# WINTER WATER CIRCULATION PATTERNS IN MUD LAKE - AN ADAPTIVE MANAGEMENT STUDY OF A BACKWATER HABITAT RESTORATION PROJECT IN POOL 11 OF THE MISSISSIPPI RIVER


By

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*Photo looking upstream into the Mud Lake HREP inlet (Courtesy of Elizabeth Bruns).*

# Winter Water Circulation Patterns in Mud Lake - An Adaptive Management Study of a Backwater Habitat Project In Pool 11 of the Mississippi River


## Abstract

U.S. Army Corps of Engineers, Rock Island District (USACE) personnel performed a dye study during March 2014 in a backwater of the Mississippi River, Pool 11, near Dubuque, Iowa. The study was conducted in response to Iowa Department of Natural Resources (IDNR) fish telemetry data which indicated that newly created dredge channels were underutilized by overwintering fish; and velocity data that indicated Mississippi River main channel flow was entering the backwater area from the dredge channel outlet. A habitat restoration project for the backwater was completed in 2005 as part of the Upper Mississippi River Restoration program. The project included creation of deep water dredge channels in the backwater adjacent to the navigation channel to provide overwintering habitat for centrarchids and associated species.

The primary purposes of the study were to determine how inflowing water disperses, both temporally and spatially, throughout the backwater complex during winter, under ice cover; and to measure velocity, a critical factor in the selection of overwintering areas utilized by centrarchids. A single slug injection of Rhodamine WT dye was dispensed immediately downstream from the inlet structure to the backwater and was tracked for more than 24 hours as it dispersed throughout the area. When initial results indicated the dye was not traversing the full length of the main dredge channel, a second injection was dispensed in the dredge channel outlet. The results of the study suggest that implementation of adaptive management measures is necessary in order to reduce dredge channel velocities to acceptable levels for overwintering fish. The results also substantiated velocity data collected by IDNR and Wisconsin Department of Natural Resources (WDNR) personnel which indicated Mississippi River main channel flow enters the backwater area from the dredge channel outlet.


## Introduction

The Pool 11 Islands Habitat Rehabilitation and Enhancement Project (HREP) under the Upper Mississippi River Restoration program includes two distinct backwater enhancement areas: Mud Lake and Sunfish Lake. A location map is included in Figure 1. All work related to the present study was performed in the Mud Lake HREP, which is located on the Mississippi River (river miles 587.6 to 589.4), approximately five miles upstream from L/D 11 and the City of Dubuque, Iowa. Construction of the Mud Lake project commenced in August 2004 and was completed in July 2005 (USACE, 2014). The HREP consists of Mud Lake at the upstream portion of the backwater area and Zollicoffer Slough at the downstream portion, with the mouth of Leisure Creek forming a depositional area between the two water bodies (see Figure 2). The recommended plan for the HREP included construction of a 3,038 m sediment deflection embankment to protect the backwater complex from sediment accretion /resuspension and mechanically dredging 8.8 ha of deep channels for fish overwintering habitat (USACE, 2001). Dredge material was used to construct the deflection embankment and an island near the lower portion of the project which was adjacent to a channel connecting Zollicoffer Slough with the main dredge channel. As part of the original design process for the Mud Lake HREP, a two dimensional hydrodynamic model (RMA-2) was utilized to evaluate various alternatives for the project. The recommended alternative included two notched rock weirs in the deflection embankment: one at the upper end and one near the middle. The primary purpose of the weirs was to allow oxygenated main channel flow into the backwater area during the winter months to help assure sufficient DO concentrations to support overwintering fish.  A DO mass balance performed during project design indicated an inflow of 1.09 cm/sec would be necessary to

