PHASE 2 Technical Memorandum for Red and Assiniboine Ammonia Criteria Study

From: M. J. Lawrence
Task Leader, Fish Behaviour Workstream

To: City of Winnipeg Project Management Committee
Study Team Members

Subject: **Fish Behaviour Technical Memorandum # FB 04**

Title: **Movements of 10 northern pike tagged with acoustic transmitters in the Red River in the vicinity of the NEWPCC effluent plume, February-March, 2000.**

Prepared by: J. B. Eddy, C. C. Barth and M. J. Lawrence

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1.0 INTRODUCTION

The ammonia criteria study was initiated by the City of Winnipeg in response to the Clean Environment Commission's recommendations to the Minister of Environment regarding water quality objectives for the Red and Assiniboine rivers within and downstream of the City of Winnipeg (Tetr*ES* Consultants Inc. 1999). The City of Winnipeg operates three water pollution control centres, the North End Water Pollution Control Centre (NEWPCC), which treats an estimated 70% of the City of Winnipeg's raw sewage (Tetr*ES* Consultants Inc. 1999), the South End Water Pollution Control Centre (SEWPCC), and the West End Water Pollution Control Centre (WEWPCC). The effluent released from the NEWPCC enters the Red River approximately 170 m upstream of the Kildonan Settlers Bridge (KSB), which is also known as Chief Peguis Bridge. Treated sewage from the NEWPCC is usually held in settling ponds for a period of four days prior to its introduction to the Red River. However, during periods of high run off or precipitation the NEWPCC can become overloaded, and the resulting release of effluents periodically causes ammonia levels in the Red River to exceeded water quality limits established by the Manitoba Surface Water Quality Objectives (Gurney, 1991; Tetr*ES* Consultants Inc. 1999). Ammonia levels have also been known to exceed water quality limits in periods of low flow, which result in effluent releases making up a much larger portion of the total volume of the river (Gurney 1991).

Ammonia, which is a toxicant to fishes and other aquatic wildlife, enters the aquatic environment from a variety of sources, including industrial wastes and sewage effluents (Thurston et al. 1981a). During winter, the effects that ammonia discharged from the NEWPCC into the Red River can have on fish and fish behaviour may be greater than during the rest of the year. This is due to a combination of factors, such as lower river flows relative to effluent discharge, low or non-existent algal uptake of ammonia, reduced rates of nitrification (i.e., bacterial degradation of ammonia), and the potential for increased sensitivity of fish to unionized ammonia toxicity at lower temperatures (Williamson 1988; Lemly 1996). As a result, the health of fish that may be attracted to the City of Winnipeg's effluent plumes during the winter months is a concern.

A better understanding of localized fish movements is required to estimate the potential exposure of fish to municipal effluent plumes. The timing, frequency, and duration of times that fish spend within and downstream of effluent plumes play an important role in determining the potential exposure to contaminants. Volumes of effluent, and the levels of ammonia, chlorine, and other chemicals that it contains, will vary over time. As a result, the timing of fish movements into areas that are affected by effluent plumes will have a direct effect on the levels of ammonia and other chemicals that the fish are exposed to. Frequency is an important consideration because it determines how often a fish will be exposed to effluent in a given period of time. However, determining the frequency of exposure for fish outside of a laboratory environment is difficult, and prior to this study, had not been studied in relation to the City of Winnipeg's effluent plumes. Duration of exposure is a particularly relevant factor in the potential chronic toxicity of contaminants to fish (i.e., effects on growth, reproduction and susceptibility to disease). The duration of times that fish remain within effluent plumes, and the ammonia concentrations that they are exposed to during these times, are important variables that must be considered when discussing the potential acute or chronic effects associated with exposure.

In March, 1999, a gillnetting survey was conducted in the vicinity of the NEWPCC effluent plume to determine the abundance and composition of fish species that may be attracted to the area during cold weather periods (Lawrence 1999). Results suggested that northern pike (*Esox lucius*) were an abundant fish species in the vicinity of the NEWPCC effluent plume in March, 1999. However, the study was not able to answer the following questions:

1) are fish attracted to the NEWPCC effluent plume during the winter months, or are fish only passing through this area?;

2) how frequently are fish moving into the effluent plume and when is this occurring?; and,

3) if fish are attracted to the NEWPCC effluent plume, how long are they being exposed to the treated effluent, and is the duration of exposure long enough to contribute to the potential chronic effects that treated sewage may have on fish populations?

To answer the above questions, a radio linked acoustic positioning system was used to record positions every 300 seconds for 10 northern pike tagged with intraperitoneally implanted acoustic transmitters in the vicinity of the NEWPCC. The tags also provided temperature information, which was used to help determine when fish were located in the direct influence of the effluent plume.

Objectives of the study were as follows:

- to determine the distribution of northern pike in relation to ammonia gradients in the vicinity of the NEWPCC effluent plume; and,
- to determine the duration of time that fish remain within the direct influence of the NEWPCC effluent plume.

2.0 METHODS

2.1 Study area

The NEWPCC effluent plume enters the west side of the Red River approximately 170 m upstream of the Kildonan Settlers Bridge. The study area consisted of the reach of the Red River approximately 1 km downstream and 500 m upstream from the NEWPCC effluent outfall. Although the Red River changes direction just downstream of the Kildonan Settlers Bridge, the river generally flows in a south to north direction. In this report the right hand bank when facing upstream is referred to as the west bank, and the opposite bank is referred to as the east bank (Figure 1).

2.2 Tracking system

Fish were tracked with two radio-linked acoustic positioning arrays (VRAP) manufactured by VEMCO Ltd. One array was placed upstream, and one downstream of the Kildonan Settlers Bridge, in the configuration shown in Figure 2, on February 13, 2000. Testing of the acoustic positioning system was completed on the same day. Each array consisted of three stationary receivers (either frozen into the ice or anchored to the river bottom) (Figure 3), which communicated via VHF radio modems to a computer controlled base station positioned inside the base of the Kildonan Settlers Bridge. Each buoy contained an omni-directional hydrophone, a frequency synthesized ultrasonic receiver, a two-way radio link and a microprocessor controller. The base station consisted of a two-way radio, an interface box with signal timer, and a laptop computer for each array loaded with the appropriate software. The base station was programmed to communicate with each receiver individually, and to automatically listen to a different prescribed frequency every 30 seconds. Acoustic signals of up to ten distinct frequencies (from the ten tagged northern pike) were received by each receiver. The difference in the length of time that it took for a signal to travel from a tag to each individual receiver determined the distance that the fish containing that tag was from that receiver. These distances where then used by the system to plot the location of the fish in relation to the three receivers in an acoustic array by triangulation.

Positions for each tag relative to the array were determined every 300 seconds. Temperature data were encoded by the tags as ping information and transmitted to the base station, automatically decoded, and stored along with the corresponding positional data. Tracking was initiated as soon as tagged fish were released to the Red River. The movements of tagged fish were monitored continuously until February 26, when unseasonably warm weather caused an early breakup along the Red River, and unstable ice conditions forced the removal of the stationary receivers. After the removal of the VRAP arrays, it was no longer possible to triangulate the position of each fish. To further monitor the presence of tagged fish in the vicinity of the NEWPCC plume a VEMCO VR-60 portable ultrasonic receiver was used. The VR-60 ultrasonic receiver is capable of detecting signals from acoustic tags up to a distance of 800 m (Barth and Lawrence 2000), but is incapable of decoding the temperature information transmitted from each tag. As a result, data collected between February 27 and March 9 were limited to determining whether a specific fish was present or absent in the vicinity of the NEWPCC effluent plume.

2.3 Transmitters

Ten V16T - 4H temperature transmitters were used in the study (VEMCO Ltd.). These tags were 68 mm long, weighed 12 g in water, and had a battery life of 108 days. To activate each tag, two protruding wires located on the anterior end of each transmitter were cut to approximately 1 cm lengths, stripped of insulation, twisted together and soldered. The soldered wires, were then epoxied to the transmitter for protection. Prior to being inserted into a fish, each transmitter was air tested with a portable VR-60 ultrasonic receiver to ensure that a recognizable pulse was being transmitted. Tags were labelled with the manufacturer's name and address and a four-digit number, which was also used in this study to identify each fish.

2.4 Fish Tagging

To reduce fish stress, and ensure that they were in good condition for internal tagging, fish were captured by angling rather than gill nets. Angling equipment consisted of *Polar* brand tip-ups loaded with 30 lb test black nylon fishing line tied to a "quick strike" rig baited with frozen smelt. The "quick strike" rig consisted of two barbless treble hooks, one fixed to the bottom of the rig, and the other free moving. The fixed hook was hooked through the head of the smelt, and the free moving hook through the smelt's body, which maintained the smelt in a horizontal position in the water column. The bait was positioned approximately 30 cm off the bottom. Tip-ups were set in depths ranging from 1 to 5 m within an area ranging from approximately 100 m to 250 m downstream of the NEWPCC outfall along the west bank. A small aluminum boat was used to set tip-ups in areas with very thin ice, such as those immediately downstream of the NEWPCC outfall, (Figure 4).

Captured fish that were large enough for internal tagging (>1100 g) were anaesthetized by immersing the fish in a tub of water treated with clove oil until loss of equilibrium was observed. The fish was then measured for fork length (±1 mm), and weighed (±25 g) prior to tagging. Tag weight in water was no greater than 1.0% of the weight of the smallest fish that was tagged, well under the 2.5% recommended by Ross and McCormick (1981).

Acoustic tags were inserted into fish through a small (approximately 1.5 cm long) mid-ventral incision (Figures 5 and 6). Once the tag was properly fit into the peritoneal cavity, three sutures were used to close up the incision (Figures 7 and 8). Surgeries lasted less than two minutes. After the surgical procedure was completed, fish were transferred to a tub of fresh river water to allow them to be monitored for signs of recovery. Once fish regained their equilibrium they were released back into the river within 50 m of their point of capture.
Tagging began on February 14, 2000 and ended on February 19. Two fish were tagged on February 14, two on February 15, two on February 16, one on February 17, two on February 18, and one on February 19. A summary of tag number, tag frequency, fork length, weight, and tagging date for each fish is provided in Table 1.

2.5 Data Presentation

A map of ammonia concentrations in the Red River ranging from the NEWPCC outfall downstream to the Kildonan Settlers Bridge, was provided by Tetr*ES* Consultants Inc.. This map was produced with CORMIX (Cornell University Mixing Zone Model), a widely accepted computer modelling tool used in the evaluation of effluent discharge plumes (Jirka et al. 1996). This program can be used to predict the trajectory of water quality parameters (in this case ammonia) in relation to thermal effluent plumes at the point they are discharged into a water body. The model was applied to the NEWPCC thermal effluent plume at the point where it enters the Red River. Outputs from CORMIX were plotted on maps, such as the one provided in Figure 9. The map used in this report provides an indication of “average” ammonia concentrations that fish may have encountered in this reach of the Red River from February 14 to February 24, 2000.

The acoustic positioning system produced position data tables for both the stationary receivers and individual fish using an XY coordinate system. Fish positions that were in range of the acoustic arrays were recorded, along with the date, time, fish ID number, and temperature. Two data files for each fish were collected on a daily basis, one from each array of buoys. These data were then transferred to a spreadsheet program (Microsoft Excel 2000), plotted on a grid coordinate system in Map Maker 2.0, and overlaid on the CORMIX plotted map of the “average” ammonia concentrations in the NEWPCC plume. The resulting maps showing fish positions during the study period were then transferred to Corel Draw 8.0 for further data analysis and report presentation. Figures 10 to 55 illustrate daily positional data for individual fish in the vicinity of the NEWPCC effluent plume, and in relation to “average” modelled ammonia concentrations. Fish positions on the maps often overlap for time periods when fish were located consistently in the same location. This was taken into account during data analysis. However, overlapping points in Figures 10 to 55 may cause fish to appear to have less plotted locations and to have occupied certain areas for shorter time periods than they actually had.

The volume of effluent discharged from the NEWPCC varies over the course of a day. The effluent plume shown in Figures 10 to 55 does not account for this daily variance in the volume of discharge, or the potential for a daily variance in ammonia concentrations discharged from the NEWPCC. During February, the volume of effluent discharged from the NEWPCC is lowest between 00:00 and 06:00 hours, rises to a daily peak between 11:00 and 12:30, remains relatively high until approximately 18:00, and gradually declines after this time (Bob Ross, City of Winnipeg Water and Waste *pers. comm*.). To consider timing of fish movements in relation to the volume of effluent discharge from the NEWPCC, the positional data for each day were divided into seven time intervals (00:00 to 01:59, 02:00 to 05:59, 06:00 to 09:59, 10:00 to 13:59, 14:00 to 17:59, 18:00 to 21:59, and 22:00 to 23:59). These intervals reflect when effluent volume was typically low, increasing, peaking, at high levels and declining (Table 2). Each fish individual fish detection is colour coded to correspond with the time interval in which it occurred. This provided an indication of whether the typical variations in the characteristics of the NEWPCC plume may have influenced when fish utilized the plume area.

3.0 RESULTS

3.1 Locations of Fish Within the Study Area and in the NEWPCC Plume

A summary of the time intervals that each tagged fish was located in the study area, and the number of times that it was located in the NEWPCC plume is presented in Table 3. The term “plume” in this paper is used to describe the CORMIX modelled portion of the NEWPCC plume presented in Figure 9, which represents the area of the river that probably contained the highest levels of ammonia during the study period. The highest number of fish detected in the study area in any day occurred on February 18 (eight fish detected out of nine tagged) followed by February 19 (seven fish detected out of ten tagged). The number of fish detected on each day then slowly declined to a low of two fish on February 24, the last day that fish locations were plotted before the stationary receivers were removed.

To examine whether or not there were trends in the time periods when fish were located in the NEWPCC plume the percentage of total detections in the plume was compared to the predicted percentage of detections in the plume if no trends had occurred (Table 4). To facilitate comparisons, the length of time intervals was equalized by combining the 00:00 to 01:59 interval for each day with the 22:00 to 23:59 interval from the previous day. The time interval in which fish were the located in the plume the least frequently was between 06:00 and 9:59. The frequency of locations in the plume was slightly higher from 10:00 to 13:59 and increased again in the time period ranging from 14:00 to 17:59. The greatest number of times that fish were located within the NEWPCC plume was usually between 18:00 and 21:59, followed by 22:00 to 01:59. The frequency of detections in the time interval between 02:00 and 05:59 generally decreased. Temperature data indicated that when fish were located in the NEWPCC plume their temperature readings were generally higher than when they were located outside of the plume.

3.2 Locations of Individual Fish During the Study Period

Of the 10 northern pike tagged in the vicinity of the NEWPCC effluent plume, each fish was located in the study area from a minimum of 3 days to a maximum of 21 days between February 14 and March 9. The following sections provide a more detailed description of individual fish locations and daily fish movements.

Fish # 7958

Fish # 7958 was tagged and released on February 14 at approximately 13:30 and was detected in the study area on February 14, 15, and 16. Fish # 7958 was located by both arrays of stationary receivers, ranging from the abandoned railway bridge to an approximate distance of 1 km downstream of the Kildonan Settlers Bridge. The movements of Fish # 7958 on February 16 are illustrated in Figure 10.

After it was tagged and released, Fish # 7958 was located under the Kildonan Settlers Bridge. Approximately 25 hours later this fish moved upstream, in the afternoon on February 15, to a point near stationary receiver # 1487. At approximately midnight on February 16, the fish moved downstream, and was consistently located within the NEWPCC effluent plume for at least 6 hours between midnight and 06:00. Fish # 7958 then left the NEWPCC effluent plume and gradually moved downstream of the Kildonan Settlers Bridge, where it was last located at 18:48 on February 16, near stationary receiver # 2060. After this time, the fish moved downstream out of the range of detection.

Fish # 7959

Fish # 7959 was tagged and released on February 14 at approximately 13:00. This fish was detected in the study area for a total of 21 days, 10 days between February 14 and February 24 with the stationary receivers, and each day between February 28 and March 9 (11 days) with the portable VR-60 receiver. The daily locations of Fish # 7959 in relation to the NEWPCC effluent plume are provided in Figures 11 to 18, for February 16, 17, and 19 to 24, respectively.

Fish # 7959 was located in the study area for the longest duration of all fish tagged. This fish was located throughout the study area ranging from the abandoned railway bridge to stationary receiver # 2060, approximately 1 km downstream of the Kildonan Settlers Bridge. Fish # 7959 was also located on February 18 underneath the Kildonan Settlers Bridge 8 times between 20:40 and 22:34. These were the only detections of this fish on this date and no figure is provided. Two commonly occupied locations were observable for Fish # 7959. The most common location was the area upstream of the plume between the outfall and stationary receiver # 1487. To a lesser extent, this fish was also frequently located along the west bank downstream of the NEWPCC outfall.

With the exception of February 18, between February 16 and 22, Fish # 7959 exhibited a similar pattern of movement. Generally, this fish would enter the plume area in the afternoon, between 14:00 and 17:00 hours, where it would remain for varying durations of time. Following this period of consistent detections within the plume, the fish would move away from the area. This movement usually occurred between approximately 00:00 and 01:00. Fish # 7959 would then move upstream of the outfall towards stationary receiver # 1487, where it was generally located between 01:00 and 14:00. Fish # 7959 was not located in the NEWPCC on February 23 and 24. During these two days all detections for this fish were upstream of the outfall.

Fish # 7959 was periodically located inside the plume at different times over the course of the day on February 17 and 19. Data from these days indicate that this fish may move in and out of the plume several times over the course of one day. Fish positions from February 16, 18, 19, 21 and 22 indicate that fish # 7959 was often located in the NEWPCC effluent plume for extended durations. The longest period of time that Fish # 7959 was located in the NEWPCC effluent plume occurred on February 21 and 22, when it was consistently located immediately downstream of the outfall for approximately nine hours. Durations as long as 2, 3.5, and 6.5 hours were also observed on February 16, 18 and 19, respectively.

Fish # 7960

This fish was tagged and released on February 15 prior to 15:30 and was detected in the study area during a total of four days between February 15 and February 24. Fish # 7960 was also detected by the portable receiver on one day (March 1) between February 28 and March 9. The daily locations of Fish # 7960 in the vicinity of the NEWPCC plume are illustrated in Figures 19 to 22.

This fish did not show any consistent patterns in its movements and moved widely throughout the study area. Fish # 7960 was active both upstream and downstream of the Kildonan Settlers Bridge, being detected by both arrays of stationary receivers. In general, Fish # 7960 remained in the area under or slightly downstream of the Kildonan Settlers Bridge from the time it was tagged on February 15, until after 02:00 on February 16. The fish then moved downstream along the west bank until 04:27, the last located position of this fish on February 16. After this point Fish # 7960 appears to have moved downstream out of range of the stationary receivers and was not detected again until February 18. Fish # 7960 returned to the location just downstream of the Kildonan Settlers Bridge on

February 18 and remained in this area until approximately 14:00 hours. At this point the fish moved upstream to a location near the abandoned railway bridge. Fish # 7960 generally remained upstream of the outfall between 18:00 and midnight. However, on three separate occasions between 18:00 and 21:59 this fish was also located in the NEWPCC plume area. Fish # 7960 continued to be located upstream of the NEWPCC outfall in the vicinity of stationary receiver # 1487 on February 19 until just after 11:00. The fish was then located in the NEWPCC effluent 4 times between 11:13 and 12:27, before moving back upstream and out of the study area.

