent of the survey reach. Two primary survey techniques were used. To capture the full extent of the plume including the cross-stream variability in concentration, serpentine surveys were conducted and consisted of bank-to-bank “zig-zags” as the vessel transited the length of the treatment reach. Typically, serpentine surveys will also include surveying of side embayments and slips if time permits. The second survey technique employed was streamwise or longitudinal transects of the dye plume, with the survey vessel following the approximate centerline of the channel. The longitudinal

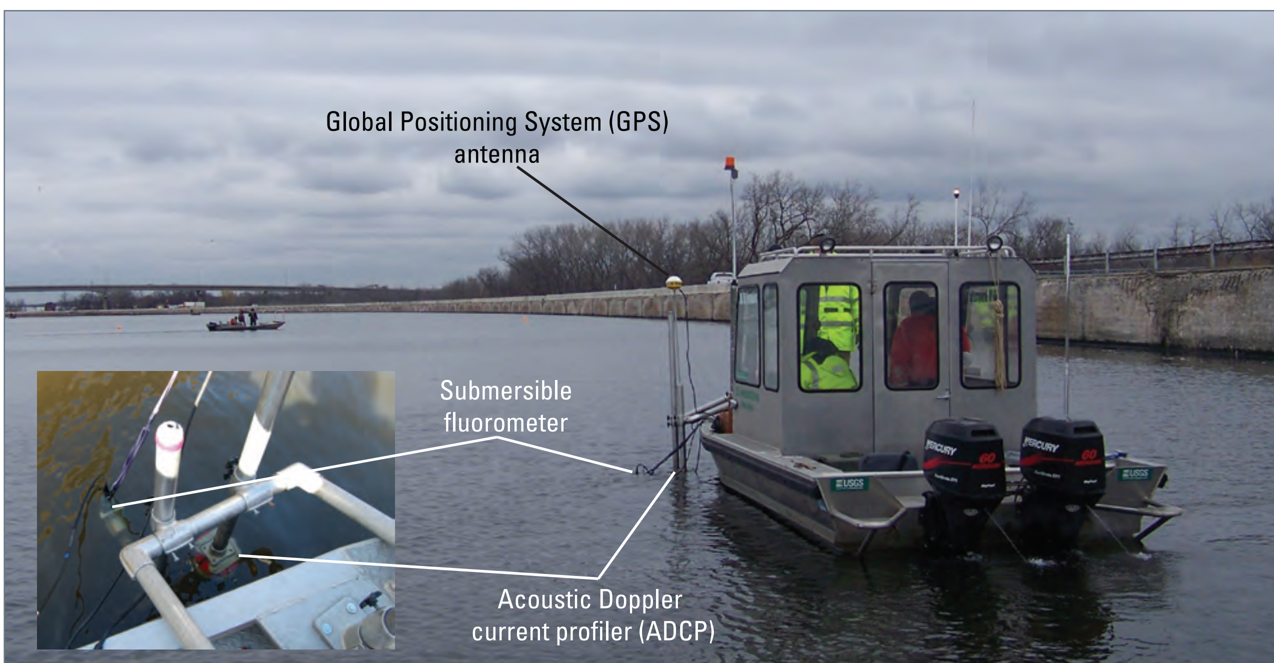


Figure 12. One of the two real-time piscicide/dye tracking vessels used in the 2009 and 2010 rotenone treatments (photograph by J. Duncker, U.S. Geological Survey). The vessel is in the Chicago Sanitary and Ship Canal, with fish collection boats in the background.

survey method is more efficient and allows the survey vessel to complete each reach survey in less time, but it does not measure the cross-stream variability of dye concentration. In both the 2009 and 2010 surveys, as the dye plume grew in time, it became necessary to transition from primarily serpentine surveys to primarily longitudinal surveys to keep up with the expanding dye plume. The rover boat maintained constant communication with the fixed-position boat and shore-operations personnel to provide information on the location of the leading and trailing edges of the dye plume. In the 2010 Little Calumet River survey, both vessels acted as rovers and mapped the dye plume (splitting the survey reach) since the rotenone treatment was performed during a "no–net-discharge" condition and no fixed-position boat was used (though both vessels made periodic discharge measurements inside and outside of the treatment reach).

In addition to real-time fluorometry, discrete grab samples were periodically collected from surface-water bodies in the study reach (and adjacent groundwater wells in the CSSC; see appendix 1, table 1–2) throughout the duration of the treatment to provide redundancy in the case of instrument failure and for monitoring for any trace of dye in adjacent wells (only for the CSSC). Samples were stored in opaque brown 125-mL HDPE plastic bottles and analyzed by using a temperature-compensated Turner 10-AU benchtop fluorometer.

Positional Data

Georeferenced data is essential for real-time tracking and documentation. Positional data were acquired by using a Trimble AG132 differential GPS receiver with submeter accuracy (fig. 12). Submeter accuracy was achieved by using the Wide Area Augmentation System (WAAS) signal for differential correction. This service requires no subscription fee and is available in nearly all of North America. Submeter accuracy is recommended for nearly all studies, though it may be necessary to use real-time kinematic (RTK) GPS receivers for vary narrow streams when positional accuracy is essential (centimeter accuracy). Positional data were displayed and logged in the navigation software HYPACK® (version 2009) running on a ruggedized laptop personal computer. Important navigational features such as locations of the injection point, booster-station location, known leakage points, and deactivation points were preloaded into the navigational software for reference while tracking. The GPS antenna was placed atop the mast directly above the fluorometer and high enough off the water surface to avoid multipath errors caused by the boat cabin (fig. 12). Data were streamed from the GPS receiver to the computer via an RS232 connection. The GPS was programmed to sample once per second. The GPS signal was spilt and merged with the ADCP data-collection software for georeferencing of the velocity data as well.

Fluorometry

Submersible fluorometers from several manufacturers were used in the 2009 and 2010 studies discussed in the report. In the 2009 survey, a manned boat was equipped with a bow-mounted YSI 6920 multiparameter sonde with a 6130 submersible fluorometer (and sensors for measuring specific conductance, temperature, turbidity, and pH) (fig. 12). The sonde was powered with internal batteries and logged to a personal computer by using YSI EcoWatch® software in real-time data display mode. Data were streamed from the sonde to the computer via an RS232 connection. The sonde clock and computer clock were synchronized to allow georeferencing of the data by assigning position based on time stamps. A second boat was equipped with a Turner Designs C3 submersible fluorometer and differential GPS receiver. The boat-mounted C3 unit was powered with AC power provided by a small generator. Data were logged within the Turner C-Soft® software package (version 2.1.0) operated in real-time display with logging capability and interfaced with a personal computer via an RS-232 connection. The C3 fluorometers were running firmware version 2.20 and were programmed to sample once every second.

Instrument calibration methods and settings were the same between both the 2009 and 2010 applications. Calibration of the submersible fluorometers first required the preparation of a standard. Prior to preparation of the standards and injection of dye, 5-gal grab samples were collected from each predetermined fluorometer deployment site. The standards for each trial were prepared volumetrically, starting with a 100-ppb concentration of Rhodamine WT dye in deionized water. The final 1-ppb standards for each fluorometer were created by making the final dilution with water collected from each deployment site. However, a 10-ppb standard was prepared as a byproduct of producing the 1-ppb standard and would later be used for calibration verification and calibration maintenance for the Model 10 fluorometer. 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 fluoroescence. The submersible fluorometer calibration process requires a large amount of standard to be prepared (approximately 2 L minimum), owing to the size of the sensors and to the need for enough space around the units to reduce the influence of external factors from outside the calibration container. Calibration of the instruments requires the use of a container that is large enough to allow adequate and even space all around the sensor, that has sufficient depth to submerge the sensor optics, that does not fluoresce, and that preferably has a dark bottom. For these trials, modified translucent containers were used, and a piece of black asphalt mat was placed beneath the containers to ensure a dark-colored bottom. Further, a ringstand was used for supporting the sensors in the calibration containers to maintain a steady position during the calibration process.

The volumetrically prepared standards were used to establish the 1-ppb calibration for the Turner Designs Model 10 benchtop fluorometer. Prepared standards of 10 ppb and 100 ppb were checked on the Model 10 to verify that the calibration was correct for higher concentrations. All field fluorometers were calibrated with the same prepared standard for each study. The calibration process required the use of the collected deployment-site water as a blank (0.0 ppb). The instruments use the slope between the blank and the standard to establish a linear relation between fluorescence and dye concentration. To reduce the probability of false readings and poor calibration, the instrument wipers were set to wipe three times prior to calibration to ensure that no bubbles were attached to the surface of the optics during calibration. The optics were blotted dry with laboratory tissues between submergences in the blank and standard to reduce the chances of cross contamination and dilution of the standard. After calibration of each instrument, the fluorometers were left in the 1-ppb standard for a few seconds, rinsed and dried, and then submerged into the 10-ppb standard to ensure that they were reading the correct concentrations before the recording schedule and interval were set. When the fluorometers were determined to be reading properly, they were removed from the standard, rinsed with deionized water, and blotted dry to prepare them for deployment. The prepared standards were retained in 1-L amber glass bottles and were later used in maintaining calibration of the Turner Designs Model 10 fluorometer while analyzing the grab samples that were collected during the CSSC treatment. The standards and site-collected blanks were also kept for reference in the event that any of the discrete grab samples needed to be reviewed or if a fluorometer needed to be recalibrated for some reason.

The 2010 survey used two boats; but, unlike the 2009 survey, both boats were equipped with Turner Designs C3 fluorometers. During the 2009 survey in which a YSI 6120 fluorometer was used on the rover boat, it was determined that the noise level in the Turner C3 was much lower than the YSI 6130, providing greater confidence in the delineation of the plume. Therefore, in 2010, both boats were equipped with Turner C3 fluorometers and ran the C-Soft software for data display and logging. The addition of a turbidity sensor to the C3 fluorometer provided added confidence in the field that increases in turbidity were not mistaken for fluorescence due to the presence of dye. Turbidity can change the background fluorescence and lead to false detections of dye presence in these sensitive instruments.

Discharge Measurements and Velocity Mapping

Each survey vessel equipped with a mobile fluorometer was also equipped with a Teledyne RDI Rio Grande ADCP. The ADCP was bow mounted on a 2-in. aluminum pipe and placed close to the fluorometer and below the GPS antennae (fig. 12). This arrangement allowed the ADCP and fluorometer to share the same GPS antenna while minimizing offset errors in position. Velocity data from the ADCP were collected by using the manufacturer's WinRiver II software on the same laptop computer used for the GPS and fluorometer. The ADCP communicated with the computer via an RS232 connection. For the 2009 surveys in the CSSC, the boats were equipped with 600–kilohertz (kHz) ADCPs; for the 2010 survey in the Little Calumet River, the boats were equipped with 1,200-kHz ADCPs. 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 treatment reach.

Fixed Instrumentation

To document the traveltime of the dye plume throughout each study reach, a set of submersible fluorometers was deployed at fixed locations spanning the full length of the study reach. Turner Designs C3 submersible fluorometers with battery packs and shade covers were used at each deployment location (fig. 13). Prior to deployment, all fluorometers were calibrated as described earlier in this document. The fluorometers were suspended from nylon lines near middle depth in the water column and in protected locations where necessary. The sampling interval for all fluorometers was set at 3 minutes. Prior to each reading, the fluorometer was programed to run the wiper, cleaning the optical sensors. All fixed fluorometers were equipped with turbidity and temperature sensors. Fluorometers were recovered after the expected passage of the dye based upon estimated time for the entire plume to pass (including the trailing edge).

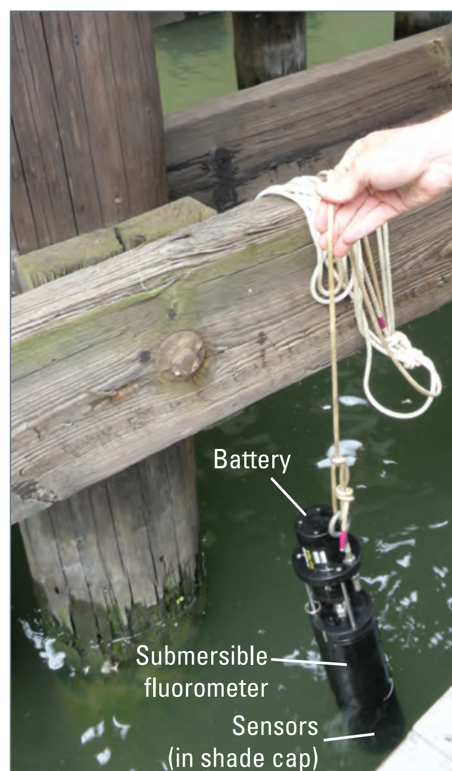


Figure 13. Photograph of a typical setup for deployment of a fixed-position submersible fluorometer (photograph by R. Jackson, U.S. Geological Survey).

In 2009 in the CSSC, six submersible fluorometers were deployed in the canal at fixed locations for documentation of the dye-plume passage at a stationary reference point (see fig. 16 and table 2 in the next section). The spacing of the fluorometers was approximately every mile, starting 1.4 mi downstream from the injection site. A malfunction caused by the firmware in the fluorometer FL296 located 1.4 mi downstream from the injection site caused it to start logging data about 9 hours after the start of the injection, resulting in a loss of data on the rising limb of the concentration curve.