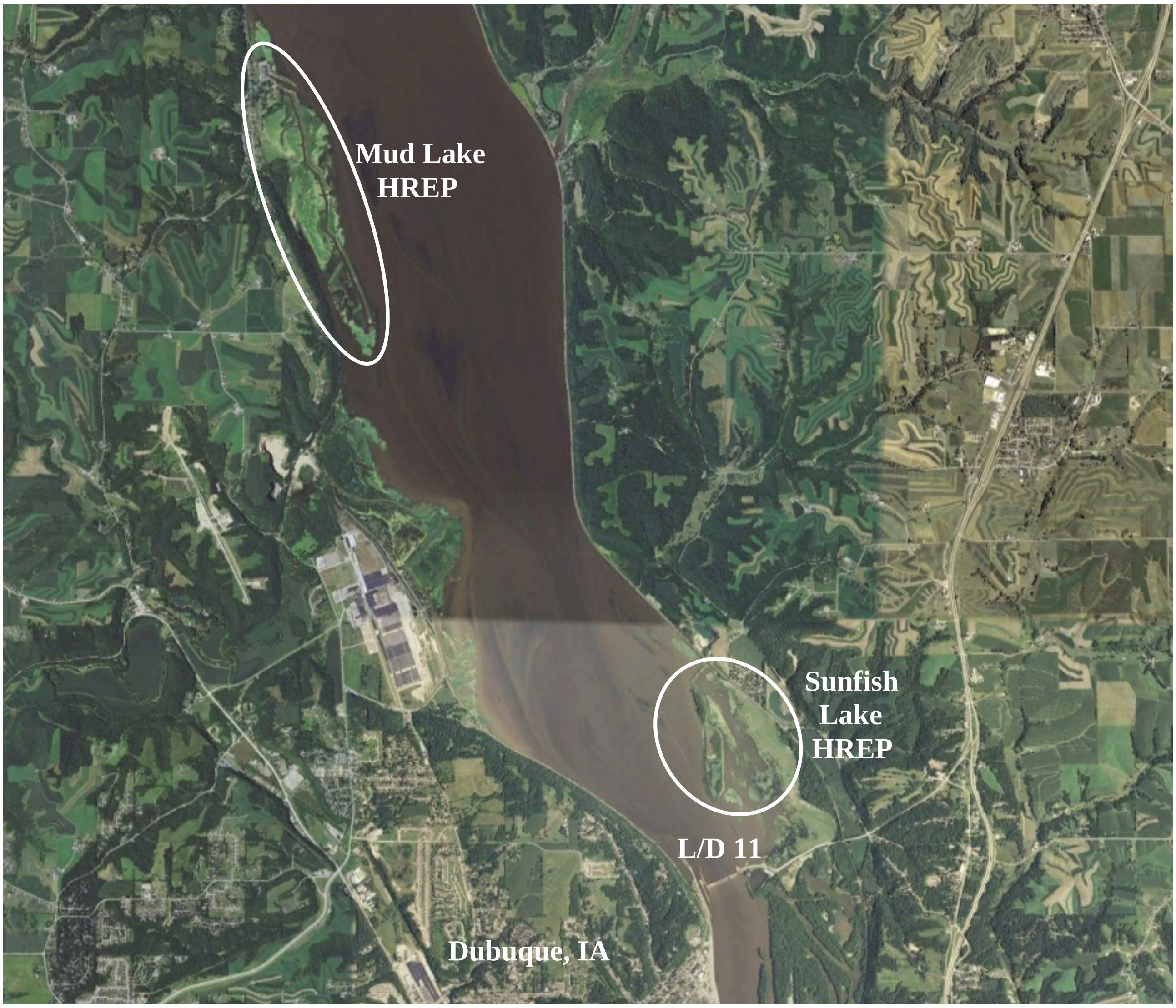


***Figure 1.  Location map for the Mud Lake and Sunfish Lake HREPs.***

maintain a DO of 5 mg/L in the backwater.  The RMA-2 model was used to size the inlets for the required inflow.  Following project construction, both USACE and IDNR personnel measured velocities in the dredge channels that were excessive for overwintering centrarchids.  In 2006, adaptive management measures were incorporated to reduce the inflow.  The opening in the middle of the deflection embankment was completely filled with rock, while the opening at the upper end was partially filled.  This resulted in a significant reduction in velocity in the dredge channels during ensuing winters; however, IDNR fish telemetry studies have indicated the HREP is still underutilized by overwintering centrarchids and velocities continue to be excessive.  According to Scott Gritters (IDNR, personal communication, April 2, 2014), at the start of winter, centrarchids in the HREP prefer to stage in areas with zero flow.

In addition to issues involving velocity magnitude, velocity direction has also been a concern.  A study performed jointly by IDNR and WDNR staff on February 22, 2008 indicated Mississippi River main channel flow enters the backwater area from the dredge channel outlet.  The present study was performed

***Figure 2. Mud Lake HREP project features.***

in order to better define velocities and circulation patterns in the backwater complex in an effort to explain the underutilization of Mud Lake by overwintering fish.

## Methods

As part of the district's HREP performance evaluation monitoring program, USACE personnel performed water quality sampling at Mud Lake on March 6, 2014. This trip provided an opportunity to gather reconnaissance data for the upcoming dye study. The inlet structure was investigated in order to determine ice coverage and an appropriate method for dispensing the dye, and velocity measurements were taken in order to estimate dye travel times. Ice condition and thickness were also determined at several sites in order to assess the level of effort that would be required for completing the dye study.

Sample site locations were determined prior to performing the dye study by utilizing Google Earth Pro software. Historical imagery was viewed in order to select a recent image (September 22, 2011) that provided the best view of the dredge channels and other deep areas in the backwater complex, which were readily recognized as areas devoid of emergent vegetation. The software pointer was placed on the location of each proposed sampling site and the geographical coordinates were recorded. Most of the sampling sites were located in dredge channels, while some were located in Zollicoffer Slough and other areas throughout the backwater. In this initial exercise, 21 sampling locations were identified (see Figure 3).

The fluorescent dye used for the study was a 20 percent solution of Rhodamine WT manufactured by Crompton and Knowles. To determine the amount of dye required for the study, the area of the backwater was estimated using the ruler function in Google Earth Pro. Average water depths were estimated for the dredge channels (1.5 m), Zollicoffer Slough (2.7 m) and the remainder of the backwater complex (0.3 m). The depth for each stratum was multiplied by the area to calculate water volume. The three volumes were added to determine the total water volume of the backwater complex (534,128 $m^3$). This value was compared to the volume calculated for Spring Lake (11,280,000 $m^3$), where a previous dye study was conducted. In the Spring Lake study, it was estimated that 3.5 liters of dye would be required to dye the lake to a concentration of 100 ppt (Bierl, 2002), the approximate level of detection. The volume of Spring Lake is considerably greater than Mud Lake; however, to account for dye fluorescence decay which may have occurred during storage, it was conservatively estimated that 3.75 liters of dye would be sufficient for the Mud Lake study.