Fish # 7961

Fish # 7961 was tagged and released on February 16 at approximately 11:00 and was detected in the study area for a total of five days between February 16 to 19 and February 23. The daily locations of Fish # 7961 for February 16 to 19 are illustrated in Figures 23 to 26.

The range of locations for fish # 7961 was the entire length of the study area between the abandoned railway bridge downstream to receiver # 2060 (1 km downstream of the NEWPCC outfall). This fish was most frequently located in one of three positions. From just after it was tagged on February 16 until approximately 24 hours later on February 17 Fish # 7961 was located near the east bank of the river, just upstream of the Kildonan Settlers Bridge in the vicinity of stationary receiver # 2062. The fish then moved upstream of the outfall in the vicinity of receiver 1487. The third location that Fish # 7961 was commonly located was along the west bank of the Red River immediately downstream of the NEWPCC outfall.

Fish # 7961 was located in the NEWPCC effluent plume from approximately 18:00 hours on February 17 until 01:00 on February 18, a period of about 7 hours. Throughout February 18 this fish periodically moved between a point approximately halfway between receiver 1487 and the outfall and within the NEWPCC plume along the west bank. During this period, Fish # 7961 remained within the plume as long as 5 hours, from 19:00 to midnight. On both February 18 and February 19, this fish was frequently located in the NEWPCC effluent plume between 10:00 and 13:59. Fish # 7961 appeared to be highly active during this time period on both of these days, and was also located both upstream of the outfall and downstream of the Kildonan Settlers Bridge. After February 19, this fish was not located again until February 23, when it was detected once downstream of the

Kildonan Settlers Bridge (no figure provided).

Fish # 7962

This fish was tagged and released on February 15 at approximately 17:00 and was detected in the study area for a total of four days between February 15 and 18. The daily locations for this fish are illustrated in Figures 27 to 29.

Fish # 7962 was the only fish tagged in this study that spent the majority of its time in the study area downstream of the Kildonan Settlers Bridge. After being tagged on February 15, this fish moved to the east bank of the river under the Kildonan Settlers Bridge. It spent the majority of its time on February 15 in this location, but was also periodically detected in the NEWPCC plume for periods of up to two hours. On February 16, Fish # 7962 was located near the east bank of the river across from the outfall until 01:26, when it moved downstream into the plume, and was later located just before 02:00 downstream of the Kildonan Settlers Bridge. The fish moved into the plume again after after 02:00 and at 03:41 was located at a point just upstream of the outfall. All locations for the remainder of the day were downstream of the Kildonan Settlers Bridge, ranging as far as the downstream limits of the study area. Fish # 7962 was very active during this period and remained in only one area, just upstream of stationary receiver 2060, for an extended period of time. This fish was only accurately located two times on February 17, just downstream of the Kildonan Settlers Bridge (no figure), and four times on February 18, also downstream of the Kildonan Settlers Bridge. During these last two days, Fish # 7962 was probably spending a large portion of its time downstream of the study area.

Fish # 7963

Fish # 7963 was tagged and released on February 16 just before 15:00. This fish was detected in the study area for a total of 14 days, each day between February 16 and February 24 with the stationary receivers, and each day between February 28 and March 3 with the portable VR-60 receiver. The daily locations of Fish # 7963 in the vicinity of the NEWPCC effluent plume from February 16 to 24 are illustrated in Figures 30 to 38.

Fish # 7963 was the only fish that was located by the stationary receivers for every possible day between the time it was tagged and the removal of the receiver arrays. This fish utilized the entire length of the study area, ranging from receiver # 2060, upstream to the abandoned railway bridge. Fish # 7963 was most frequently located upstream of the NEWPCC plume in the area between stationary receiver # 1487 and the outfall.

After being tagged on February 16, this fish moved downstream of the Kildonan Settlers Bridge to receiver # 2060. However, by 16:00 on February 17 this fish had moved back upstream of the NEWPCC outfall. Fish # 7963 was located over a wide portion of the study area between February 16 and February 18, after which time its range of movements were almost entirely confined to the area between stationary receiver # 1487 and the outfall. On February 18 between 05:48 and 10:00 this fish was consistently located in the NEWPCC effluent plume, a period of approximately 4 hours. This was the longest duration that this fish was continuously located within the plume. Between February 19 and 24, fish # 7963 was only located in the NEWPCC effluent plume for a few times on any given day. On February 20, this fish was consistently located in the effluent plume for 1 hour and 43 minutes between 16:13 and 18:00. On other days the fish was only located in the plume for short periods of time. Between February 19 and February 24 Fish # 7963 was occasionally located just upstream of the outfall but was not actually in the NEWPCC plume.

Fish # 7964

Fish # 7964 was tagged and released on February 18 at approximately 12:30 and was detected in the study area during a total of three days between February 18 and February 24. The locations of fish # 7964 in the vicinity of the NEWPCC plume are presented in Figures 39 to 41.

The movements of Fish # 7964 in the study area ranged between a point slightly downstream of the Kildonan Settlers Bridge and the abandoned railway bridge. The majority of detections for this fish were in an area between the outfall and receiver # 1487. Movements into the NEWPCC plume by Fish # 7964 took place between 20:10 to 20:35 on February 18, 17:40 to 20:24 and 22:29 to 23:57 on February 19, and 02:20 to 02:54 on February 20. Periods when Fish # 7963 was located in the plume were usually followed by periods upstream of the plume between receiver # 1487 and the outfall area. The longest time period that this fish was consecutively located in the plume was approximately 2 hours 45 minutes on February 19. On February 20 between 10:22 and 11:00 this fish moved rapidly downstream and appeared to move out of the study area.

Fish # 7965

Fish # 7965 was tagged and released on February 17 at approximately 16:40 and was detected in the study area for a total of four days between February 17 and February 20. The locations of fish # 7965 in the vicinity of the NEWPCC plume are presented in Figures 42 to 44.

The movements exhibited by this fish in the study area ranged from upstream of the abandoned railway bridge, to approximately 200 m downstream of the Kildonan Settlers Bridge. The majority of locations were upstream of the the NEWPCC outfall near the abandoned railway bridge. With the exception of the day it was tagged (February 17), Fish # 7965 was not located in the plume. On February 20, this fish was only located once near the east bank or the river across from the outfall at 09:50 (no figure provided).

Fish # 7965 was located at least once upstream of the abandoned railway bridge, and the absence of this fish during a large portion of the days that it was tagged suggest that this fish was probably moving in and out of the upstream end of the study area. The single detection of Fish # 7965 downstream of the Kildonan Settlers Bridge at 13:56 on February 18 and single detection of this fish on February 20 suggest that this fish may have been moving over long distances through the study area over relatively short periods of time.

Fish # 7966

This fish was tagged and released on February 18 at approximately 13:00 and was located in the study area for a total of six days between February 18 and February 24. The locations for Fish # 7966 in the vicinity of the NEWPCC plume are presented in Figures 45 to 50.

The movements of Fish # 7966 in the study area ranged from the abandoned railway bridge to a point approximately 300 m downstream of the Kildonan Settlers Bridge. This fish was frequently located in the plume during different periods of the day, but was also located downstream of the Kildonan Settlers Bridge and upstream of the outfall area on a daily basis. There was no obvious pattern to the daily movements of Fish # 7966 and periods of exposure to the effluent plume varied daily.

Fish # 7966 was located in the NEWPCC effluent plume on February 19 during three different time intervals, on February 20 during four different time intervals, and on February

22 during three different time intervals. All but one of the locations for this fish on both February 21 and February 23 were upstream of the outfall and outside of the plume. The longest duration that this fish was consistently located in the effluent plume is difficult to determine. On February 22, this fish was located along the west bank in the effluent plume on several occasions between 01:00 and 09:59. However, periodic locations also occurred downstream of the Kildonan Settlers Bridge during this time, which indicates that the fish may have been moving in and out of the plume.

Fish # 7966 appeared to be more active in the study area during the early morning hours of the day corresponding with time period 02:00 to 05:59 and 06:00 to 09:59. This varies from the trends observed in the other tagged fish, which were generally the most active between 14:00 and 01:59.

Fish # 7967

Fish # 7967 was tagged and released on February 19 at approximately 13:00. This fish was located in the study area for the next five days (February 19 to February 23), and with the portable receiver each day between February 28 and March 3 (5 days). The locations of Fish # 7967 in the study area are presented in Figures 51 to 55.

Fish # 7967 was located in the study area from the abandoned railway bridge to approximately 300 m downstream of the Kildonan Settlers Bridge. This fish was most frequently located in the area between receiver # 1487 and the NEWPCC outfall. Locations of Fish # 7967 downstream of the Kildonan Settlers Bridge and near the west bank immediately downstream of the NEWPCC outfall were also common. The movements of Fish # 7967 frequently covered large portions of the study area in short periods of time.

The duration of time that Fish # 7967 was located in the NEWPCC effluent plume varied between brief and extended periods of time. The longest duration of time occurred on February 22 between 09:43 and 14:00, a period of 4 hours and 17 minutes. This fish was also located in the plume on February 23 from 06:00 to 09:59, before moving downstream of the Kildonan Settlers Bridge. Fish # 7967 was located in the plume during four separate time periods on February 20, two separate time periods on February 21, three on February 22 and two on February 23. February 19 was the only day that Fish # 7967 remained upstream of the outfall area and was not located in the plume.

From midnight until just after 10:00 on February 23, Fish # 7967 gradually moved under the Kildonan Settlers Bridge, the last detection of this fish by the arrays. After this time, Fish # 7967 appears to have left the study area and was not detected again until four days later, when it was detected with the portable receiver each day between February 28 and March 3.

4.0 DISCUSSION

4.1 Preference and Avoidance Behaviour

This study is essentially an examination of whether or not northern pike displayed detectable preference or avoidance behaviour in relation to the NEWPCC effluent plume. While Cherry and Cairns (1982) discussed the difficulties involved in the use of behavioural indices of pollution, they specifically stated that these types of studies can be a very effective method for determining how effluent plumes alter the distributions of fish and other mobile aquatic organisms. The use of preference and avoidance studies are particularly useful for determining if the temperature attraction that fish display for thermal plumes during cold water periods is strong enough to override any natural avoidance responses that these fish may have to the potentially harmful chemicals that plumes may contain (Cherry and Cairns 1982). Examples of preference and avoidance behaviour by fish in relation to varying concentrations of potentially harmful chemicals can be found throughout the literature. However, the vast majority of these studies are under laboratory conditions (Fava and Tsai 1976; Larrick *et al.* 1978; Cherry and Cairns 1982; Smith and Bailey 1990). The relatively few field studies that have been conducted have usually involved the use of caged fish (Osborne *et al.* 1981), or have been restricted to examining the species abundance or composition of the fish community downstream of effluent outfall locations (Giattina *et al.* 1981; Paller *et al.* 1988). The use of preference and avoidance studies can provide important site and species specific information on the behaviour of fish in relation to thermal effluent plumes that would be unavailable through laboratory tests alone.

Prior to this study, most data collected concerning the attraction or avoidance of fish to effluent plumes were limited to the presence or absence of the fish in the area at a particular point in time. The methods used in this study allowed the movements of individual fish to be monitored in much greater detail than is possible with relative abundance studies. The use of wild fish also enabled data to be collected on the unrestricted movements of tagged fish, which are more likely to accurately represent what occurs under typical conditions than the behaviour of caged fish would. Freedom to move within or even out of the study area allowed the tagged fish to select the timing, frequency, and duration of time that they interacted with the NEWPCC effluent plume. This made it possible to examine whether northern pike appeared to exhibit an attraction or avoidance response to the plume, and if there were notable patterns in the timing, frequency, and duration of these interactions in terms of both general movements and the movements of individual fish. This study is the first site specific study designed to monitor fish movements in relation to municipal water treatment centre effluent plumes in the Red River in Canada.

4.2 Preference and Avoidance of Effluent Plumes

Fish are known to exhibit certain behavioural modifications in the presence of polluted water that allow them the escape or avoid harmful conditions (Larrick *et al*. 1978). However, the majority of research in this area has been restricted to laboratory studies. The precision to which fish can detect differences in the concentration of harmful chemicals in their environment varies from species to species and between types of chemicals. One chemical that most species of fish have been shown to be able to detect at even low concentrations is chlorine (Larrick *et al*. 1978), which is often found in effluent streams that contain municipal waste. Additionally, it has been reported that some fish appear to be able to develop the ability to detect certain harmful chemicals such as chlorine more quickly with successive exposures (Larrick *et al*. 1978).

While it may seem unlikely that fish would willingly enter effluent plumes that contain potentially harmful levels of chemicals, such as ammonia and chlorine, there is evidence that they will do so under certain conditions (Cherry and Cairns 1982). Such incidences may partially be due to the fact that for many chemicals their presence at harmful levels in the aquatic environment is a relatively recent phenomenon. As a result, there has not been enough time for fish to develop an instinctive avoidance reaction to such compounds (Scherer 1992). Laboratory tests are useful for determining whether a species of fish can detect potentially harmful chemicals, and if they can be detected whether or not the fish will actively avoid them. Alternately, these tests may indicate that fish lack the ability to detect and/or avoid potentially harmful chemicals, or even that they act as an attractant, which makes such substances even more dangerous (Scherer 1992).

The potential for fish to be attracted to plumes that contain potentially harmful chemicals can be elevated in the case of thermal plumes, which attract fish more strongly during the cold water season. The presence of warmer water can lure fish into an effluent plume if the thermal attraction is strong enough to override any avoidance response to such chemicals as chlorine and ammonia, or if the fish are unable to detect these chemicals (Cherry and Cairns 1982). It has also been suggested that fish will move into an effluent plume for short periods of time and move out again before irreversible adverse effects can occur. These excursions indicate that the fish either do not detect the boundaries of the plume, or ignore it due to the presence of more powerful stimuli, such as the presence of potential prey organisms within the plume (Osborne *et al.* 1981). In situations were effluent plumes act as a fish attractant, the increased duration of time that fish are in contact with effluent containing waters increases the potential for toxic effects to occur (Smith and Bailey 1990).

Avoidance of sewage discharge, rather than lethal effects, has often been used to explain the low densities of fish downstream of many plume areas (Fava and Tsai 1976; Osborne *et al.* 1981). The avoidance of sewage effluents by fish appears to be caused primarily by the presence of chloramines rather than the presence of ammonia or other chemicals. Fava and Tsai (1976) found that blacknose dace did not avoid sewage effluent which did not contain chlorine, or ammonium chloride solutions in concentrations up to 270 mg/litre of ammonia-nitrogen. However, these fish did avoid effluent that contained chloramines, or free chlorine, with avoidance increasing as total chlorine concentrations increased. The type of chlorine present in effluent plumes has also been shown to influence avoidance reactions. Most species of fish appear to be more sensitive to free residual chlorine (which acts as an external irritant to gill tissues) (Cherry and Cairns 1982), but other species are more sensitive to chloramines (which reduces the oxygen carrying ability of fish blood) (Fava and Tsai 1976). These sensitivity differences may lead to different reaction times for avoidance behaviours, depending on species and the chemical composition of an effluent plume.

Results of a gillnetting survey conducted during March 1999 (Lawrence 1999) suggested that northern pike made up a large proportion of the fish catch in the vicinity of the NEWPCC. Results of the same study also suggested that northern pike were more frequently captured at locations near the outfall area. Comparisons of these results with gillnetting catches in February 1999 in other areas of the Red River in the city of Winnipeg revealed that the relative abundance of northern pike was several orders of magnitude greater in the vicinity of the NEWPCC (Remnant *et al.* 2000). Out of 33 segments sampled in the Red River in February and March 1999, a total of 8 northern pike were captured. Of these 8 pike, 7 were captured in areas outside the city limits and only one was captured within the city limits (Remnant *et al.* 2000). It is possible that the two bridges in the vicinity of the NEWPCC contribute to higher catches of northern pike by providing structural diversity and acting as current breaks. However, in the study by Remnant *et al.* (2000) winter catches of northern pike were not notably higher in the vicinity of bridges.

The results of this study indicate that northern pike are attracted to vicinity of the NEWPCC plume. All of the fish remained in the study area for at least three days following the tagging procedure, and one fish remained in this area for at least 21 days. It is probable that northern pike actually remain in the vicinity of the NEWPCC plume for much longer periods of time, which would increase the potential duration of exposure to elevated levels of ammonia. The date that northern pike actually moved into the area is unknown and it is possible that they had been there since the beginning of winter. The movement of fish out of the area at the end of the study period corresponded with warmer air temperatures, rainfall, increased surface runoff, and the breakup of ice cover, which may have triggered increased fish activity levels.

Although fish appeared to be attracted to the NEWPCC plume, they did not spend all of their time within the plume itself. The area in which fish were most consistently located was just upstream of the outfall. This suggests that fish were attracted to the area, but only exposed themselves to the NEWPCC effluent plume intermittently. Even though the plume appeared to act as a fish attractant, the fact that fish were most commonly located upstream of the outfall is an indication that for the majority of the time fish may have been avoiding direct contact with the plume itself. Movements into the plume may have been related to feeding or other activities, and were often of short in duration, followed by a return to waters upstream of the outfall.

4.3 Northern Pike Movements in Relation to the NEWPCC Plume

Following tagging, a period of relative inactivity was observed for nearly all northern pike. The duration of this period ranged from 3 to 36 hours. This was probably a period in which fish were recovering from any stress related to the tagging procedure. However, with the possible exception of Fish # 7958, all tagged fish appeared to resume normal activity levels following this period of recovery. This period of inactivity was similar to that observed by Lucas (1990), who reported that northern pike tagged with intraperitoneally implanted acoustic transmitters were generally inactive for several hours after release, but after one day appeared to resume normal behaviour and activity patterns. Lucas (1990) also suggested that this period of initial inactivity was probably associated with postoperative recovery.

Northern pike were most frequently located upstream of the NEWPCC in an area between stationary receiver # 1487 and the NEWPCC outfall. The next most frequent area that fish were located was along the west bank between the NEWPCC outfall and 150 m downstream of the outfall. Some locations within the study area that appeared to be only infrequently utilized, if at all, included the area within the direct trajectory of the NEWPCC outfall and the east bank of the Red River across the river from the outfall. Fish were more frequently located upstream of the Kildonan Settlers Bridge than downstream of this bridge. This suggests that these fish were attracted to the vicinity of the NEWPCC plume. However, the high number of locations upstream of the outfall also suggests that fish avoided the actual plume itself during specific periods of time.