In 2010 in the Little Calumet River, one submersible fluorometer was deployed in the river and two were deployed in the Calumet Sag Channel. Fluorometers were placed at 4.20, 8.16, and 15.64 mi downstream from O'Brien Lock and Dam. Fewer fluorometers were deployed because of the zero-net-discharge application strategy for the rotenone. Little downstream advection was expected until the river was flushed, so the main purpose of the fixed fluorometers was to document the travel-time of the dye during the flush.

Documentation of Two Rotenone Applications Using Rhodamine WT Dye

Data collected during the real-time piscicide tracking using Rhodamine WT dye allowed for detailed documentation of the transport of rotenone within each of the study reaches. This section is dedicated to presenting the data for the case studies on the Chicago Sanitary and Ship Canal and the Little Calumet River in Illinois. Data from each case study are separated into visualizations and discussion of the velocity distribution, followed by presentation and discussion of the transport of dye and piscicide within each study reach.

Chicago Sanitary and Ship Canal

Two survey boats equipped with fluorometers and ADCPs tracked the injection of rotenone in the CSSC between December 2 and December 4, 2009. Approximately 36 hours of real-time continuous tracking covered more than 200 mi of survey lines and yielded approximately 211,000 georeferenced measurements of dye concentration, more than 700,000 velocity profiles, 2.8 million bathymetric soundings, and 50 discharge measurements. In addition, fixed instrumentation yielded more than 4,600 samples of dye concentration from 6 locations within the canal. Many of these data were used in real time to support rotenone application, transport, and deactivation strategies conducted by a multiagency rapid response group. It is important to note that data presented in the following sections were generally available in real time in their most basic format (dye concentration and velocity maps were not available until post processing was complete). Field personnel interpreted the incoming data and relayed the information to shore personnel conducting the rotenone treatment. These data have been compiled, processed, and analyzed to document and visualize the 2009 rotenone treatment in the CSSC.

Discharge

Discharge in the CSSC during the rotenone treatment in December 2009 was generally steady and closely matched the target 2,400 ft^3/s discharge prescribed by the rapid response workgroup. Based on 130 individual transects of the canal collected over 17.5 hours from the start of the dye injection to the time the leading edge reached Lockport Lock and Dam, the mean discharge was 2,370 ft^3/s and the standard deviation was 128 ft^3/s. These measurements were made by the fixed-position boat at various cross sections throughout the survey reach. Discharge data display a slightly upward trend in time (slope = 1.115), resulting in an increase in mean discharge of about 145 ft^3/s over the 17.5-hour period. Discharge was controlled primarily by the Lockport Powerhouse by regulating the amount of water passing through the powerhouse turbines. Leakage through the closed lock gates of approximately 300 ft^3/s was accounted for by powerhouse personnel. Variations in the discharge during the treatment may be due, in part, to disturbances originating elsewhere on the system (for example, lockages at O'Brien Lock and Dam or Chicago Lock) and propagating down the canal to Lockport, causing variations in stage (Jackson and others, 2012).

In addition, the significant disturbance to the flow in the canal caused by the Midwest Generation powerplant (Will County Generating Station) just downstream from the dispersal barrier (fig. 1) may affect discharge in the canal in the study reach. The coal-fired powerplant was continually withdrawing approximately 1,900 ft^3/s from the canal at the intakes approximately 1.8 mi downstream from the injection point (fig. 1) and returning the water to the canal approximately 1,000 ft downstream. This withdrawal amounts to about 81 percent of the discharge in the canal.

Velocity Distributions

More than 700,000 georeferenced velocity profiles collected by two survey vessels over the duration of the rotenone treatment reveal relatively uniform velocity distributions in the main channel of the canal (fig. 14). However, low-velocity stagnation zones in the main channel formed between the powerplant intakes and outfall and near the entrance to the closed Lockport Lock. Dead zones in side embayments at channel expansions and in barge slips exhibited near-zero velocity (fig. 14). These velocity data were depth-averaged and then averaged in time over 30-second intervals by using the Velocity Mapping Toolbox (Parsons and others, 2013) prior to surface generation through ordinary kriging. General circulation patterns identified in figure 14 were visualized by viewing the data as vectors (not shown).

The 81-percent withdrawal of water from the canal at the Midwest Generation powerplant downstream from the dispersal barrier creates a stagnation zone between the intakes and the outfall of the powerplant (fig. 14, inset 1). Within this zone, the relatively uniform main-channel velocity of approximately 0.5 foot per second (ft/s) is disrupted and rapidly drops to

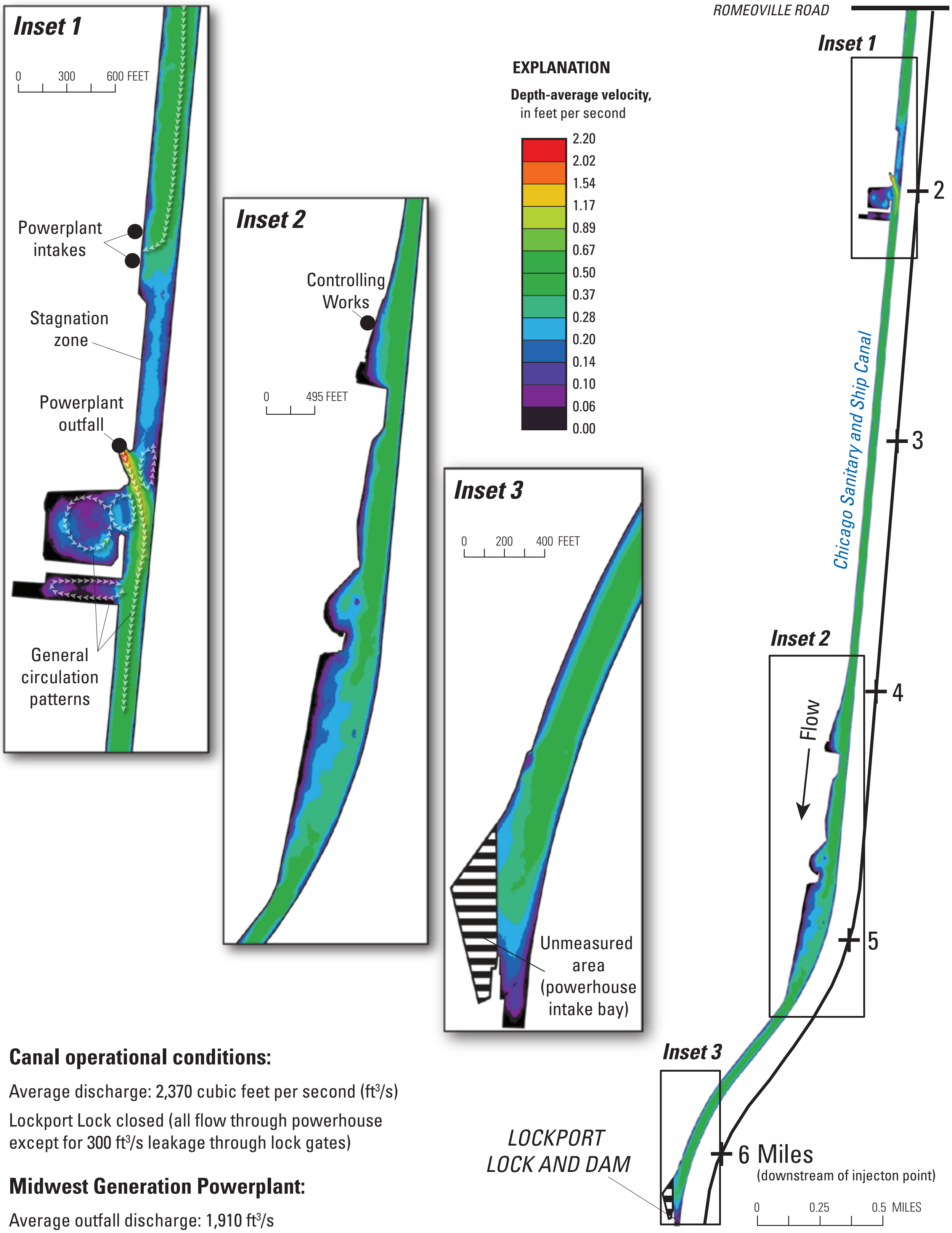


Figure 14. Depth-averaged velocity measured in the Chicago Sanitary and Ship Canal, near Romeoville, Illinois, December 2–4, 2009, during the rotenone treatment. General circulation patterns shown in inset 1 are summarized from these data, visualized as velocity vectors (not shown because of the high number of data points).

0.2 ft/s or less. Downstream at the outfall, the velocity ranges up to 1.5 ft/s in the main channel in the local vicinity of the outfall and return to a uniform 0.5 ft/s by about 700 ft downstream from the outfall (fig. 14, inset 1). The jet-like discharge of water from the outfall at an angle of approximately 27 degrees to the main canal creates a cross-channel current that forms recirculation zones on either side of the discharge jet. The recirculation at the downstream end of the stagnation zone (fig. 14, inset 1) was visually apparent in the field through trapped debris (fig. 15). This stagnation zone between the powerplant intakes and outfall and the recirculation zone within it were a trap for rotenone and dye, as described in the next section, "Transport of Dye and Piscicide."

Dead zones with near-zero net velocity were located within the two slips downstream from the powerplant (fig. 14, inset 1), in the Lockport Controlling Works embayment, and in the west end of the channel expansion approximately 1 mi downstream from the Controlling Works (fig.14, inset 2). These dead zones have limited exchange of water with the main canal and present challenges for uniform application of rotenone. Any contaminant transported down the canal will slowly mix into these zones through the action of secondary currents and turbulence and, once trapped in these zones, will remain there long after the passage of the contaminant in the main channel. For this reason, these dead zones were targeted for manual applications of rotenone from moving boats as the main rotenone plume passed each site. In addition, each dead zone was deactivated manually after passage of the rotenone plume.

Transport of Dye and Piscicide

Data collected during 23 surveys through the dye/rotenone plume over the course of nearly 30 hours of real-time tracking (table 1) reveal the evolution of the dye/rotenone plume as it is transported downstream and eventually passes through Lockport Powerhouse (fig. 16). As the plume enters the survey reach just downstream from the dispersal barrier, it is quickly collected by the intakes of the Midwest Generation powerplant and emerges from the plant outfall 1,000 ft downstream within minutes (fig. 16, survey 9). Initially, untreated water is trapped between the powerplant intakes and outfall (fig. 16, surveys 9–11), but dye/rotenone is mixed into the main-channel stagnation zone from both upstream and downstream and achieves full concentration by survey 15 (approximately 4 hours after the full-concentration plume first reached the stagnation zone (table 1)). In a similar manner, dye/rotenone is slowly mixed into the dead

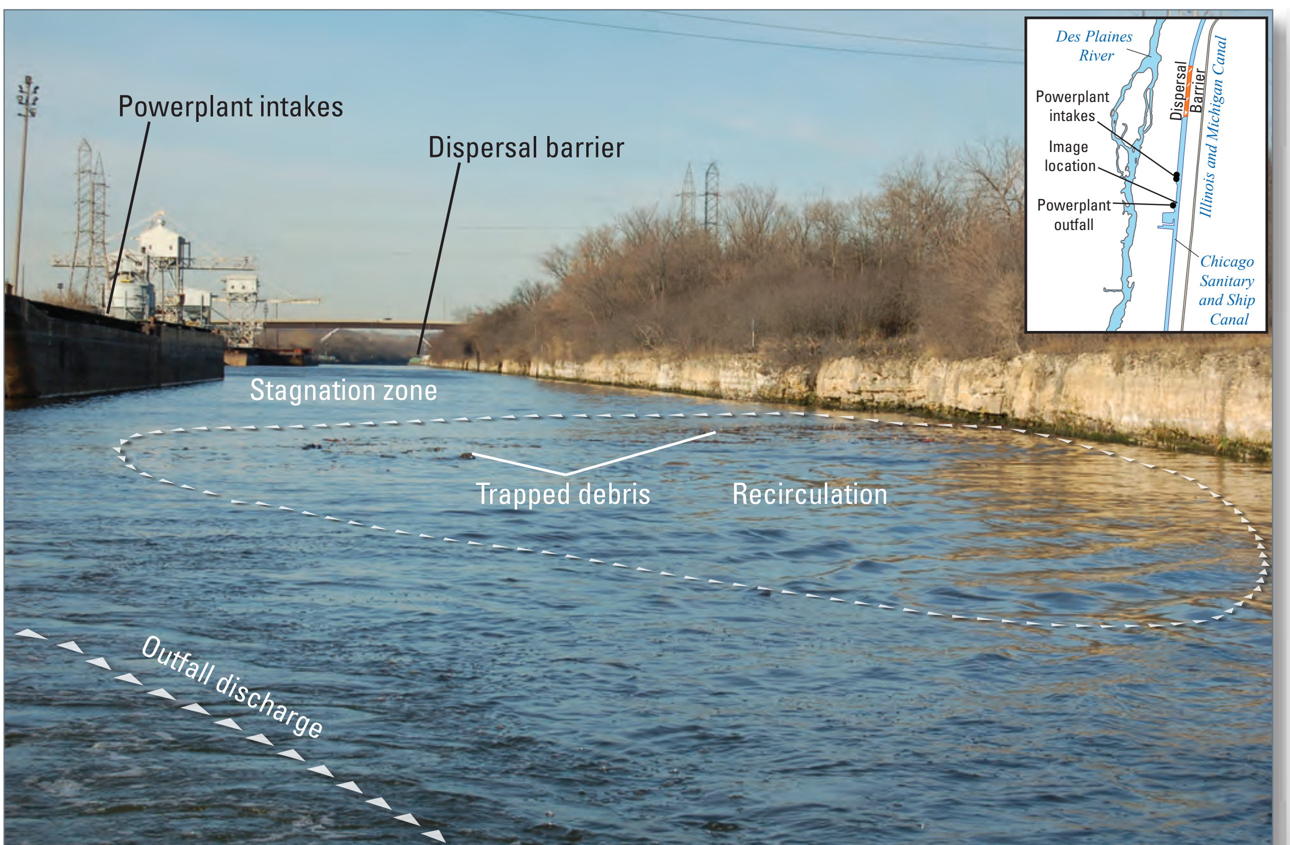


Figure 15. Photograph of a recirculation zone with trapped debris just upstream from the outfall of the Midwest Generation outfall in the Chicago Sanitary and Ship Canal, near Romeoville, Illinois (photograph by R. Jackson, U.S. Geological Survey). Inset figure shows image location.