Waypoints stored on a GPS (Trimble TSC1 datalogger/Pro XR receiver) were used to locate the 21 sampling sites on the first day of the study (March 10, 2014). The sites were marked with orange spray paint, holes were drilled through the ice and measurements were taken. Sites 2, 8, 9, 10 and 19 were found to have insufficient water depth to allow for collection of a representative water sample; thus, these sites were eliminated from further study. Site 12, located on the river side of the rock-filled notch in the deflection embankment was also dropped from further study when water was observed flowing from the river side of the notch to the backwater side (this site was initially considered due to the possibility of dye exiting the backwater area here). At the remaining sites, water depth, ice thickness, snow depth, dissolved oxygen (DO), water temperature and velocity were recorded. DO and water temperature values were measured at the surface (10 cm below the bottom of the ice), mid-depth (1/2 the water depth) and bottom (10 cm above the bottom) with a YSI Pro ODO Meter. A Sontek FlowTracker ADV was used for taking velocity measurements at the surface. At selected sites, pH was measured at the surface with an Extech Instruments pH100 meter and a depth integrated water sample was collected and analyzed for background fluorescence with a Turner Designs Model 10-AU fluorometer.

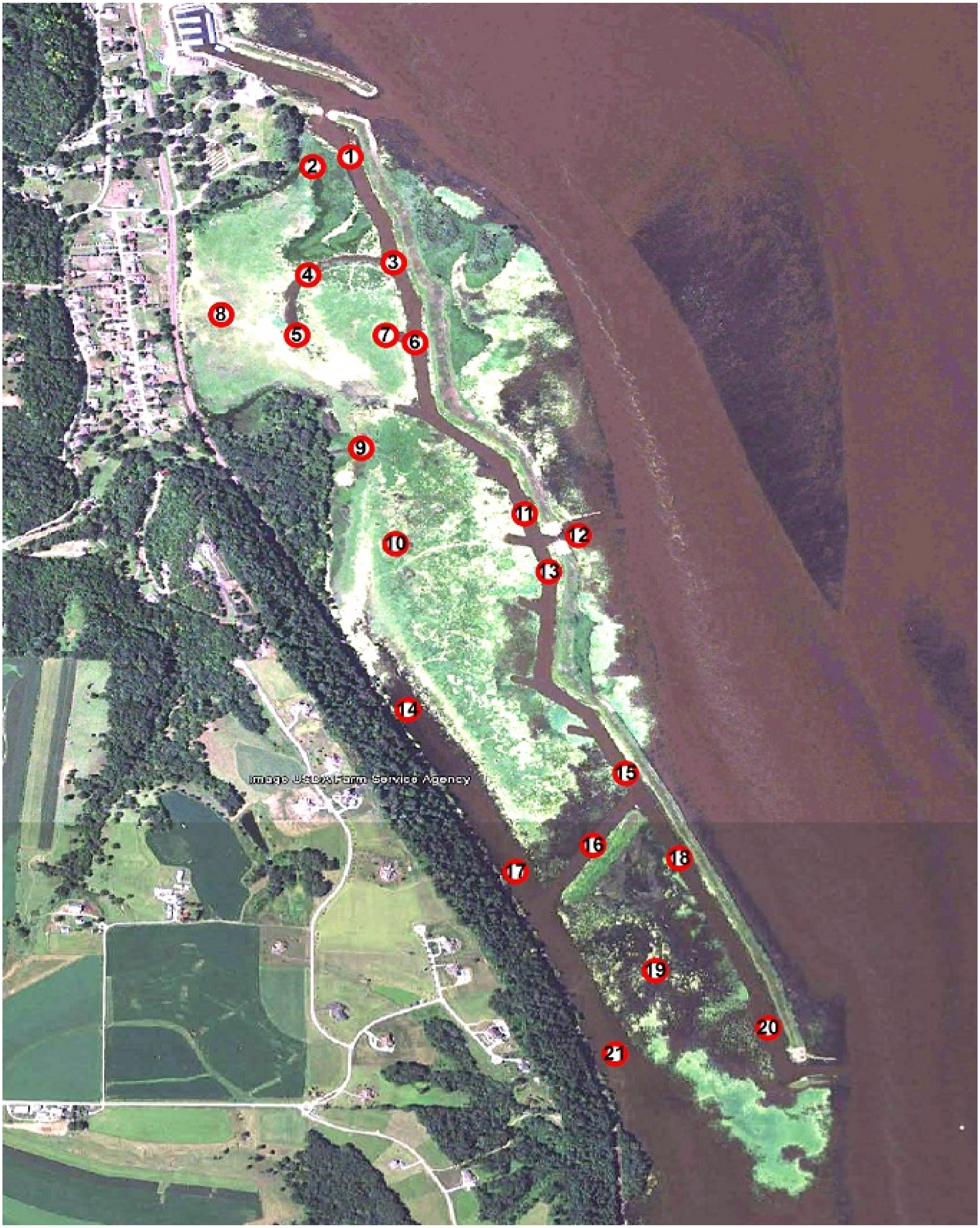


*Figure 3.  Mud Lake HREP initial 21 sampling locations.*

On the morning of March 11, 2014, water collected from the inlet channel of the backwater area was mixed with Rhodamine WT dye in a 151 liter plastic drum fitted with a spigot and a one meter discharge tube (see Figure 4). In order to facilitate assimilation of the dye with the inflow, 3.75 liters of dye were mixed with 121 liters of river water. This helped reduce the viscosity of the dye and equilibrate the temperature of the dye with that of the inflowing river water in order to allow for more complete mixing. A single slug injection of the dye commenced at 0830 hours and was completed by 0900 hours. The dye was then tracked.