Patterns in daily fish movements were also observed. In general, fish were relatively inactive between 02:00 and 05:59. Locations of fish during these hours were generally concentrated upstream of the NEWPCC between receiver # 1487 and the NEWPCC outfall over a relatively small area. Fish were only infrequently located in the NEWPCC effluent plume during these times. Movements into the plume generally became more frequent as the day progressed. The time period between 10:00 and 13:59 often corresponded with an increased frequency of intermittent movements into the NEWPCC effluent plume in comparison with the period 02:00 to 05:59. Although intermittent periods of activity were observed during this time period, fish were not consistently located in the plume between these hours. During the 10:00 to 13:59 and the 14:00 to 17:59 time intervals fish gradually increased the frequency of their movements into the effluent plume and other locations downstream of the outfall. Consistent locations along the west bank immediately downstream of the outfall were most frequently observed between 18:00 and 01:59, with the majority of these detections occurring from 18:00 to 21:59. The low levels of activity for northern pike during a large portion of the daylight hours, and the high levels of activity during a large portion of the night hours in this study was unexpected, as northern pike are visual predators, and are considered to be generally inactive at night (Diana 1980; Lucas 1990).

The number of times that tagged northern pike were located within the NEWPCC plume during the study period is probably underestimated for several reasons. The shallow water and associated ice cover that was found in this area could have caused acoustic signals to be reflected and misdirected. This would have reduced the number of detections that were able to be accurately plotted. Increased turbulence, which interferes with the clarity of acoustic signals, and changes in water temperature, which can distort the signals that acoustic tags transmit, at the outfall would also have reduced the number of detections in the plume. When error from these sources was too great, the tracking system would not have plotted their locations. A similar problem exists if fish are moving too quickly, which could have occurred if fish in the outfall were attempting to feed on forage fish. In addition, if fish were moving into and out of the plume for only short periods of time that occurred between periods in which their tag frequency was being scanned (30 seconds at 300 second intervals) then they would not have been located within the plume.

4.4 Ammonia Toxicity to Fish

In water, ammonia is found in both ionized (NH_4^+) and un-ionized (NH_3) forms, with un-ionized ammonia being the form which is responsible for most toxic effects (Thurston *et al*. 1984; Bader and Grizzle 1992). The toxicity of effluents that contain ammonia is related to both pH and temperature, as the concentration of un-ionized ammonia increases as either of these two water parameters increase. However, the toxicity of un-ionized ammonia has been shown to increase as temperature decreases (Thurston and Russo 1983). This means that fish exposed to effluent plumes in the winter may be more susceptible to toxic effects. Additional factors that affect the relative toxicity of un-ionized ammonia to fish include salinity, life stage, fish size and species, dissolved oxygen, calcium and carbon dioxide concentrations (Bader and Grizzle 1992).

The fluctuations that tend to occur in sewage effluent as a result of household water use patterns can result in several peaks in flow, and ammonia levels, throughout the day, rather than a steady flow with constant ammonia concentrations (Thurston *et al.* 1981b). This can in turn effect the susceptibility that local fish populations have to ammonia levels and may dictate the timing, frequency, and duration of time that fish spend in plume areas. There is evidence that fish can develop an increased resistance to ammonia levels following exposure to sublethal levels (Colt and Tchobanoglous 1976; Thurston *et al.* 1981b). However, fish may be better able to withstand a fixed concentration of ammonia over a given time period than they are to fluctuating concentrations with a similar mean value (Thurston *et al.* 1981b). Fish have also been reported to have the ability to enter waters that contain acutely toxic (96-h LC 50) concentrations of ammonia without suffering any obvious long-term effects, as long as these trips are followed by periods of in which they are in waters that contain ammonia concentrations below acute toxicity levels (Thurston *et al.* 1981b).

In this study northern pike were usually located outside of the NEWPCC plume during the 06:00 to 19:59 time interval. This time interval corresponds with the lowest daily volume of effluent discharge, before effluent discharge to the Red River begins to increase towards a peak between 11:00 and 12:30 (Bob Ross, City of Winnipeg Water and Waste *pers. comm*.). Between 14:00 and 21:59 the frequency of fish locations inside the plume tended to increase over time, as effluent volume began to decline. The majority of locations inside of the plume, and most of the longer periods in which fish remained there, took place between 18:00 and 23:59. This is the period of time when effluent volume would be declining towards the lowest levels. Northern pike appear to be located inside of the plume primarily during periods in which the volume of ammonia being discharged into the river is likely to be declining, but still moderately high.

5.0 CONCLUSIONS

Northern pike were attracted to the vicinity of the NEWPCC effluent plume during the study period (February 14 to March 9, 2000). During this period, individual fish remained in the vicinity of the NEWPCC plume for extended periods of time, at least 21 days. The fish were, therefore, exposed to elevated levels of ammonia for longer periods of time than they would have been if they had just been passing through the area. However, northern pike that were tagged with acoustic transmitters displayed definite preferences for certain areas in the vicinity of the NEWPCC plume. The area where fish were most frequently located was upstream of the NEWPCC outfall and downstream of stationary receiver # 1487. This area was outside the direct influence of the plume and would not have had significantly elevated ammonia levels or warmer water temperatures.

Tagged fish were next most frequently located in an area that was immediately downstream of the NEWPCC outfall, along the west bank of the river. This area was in the direct influence of the effluent plume and would have contained elevated ammonia levels and warmer water temperatures. Movements into the plume may have been related to feeding or other activities, and were often of short duration, followed by a return to waters upstream of the outfall. Northern pike were detected throughout the study area, and occasionally moved out of the range of detection in both upstream and downstream directions. Fish activity levels generally increased as the day progressed.

The amount of time that individual northern pike were located in the direct influence of the NEWPCC effluent plume varied between single detections (a few seconds to a few minutes) to periods of up to 10 hours. However, certain aspects of fish behaviour that appeared to reduce exposure levels included:

- northern pike tended to be located within the plume for shorter periods of time during periods of peak effluent discharges. This resulted in fish spending less time in the plume during periods when there were likely to be higher volumes of ammonia;

- northern pike were detected in the NEWPCC plume less frequently during periods that were likely to have high volumes of ammonia; and,

- most northern pike movements into the plume were short in duration and were usually followed by a longer period of “recovery” time outside of the direct influence of the plume.

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Table 1. Summary of tag number, frequency, fork length, weight, tagging date, and time tagged for 10 northern pike tagged in the vicinity of the NEWPCC plume February, 2000.

Species	Tag #	Tag Frequency	Fork length (mm)	Weight (g)	Date	Time
Northern pike	7958	50	520	1150	14-Feb	13:00
Northern pike	7959	54	830	4500	14-Feb	13:30
Northern pike	7960	57	896	9500	15-Feb	14:30
Northern pike	7962	60	625	1900	15-Feb	17:00
Northern pike	7961	65.5	750	3750	16-Feb	11:00
Northern pike	7963	69	618	1700	16-Feb	14:55
Northern pike	7965	72	878	5600	17-Feb	16:40
Northern pike	7964	75	760	4500	18-Feb	12:00
Northern pike	7966	76.8	540	1550	18-Feb	12:30
Northern pike	7967	78	765	3750	19-Feb	13:00

Table 2. Description of the colour coded time intervals used to illustrate tagged fish locations in relation to typical daily variations in the volume of the NEWPCC effluent plume.

Time Interval	Location Symbol Colour	Relative Volume of Effluent
00:00 to 01:59		Low
02:00 to 05:59		Low
06:00 to 09:59		Moderate (increasing)
10:00 to 13:59		High
14:00 to 17:59		Moderate
18:00 to 21:59		Moderate (decreasing)
22:00 to 23:59		Low

Table 3. Time intervals in which tagged northern pike were located within the study area, and the number of times they were located within the NEWPCC plume during each time interval.

Date	14-Feb							15-Feb						
Fish #	00:00-01:59	02:00-05:59	06:00-09:59	10:00-13:59	14:00-17:59	18:00-21:59	22:00-23:59	00:00-01:59	02:00-05:59	06:00-09:59	10:00-13:59	14:00-17:59	18:00-21:59	22:00-23:59
7958				**								22	21	11
7959				**										
7960												**24	40	25
7961														
7962												**1	12	16
7963														
7964														
7965														
7966														
7967														
Total (hits)												47	73	52

Date	16-Feb							17-Feb						
Fish #	00:00-01:59	02:00-05:59	06:00-09:59	10:00-13:59	14:00-17:59	18:00-21:59	22:00-23:59	00:00-01:59	02:00-05:59	06:00-09:59	10:00-13:59	14:00-17:59	18:00-21:59	22:00-23:59
7958	12	7												
7959				5		15	10				1	2		
7960	14	15												
7961				**11	23								12	13
7962	5	3												
7963					**32	9	3							
7964														
7965												**		
7966														
7967														
Total (hits)	31	25	0	5	55	24	13	0	0	0	1	2	12	13

Date	18-Feb							19-Feb						
Fish #	00:00-01:59	02:00-05:59	06:00-09:59	10:00-13:59	14:00-17:59	18:00-21:59	22:00-23:59	00:00-01:59	02:00-05:59	06:00-09:59	10:00-13:59	14:00-17:59	18:00-21:59	22:00-23:59
7958														
7959									3	2	1	1	8	
7960						3					4			
7961	6	4	6	16		21	2				7			
7962														
7963		14	20		1	3						1		
7964				**		3						2	6	6
7965														
7966				**								2	2	2
7967												**		
Total (hits)	6	18	26	16	1	30	2	0	3	2	12	6	16	8

Date	20-Feb							21-Feb						
Fish #	00:00-01:59	02:00-05:59	06:00-09:59	10:00-13:59	14:00-17:59	18:00-21:59	22:00-23:59	00:00-01:59	02:00-05:59	06:00-09:59	10:00-13:59	14:00-17:59	18:00-21:59	22:00-23:59
7958														
7959					9	22							22	4
7960														
7961														
7962														
7963					7									
7964		3												
7965														
7966		3	6	1	2			2	2	7				
7967				6	3	2	5	6					2	1
Total (hits)	0	6	6	7	21	24	5	8	2	7	0	0	24	5

Date	22-Feb							23-Feb							24-Feb						
Fish #	00:00-01:59	02:00-05:59	06:00-09:59	10:00-13:59	14:00-17:59	18:00-21:59	22:00-23:59	00:00-01:59	02:00-05:59	06:00-09:59	10:00-13:59	14:00-17:59	18:00-21:59	22:00-23:59	00:00-01:59	02:00-05:59	06:00-09:59	10:00-13:59	14:00-17:59	18:00-21:59	22:00-23:59
7958																					
7959				7	10		9														
7960																					
7961																					
7962																					
7963											1			1						1	
7964																					
7965											1										
7966																					
7967			2	11			2		25	2											
Total (hits)	0	0	2	18	10	0	11	0	25	2	2	0	0	1	0	0	0	0	0	1	0

** = Time interval fish was tagged in, shaded cells indicate periods in which fish were detected in the study area.

Table 4. Oberved versus expected percentage of fish detections in the NEWPCC plume for each time interval, and grouped time intervals, February 15-24, 2000.

Time Interval	15-Feb	16-Feb	17-Feb	18-Feb	19-Feb	20-Feb	21-Feb	22-Feb	23-Feb	24-Feb	Total	Observed	Expected	Rank
02:00-05:59	0	25	0	18	3	6	2	0	25	0	79	11.3%	16.7%	4
06:00-09:59	0	0	0	26	2	6	7	2	2	0	45	6.4%	16.7%	6
10:00-13:59	0	16	1	16	12	7	0	18	2	0	72	10.3%	16.7%	5
14:00-17:59	47	55	2	1	6	21	0	10	0	0	142	20.3%	16.7%	3
18:00-21:59	73	28	12	30	16	24	24	0	0	1	208	29.7%	16.7%	1
22:00-01:59*	83	13	19	2	8	13	5	11	1	0	155	22.1%	16.7%	2
Total	203	137	34	93	47	77	38	41	30	1	701	100%	100%	

Grouped Intervals	Total	Observed	Expected
14:00 - 01:59	505	72%	50%
02:00 - 13:59	196	28%	50%

* The 00:00-01:59 interval was added to the 22:00-23:59 interval of the previous day in order to standardize the length of each time interval and facilitate comparisions.

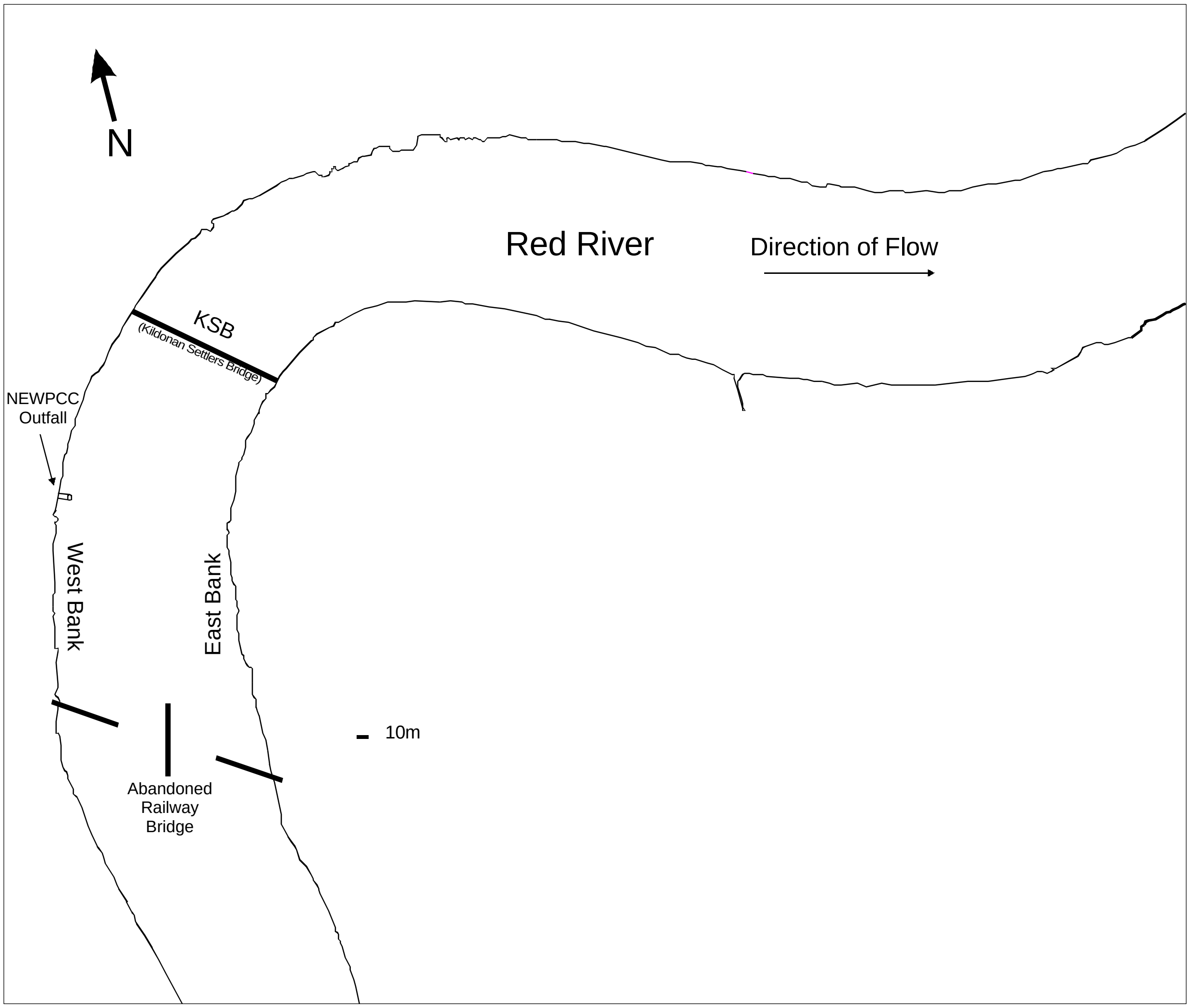

Figure 1. The Red River in the vicinity of the NEWPCC municipal effluent outfall.

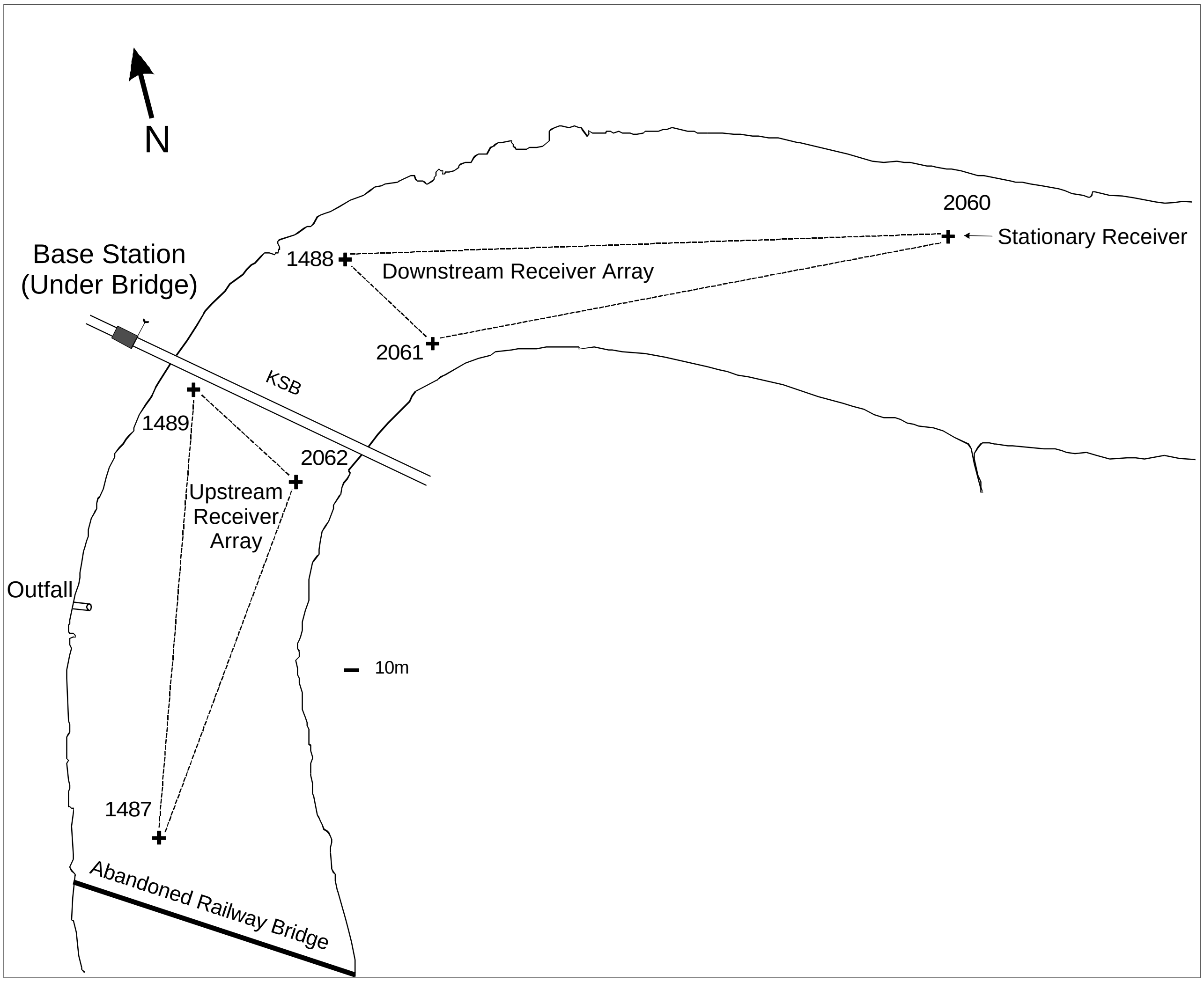

Figure 2. Locations of stationary receivers, upstream and downstream receiver arrays, and base station.