Table 1. Summary table of streamwise surveys of the Chicago Sanitary and Ship Canal near Romeoville, Illinois, during the rotenone treatment, December 2–4, 2009.

[Dye injection start December 2, 2009, at 19:51; dye injection end December 3, 2009, at 04:47]

Survey number	Direction	Start time, in hours since start of injection	End time, in hours since start of injection	Mean time, in hours since start of injection
6	Upstream	2.87	3.60	3.23
7	Downstream	3.65	4.13	3.89
8	Upstream	4.28	4.97	4.63
9	Downstream	5.07	5.38	5.23
10	Upstream	5.60	6.25	5.93
11	Downstream	6.45	6.87	6.66
12	Upstream	6.98	8.07	7.53
13	Downstream	8.12	8.78	8.45
14	Upstream	9.28	10.00	9.64
15	Downstream	10.00	10.57	10.28
16	Upstream	10.87	11.93	11.40
18	Downstream	13.27	14.05	13.66
19	Upstream	14.10	15.93	15.02
21	Downstream	16.03	16.97	16.50
22	Upstream	17.37	18.45	17.91
23	Downstream	18.47	19.40	18.93
24	Upstream	19.42	20.58	20.00
25	Downstream	20.65	21.45	21.05
28	Upstream	22.80	23.97	23.38
29	Downstream	24.33	25.62	24.98
30	Upstream	25.65	26.65	26.15
31	Downstream	26.68	27.88	27.28
33	Upstream	28.12	28.47	28.29

zones within the slips 2 mi downstream from the injection point. Although not every survey of the plume covered the slips, surveys that did enter the slips (surveys 8,10,12,14,16, 24, and 29) revealed that the dye concentrations in the slips never achieved full strength (approximately 10 ppb). This finding validates the need to apply rotenone to each of these two slips manually to achieve uniform rotenone concentrations throughout the treatment reach. The dead zones associated with the Controlling Works embayment and the channel expansion near mile 5 show better exchange of dye and rotenone with the main channel compared to the slips (fig. 16, surveys 19, 22–24, and 29), though fewer surveys included these areas because of interference with manual application efforts, fish-collection efforts, access issues due to shallow depths, and limited time.

The trailing edge of the dye/rotenone plume entered the study reach at approximately 13.3 hours after the start of the injection (fig. 16, survey 18). As expected, the stagnation zone between the Midwest Generation powerplant intakes and outfall trapped the dye/rotenone for a significant period of time following the passage of the trailing edge downstream. The stagnation zone did not return to background dye concentrations until about 21 hours after the injection (fig. 16, survey 25). Likewise, the slips near mile 2 trapped dye and rotenone and, although the smaller of the two slips returned to background concentrations of dye by survey 29, the larger slip continued to have above-background dye concentrations (2–3 ppb) at approximately 25 hours after injection. These slips were not surveyed after survey 29. The trapping capability of these dead zones is quite apparent in figure 16, survey 29, which shows the trailing edge of the plume in the main channel located 4.5 mi downstream from the injection point and 2.5 mi of "clear" water between the large slip (which still contained dye) and the main-channel trailing edge. Once again, although fewer surveys entered the dead zones between miles 4 and 5.2 (fig. 16), there appeared to be less trapping of dye in these dead zones compared to the slips (note in survey 29 the main channel dye concentration near mile 4.5 matches closely with the embayment concentration).

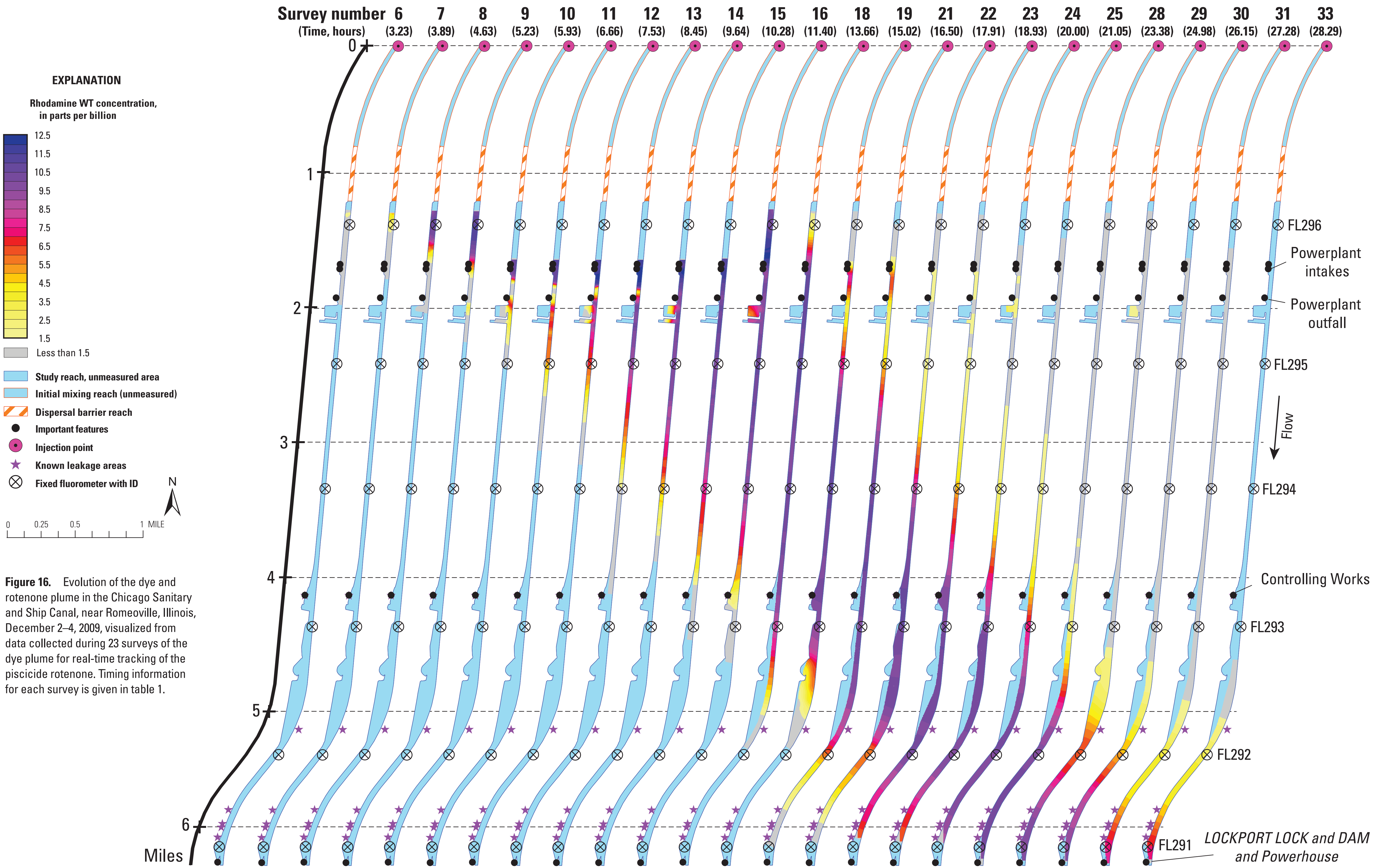


Figure 16. Evolution of the dye and rotenone plume in the Chicago Sanitary and Ship Canal, near Romeoville, Illinois, December 2–4, 2009, visualized from data collected during 23 surveys of the dye plume for real-time tracking of the piscicide rotenone. Timing information for each survey is given in table 1.

Because of the slow release of the dye/rotenone from dead zones in the reach, the trailing edge of the dye was drawn out into a long tail, and dye concentrations were still above background values at Lockport Lock and Dam (FL291) 37 hours after the injection (fig. 17 and table 2). In addition, the variability in the rising limb and plateau concentration of each concentration curve are affected, in part, by the passing of the dye through the Midwest Generation powerplant, which artificially transported dye out ahead of the leading edge—causing dye to accumulate in the stagnation zone—and transported untreated water out in front of the trailing edge. With the exception of FL292, which had some unexplained fluctuations, the variability in the concentrations curves was least at the downstream end of the reach, furthest from the Midwest Generation plant. The significant variability of FL296, which was upstream from the intakes of the powerplant, may be due in part to localized flow causing incomplete mixing across the canal in the vicinity of the fluorometer and the accumulation of dye just upstream from the plant intakes. (The highest concentrations observed by the survey boats were just upstream from the plant intakes; for example, fig. 16, survey 16.)

Traveltime information extracted from the boat-mounted and fixed-position fluorometers agrees well with empirical predictions from a preliminary dye study (mock rotenone injection) on this system completed in November 2009 (see appendix 1) (fig. 18). For the first 4.5 mi of the injection reach, the predicted leading-edge arrival time was within about 15 minutes of the observed leading-edge arrival time, with the exception of FL295, which was mounted about 2,500 ft downstream from the powerplant outfall and was likely affected by the transport of the dye through the plant (the dye arrived about 45 minutes earlier than expected at this site). The linear prediction for the leading-edge arrival time underestimates the transport time downstream from mile 5 (fig. 18 and table 2) primarily because of the expansion of the channel and the associated decrease in the mean channel velocity (shown in fig. 14, inset 2). This wide reach causes a shift in the traveltime curve that is not accounted for by the single linear prediction curve.

Table 2. Summary of fixed-fluorometer deployments in the Chicago Sanitary and Ship Canal near Romeoville, Illinois, during the rotenone treatment, December 2–4, 2009.

[N/A, not applicable; dye injection start December 2, 2009, at 19:51; dye injection end December 3, 2009 at 04:47; injection duration of 8.933 hours; T_{Lp}, predicted leading edge arrival time (see appendix 1); x, distance downstream from injection (in miles)]

Name	Type	Serial number	Distance downstream from injection, in miles	Notable times, in hours since the start of the Rhodamine WT injection					Plateau duration (within 95 percent of peak concentration), in hours
				Leading edge arrival time	Predicted leading edge arrival time (preliminary study; $T_{Lp} \approx 2.4235x$)	Peak arrival time	Trailing edge (10 percent peak) arrival time	Trailing edge (1 percent peak) arrival time	
FL296	Turner C3	2300165	1.4	N/A	3.39	11.25	13.55	14.05	N/A
FL295	Turner C3	2300151	2.43	5.11	5.89	13.61	18.71	26.26	3.65
FL294	Turner C3	2300174	3.35	8.40	8.12	15.25	20.90	24.15	3.90
FL293	Turner C3	2300150	4.37	10.37	10.59	17.67	24.82	32.47	4.10
FL292	Turner C3	2300166	5.35	14.25	12.97	22.05	31.45	37.65	5.80
FL291	Turner C3	2300164	6.17	16.90	14.95	24.30	33.45	N/A	3.75