***Figure 4. Dye delivery apparatus.***

A water sample was collected at each site with a 2.8 m length of ½-inch diameter EMT conduit with back-to-back #0 conduit hangers fastened near one end (see Figure 5). A 40 ml, amber glass vial with silicon septum screw cap was snapped into place in the conduit hanger. The narrow opening of the cap (following removal of the silicon septum) allowed the bottle to fill relatively slowly; thus, allowing for sample collection throughout the depth profile. The sampling apparatus was lowered into the hole until it approached the bottom and was then raised at the same rate. This allowed for a depth integrated sample. Following collection, a portion of the sample was poured into a 13 mm cuvette and immediately analyzed for the presence of dye with the fluorometer. This process helped assure the temperature of all samples was similar; thus, minimizing the impact of temperature variation on dye concentration. According to Johnson (1984), Rhodamine WT fluorescence decreases approximately five percent for every 2°C increase in temperature. In order to prevent cross-contamination, the sampling apparatus and ice auger/chisel were rinsed with non-dye tainted river water after each sample containing dye was collected. DO, water temperature and velocity measurements were taken at selected sites to determine if these parameters changed significantly from day one of the study.


***Figure 5. Dye sampling apparatus.***

Once dye tracking commenced, additional sampling sites were identified (see Figure 6) in order to locate the leading edge of the dye at various times. When the sampling results indicated dye had not reached site 18 at the predicted time, a second dye injection was made in the dredge channel outlet to validate velocity data collected by IDNR and WDNR personnel in 2008 which indicated Mississippi River main channel flow enters the backwater area from the dredge channel outlet. The second slug injection of dye commenced at 1214 hours and was completed by 1224 hours on March 12, 2014. This injection was administered in a similar fashion as the first injection; however, approximately one-half the amount of dye and river water was mixed in the drum. Water samples were collected at the three sampling sites located near the outlet (sites 26-28) in order to verify the dye's direction of travel.

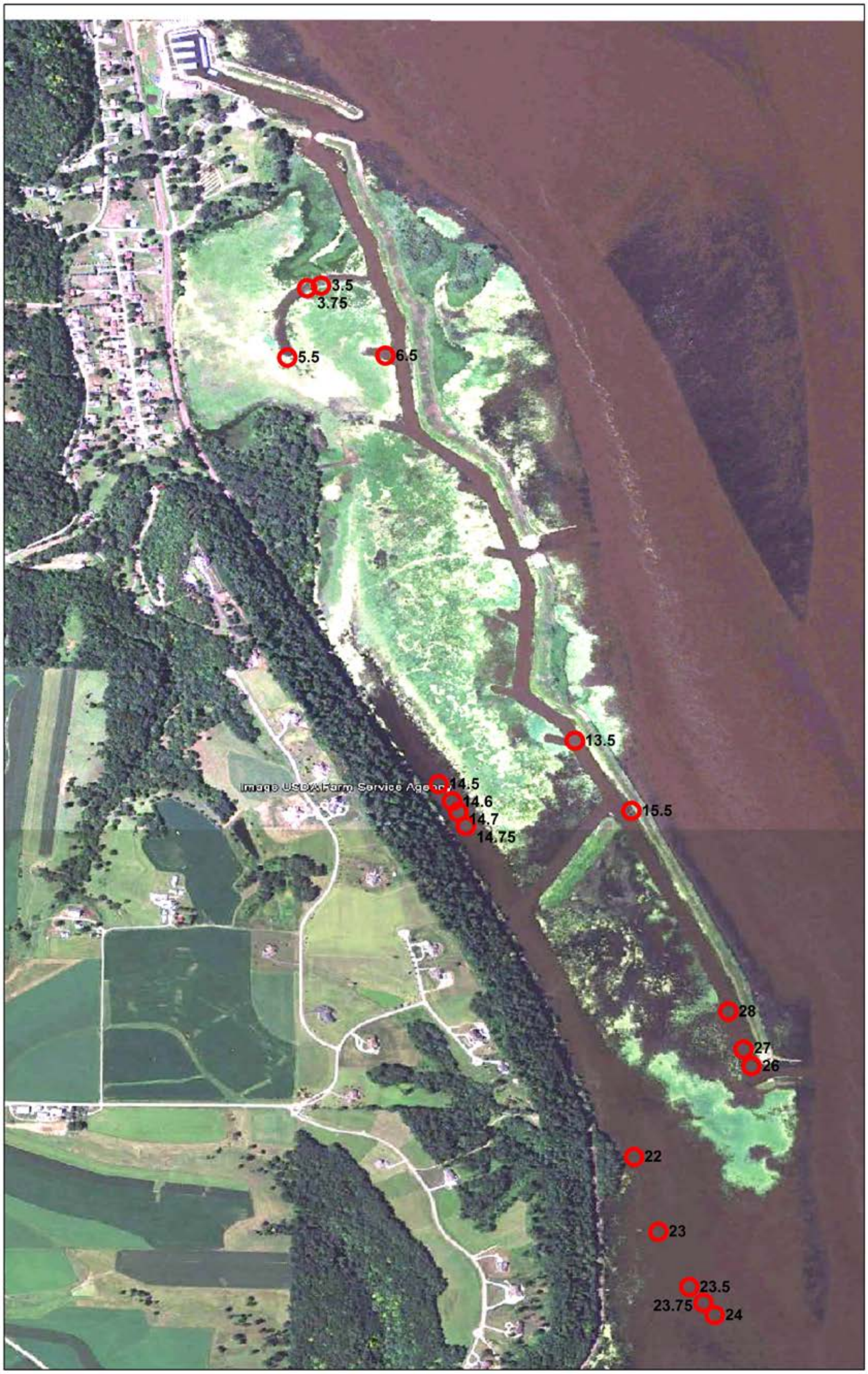


*Figure 6. Mud Lake HREP additional sampling sites.*

## Results and Discussion

The Mississippi River elevation during the study was close to the long-term historic average as measured at the Lock and Dam 11 gage (see Figure 7). Over the course of the study, the river rose approximately 0.5 feet. The 6:00 a.m. river elevations on March 10, 2014 and March12, 2014 were 605.61' and 606.07' upstream at the Guttenberg, Iowa gage and 593.62' and 594.15' downstream at the Lock and Dam 11