Figure 3. Stationary receiver frozen into the ice in the vicinity of the NEWPCC.

Figure 4. Angling downstream of the NEWPCC outfall on the Red River, February 2000.

Figure 5. Preparation of northern pike for mid-ventral incision, February 2000.

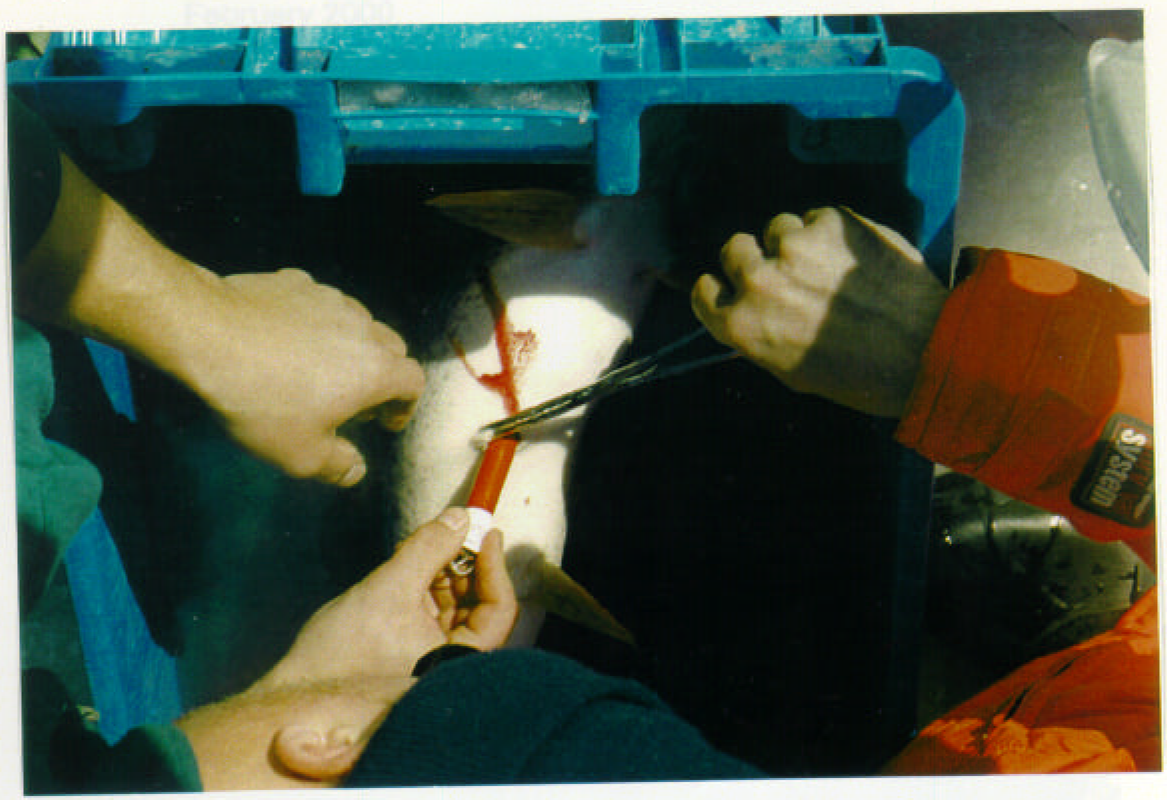

Figure 6. Insertion of acoustic tag into peritoneal cavity, February 2000.

Figure 7. Suturing mid-ventral incision following insertion of acoustic tag, February 2000.

Figure 8. Completed suture of tagged northern pike, February 2000.

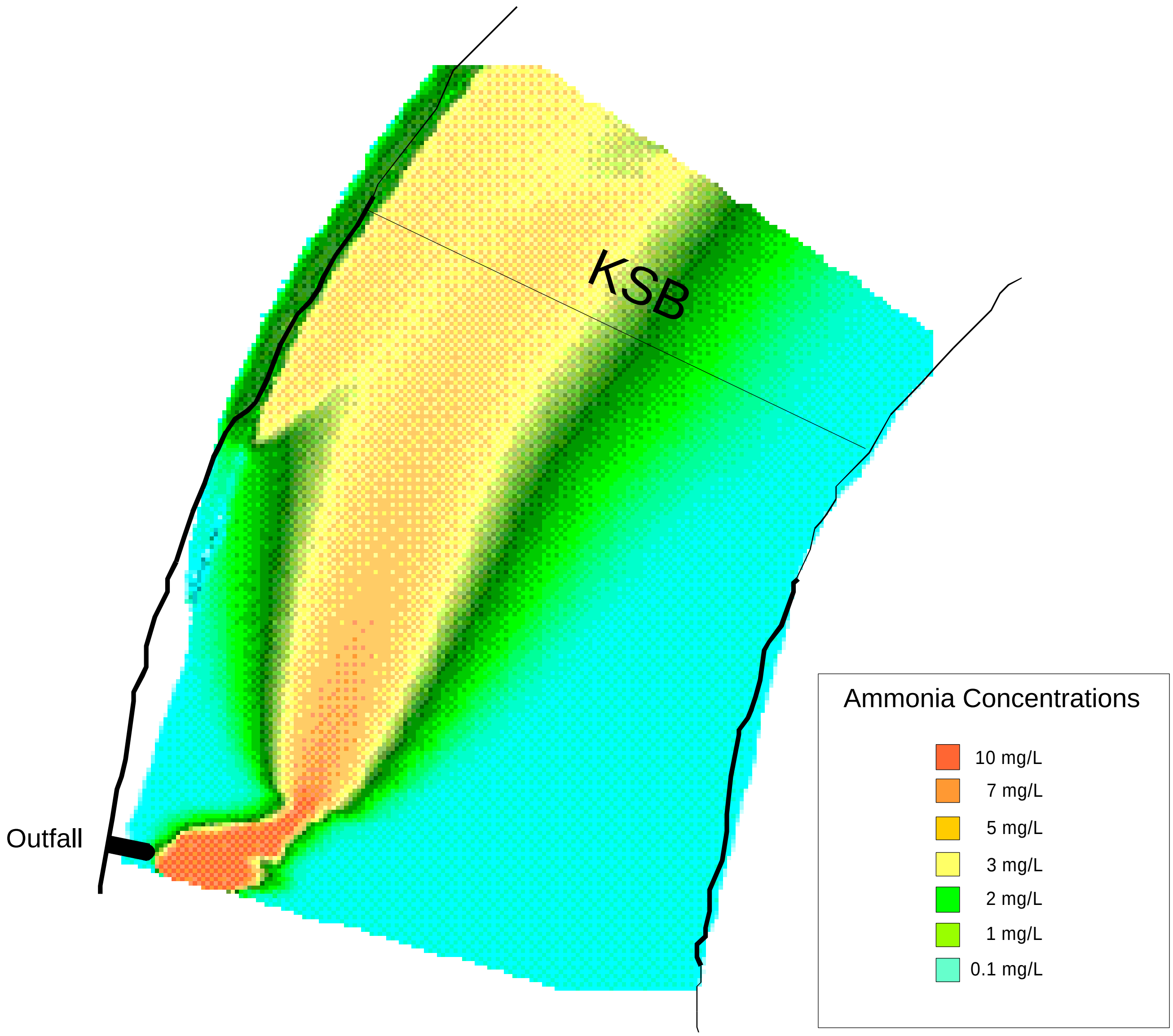

Figure 9. CORMIX model map of ammonia plume provided by Tetr ES Consultants Inc.

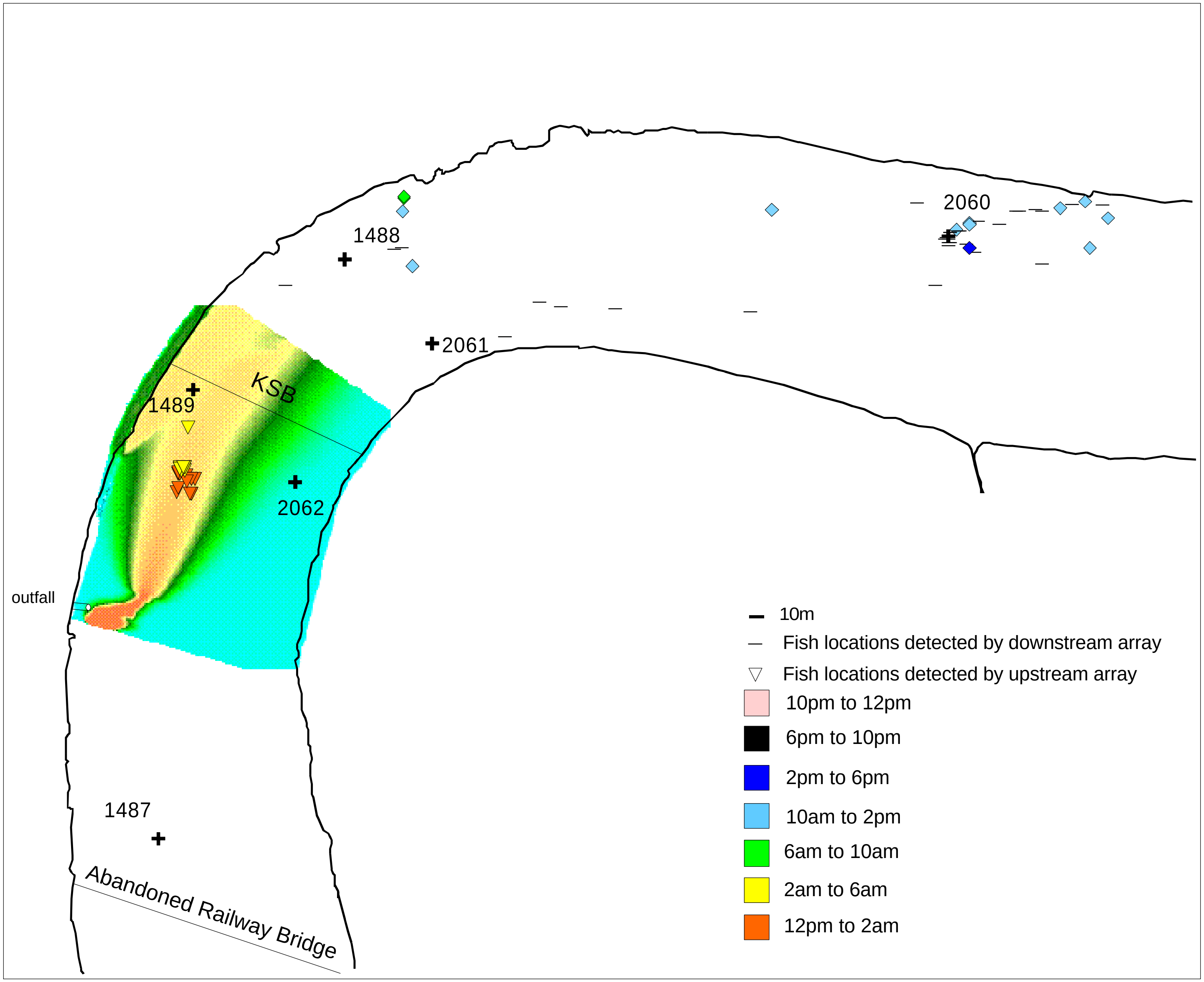

Figure 10. Positional data for Fish # 7958 in the vicinity of the NEWPCC plume, February 16, 2000.

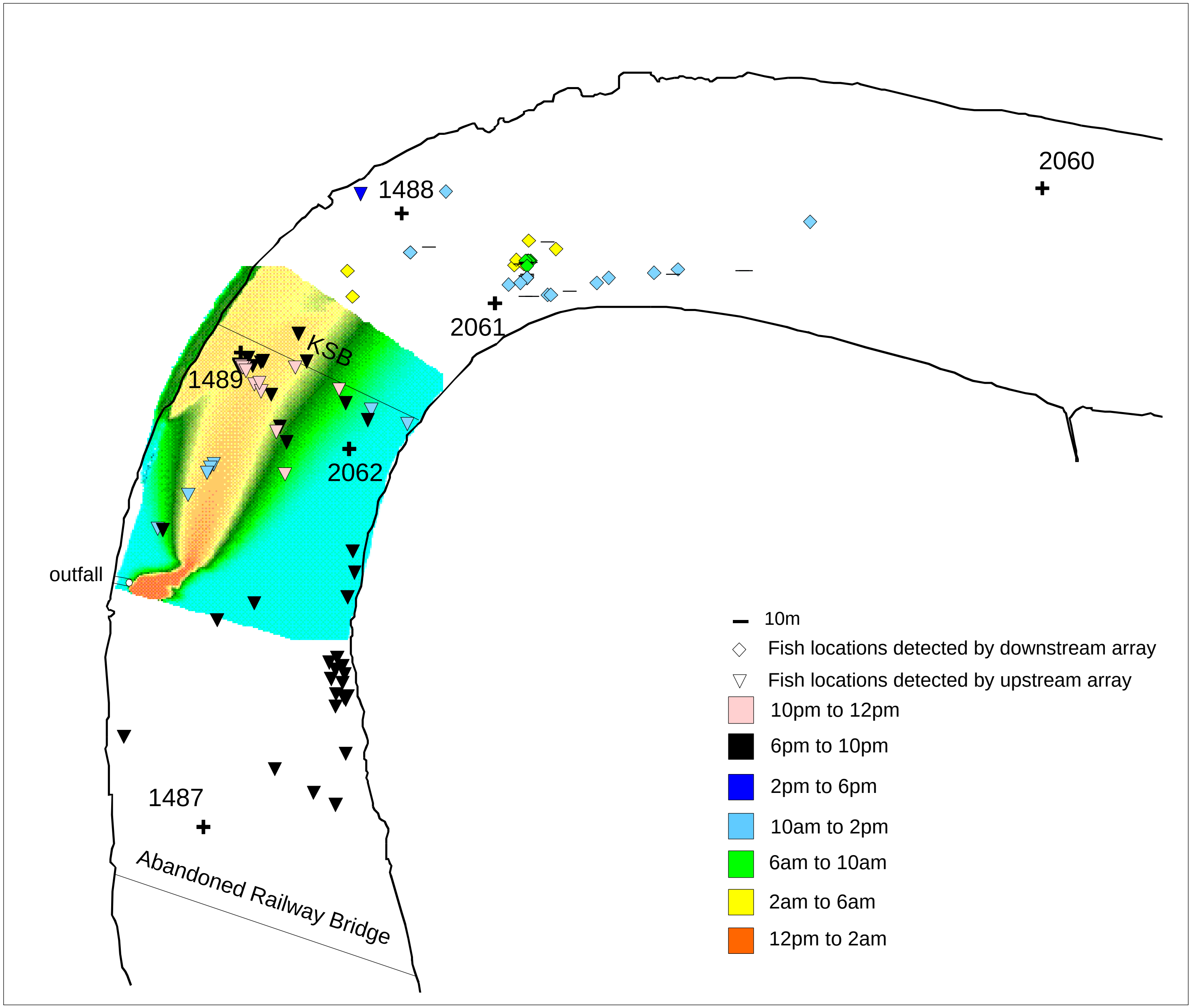

Figure 11. Positional data for Fish # 7959 in the vicinity of the NEWPCC plume, February 16, 2000.

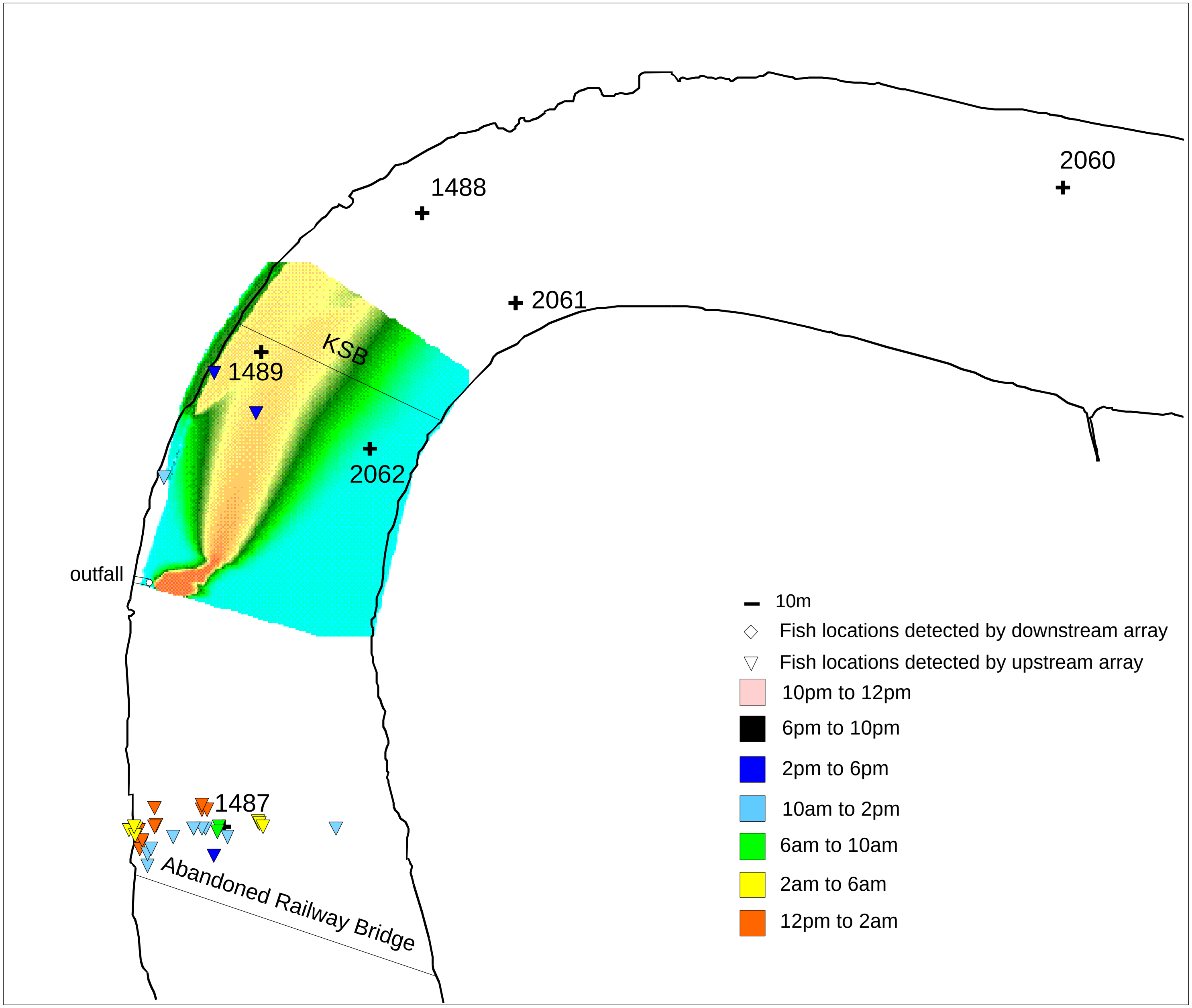

Figure 12. Positional data for fish # 7959 in the vicinity of the NEWPCC plume, February 17, 2000.