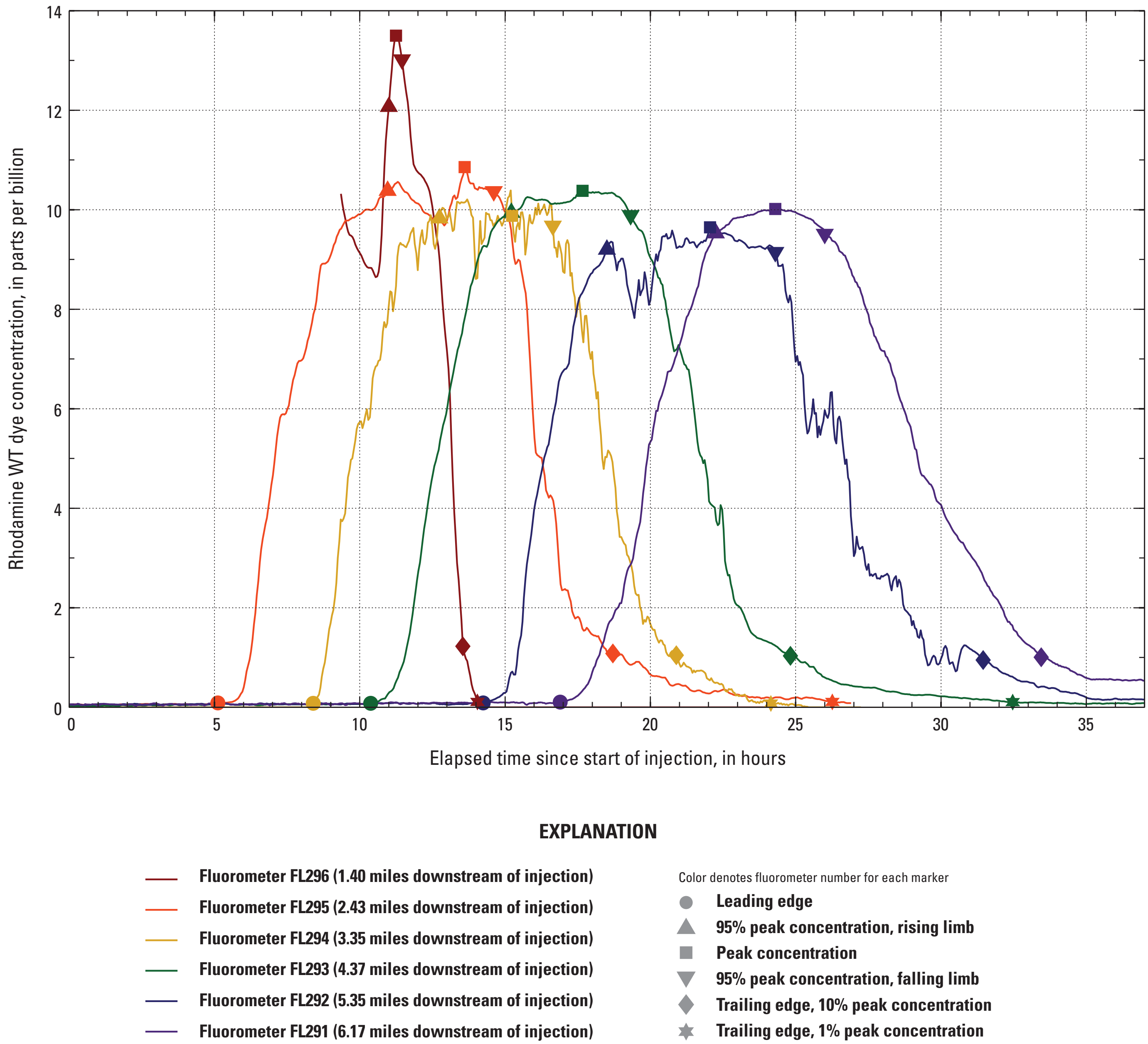


Figure 17. Dye-concentration breakthrough curves for six fixed-position fluorometers deployed in the Chicago Sanitary and Ship Canal, near Romeoville, Illinois, December 2–4, 2009. Notable points on each curve (leading edge, peak, trailing edge, and plateau boundaries) are marked. Exact times of each point are given in table 2. Fluorometer FL296 malfunctioned and did not log data for the first 9 hours of the deployment.

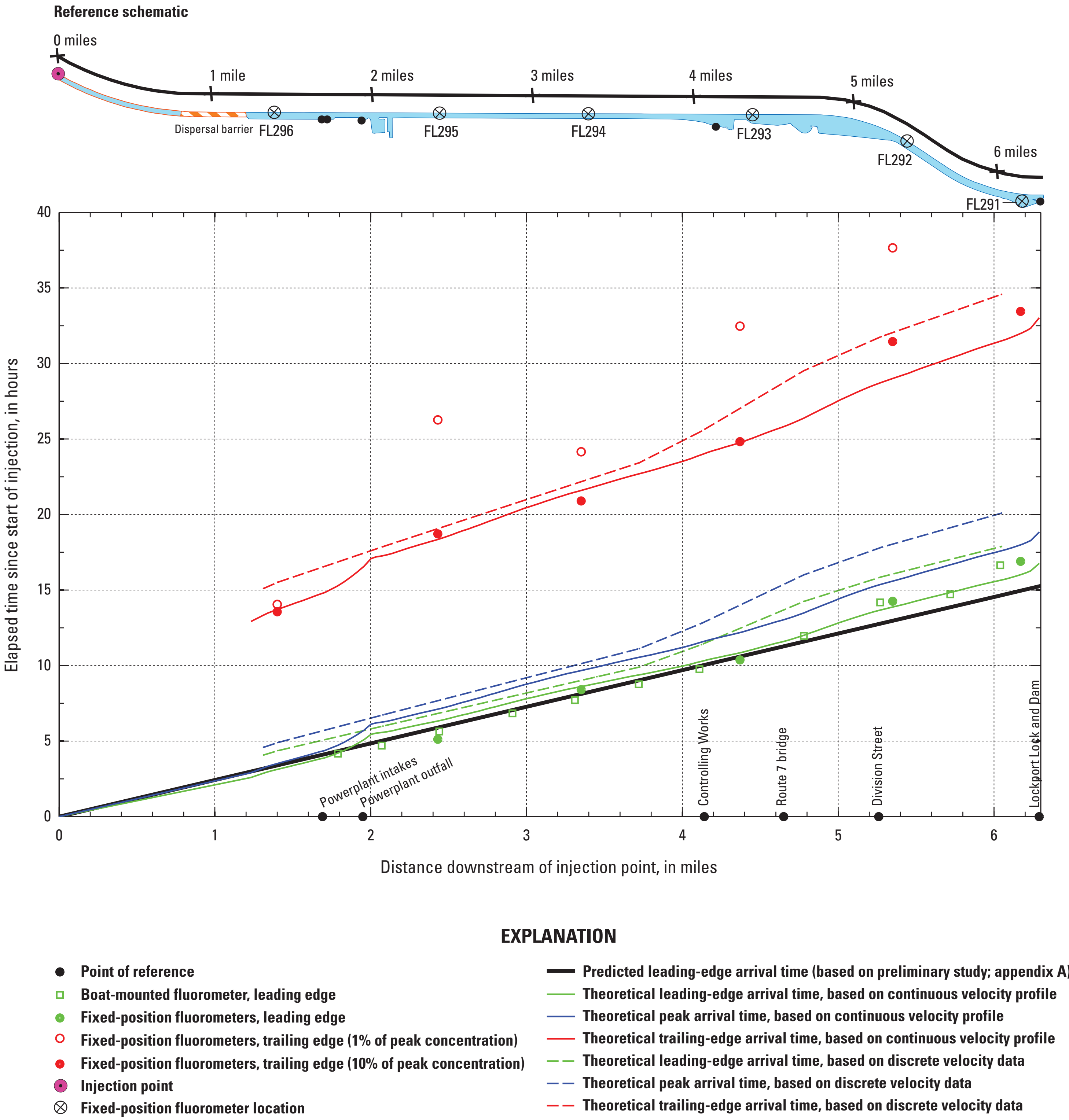


Figure 18. Observed and predicted traveltime curves for rotenone and Rhodamine WT dye in the Chicago Sanitary and Ship Canal, near Romeoville, Illinois, December 2–4, 2009. A reference schematic is provided for visualization purposes.

The traveltime of the leading and trailing edges can also be estimated by using methods described by Jobson (1996) if the traveltime of the peak is known. To estimate the traveltime of the peak, velocity data collected during the surveys were used. One set of data came from the mean cross-sectional velocity estimated from discharge measurements at fixed cross sections in the canal (from the fixed-position boat), and the second set of data came from depth-averaged velocities (with temporal averaging of 30 seconds) during a single streamwise transect of the canal during survey 28 by the rover boat. Traveltime of the peak of a slug injection T_p is estimated as the sum of the measured velocity for each subreach times the length of each subreach (subreaches are defined by the area between each velocity observation point) (blue lines, fig. 18). Once the traveltime of the peak of the slug is determined, the traveltime of the leading edge T_L can be estimated as $T_L = 0.890*T_p$ (fig. 18, green lines). The time (in hours) at which the concentration equals 10 percent of the peak concentration T_{T10} can be estimated as

$$T_{T10} = T_L + \frac{2\times10^6}{3600\times1025\times T_p^{-0.887}} \quad (1)$$

Because this injection was a continuous injection and not a slug injection, the duration of the injection (8.933 hours) added to T_{T10} gives an estimate of the arrival of the trailing edge at 10 percent of the peak concentration (fig. 18, red lines).

Traveltime estimates based on Jobson (1996) slightly overestimate the arrival of the leading edge near the outfall of the powerplant (fig. 18, miles 2–3) but produce good predictions of the leading-edge arrival time in the lower half of the reach, especially within the expansion zone near mile 5. The higher resolution of the velocity data during the streamwise transect seems to produce a better prediction (fig. 18, solid green line) than velocity data based on cross-sectional mean velocity from discharge measurements (fig 18, dashed green line). The trailing edge at 10 percent of the peak concentration is well predicted by the methods of Jobson (1996), with slightly better prediction using velocity data from the streamwise profile (fig. 18, solid red line). However, the method underestimates the traveltime in the lower 1.3 mi of the survey reach. The agreement of these predictions with observations suggest that if dye study data are not available for making predictions of traveltimes of contaminants in a channel, a streamwise velocity profile of the channel (under steady-flow conditions) can be used in conjunction with the methods of Jobson (1996) to estimate the traveltimes of the peak, leading edge, and trailing edge at 10 percent of the peak concentration. Although the estimates from Jobson (1996) are derived from large datasets encompassing numerous sites, caution should be applied when applying these estimates, especially if the site displays unique hydraulic conditions.

No dye was detected in periodic samples from monitored drinking-water wells adjacent to the CSSC (see appendix 1, figure 1–1 and table 1–2) from the time of the injection through 12:00 on December 4, 2009. Background fluorescence for all wells fluctuated up to about 0.13 ppb, and concentrations varied from 0.01 to 0.25 ppb for all wells. The observation of no well contamination is consistent with the results of the mock dye injection presented in appendix 1. In addition, rotenone's relatively high sediment adsorption rate suggests that the expected leaching distance for rotenone into soils is small (Dawson, 1986). Finlayson and others (2001) monitored 26 wells adjacent to treatment sites in California between 1987 and 1997 and found no evidence of rotenone contamination in any of the wells, including shallow wells within 10 feet of rotenone-treated water bodies. At all sites, sampling proceeded for at least 30 days after treatment.

Little Calumet River

Two survey boats equipped with fluorometers and ADCPs tracked the injection of rotenone in the Little Calumet River between May 20, 2010 and May 24, 2010. Approximately 95 hours of real-time tracking yielded approximately 170,000 georeferenced measurements of dye concentration, more than 165,000 velocity profiles, 660,000 bathymetric soundings, and 87 discharge measurements. In addition, fixed instrumentation yielded more than 19,000 samples of dye concentration from 3 locations within the river and Calumet Sag Channel. Many of these data were used in real time to support rotenone application, transport, and deactivation strategies conducted by a multiagency rapid response group. Real-time tracking of the rotenone was essential in this large-scale application, owing to the zero-flow application strategy and the prior knowledge that a true zero-flow condition is not possible in this reach of the Little Calumet River because of wind forcing, inflows, and the hydraulic connection to the highly unsteady CSSC. The data presented in the following sections were generally available in real time in their most basic format. Field personnel interpreted the incoming data and relayed the information to shore personnel conducting the rotenone treatment and deactivation. These data have been compiled, processed, and analyzed to document and visualize the 2010 rotenone treatment in the Little Calumet River.

Discharge

In spite of efforts to generate a no-flow condition within the rotenone treatment reach of the Little Calumet River, discharge within the reach was highly variable and resulted in a net downstream export of water from the treatment reach. Thirty-six discharge measurements made near the block net at the downstream end of the treatment reach over 4 days revealed a highly variable flow regime that fluctuated between −654 ft^3/s and 619 ft^3/s, with a mean discharge of 39 ft^3/s and a median discharge of 45 ft^3/s (table 3). The velocity distribution at the block nets was often of a bidirectional nature with the upper section of the water column moving in an opposite direction from the lower section of the water column. Such bidirectional flows can occur in response to wind-driven surface currents combined with the close-ended system produced by O'Brien Lock and Dam (surface currents driven by wind towards the lock are stopped by the lock and reflected as deep underflows in the opposite direction away from the lock). Although some of the observed flow variability is likely due to the response of the system to wind forcing, flow variability is also produced in this reach by variability in the output of the Grand Calumet River and the Little Calumet River at the junction with the Calumet Sag Channel, as well as changes in the outfall discharge of the Calumet Water Reclamation Plant at Acme Bend. On May 21, 2010, at 15:00, the Grand Calumet discharge was measured at 124 ft^3/s, though it likely varied considerably during the rotenone treatment. The Calumet Water Reclamation Plant outfall varied between 316 and 524 ft^3/s during the treatment, with the highest flows on May 22, 2010, in response to stormwater runoff the previous day. (The plant treats and discharges water received from combined sewers and therefore fluctuates with stormwater runoff.) On May 24, 2010, the opening of the sluice gates at O'Brien Lock and Dam to flush the treated water downriver for deactivation produced a flow of approximately 3,333 ft^3/s and lasted for just over 3 hours.

Variability in discharge within the treatment reach is also likely due, in part, to the propagation of disturbances into the reach from other points in the CAWS. Discharge data measured near the block net from May 20 to May 21, 2010, reveal a regular periodicity with a period of approximately 8 hours. This period is nearly twice the 4.1-hour period of the mode 1 seiche (an oscillation of the surface of a landlocked body of water with the greatest wavelength) for the reach between the Lockport Lock and Dam on the CSSC and the O'Brien Lock and Dam on the Little Calumet River (Jackson and others, 2012). With a discharge sampling interval of around 2 hours, it does not appear that the discharge record was undersampled, so a 4-hour period in the data could have been resolved, if present. Therefore, the periodicity in discharge seen during May 20–21, 2010, appears to not originate from seiche activity in the CAWS.