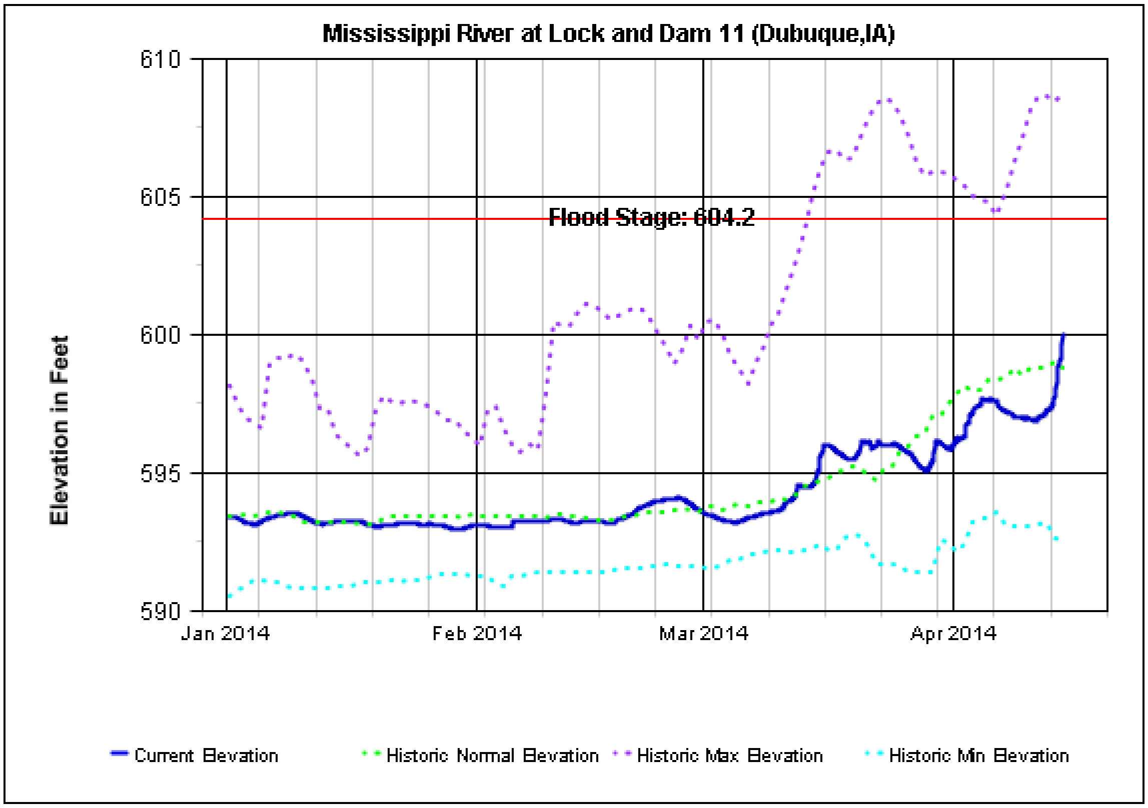


***Figure 7. Mississippi River elevation at L/D 11 (Dubuque, IA).***

gage, respectively. Field data collected on March 10, 2014 are given in Table 1. The winter of 2013/2014 was one of the coldest on record; thus, ice thickness was much greater than during a typical winter, with values ranging from 27.9 cm at site 16 to 66.0 cm at site 17. The combination of thick ice and shallow water depth at sites 2, 8, 9, 10 and 19 precluded collection of a representative water sample; therefore, these sites were eliminated from further study. Site 12, which was initially considered due to the possibility of dye exiting the backwater area here, was also dropped from further study when water was observed flowing from the river side of the rock-filled deflection embankment notch into the backwater side. The remaining sites, all located within dredge channels or in Zollicoffer Slough, had water depths ranging from 1.49 m at the upper end of Zollicoffer Slough (site 14), to 2.74 m at the lower end of Zollicoffer Slough (site 21). The average depth of sites located in dredge channels was 1.89 m, with the deepest area (> 2.0 m) located in the middle of the main dredge channel (sites 11, 13 and 15) and the shallowest area (1.50 m) at site 20, near the dredge channel outlet. Snow was present at all sites with depths ranging from 2.5 cm at several locations to 10.2 cm at site 17. All surface DO values in the backwater area were below saturation, but were more than sufficient to support aquatic life. Concentrations varied little, ranging from 11.34 to 12.34 mg/L. Mid-depth and bottom DO concentrations were similar to surface values, except for sites 4, 5, 14 and 21, where bottom concentrations were lower. The most prominent stratification occurred in the curved dredge channel in Mud Lake (sites 4 and 5). Here, in addition to low bottom DO concentrations (3.66 and 1.92 mg/L, respectively), velocity was also low (0.32 and 0.35 cm/s, respectively). Stratification was less prominent