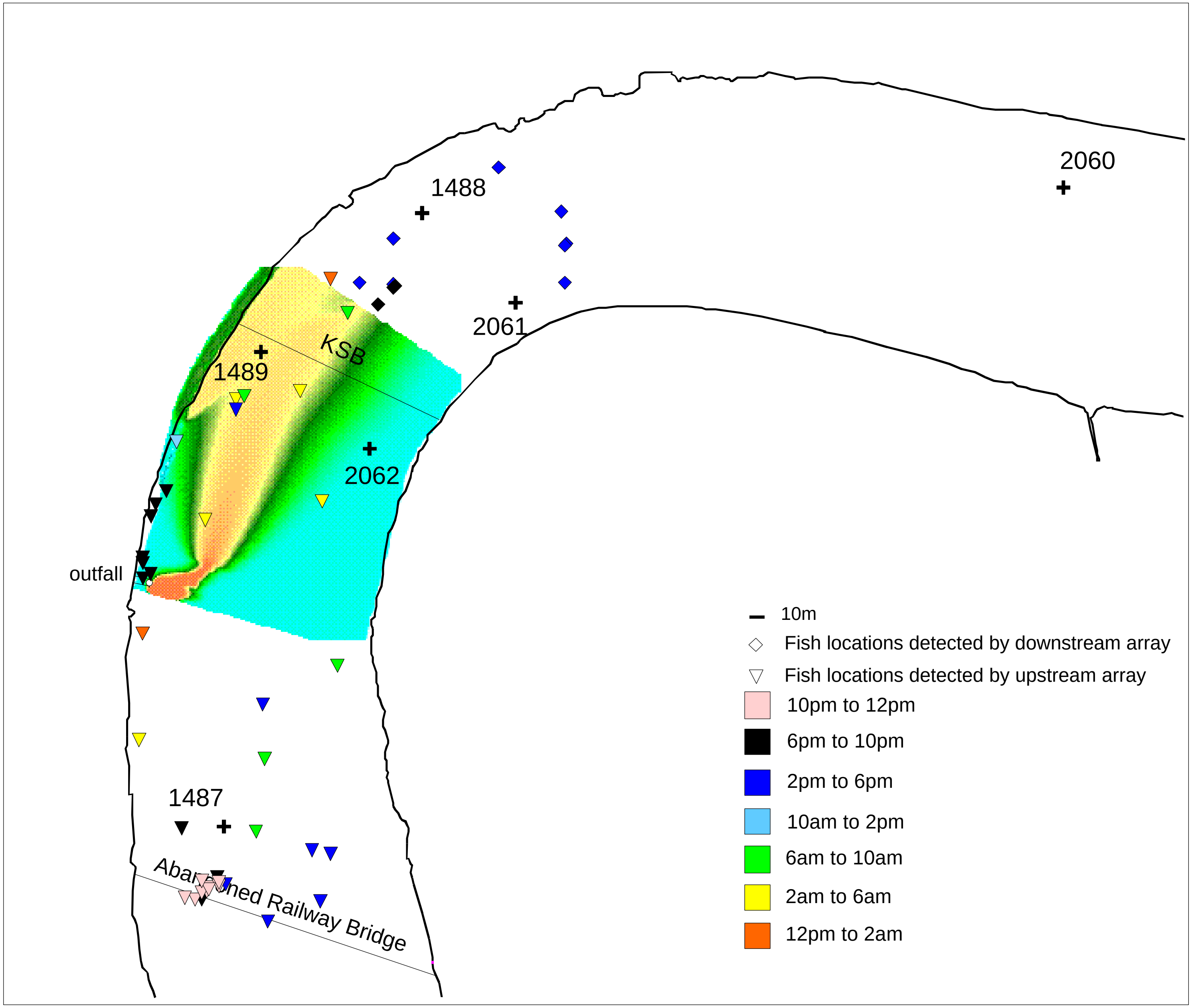

Figure 13. Positional data for Fish # 7959 in the vicinity of the NEWPCC plume, February 19, 2000.

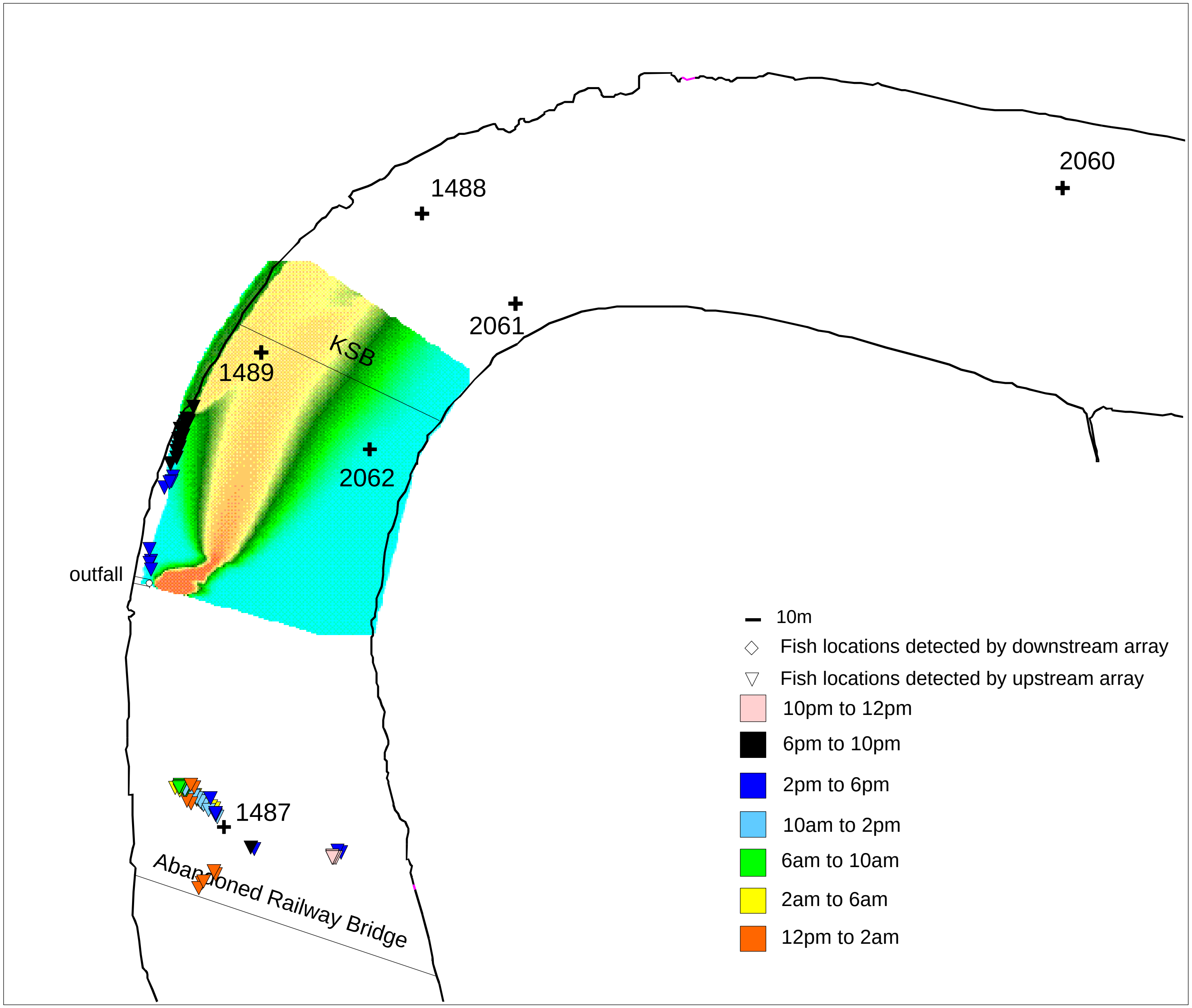

Figure 14. Positional data for Fish # 7959 in the vicinity of the NEWPCC plume, February 20, 2000.

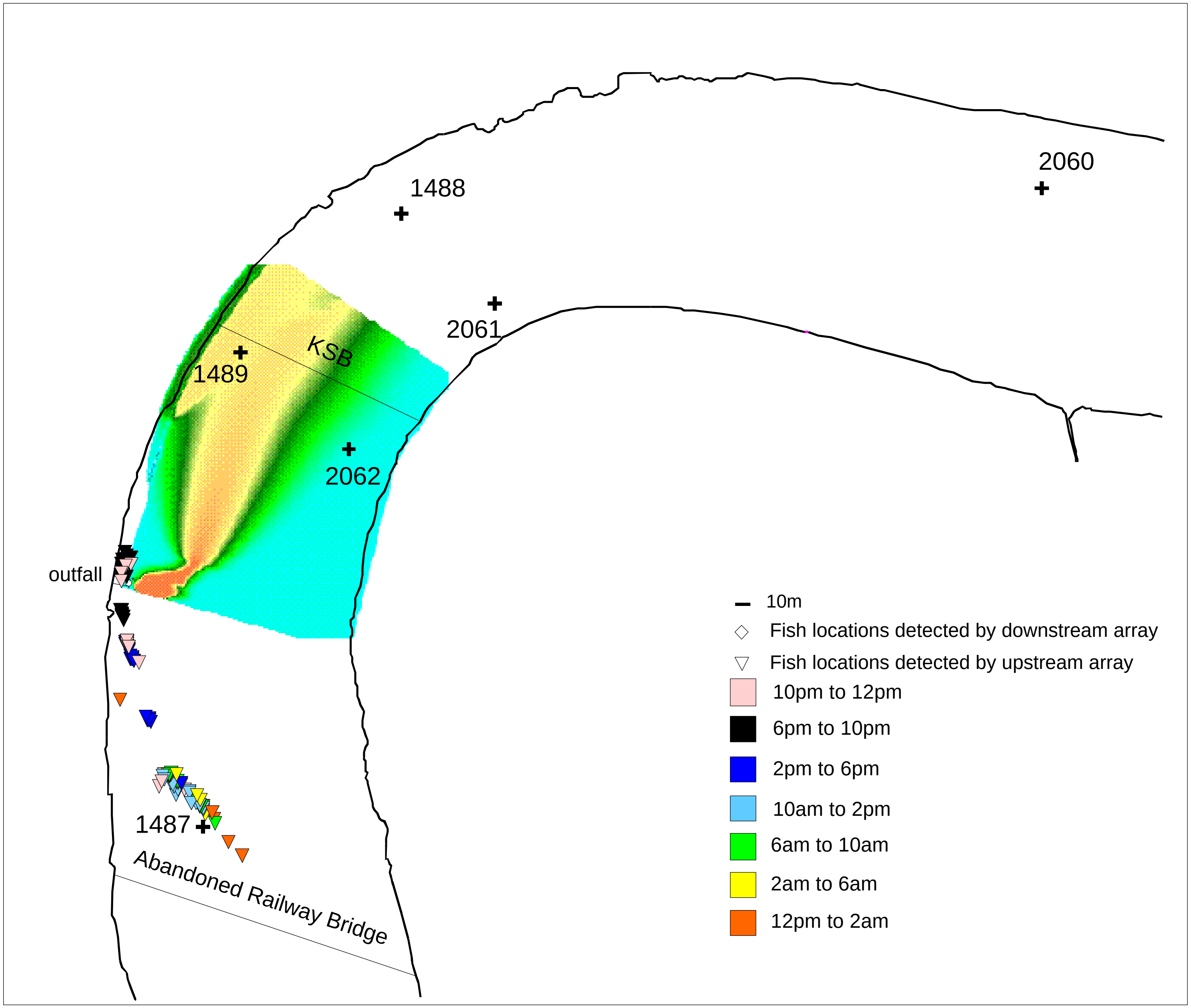

Figure 15. Positional data for Fish #7959 in the vicinity of the NEWPCC plume, February 21, 2000.

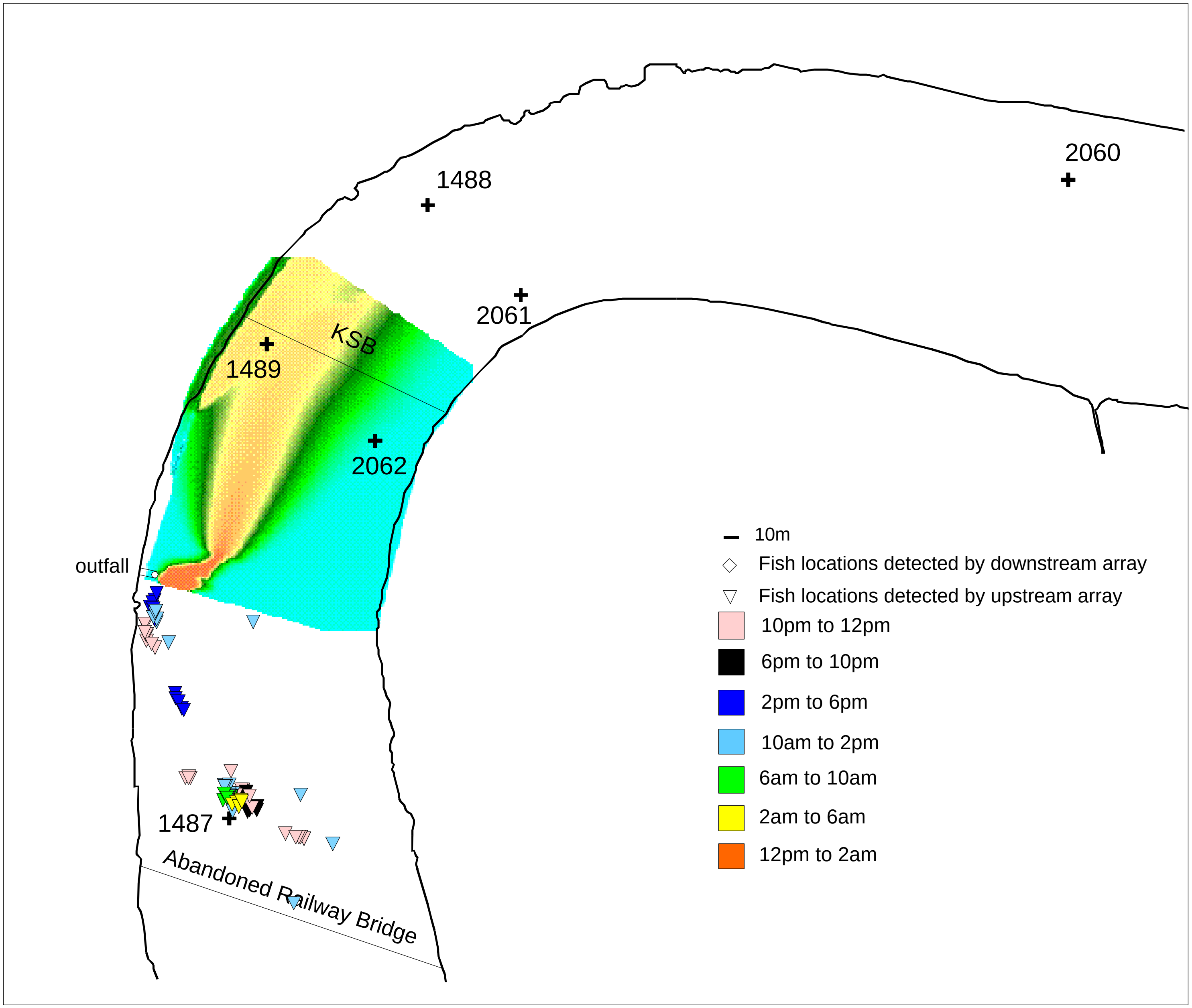

Figure 16. Positional data for Fish # 7959 in the vicinity of the NEWPCC plume, February 22, 2000.