Velocity Distribution

More than 165,000 profiles of three-dimensional velocity collected by two survey vessels were used to characterize the velocity distribution in the Little Calumet River during the rotenone application, May 20–23, 2010. Depth-averaged velocity distributions based on all available data for each day of the survey reveal nearly quiescent water (< 0.2 ft/s) within the rotenone application reach and downstream from the block nets to near the apex of Acme Bend, where the outfall of the Calumet Water Reclamation Plant produces much higher velocities (up to 1.5 ft/s) and large zones of recirculation (figs. 19 and 20). Localized increases in velocity also occurred on May 21, 2010, near the mouth of the Grand Calumet River and at several points in the application reach and further downstream. The local anomalies not associated with inflows or outfall locations are likely caused, in part, by wind-driven flows, wakes from other boats, and local disturbances captured in the dataset.

The outfall of the Calumet Water Reclamation Plant is on the outside bank of Acme Bend near the apex of the bend and dominates the local hydrodynamics within the bend (fig. 20). The outfall jet crosses the entire 760-ft width of the channel and impinges on the inner bank. The jet splits at the inner bank and causes two large counter-rotating eddies, one upstream and one downstream from the outfall, both of which span the full width of the channel. The downstream eddy is approximately twice the size of the upstream eddy, based on the horizontal extent of the recirculation zone. Both eddies create the development of weaker recirculation cells further upstream and further downstream from the eddies (fig. 20). The large, elongated circulation cells on the upstream arm of Acme Bend produce weak (< 0.42 ft/s) downstream flow near both banks and a weaker (< 0.25 ft/s) upstream flow in the center of the channel. The centers of the eddies have very low velocities (< 0.08 ft/s). This circulation pattern produces a stagnation zone just upstream from the outfall and appears to arrest the downstream movement of water as is evident in the three aerial images from 2002 and 2005, where a sharp contrast in water color (likely due to turbidity) is seen at this stagnation zone. The upstream water mass is slowly mixed into the outfall jet by the upstream eddy as it rotates, diluting the upstream water mass and leaving little evidence of the turbidity difference on the downstream side of the outfall. On the basis of the aerial imagery and records of daily discharge from the outfall, it appears that this circulation pattern is a reccurring feature in this reach for outfall discharge of at least 300 ft^3/s and greater. The formation of such a recirculation at Acme Bend can trap contaminants upstream of the outfall for significant periods (days) and provide gradual dilution of the contaminant through mixing.

Depth-average velocities immediately downstream from O'Brien Lock and Dam were as high as 5 ft/s following the opening of the sluice gates at the dam during rotenone deactivation on May 24, 2010 (fig. 21). The outflow from the sluice gates hugged the left bank as it exited the reach adjacent to the lock bay and created two large eddies, one within the main channel and one just downstream from the lock bay. The flow was highly turbulent and variable within approximately 1,000 ft of the sluice gates. Further downstream, the velocity decreased (< 2 ft/s) and became more organized, with the fastest flow near the center of the channel. Flows were generally less than 1 ft/s downstream from the confluence with the Grand Calumet River.

Table 3. Summary of discharge measurements associated with the rotenone application in the Little Calumet River, Illinois, May 20–24, 2010.

[*Data provided by the Metropolitan Water Reclaimation District of Greater Chicago]

Location	Date	Time	Discharge, in cubic feet per second
Little Calumet River near the block net	May 20, 2010	8:30	59
	May 20, 2010	10:30	-79
	May 20, 2010	11:00	60
	May 20, 2010	11:15	-73
	May 20, 2010	11:40	1
	May 20, 2010	15:40	-654
	May 20, 2010	19:35	491
	May 20, 2010	21:25	-43
	May 20, 2010	23:25	-450
	May 21, 2010	1:35	197
	May 21, 2010	3:35	572
	May 21, 2010	5:35	-222
	May 21, 2010	7:35	-164
	May 21, 2010	7:40	-92
	May 21, 2010	9:15	68
	May 21, 2010	10:50	38
	May 21, 2010	11:05	619
	May 21, 2010	13:00	299
	May 21, 2010	13:20	40
	May 21, 2010	14:25	45
	May 21, 2010	16:45	101
	May 21, 2010	17:30	-19
	May 21, 2010	19:45	-251
	May 22, 2010	7:45	220
	May 22, 2010	9:25	348
	May 22, 2010	12:05	221
	May 22, 2010	13:15	187
	May 22, 2010	13:50	195
	May 22, 2010	15:30	-400
	May 23, 2010	8:35	111
	May 23, 2010	8:35	112
	May 23, 2010	14:50	163
	May 24, 2010	8:40	-164
	May 24, 2010	11:10	-120
	May 24, 2010	17:20	-49
Calumet River downstream of O'Brien Lock and Dam	May 24, 2010	15:00	3333
Grand Calumet River at the confluence with the Little Calumet River	May 21, 2010	8:35	124
Calumet Water Reclamation plant outfall*	May 20, 2010	Daily average	330
	May 21, 2010	Daily average	465
	May 22, 2010	Daily average	524
	May 23, 2010	Daily average	316
	May 24, 2010	Daily average	395

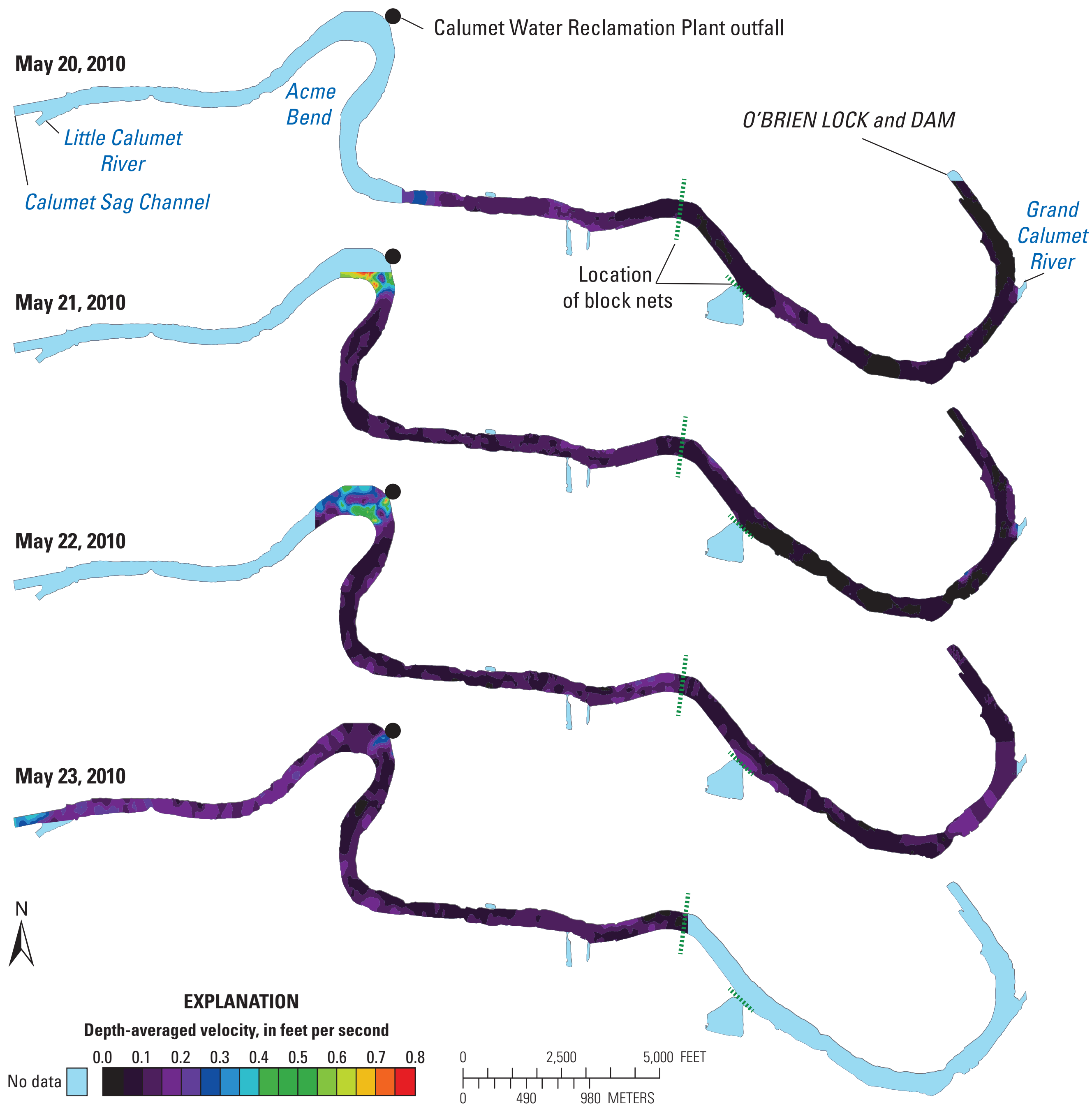


Figure 19. Distributions of depth-averaged velocity magnitude in the Little Calumet River (Illinois) during the rotenone application, May 20–23, 2010. Raw data were depth-averaged prior to applying a 30-second temporal average to reduce noise (Parsons and others, 2013). Ordinary kriging was used to generate surfaces from discrete data points.

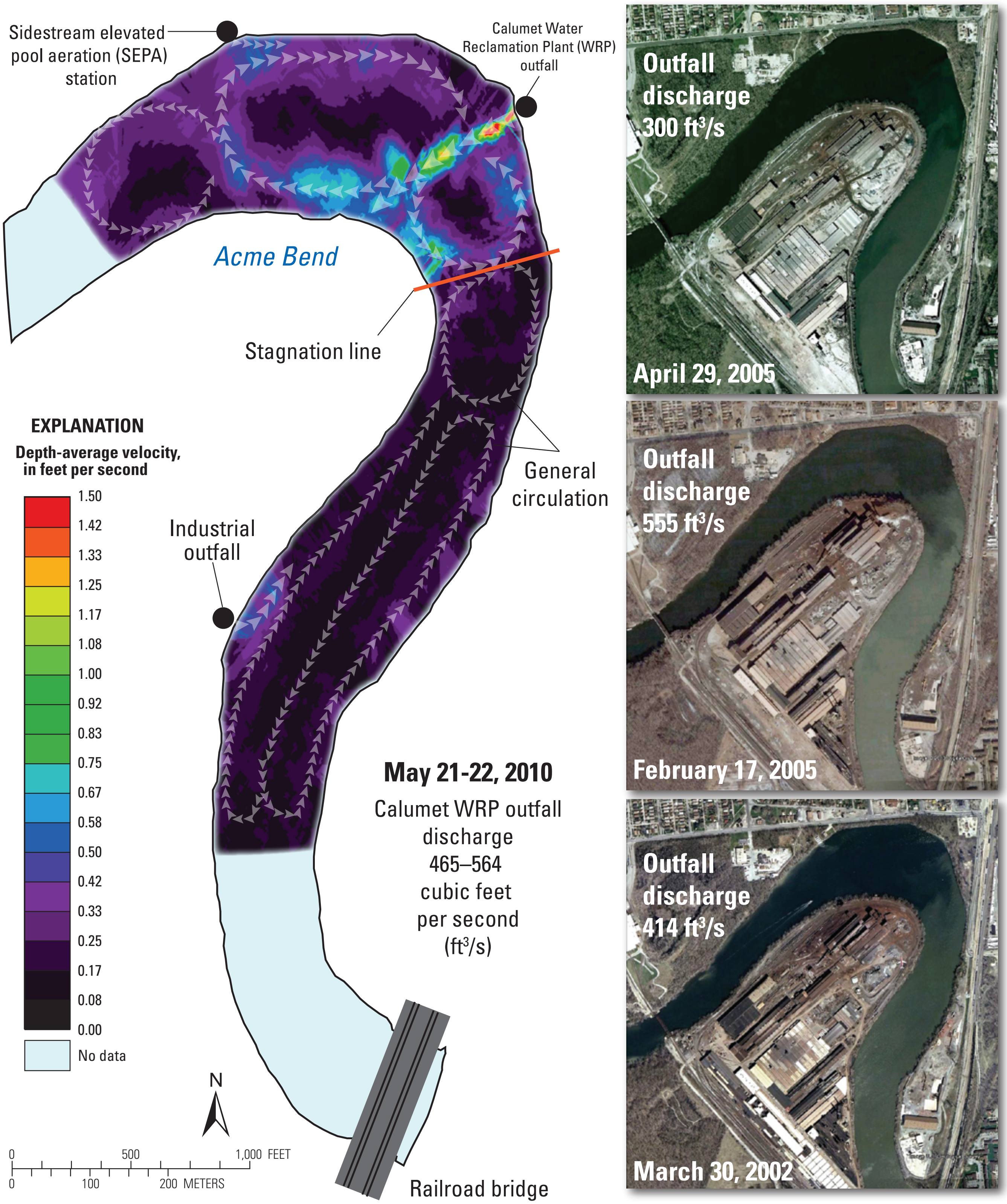


Figure 20. Distributions of depth-averaged velocity magnitude in the Little Calumet River (Illinois) at Acme Bend during the rotenone application, May 21–22, 2010. No temporal averaging was applied to these data so as to maximize the spatial resolution. Ordinary kriging was used to generate surfaces from discrete data points. General circulation cells defined using observed velocity vectors (not shown). Inset aerial imagery from three dates courtesy of Google Earth®.