*Table 1. Field data collected on March 10, 2014, prior to dye dispersal.*

| Site* | Time | Water Depth (m) | Ice (cm) | Snow (cm) | D.O. (mg/L) | Water Temp. (°C) | Velocity (cm/s) | pH | Dye Blank (µg/L) |
|---|---|---|---|---|---|---|---|---|---|
| 1S | 1708 | 1.89 | 35.6 | 2.5 | 12.34 | 0.5 | 6.17 | 7.62 | 0.770 |
| M | | | | | 12.37 | 0.4 | | | |
| B | | | | | 12.38 | 0.3 | | | |
| 3S | 1640 | 1.78 | 45.7 | 2.5 | 12.21 | 0.5 | 5.37 | | |
| M | | | | | 12.24 | 0.4 | | | |
| B | | | | | 12.21 | 0.4 | | | |
| 4S | 1653 | 1.88 | 53.3 | 7.6 | 11.97 | 0.7 | 0.32 | | |
| M | | | | | 12.00 | 0.7 | | | |
| B | | | | | 3.66 | 1.4 | | | |
| 5S | 1550 | 1.98 | 58.4 | 5.1 | 11.58 | 0.7 | 0.35 | 7.48 | 0.953 |
| M | | | | | 11.88 | 0.8 | | | |
| B | | | | | 1.92 | 1.6 | | | |
| 6S | 1627 | 1.85 | 48.3 | 7.6 | 11.98 | 0.6 | 5.20 | | |
| M | | | | | 12.03 | 0.4 | | | |
| B | | | | | 12.04 | 0.4 | | | |
| 7S | 1608 | 1.74 | 61.0 | 5.1 | 11.70 | 0.6 | 0.41 | | |
| M | | | | | 11.68 | 0.5 | | | |
| B | | | | | 11.62 | 0.7 | | | |
| 11S | 1519 | 2.23 | 50.8 | 5.1 | 11.71 | 0.5 | 3.94 | | |
| M | | | | | 11.64 | 0.4 | | | |
| B | | | | | 11.55 | 0.4 | | | |
| 12 | 1506 | 0.46 | 43.2 | 2.5 | 15.43 | 0.6 | | | |
| 13S | 1449 | 2.19 | 50.8 | 5.1 | 11.42 | 0.6 | 3.56 | 7.50 | 0.848 |
| M | | | | | 11.45 | 0.5 | | | |
| B | | | | | 11.43 | 0.5 | | | |
| 14S | 1238 | 1.49 | 55.9 | 5.1 | 11.34 | 0.5 | 0.24 | 7.49 | 0.731 |
| M | | | | | 11.25 | 0.4 | | | |
| B | | | | | 9.08 | 0.7 | | | |
| 15S | 1225 | 2.20 | 43.2 | 7.6 | 11.55 | 0.5 | 4.03 | | |
| M | | | | | 11.60 | 0.3 | | | |
| B | | | | | 11.50 | 0.2 | | | |
| 16S | 1213 | 1.70 | 27.9 | 7.6 | 11.93 | 0.3 | 6.55 | 7.48 | 0.737 |
| M | | | | | 11.83 | 0.3 | | | |
| B | | | | | 11.72 | 0.2 | | | |
| 17S | 1150 | 2.46 | 66.0 | 10.2 | 11.63 | 0.4 | 0.64 | | |
| M | | | | | 11.55 | 0.4 | | | |
| B | | | | | 11.35 | 0.4 | | | |
| 18S | 1127 | 1.68 | 55.9 | 5.1 | 11.68 | 0.5 | 3.02 | 7.52 | |
| M | | | | | 11.72 | 0.4 | | | |
| B | | | | | 11.77 | 0.3 | | | |
| 20S | 1049 | 1.50 | 53.3 | 7.6 | 11.62 | 0.6 | 3.60 | 7.46 | 0.754 |
| M | | | | | 11.76 | 0.2 | | | |
| B | | | | | 11.77 | 0.2 | | | |
| 21S | 1024 | 2.74 | 53.3 | 7.6 | 11.84 | 0.4 | 2.10 | 7.49 | 0.853 |
| M | | | | | 11.88 | 0.3 | | | |
| B | | | | | 8.57 | 1.0 | | | |

* "S" readings taken at 10 cm under the ice, "M" at 1/2 water depth, "B" at 10 cm off of bottom. Sites 2, 8, 9, 10 and 19 were too shallow to sample.

at sites 14 and 21 located in Zollicoffer Slough (bottom DO concentrations of 9.08 and 8.57 mg/L, respectively). A similar stratification pattern was seen with water temperature, where most values changed little throughout the depth profile and surface values ranged from 0.3 to 0.7°C. Again, sites 4, 5, 14 and 21 showed some stratification, with bottom temperatures ranging from 0.7 to 1.6°C. Another parameter which showed a narrow range of variance throughout the backwater area was pH: surface values ranged from 7.46 to 7.62. Sample fluorescence blanks were collected at sites 1, 5, 13, 14, 16, 20 and 21 in order to determine background concentrations, which ranged from 0.731 to 0.953 µg/L.

All velocity readings in the main dredge channel exceeded 3.00 cm/s, ranging from 3.02 cm/s at site 18 to 6.17 cm/s near the inlet (site 1). Surprisingly, the highest velocity measured was 6.55 cm/s at site 16, in the angled channel that connects the main dredge channel with Zollicoffer Slough. Velocity measurements at sites 18 and 20 validated the findings of a 2008 IDNR/WDNR study which indicated Mississippi River main channel flow enters the backwater area from the dredge channel outlet. During the present study, it is surmised that flow from the outlet continued up the main dredge channel past site 18 until the vicinity of the dredge material island, where it either joined the flow coming from above and was routed through the angled dredge channel to Zollicoffer Slough, or was deflected toward Zollicoffer Slough just below the island, or perhaps some combination of the two scenarios. Upon entering Zollicoffer Slough, the flow split with the majority coursing downstream. Figure 8 displays the general direction and velocity of flow in the backwater complex on March 10, 2014. Lower velocities were measured in the dredge channel in Mud Lake (0.32 and 0.35 cm/s at sites 4 and 5, respectively), in a short dredge cut off of the main dredge channel (0.41 cm/s at site 7) and at sites 14 and 17 in Zollicoffer Slough (0.24 and 0.64 cm/s, respectively).