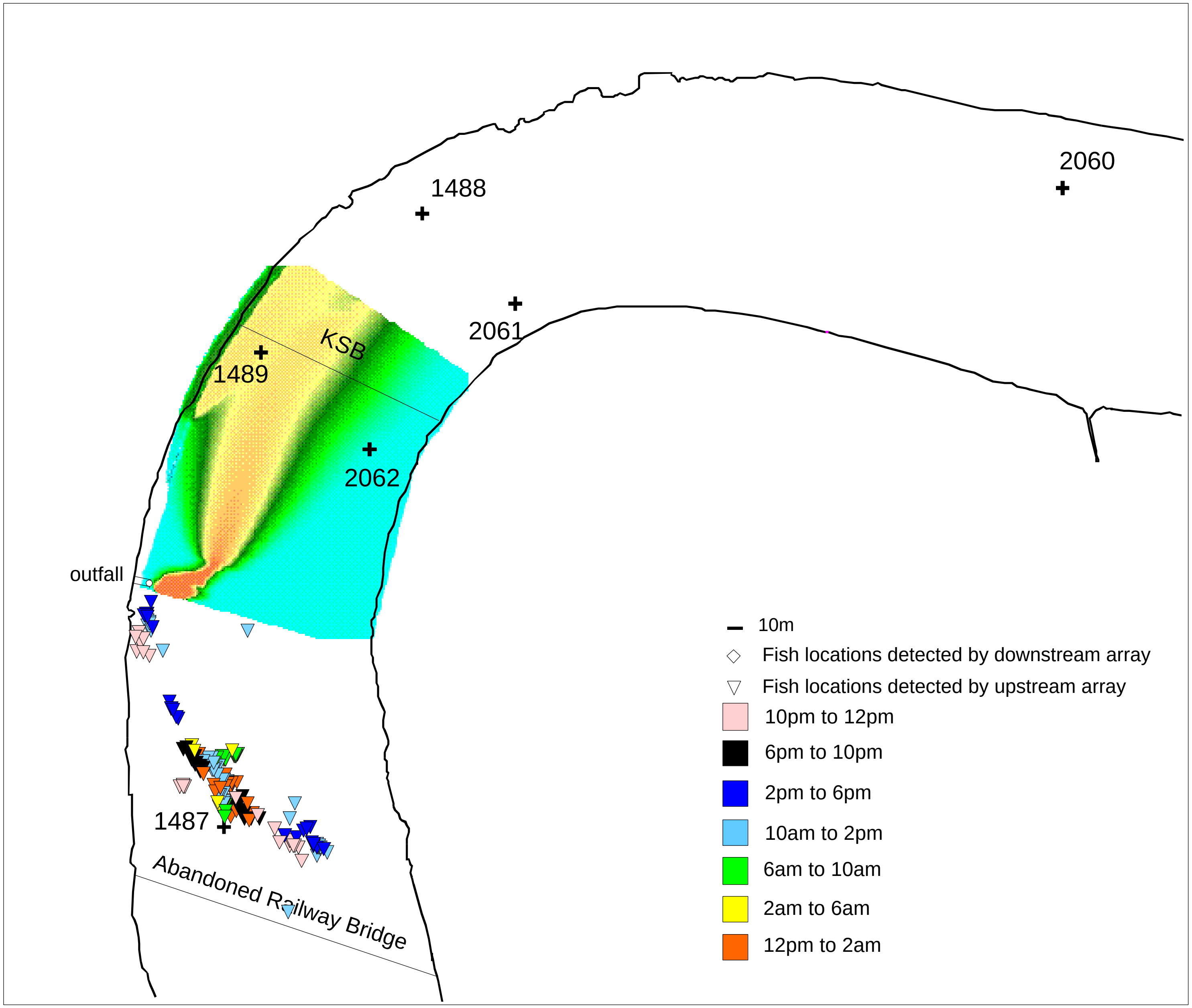

Figure 17. Positional data for Fish # 7959 in the vicinity of the NEWPCC plume, February 23, 2000.

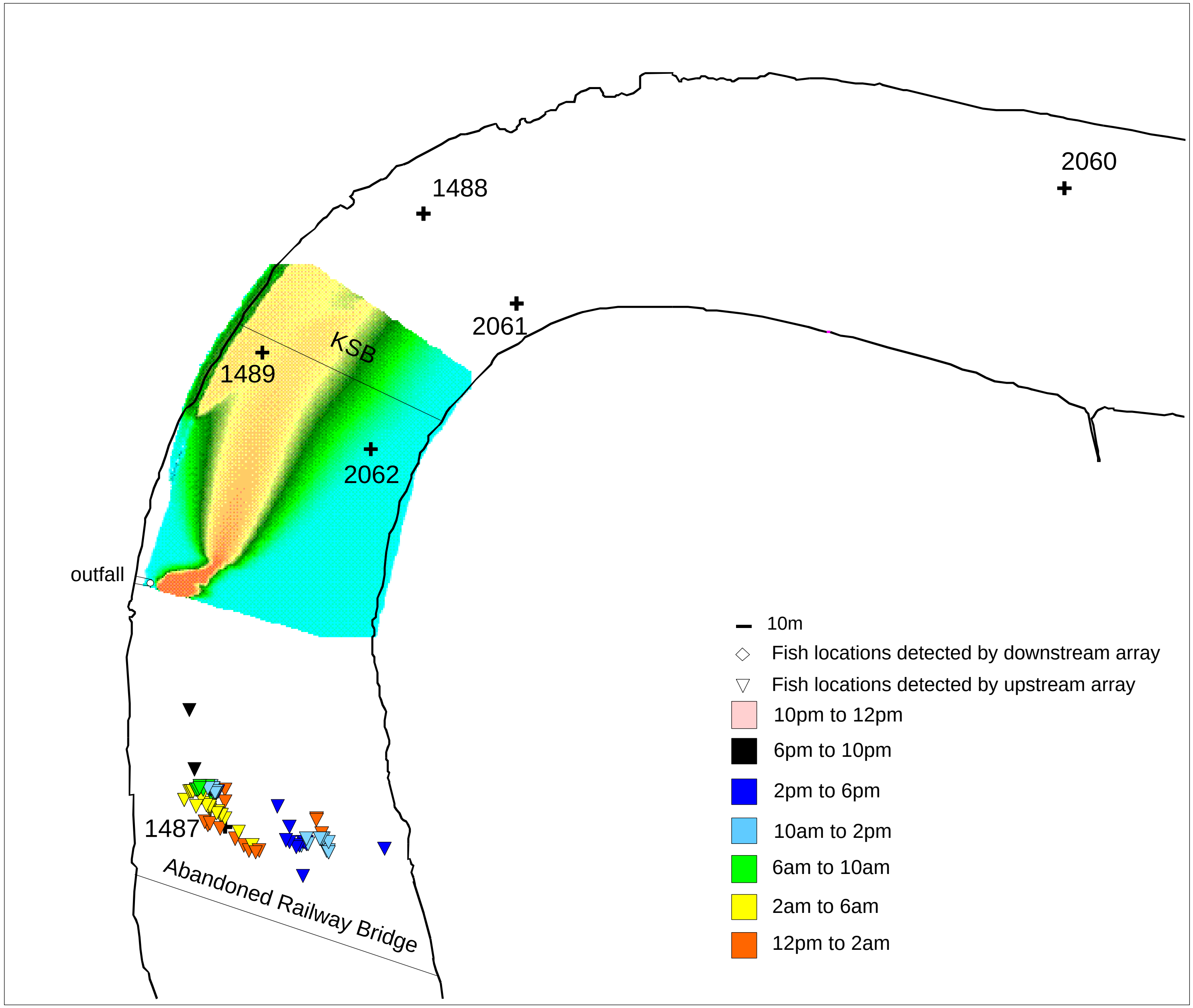

Figure 18. Positional data for Fish # 7959 in the vicinity of the NEWPCC plume, February 24, 2000.

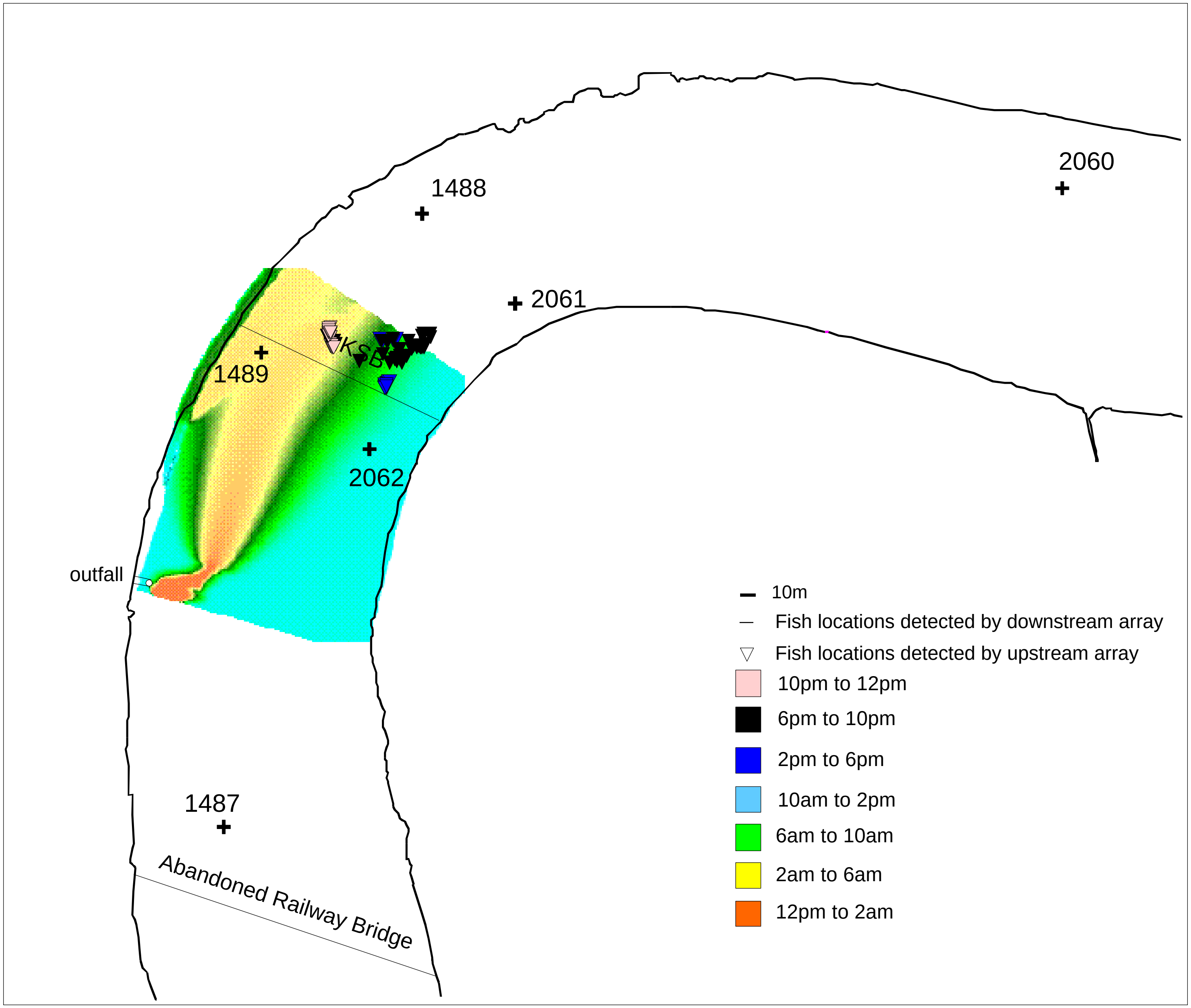

Figure 19. Positional data for Fish # 7960 in the vicinity of the NEWPCC plume, February 15, 2000.

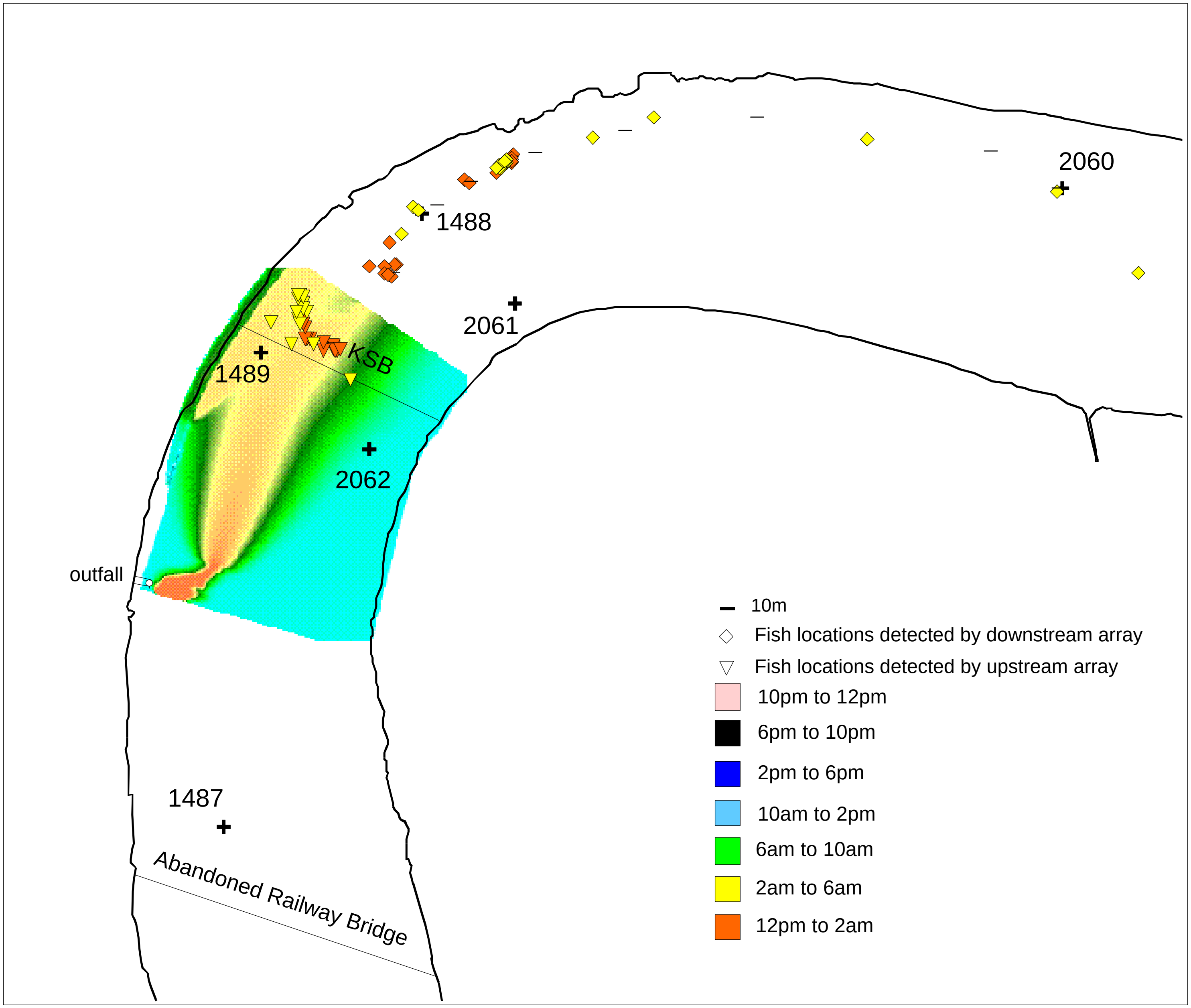

Figure 20. Positional data for Fish # 7960 in the vicinity of the NEWPCC plume, February 16, 2000.

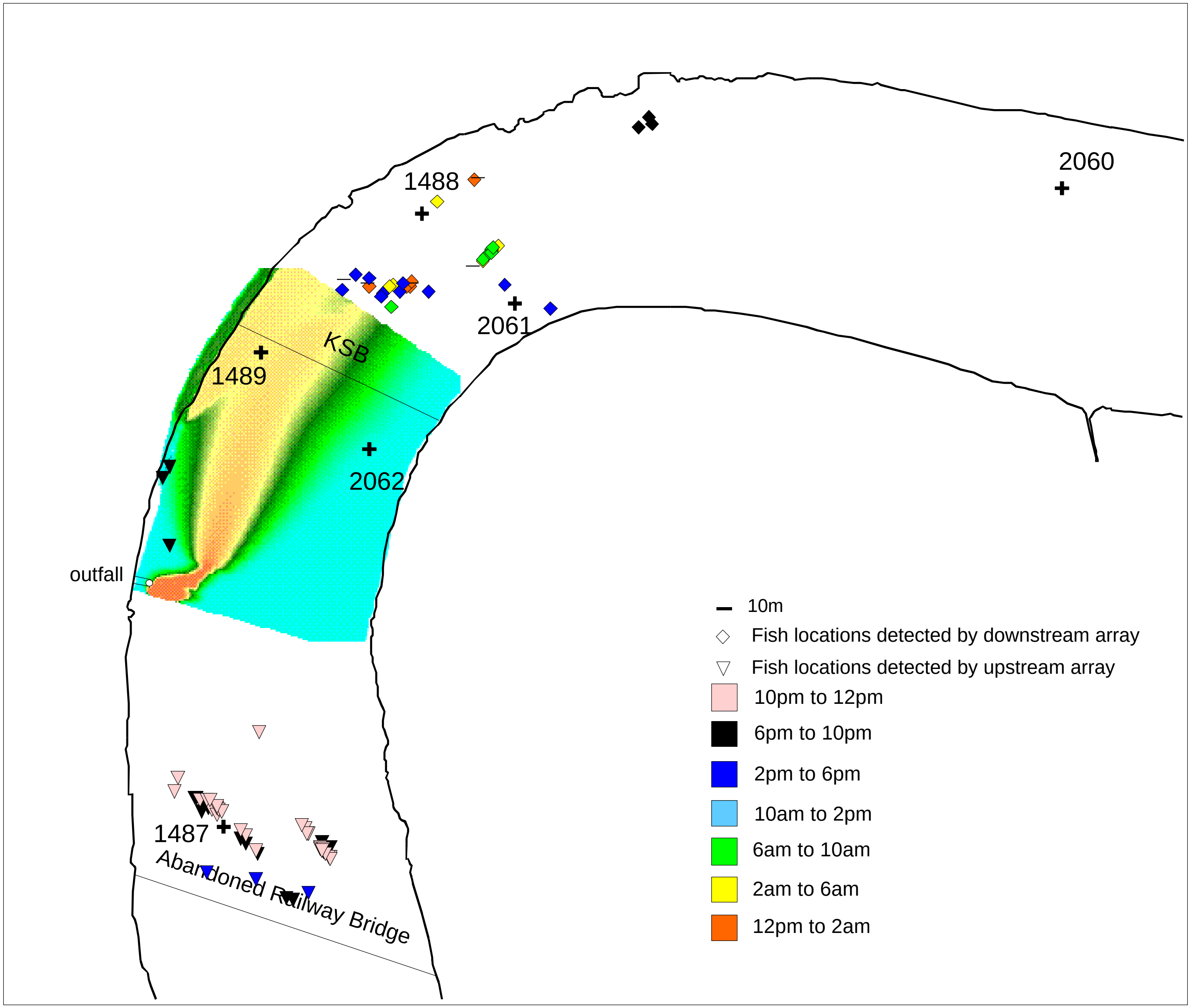

Figure 21. Positional data for Fish # 7960 in the vicinity of the NEWPCC plume, February 18, 2000.