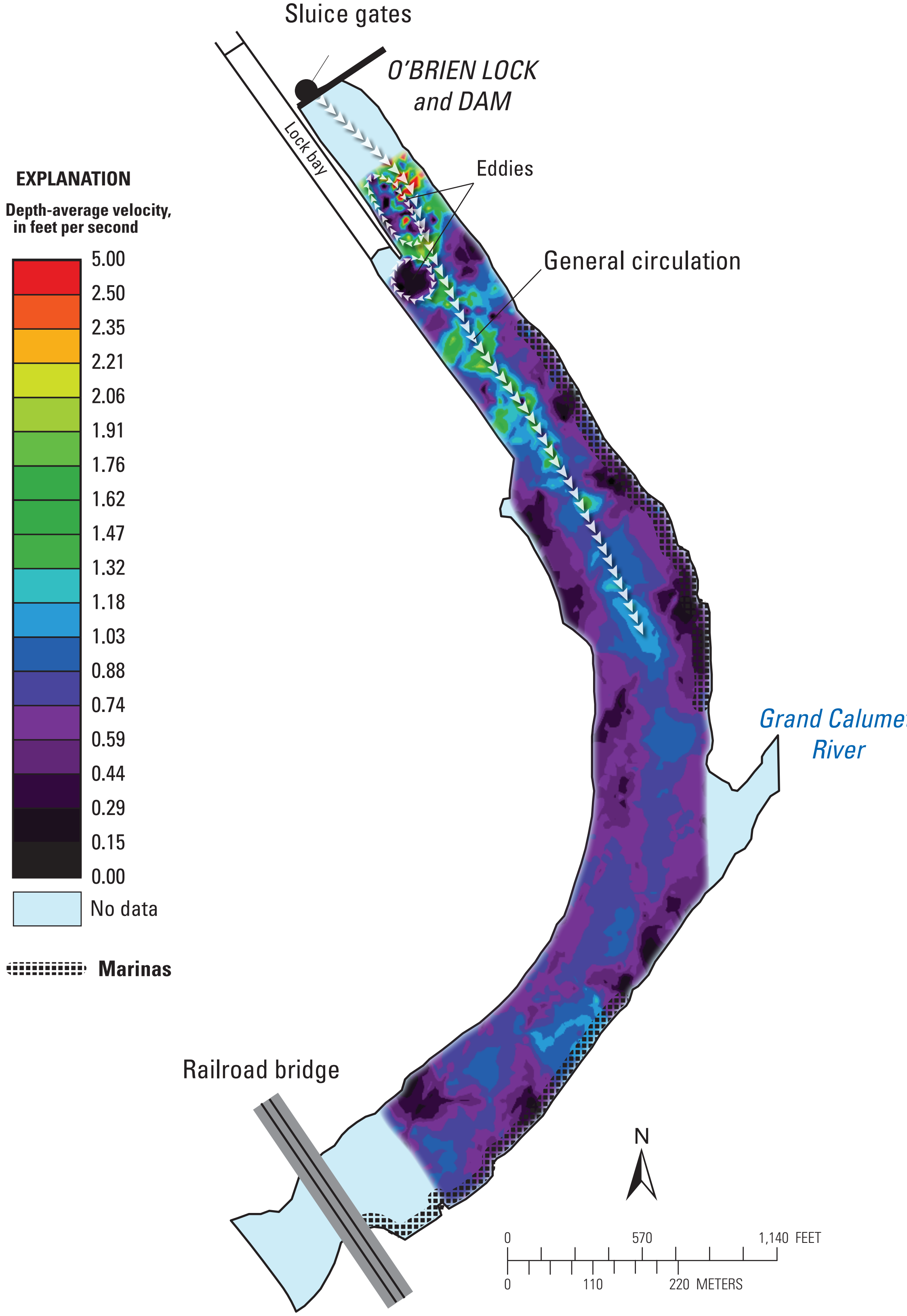


Figure 21. Distributions of depth-averaged velocity magnitude in the Calumet River (Illinois) near O'Brien Lock and Dam during the rotenone deactivation, May 24, 2010. No temporal averaging was applied to these data so as to maximize the spatial resolution. Ordinary kriging was used to generate surfaces from discrete data points. General circulation cells defined using observed velocity vectors (not shown).

Transport of Dye and Piscicide

The net export of rotenone-treated water from the application reach and subsequent downstream transport can be visualized by examining the evolution of the dye stripe injected at 12:39 on May 20, 2010, over 13 complete surveys of the plume between May 20, 2010, and May 24, 2010 (fig. 22; table 4). Seven partial surveys were omitted from this figure for clarity. Consistent with a net downstream discharge presented in the previous section, the dye stripe slowly disperses and the peak moves downstream, suggesting that rotenone-treated water was being transported through the block net and out of the treatment reach (as mentioned previously, deactivation boats applied sodium permanganate downstream from the block nets in response to real-time verification of this transport in the field). Approximately 17 hours after the start of the dye injection, dye and treated water had reached Acme Bend (fig. 22, survey 3; fig. 23). Over the next 13 hours, the leading edge of the dye plume slowly moved downstream, advancing primarily along the banks (fig. 22, surveys 5, 8, 9)—consistent with the general circulation cells depicted in figure 20. During the afternoon of May 21, 2010, at about 15:00 (about 26 hours after the start of the dye injection), a thunderstorm forced all boats (survey, deactivation, and fish collection) off the water for about 2 hours. The downstream transport of the rotenone-treated water through the block net at this time was approximately 0.2 mi (fig. 22, surveys 9 and 12), resulting in the escape of non-deactivated water from the treatment reach. Real-time tracking of the dye plume allowed this non-deactivated water mass to be tracked and subsequently deactivated before further progression downstream.

At approximately 30 hours after the dye injection, the downstream edge of the treated water reached the apex of Acme Bend and the outfall of the Calumet Water Reclamation Plant. At this point, the downstream progression of the treated water slowed considerably, and the leading edge was effectively arrested by the large eddies and stagnation zone introduced by the outfall (fig. 22, surveys 12, 14-16). The observed dye distributions for surveys 12 and 14–16 with sharp gradients just upstream from the outfall matches well with the turbidity distributions in the aerial photographs in figure 20. Dilution of the dye by the local mixing near the outfall forced any concentrations of dye beyond the apex of Acme Bend to fall below detectable limits for the next 22 hours. Between 52 and 69 hours after the initial dye injection, the flow from the outfall decreased (table 3), weakening the local circulation and mixing at the apex of Acme Bend (see fig. 19, May 23, 2010, velocity distribution), and allowed the dye and treated water plume to advect downstream past Acme Bend (fig. 22, surveys 17 and 18). By 93 hours after the initial dye injection, dye and treated water had advected past the apex of Acme Bend and into the Calumet Sag Channel (fig. 22, surveys 19 and 20). After 100 hours, no dye was detectible by the fixed fluorometer at the railroad bridge upstream from Acme Bend (fig. 23).

Table 4. Summary table of streamwise surveys of the Little Calumet River, Illinois, during the rotenone treatment, May 20–24, 2010.

[Dye injection began at 12:39 on May 20, 2010, and ended at 13:45 on May 20, 2010]

Survey number	Direction	Start time, in hours since start of injection	End time, in hours since start of injection	Mean time, in hours since start of injection
1	Upstream	5.20	5.47	5.33
2	Upstream	7.90	8.32	8.11
3	Downstream	16.78	17.77	17.27
4	Downstream	19.22	19.73	19.48
5	Upstream	19.73	20.47	20.10
6	Downstream	23.37	23.62	23.49
7	Upstream	23.62	23.83	23.72
8	Downstream	23.98	24.43	24.21
9	Upstream	24.45	25.78	25.12
10	Downstream	26.53	26.90	26.72
11	Downstream	28.75	29.87	29.31
12	Upstream	29.87	31.15	30.51
13	Downstream	43.93	45.12	44.53
14	Upstream	45.12	47.12	46.12
15	Downstream	50.57	51.45	51.01
16	Upstream	51.65	53.05	52.35
17	Downstream	67.72	69.55	68.63
18	Upstream	71.23	72.62	71.92
19	Downstream	91.90	93.15	92.52
20	Upstream	93.17	94.62	93.89

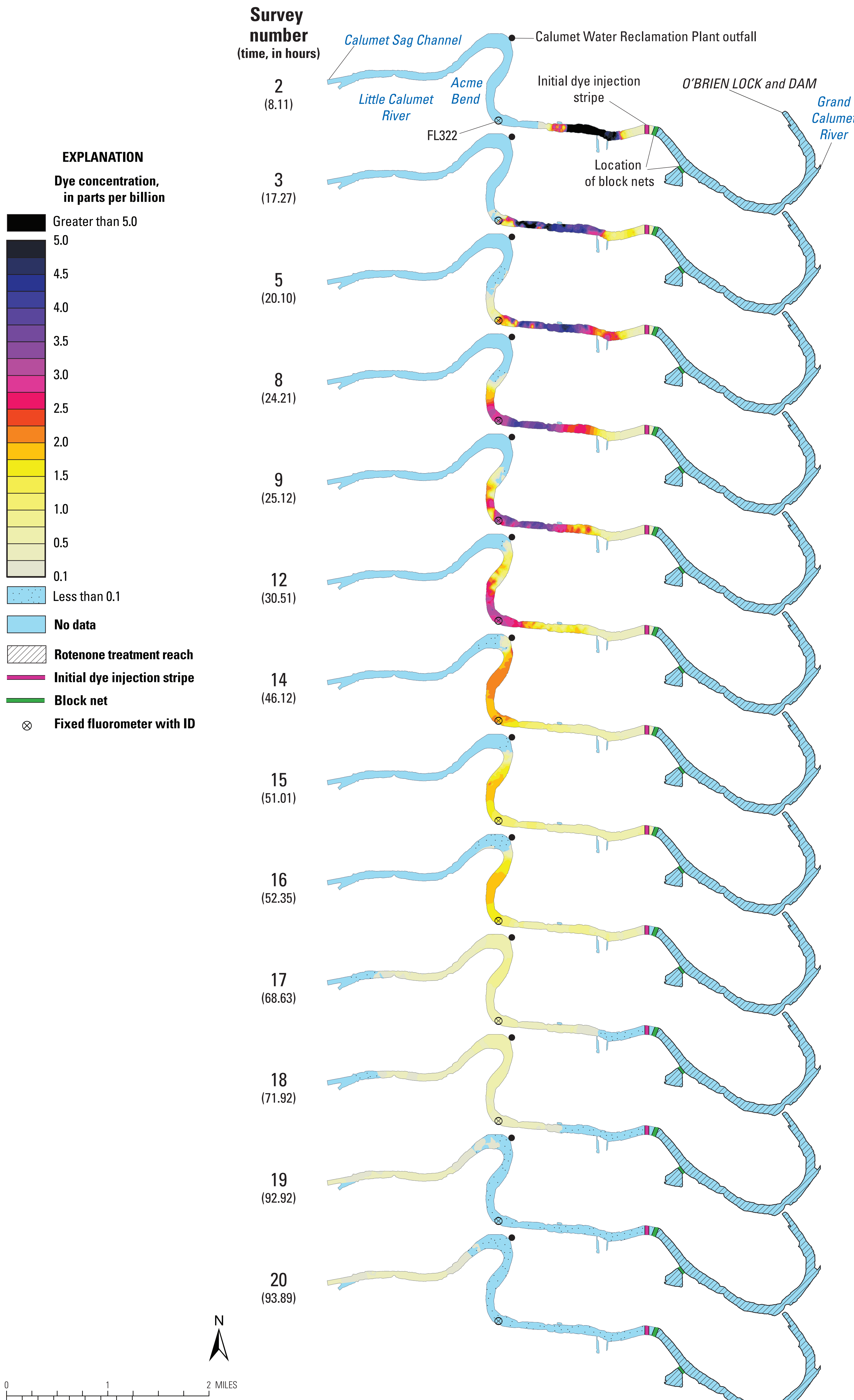


Figure 22. Distributions of dye downstream from the block net in the Little Calumet River (Illinois) during the rotenone treatment, May 20–24, 2010. Ordinary kriging was used to generate surfaces from discrete data points. No data were collected upstream (east) from the block net. Survey times are based on the mean time of the survey and are in hours after the start of the dye injection.