***Figure 8. Mud Lake HREP velocities on March 10, 2014.***

Following injection of dye at the inlet on the morning of March 11, 2014, tracking commenced. Sampling sites were added as needed in an effort to locate the leading edge of the dye before it arrived at the next established sampling point. Based on the background fluorescence concentrations measured and several initial fluorometer readings, it was determined a positive "hit" for dye would be a concentration ≥1.00 μg/L. Fluorescence concentration results for each site, including the date and time of measurement are included in Table 2. The dye had reached site 1 before there was an opportunity to collect a sample. At most sites, at least one measurement was taken before the dye was detected; thus, giving a good indication as to when the leading edge of the dye plume had arrived. At others, dye was detected on the first measurement; therefore, it was difficult to estimate how much time had lapsed since the leading edge of the dye plume had passed. No samples were collected between 2134 hours on March 11, 2014 and 0822 hours on March 12, 2014; thus, at sites 4 and 5 the dye had likely already passed before it could be detected. Dye was detected at site 5.5 at 0846 hours on March 12, 2014; however, this may have been the trailing edge of the dye plume. The dye transited the main dredge channel until it reached the dredge material island, where flow traveling up from the outlet essentially deflected the dye to the southwest. This was substantiated because the dye arrived at site 16 at 2003 hours but did not arrive at site 15.5, at the northeast tip of the dredge material island, until approximately 2107 hours. The delay in arrival of dye at site 15.5, coupled with the non-arrival of dye at site 18, indicates an upstream movement of flow in the main dredge channel below the island. It is surmised that site 15.5 is located in an eddy where the two flow paths meet; however, lacking additional data it is difficult to determine if the majority of the flow from the outlet was deflected along the upstream or downstream side of the island.

Once the dye passed site 16, it entered Zollicoffer Slough. Here, a majority of the dye flowed downstream, while a small portion traveled upstream. The approximate elapsed time (hours) the dye took to reach selected sampling sites is given in Figure 9. The leading edge of the dye reached the farthest downstream Zollicoffer Slough site (23.75) in 25.4 hours, while it took approximately 30.3 hours to arrive at site 14.6, which was located in Zollicoffer Slough, just upstream of the dredge material island.

A second dye injection took place midday on March 12, 2014 in order to verify the upstream direction of flow from the outlet. Dye was injected in the outlet at 1214 hours and after 0.5 hour had arrived at site 26 and following 2.2 hours was detected at site 28; thus, confirming the upstream direction flow.

## Conclusions and Recommendation

A Rhodamine WT dye study was performed during March 2014 in Mud Lake, a backwater of the Mississippi River, Pool 11, near Dubuque, Iowa. The study was conducted in response to the underutilization by overwintering fish of newly created dredge channels, and velocity data that indicated Mississippi River main channel flow was entering the backwater area from the dredge channel outlet. The results from the study indicate velocities in Mud Lake still exceed the level preferred by centrarchids in early winter. The results also confirmed the upstream travel of flow from the dredge channel outlet.

It is imperative that additional adaptive management measures be investigated in order to reduce velocities in Mud Lake so the area provides a viable overwintering site. It is recommended the initial RMA-2 model be revised to reflect as-built conditions and utilize data collected in the present study for model calibration. The updated model could be utilized to evaluate new adaptive management strategies for reducing/redirecting flow.

*Table 2. Rhodamine WT concentrations from samples collected on March 11 and 12, 2014.*