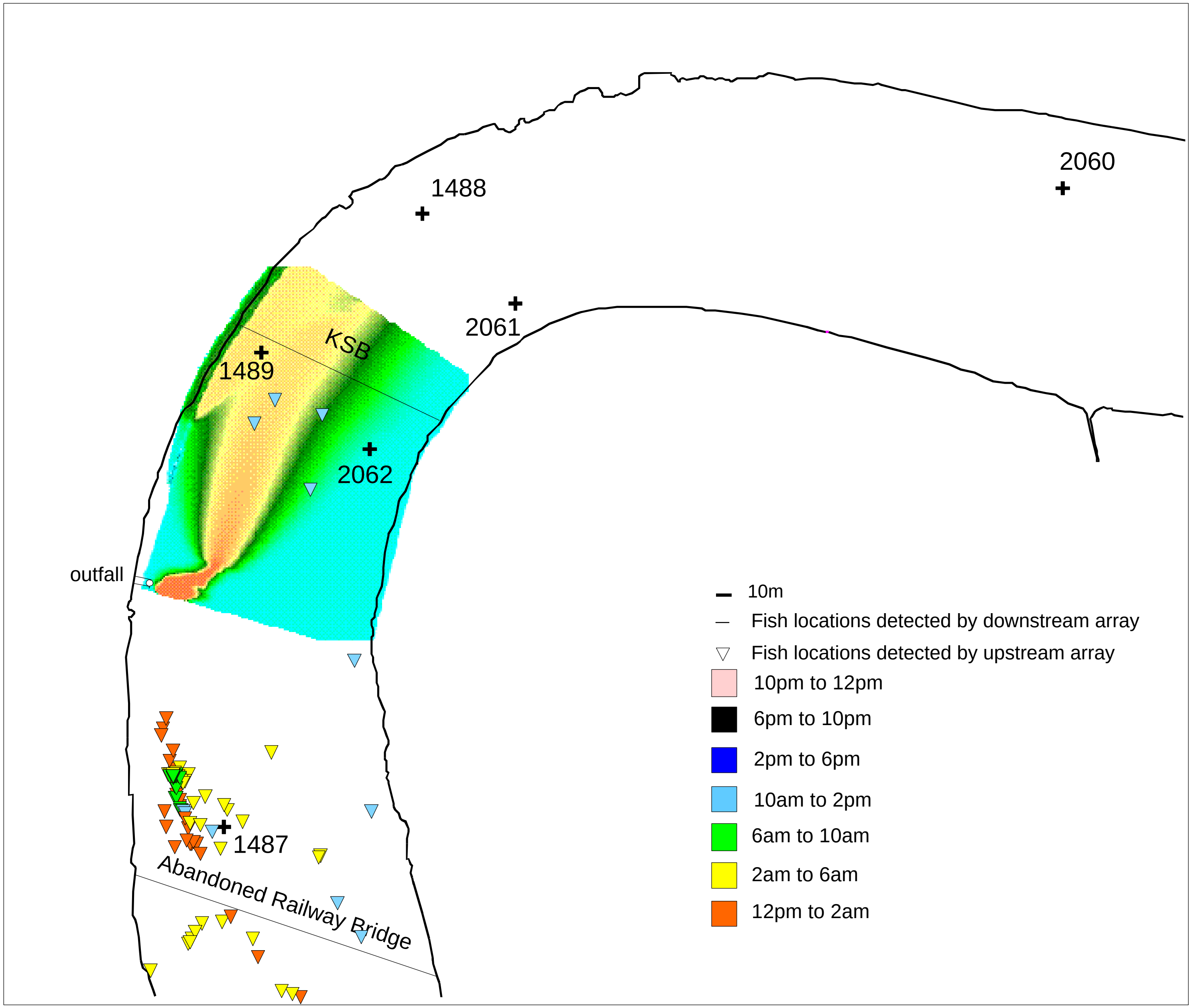

Figure 22. Positional data for Fish # 7960 in the vicinity of the NEWPCC plume, February 19, 2000.

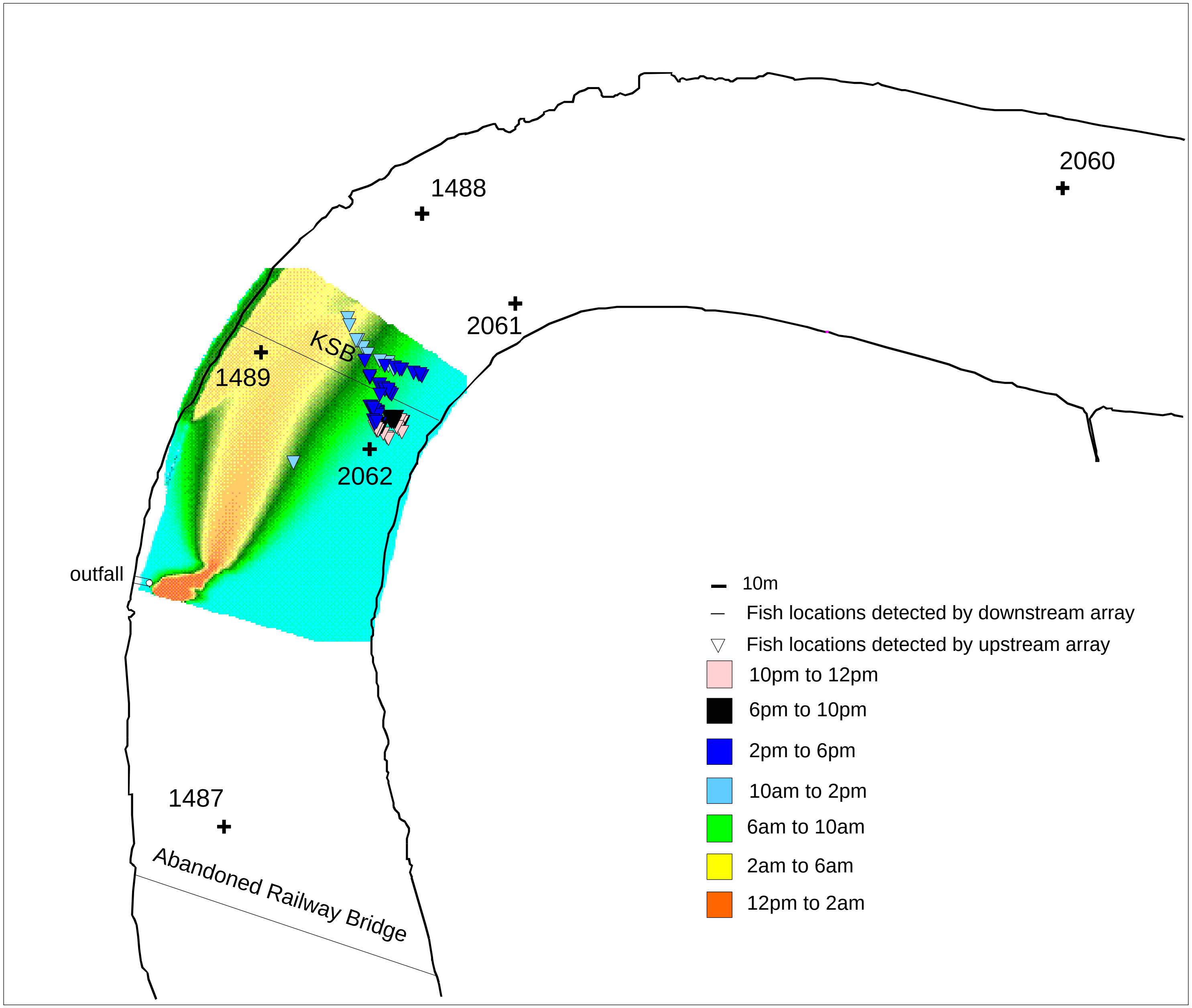

Figure 23. Positional data for Fish # 7961 in the vicinity of the NEWPCC plume, February 16, 2000.

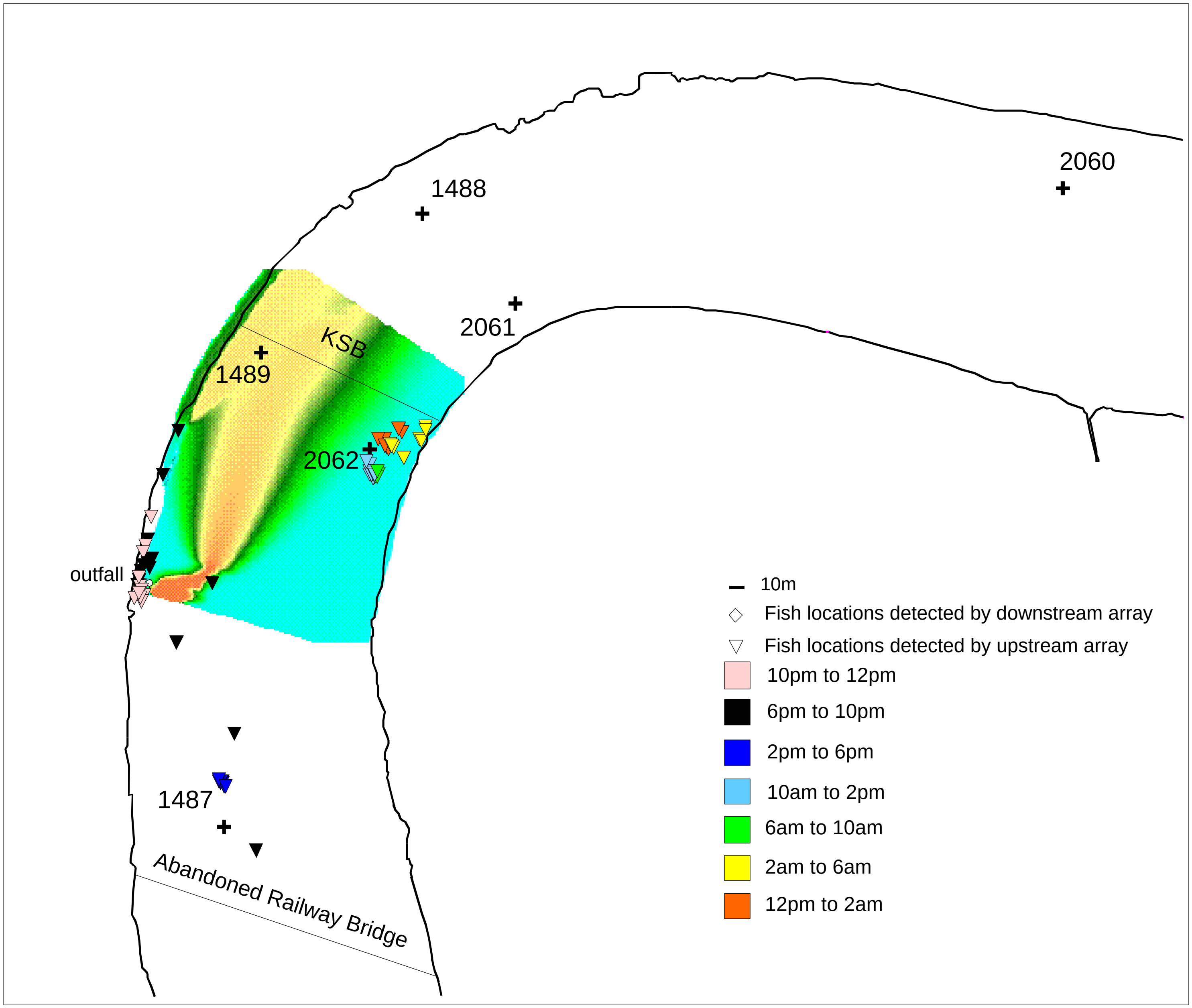

Figure 24. Positional data for Fish # 7961in the vicinity of the NEWPCC plume, February 17, 2000.

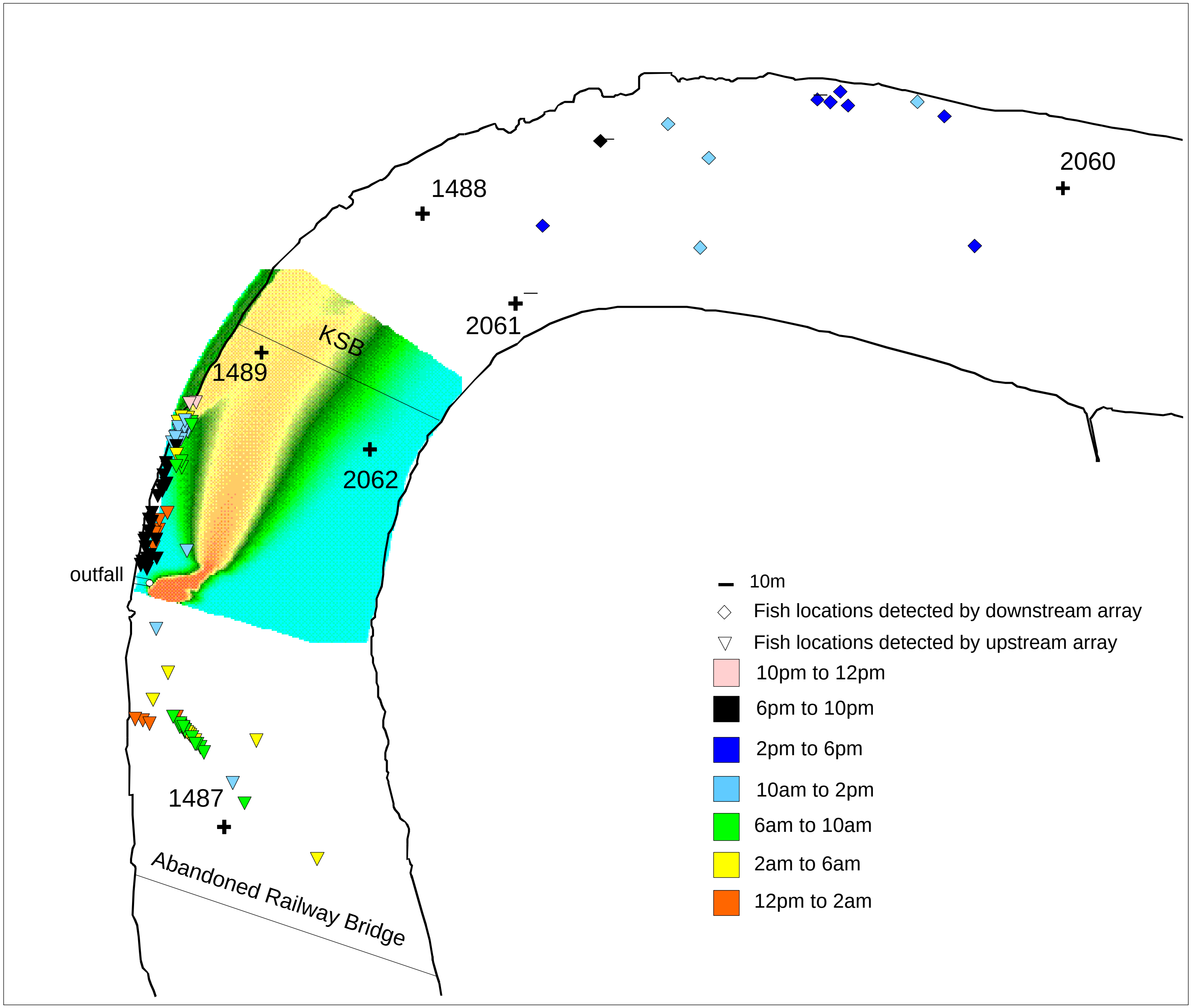

Figure 25. Positional data for Fish # 7961 in the vicinity of the NEWPCC plume, February 18, 2000.

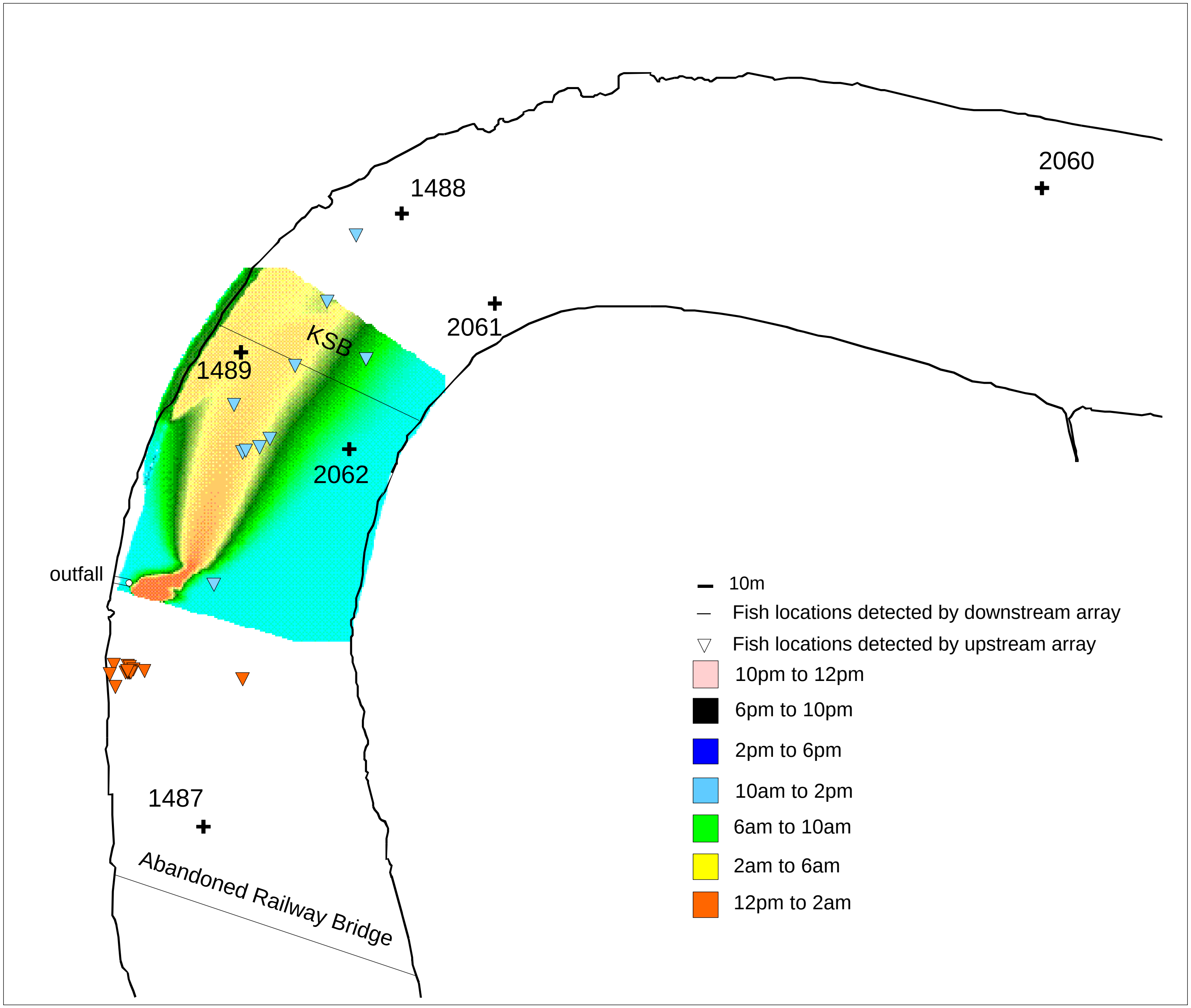

Figure 26. Positional data for Fish # 7961 in the vicinity of the NEWPCC plume, February 19, 2000.