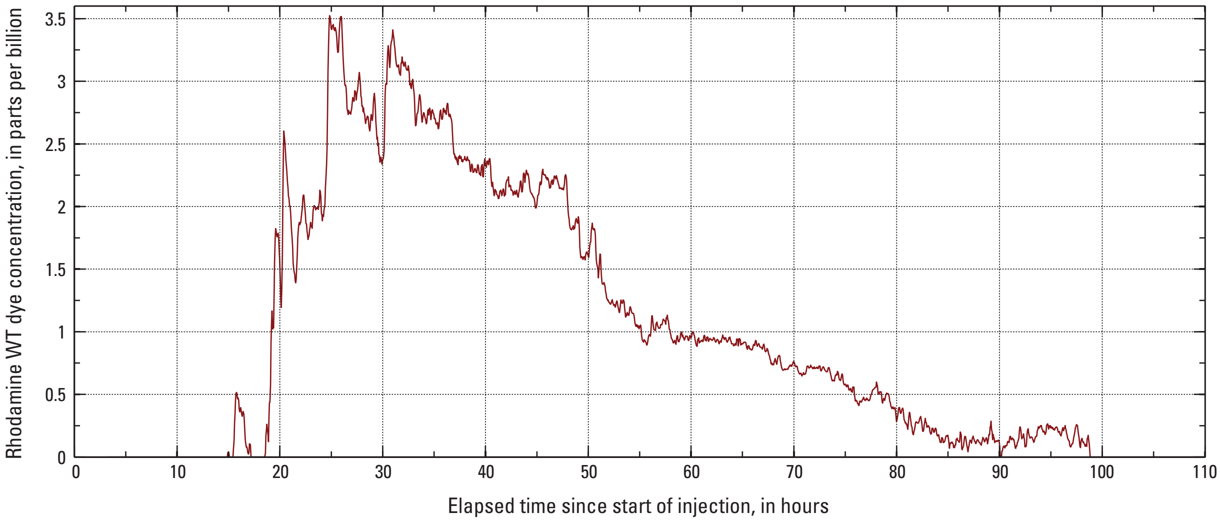


Figure 23. Dye concentration breakthrough curve for a fixed fluorometer (FL322) on a pier at the upstream end of Acme Bend underneath the railroad bridge. Data from two additional fluorometers in the Calumet Sag Channel were omitted from this plot, owing to contamination of the fluorescence data by turbidity from the Little Calumet River (Illinois) inflow.

In order to allow deactivation of the rotenone-treated water present in the first mile of waterway downstream from O'Brien Lock and Dam (where application of sodium permanganate was restricted because of the potential staining of boats in the marinas), the sluice gates at O'Brien Lock and Dam were opened and the treated water was flushed downstream for deactivation. As the sluice gates were opened, a slug of dye was added to the inflow at 13:40 on May 24, 2010. That dye quickly mixed into the turbulent water downstream from the lock and dam and was quickly diluted (fig. 24, surveys 21–22; table 5). Only a small amount of dye (2.3 L) was added to the 3,300 ft^3/s inflow to avoid worrying boat owners concerned about staining. The dye mass marked the trailing edge of the treated water mass and therefore, the strategy was to drive the dye 1 mi downstream to ensure that the rotenone-treated water was transported into the reach were deactivation could take place. Although the dye mass did not remain fully intact because of turbulent flows and dilution (fig. 24, surveys 23–25), at 3.42 hours after the dye was injected, the absence of detectable dye in the marina reach suggested adequate flushing. After the flushing and successful deactivation of the upper reach (the remainder of the reach was deactivated prior to the flushing event), the block nets were removed and commercial vessels were allowed to transit the reach.

Table 5. Summary table of streamwise surveys of the Little Calumet River, Illinois, during the rotenone deactivation, May 24, 2010.

[Dye injection occurred at O'Brien Dam sluice gates at 13:40 on May 24, 2010]

Survey number	Direction	Start time, in hours since injection	End time, in hours since injection	Mean time, in hours since injection
21	Downstream	0.30	1.05	0.67
22	Upstream	1.07	1.43	1.25
23	Downstream	1.43	1.90	1.67
24	Upstream	2.48	2.97	2.73
25	Downstream	2.97	3.87	3.42

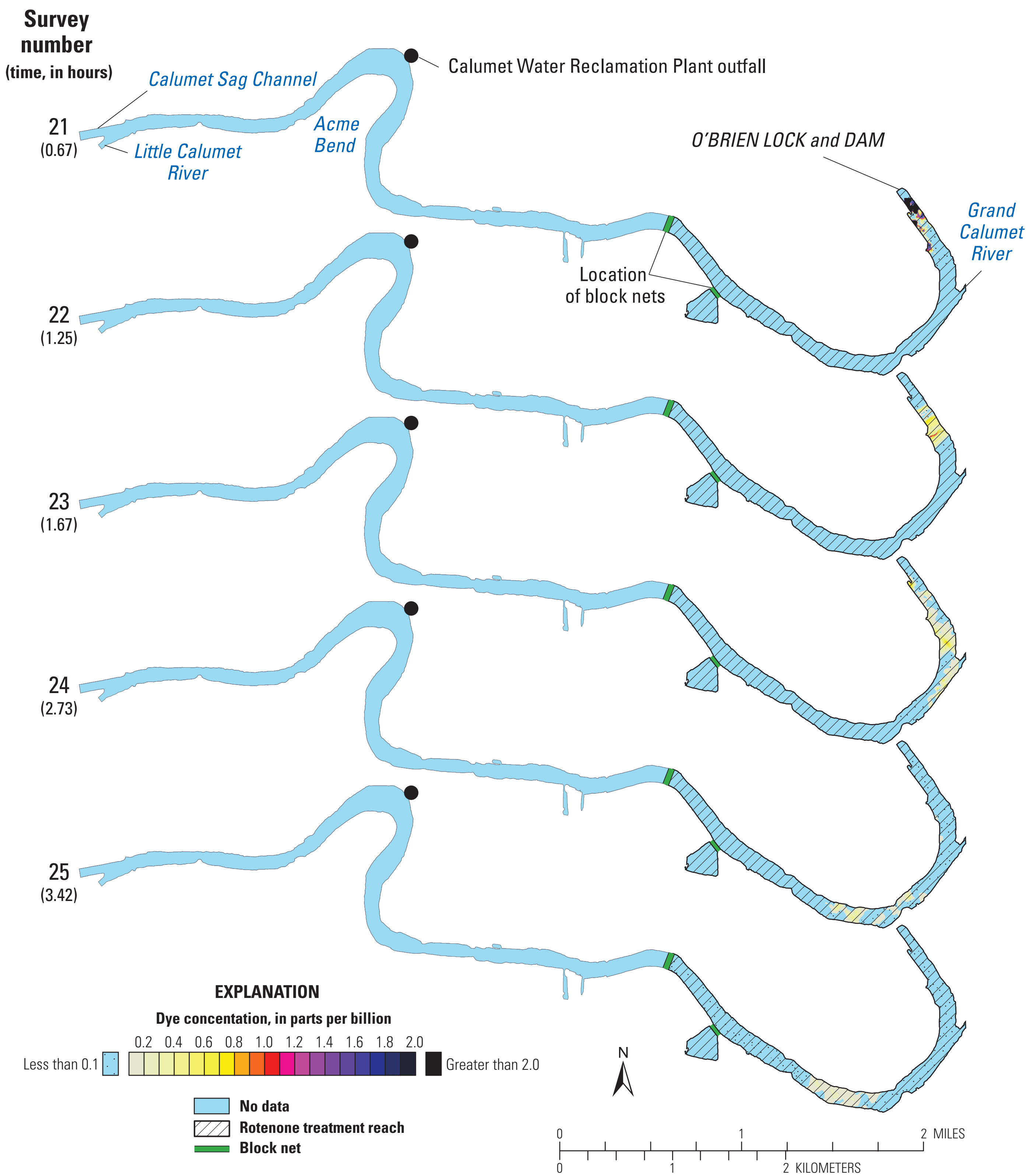


Figure 24. Distributions of dye in the Little Calumet River (Illinois) downstream from O'Brien Lock and Dam during the rotenone deactivation (flushing), May 24, 2010. Ordinary kriging was used to generate surfaces from discrete data points. No data were collected downstream (west) from the block net. Survey times are based on the mean time of the survey and are in hours after the start of the dye injection.

Summary and Conclusions

Piscicide applications in riverine environments are complicated by the advection and dispersion of the piscicide by the flowing water. Proper deactivation of the fish toxin is required outside of the treatment reach to ensure that there is minimal collateral damage to fisheries downstream or in connected and adjacent water bodies. In urban settings and highly managed waterways, further complications arise from the influence of industrial intakes and outfalls, stormwater outfalls, lock and dam operations, and general unsteady flow conditions. These complications affect the local hydrodynamics and ultimately the fate and transport of the piscicide. This report presents a technique for real-time tracking of a piscicide plume—or any passive contaminant—in rivers and waterways in natural and urban settings. This method, when combined with data logging and archiving, allows for documentation and visualization of the application and deactivation process.

Real-time tracking and documentation of rotenone applications in urban waterways was accomplished by encasing the rotenone plume in Rhodamine WT dye and using vessel-mounted submersible fluorometers together with acoustic Doppler current profilers (ADCP) and global positioning system (GPS) receivers to track the dye and map the water currents responsible for advection and dispersion. Data logging and display on a shipboard laptop computer allowed survey personnel to provide real-time feedback about the extent of the plume to rotenone application and deactivation personnel so that strategies could be adjusted in real time when necessary.

Two large-scale, complex applications of rotenone in the Chicago Area Waterway System in 2009 and 2010 to combat the invasive Asian carp are documented in this report. The application in Chicago Sanitary and Ship Canal (CSSC) in December 2009 involved more than 1,800 gallons of rotenone injected at multiple stations through a 6.2-mile reach of the canal near Lockport, Illinois. By encasing the rotenone plume in Rhodamine WT dye (dye was injected simultaneously over 9 hours with the rotenone), two survey boats were able to provide real-time feedback to shore personnel regarding the plume extent. All booster-station injections of rotenone at downstream locations, as well as deactivation stations, were reliant on the dye-tracking personnel for timing information for start and end of their operations. The data collected during the real-time tracking allowed full documentation of the rotenone treatment for archiving purposes, thus providing information for any future applications. Traveltime information extracted from the boat-mounted and fixed-position fluorometers agrees well with empirical predictions from a preliminary dye study (mock rotenone injection) on this system completed in November 2009 on the CSSC and with the methods of Jobson (1996) for traveltimes of the peak, leading edge, and trailing edge of the plume. Dye tracing combined with velocity mapping allowed the complex hydrodynamics surrounding the Midwest Generation powerplant to be documented and visualized.

Application of rotenone in May 2010 to the Little Calumet River near O’Brien Lock and Dam (Illinois) provided the opportunity for another dye-tracking support operation, but one with very different application and deactivation strategies. Instead of applying rotenone upstream and neutralizing the treated water at a downstream point, as was done on the CSSC, the application strategy on the Little Calumet River was under “near-zero-flow” conditions. Dye was injected at the upstream and downstream boundaries of the rotenone application reach and was used to track movement of water in and out of the treatment reach so that proper deactivation could occur and damage to fisheries downstream could be minimized. Although the rotenone application strategy called for zero-flow conditions on the Little Calumet River in 2010, downstream advection of treated water did occur, and dye tracing combined with velocity mapping allowed this advection to be documented and exposed the unique hydrodynamics and mixing occurring in this reach. A large recirculation zone at the apex of Acme Bend caused by the outfall of the Calumet Water Reclamation Plant nearly arrested the downstream movement of treated water and provided significant mixing and dilution of the plume.

The methods presented in this report for real-time tracking and documentation of piscicide applications in riverine environments worked exceptionally well and allowed the multiagency Asian Carp Rapid Response Workgroup to carry out large-scale rotenone applications in urban waterways in an environmentally responsible manner with minimal collateral damage to fisheries outside of the treatment reach. The large volumes of data collected during the operations allow documentation and visualization of the rotenone applications, thus providing feedback to planners and archival of the treatments for future use. The methods developed in this report are directly transferrable to piscicide applications in other water bodies, whether rivers, ponds, or lakes, and can be used for real-time tracking of any passive contaminant that may enter a water body.

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Appendix 1

Mock Rotenone Injection Using Rhodamine WT Dye in the Chicago Sanitary and Ship Canal, November 2009

To determine reach traveltimes and assess transport characteristics of contaminants, primarily rotenone, from the Chicago Sanitary and Ship Canal (CSSC) to the Des Plaines River, Illinois and Michigan (I & M) Canal, and Deep Run Creek, the USGS Illinois and Ohio Water Science Centers performed a mock rotenone injection using Rhodamine WT dye at river mile 296.7 in the CSSC just upstream from dispersal barrier 2A in November 2009. Dye was injected continuously over an 8-hour period on November 10, 2009, using the injection pump system described in the “Methods of Tracking Piscicide Applications Using Rhodamine WT” section of this report. With the exception of restricting barge traffic in the study reach and closing Lockport Lock, this tracer release mimicked the rotenone injection scheduled for December 3, 2009. Flow in the CSSC was maintained at a mean discharge of 2,450 cubic feet per second (ft^3/s) with a standard deviation of 300 ft^3/s. Mean discharges (and standard deviations) were 13.8 ft^3/s (±1.4 ft^3/s) for Deep Run Creek, 20.5 ft^3/s (±7.7 ft^3/s) for the I & M Canal, 888.5 ft^3/s (±91.8 ft^3/s) for the Des Plaines River near Lockport, and 1,703 ft^3/s (±113.2 ft^3/s) for the Midwest Generation powerplant outfall during the duration of the study.

The downstream advection and dispersion of the tracer was measured with a total of 13 fluorometers (4 in the CSSC, 5 in the Des Plaines River, 1 in Deep Run Creek, 1 in the I & M Canal, 1 mobile unit in a boat, and 1 stationary unit processing manual samples; see fig. 1–1 and table 1–1). All fluorometers were calibrated with calibration solutions produced onsite by using water from each deployment location during the final dilution. In the study reach between dispersal barrier 2A and Lockport Lock and Dam, the CSSC water-surface elevation is greater than that of the surrounding water bodies. This gradient is known to cause leakage from the CSSC to the Des Plaines River, Deep Run Creek, and possibly the I & M Canal. To assess this leakage and determine whether rotenone was likely to enter these systems above Lockport Lock and Dam, fluorometers were deployed in these reaches (table 6). In addition to the continuously monitoring fluorometers, discrete grab samples were periodically collected from surface-water bodies and groundwater wells (table 1–2) in the study reach throughout the duration of the study. Samples were stored in opaque brown 125-milliliter HDPE plastic bottles and analyzed by using a temperature-compensated Turner 10-AU benchtop fluorometer (samples were analyzed in the field for real-time feedback and then rerun in the laboratory under controlled conditions to ensure accurate readings). These samples provided a time series of dye concentration at ungaged sites and an independent measure of dye concentration at gaged sites for comparison to continuous monitors.