| Site | Date | Time | Dye (µg/L)* |
|---|---|---|---|
| 3 | 3/11/2014 | 9:33 | 0.557 |
| 3 | 3/11/2014 | 9:40 | 0.540 |
| 3 | 3/11/2014 | 9:45 | 0.732 |
| 3 | 3/11/2014 | 9:48 | 0.748 |
| 3 | 3/11/2014 | 9:50 | 0.763 |
| 3 | 3/11/2014 | 9:53 | 0.800 |
| 3 | 3/11/2014 | 9:57 | 0.775 |
| 3 | 3/11/2014 | 10:02 | 0.757 |
| 3 | 3/11/2014 | 10:07 | 1.09 |
| 3 | 3/11/2014 | 10:13 | 19.2 |
| 3.5 | 3/11/2014 | 13:30 | 0.504 |
| 3.5 | 3/11/2014 | 15:51 | 1.54 |
| 3.75 | 3/11/2014 | 17:13 | 0.833 |
| 3.75 | 3/11/2014 | 17:20 | 1.61 |
| 3.75 | 3/11/2014 | 21:34 | 0.688 |
| 4 | 3/11/2014 | 13:25 | 0.774 |
| 4 | 3/11/2014 | 15:56 | 0.681 |
| 4 | 3/11/2014 | 16:38 | 0.502 |
| 4 | 3/11/2014 | 16:57 | 0.678 |
| 4 | 3/11/2014 | 18:34 | 0.573 |
| 4 | 3/11/2014 | 18:46 | 0.539 |
| 4 | 3/11/2014 | 18:56 | 0.563 |
| 4 | 3/11/2014 | 21:33 | 0.671 |
| 5 | 3/12/2014 | 8:22 | 0.965 |
| 5 | 3/12/2014 | 8:32 | 0.781 |
| 5.5 | 3/12/2014 | 8:46 | 1.58 |
| 6 | 3/11/2014 | 10:47 | 0.629 |
| 6 | 3/11/2014 | 10:54 | 0.685 |
| 6 | 3/11/2014 | 10:59 | 0.717 |
| 6 | 3/11/2014 | 11:04 | 0.714 |
| 6 | 3/11/2014 | 11:09 | 0.757 |
| 6 | 3/11/2014 | 11:14 | 0.766 |
| 6 | 3/11/2014 | 11:19 | 0.708 |
| 6 | 3/11/2014 | 11:24 | 3.67 |
| 6.5 | 3/11/2014 | 12:24 | 1.04 |
| 6.5 | 3/11/2014 | 13:13 | 6.92 |
| 6.5 | 3/11/2014 | 15:31 | 15.5 |
| 7 | 3/11/2014 | 11:42 | 0.518 |
| 7 | 3/11/2014 | 11:49 | 0.455 |
| 7 | 3/11/2014 | 11:59 | 0.634 |
| 7 | 3/11/2014 | 12:09 | 0.678 |
| 7 | 3/11/2014 | 12:17 | 0.649 |
| 7 | 3/11/2014 | 13:11 | 0.469 |
| 7 | 3/11/2014 | 13:36 | 0.696 |
| 7 | 3/11/2014 | 14:17 | 0.635 |
| 7 | 3/11/2014 | 14:23 | 0.693 |
| 7 | 3/11/2014 | 14:28 | 0.728 |
| 7 | 3/11/2014 | 14:33 | 0.569 |
| 7 | 3/11/2014 | 14:38 | 0.594 |
| 7 | 3/11/2014 | 15:25 | 0.713 |
| 7 | 3/11/2014 | 15:33 | 0.643 |
| 7 | 3/11/2014 | 15:43 | 0.728 |
| 7 | 3/11/2014 | 16:44 | 5.37 |
| 11 | 3/11/2014 | 13:51 | 0.571 |
| 11 | 3/11/2014 | 13:58 | 0.841 |
| 11 | 3/11/2014 | 14:03 | 0.836 |
| 11 | 3/11/2014 | 14:08 | 1.03 |
| 11 | 3/11/2014 | 14:13 | 2.18 |
| 13 | 3/11/2014 | 14:46 | 0.787 |
| 13 | 3/11/2014 | 14:52 | 0.726 |
| 13 | 3/11/2014 | 14:58 | 0.767 |
| 13 | 3/11/2014 | 15:04 | 0.865 |
| 13 | 3/11/2014 | 15:09 | 0.803 |
| 13 | 3/11/2014 | 15:14 | 0.970 |
| 13 | 3/11/2014 | 15:19 | 1.39 |
| 14.5 | 3/12/2014 | 10:31 | 0.584 |
| 14.5 | 3/12/2014 | 14:53 | 0.684 |
| 14.6 | 3/12/2014 | 10:37 | 0.782 |
| 14.6 | 3/12/2014 | 14:49 | 2.33 |
| 14.7 | 3/12/2014 | 10:12 | 3.60 |
| 14.75 | 3/12/2014 | 10:25 | 4.43 |
| 15 | 3/11/2014 | 19:08 | 3.08 |
| 15.5 | 3/11/2014 | 21:07 | 6.12 |
| 16 | 3/11/2014 | 19:20 | 0.503 |
| 16 | 3/11/2014 | 19:30 | 0.485 |
| 16 | 3/11/2014 | 19:41 | 0.479 |
| 16 | 3/11/2014 | 19:51 | 0.637 |
| 16 | 3/11/2014 | 20:03 | 1.12 |
| 17 | 3/11/2014 | 21:18 | 0.471 |
| 17 | 3/12/2014 | 9:04 | 3.61 |
| 18 | 3/11/2014 | 20:11 | 0.495 |
| 18 | 3/11/2014 | 20:24 | 0.462 |
| 18 | 3/11/2014 | 20:36 | 0.461 |
| 18 | 3/12/2014 | 10:08 | 0.626 |
| 21 | 3/12/2014 | 9:13 | 3.13 |
| 22 | 3/12/2014 | 9:21 | 14.3 |
| 23 | 3/12/2014 | 9:31 | 12.3 |
| 23.5 | 3/12/2014 | 9:47 | 3.44 |
| 23.75 | 3/12/2014 | 9:52 | 1.82 |
| 24 | 3/12/2014 | 9:38 | 0.885 |
| 20** | 3/12/2014 | 13:23 | 0.760 |
| 20** | 3/12/2014 | 13:36 | 0.648 |
| 20** | 3/12/2014 | 13:46 | 77.5 |
| 26** | 3/12/2014 | 12:36 | 0.844 |
| 26** | 3/12/2014 | 12:42 | >100 |
| 27** | 3/12/2014 | 12:49 | 0.915 |
| 27** | 3/12/2014 | 12:51 | 0.974 |
| 27** | 3/12/2014 | 12:54 | 1.11 |
| 27** | 3/12/2014 | 12:58 | 0.977 |
| 27** | 3/12/2014 | 13:05 | 0.959 |
| 27** | 3/12/2014 | 13:16 | 18.1 |
| 28** | 3/12/2014 | 13:56 | 0.705 |
| 28** | 3/12/2014 | 14:03 | 0.697 |
| 28** | 3/12/2014 | 14:13 | 0.754 |
| 28** | 3/12/2014 | 14:27 | >100 |

* Shaded concentration indicates dye detected.

** Site tracked as part of second dye injection.


*Figure 9. Mud Lake HREP Rhodamine WT dye travel times (hours).*

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