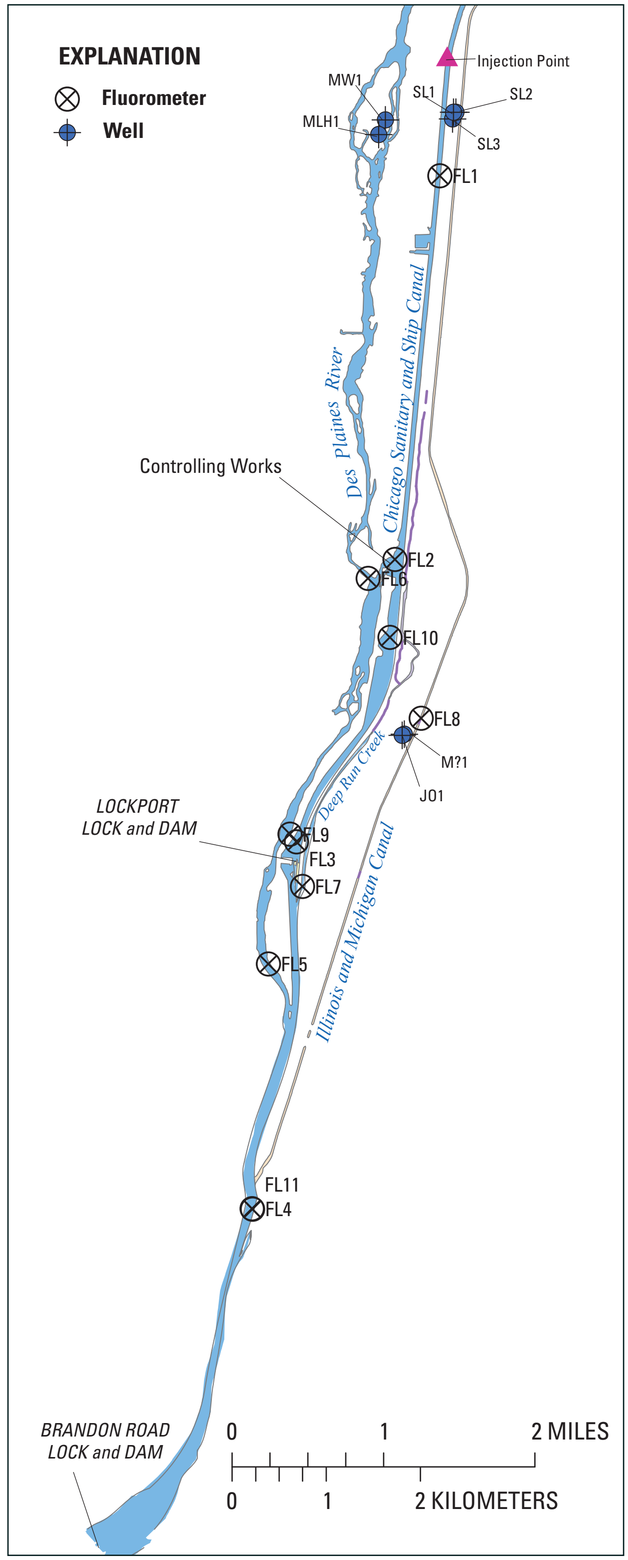

Figure 1-1. Locations of deployed fluorometers and sampled wells in and near the Chicago Sanitary and Ship Canal (CSSC), Des Plaines River, Illinois and Michigan Canal, and Deep Run Creek during a mock rotenone injection on November 10–12, 2009. The 8-hour continuous injection took place at river mile 296.7 on the CSSC just upstream of the dispersal barriers.

Table 1–1. Fluorometers deployed in the Chicago Sanitary and Ship Canal (CSSC), Des Plaines River, Deep Run Creek, and Illinois and Michigan (I & M) Canal during a mock rotenone injection, November 10–12, 2009.

Name	Longitude	Latatitude	Instrument	Water body	Description	Sampling rate, in minutes
FL1	-88.060502	41.6350393	Turner Designs C3	CSSC	Above Midwest Gen. Intakes	5
FL2	-88.065598	41.5983956	Turner Designs C3	CSSC	At Control Works	5
FL3	-88.077674	41.5713618	Turner Designs C3	CSSC	At Lockport Lock	5
FL4	-88.082669	41.5363044	Turner Designs 10-Au	Des Plaines River	At Ruby Street Bridge	0.5
FL5	-88.081031	41.5596901	Turner Designs C3	Des Plaines River	Below Lockport Lock	5
FL6	-88.068982	41.5965672	Turner Designs SCUFA	Des Plaines River	Upstream of Control Works	2
FL7	-88.076845	41.5671211	Turner Designs C3	Deep Run Creek	At Lockport Lock	5
FL8	-88.062034	41.5832952	Turner Designs C3	I & M Canal	At Division Street	5
FL9	-88.078515	41.5720859	Turner Designs SCUFA	Des Plaines River	Near leakage at weir 1 mouth	2
FL10	-88.066112	41.5909556	YSI 6130	CSSC	At Route 7	5
FL11	-88.082723	41.5363332	Turner Designs C3	Des Plaines River	At Ruby Street Bridge	5
FL12	N/A	N/A	YSI 6120	CSSC/Des Plaines	Mobile (boat) unit	0.0167
FL13	N/A	N/A	Turner Designs Model 10	N/A	Sample Processing Unit	N/A

Table 1–2. Locations of sampled wells during a mock rotenone injection, November 10–12, 2009. Wells were sampled between three and five times per day.

Well name	Longitude	Latitude	Description
SL1	-88.0589722	41.6404722	East side of CSSC near Romeoville Road
SL2	-88.0585556	41.6411111	East side of CSSC near Romeoville Road
M?1	-88.0641293	41.5817614	East side of CSSC near Division Street
AW1	-88.0675	41.6403056	West side of Des Plaines River near Romeoville Road
SL3	-88.0588611	41.6411111	East side of CSSC near Romeoville Road
MLH1	-88.0683333	41.6388889	West side of Des Plaines River near Romeoville Road
JO1	-88.0644167	41.5816389	East side of CSSC near Division Street

Data from all fixed fluorometers were combined with data from the boat-mounted fluorometer and samples from nearby drinking-water wells to provide observations of the reach traveltimes, to allow planners of the rotenone application to estimate timing of booster injections and deactivation operations, and to determine the potential for collateral damage to fisheries in the Des Plaines River, Deep Run Creek, and Illinois and Michigan Canal and the potential for contamination of nearby drinking-water wells. These data are summarized in figure 1–2 for the leading and trailing edge of the dye plume in the CSSC and in table 1–3 for the CSSC, Des Plaines River, and Deep Run Creek. Empirical traveltime estimates used to predict the arrival of the leading edge and trailing edge of the plume are given in figure 1–2.

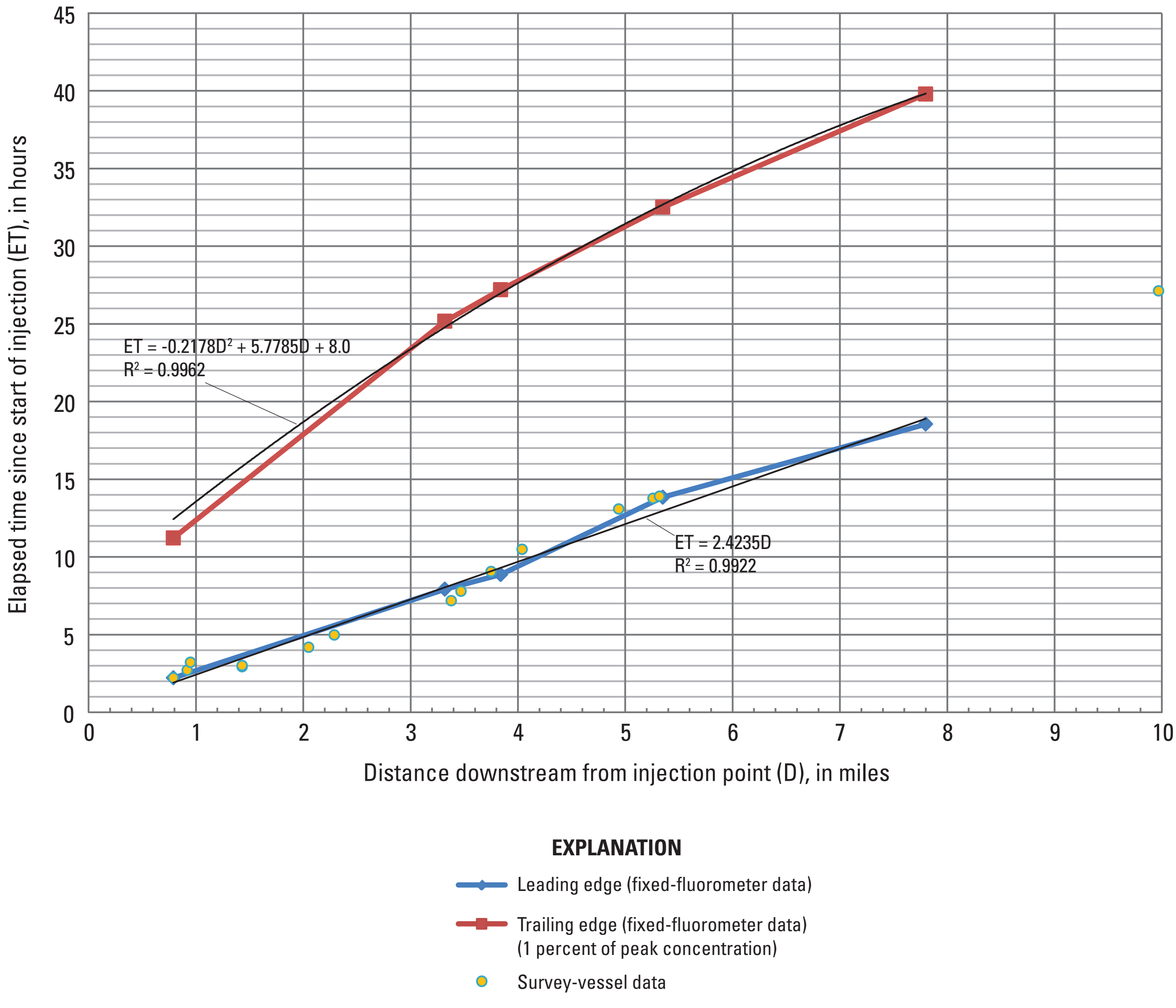

Figure 1–2. Traveltime observations for the dye plume injected in the Chicago Sanitary and Ship Canal as a mock rotenone injection on November 10–12, 2009. Times reflect an 8-hour continuous dye injection at river mile 296.7 with a mean discharge of 2,450 cubic feet per second and Lockport Lock active. Empirical equations for the elapsed time (ET) since the start of the injection for the leading edge and trailing edge to reach a point D miles downstream of the injection were found using a least-squares fit to the data and are displayed on the figure.

Data from the I & M Canal and nearby groundwater wells showed no evidence of dye contamination. Data from the I & M Canal remained below 0.21 part per billion (ppb), with fluctuations up to 0.17 ppb but with no definitive signature of contamination from the dye injected in the CSSC. Seven groundwater wells sampled in the vicinity of the CSSC and were found to have baseline concentrations (fluorescence) from 0 ppb to 0.1 ppb and fluctuations of up to 0.04 ppb. Well data showed no response to the injected dye in the CSSC within the 56 hours after the injection (all concentrations were less than 0.15 ppb). Rotenone-application planners were primarily concerned about contamination of the wells within the first 48 hours following the application. After 48 hours, the natural breakdown of rotenone in the groundwater system made it less of a concern to application personnel. In addition, rotenone's relatively high sediment adsorption rate suggests that the expected leaching distance for rotenone into soils is small (Dawson, 1986). Finlayson and others (2001) monitored 26 wells adjacent to treatment sites in California between 1987 and 1997 and found no evidence of rotenone contamination in any of the wells, including shallow wells within 10 feet of rotenone-treated water bodies. At all sites, sampling proceeded for at least 30 days after treatment.

Table 1–3. Dye-plume arrival times and peak concentrations for fluorometers deployed in the Chicago Sanitary and Ship Canal (CSSC), Des Plaines River, Deep Run Creek, and Illinois and Michigan (I & M) Canal during a mock rotenone injection, November 10–12, 2009.

Site	Distance downstream of injection, in miles	Leading edge arrival time, in hours since start of injection	Peak dye concentration, in parts per billion
FL1	0.79	2.21	12
FL2	3.32	7.92	11.49
FL10	3.84	8.86	11.94
FL3	5.35	13.84	10.55
FL11	7.8	18.54	6.98
FL7	N/A	15.35	4.54
FL5	N/A	14.68	0.14
FL9	N/A	11.85	1.74

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