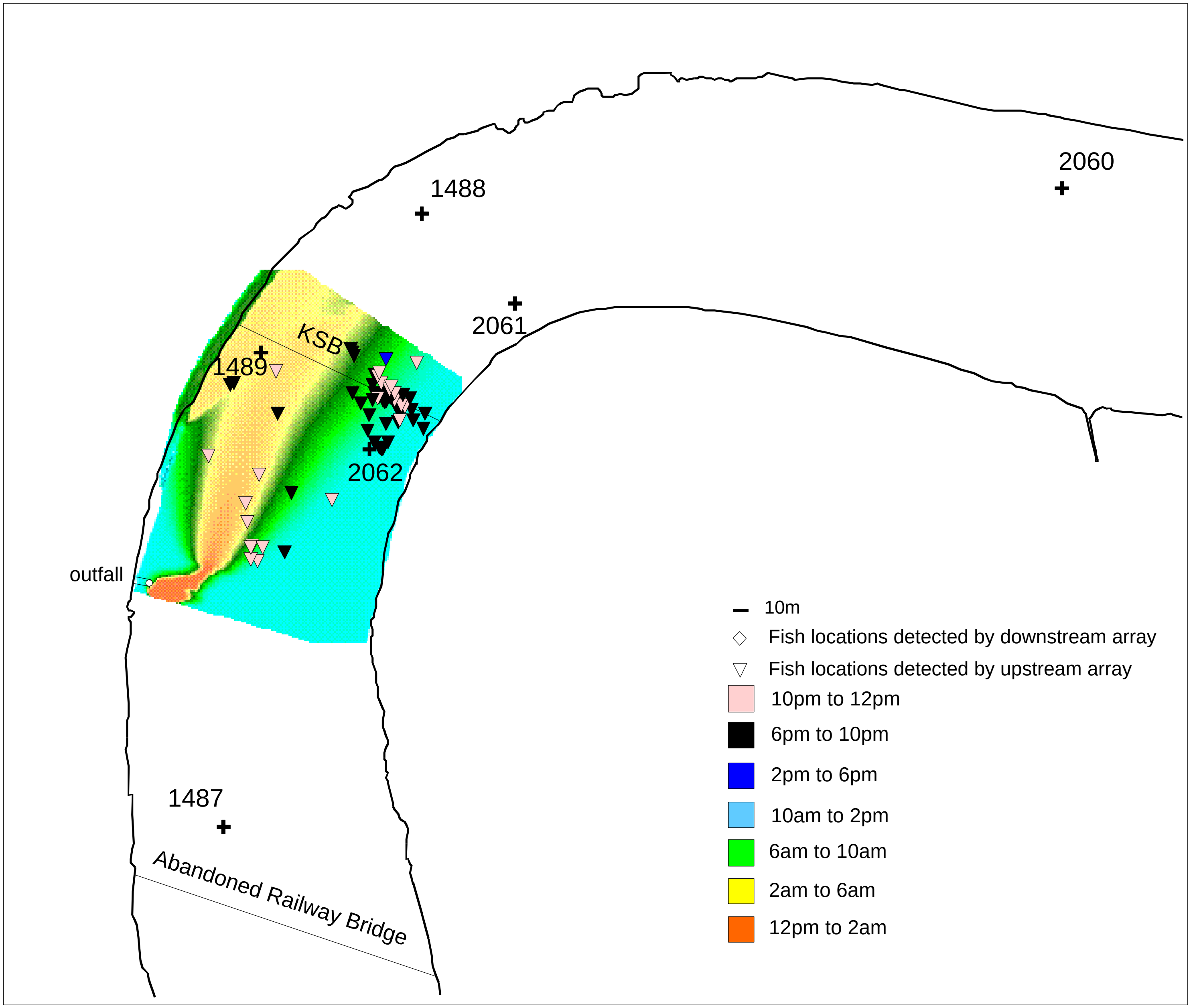

Figure 27. Positional data for Fish # 7962 in the vicinity of the NEWPCC plume, February 15, 2000.

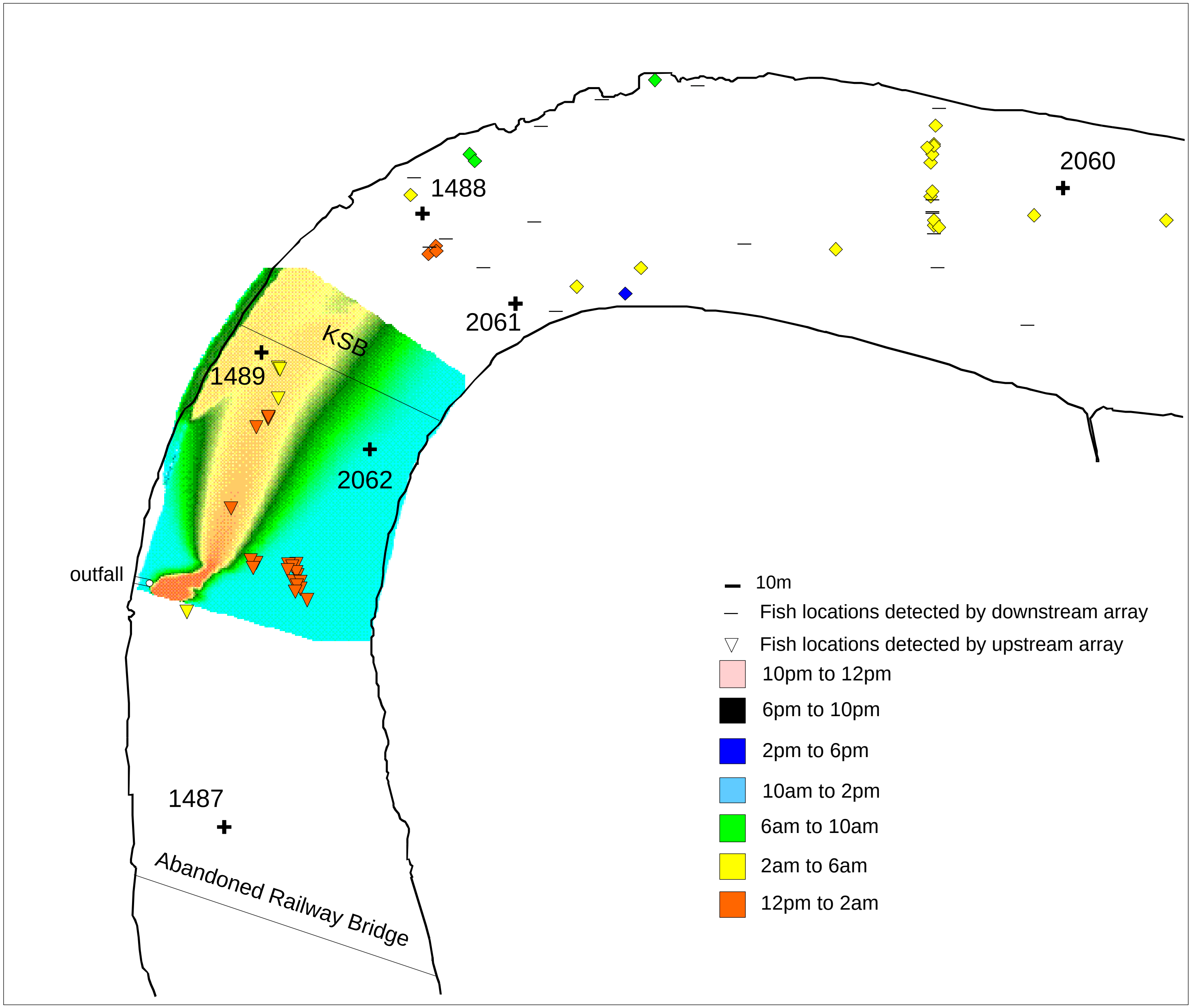

Figure 28. Positional data for Fish # 7962 in the vicinity of the NEWPCC plume, February 16, 2000.

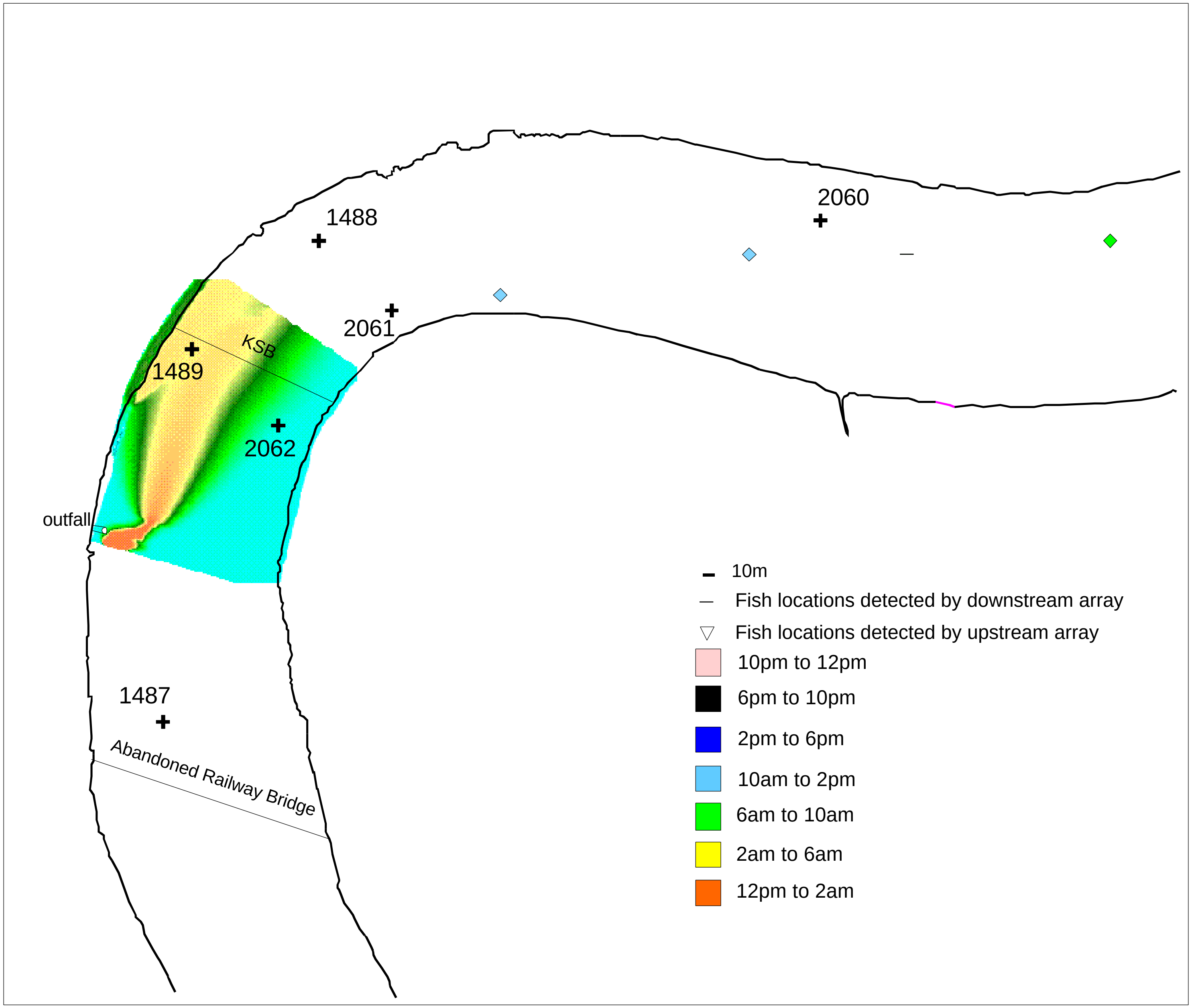

Figure 29. Positional data for Fish # 7962 in the vicinity of the NEWPCC plume, February 18, 2000.

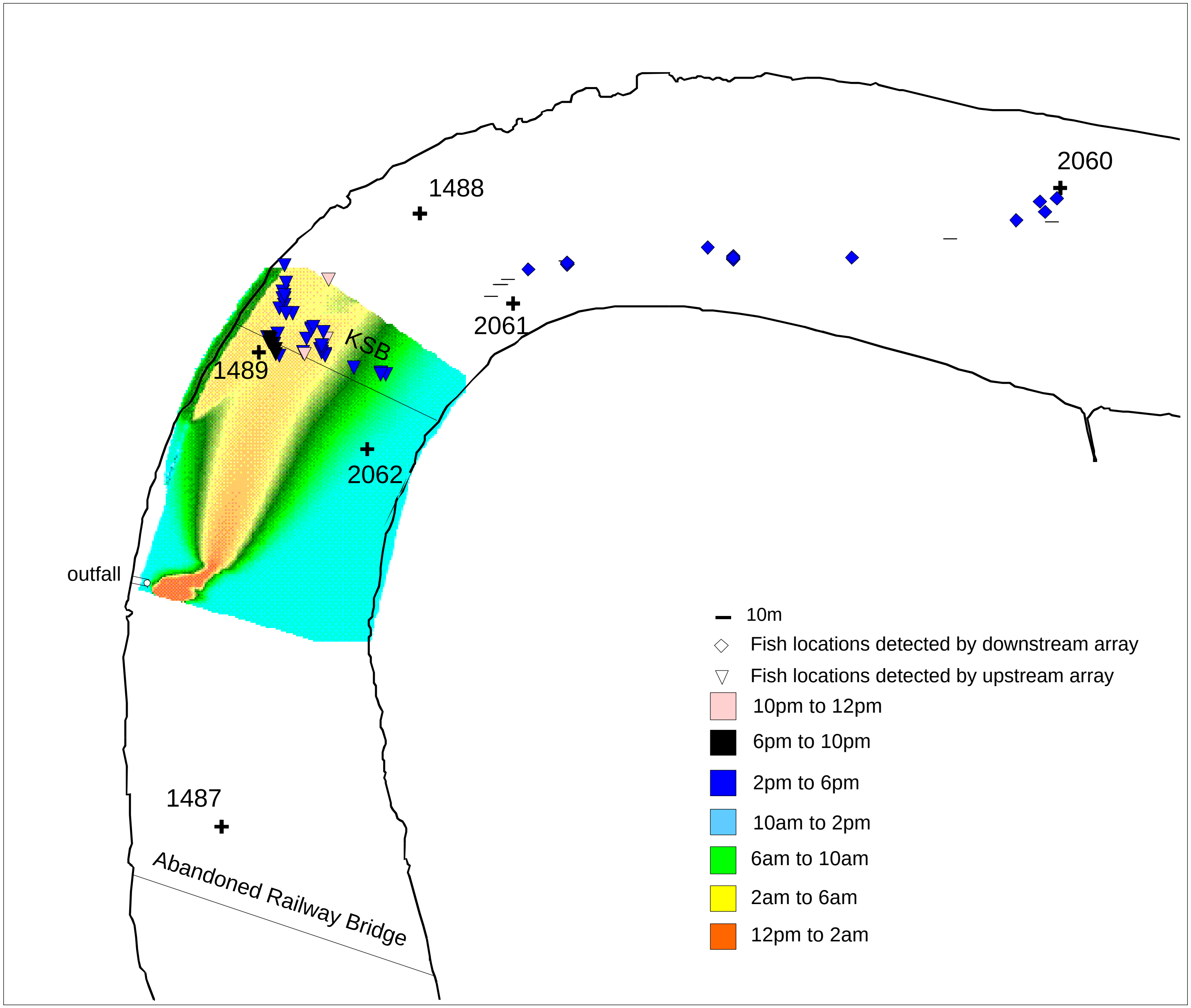

Figure 30. Positional data for Fish # 7963 in the vicinity of the NEWPCC plume, February 16, 2000.

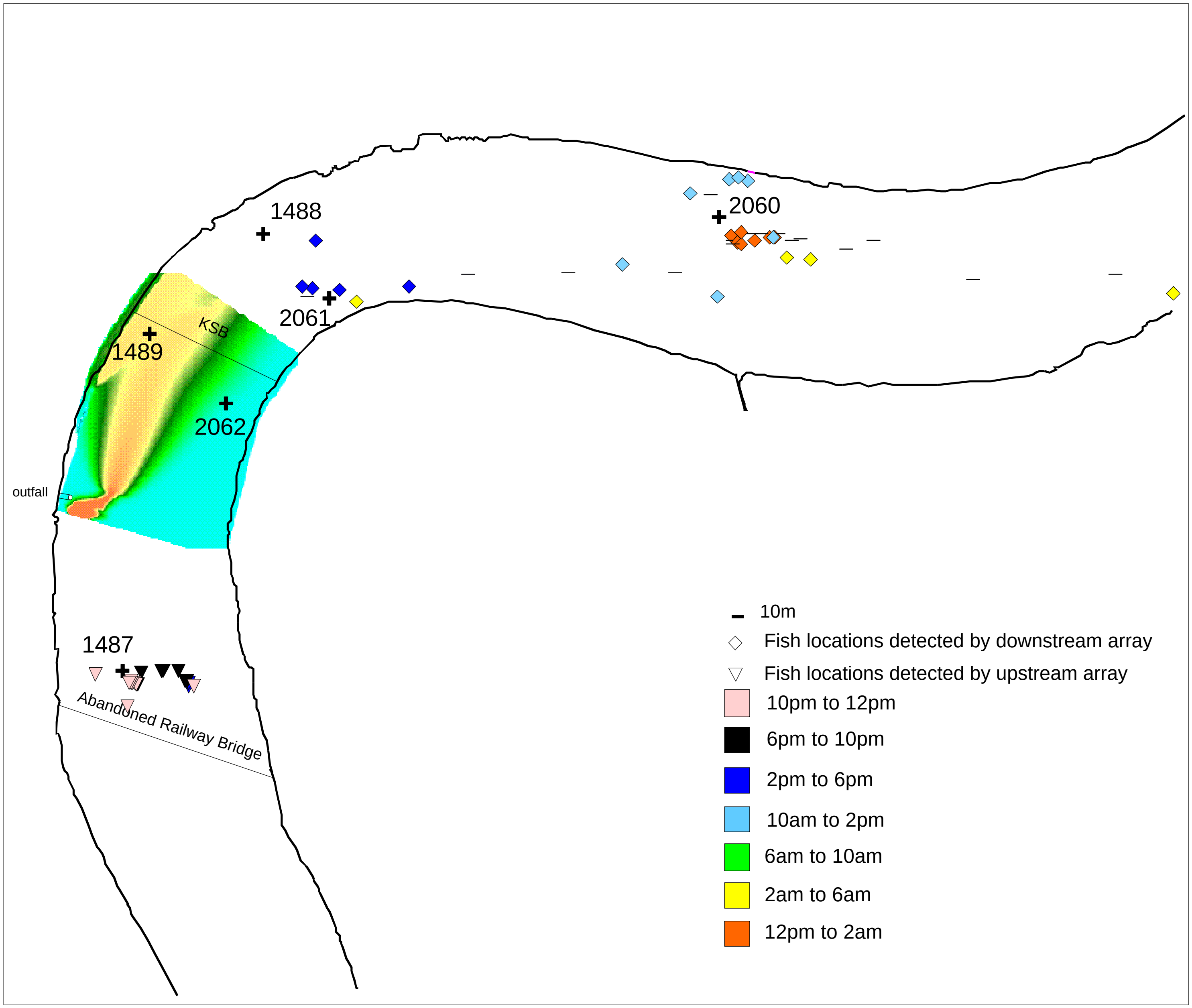

Figure 31. Positional data for Fish # 7963 in the vicinity of the NEWPCC plume, February 17, 2000.

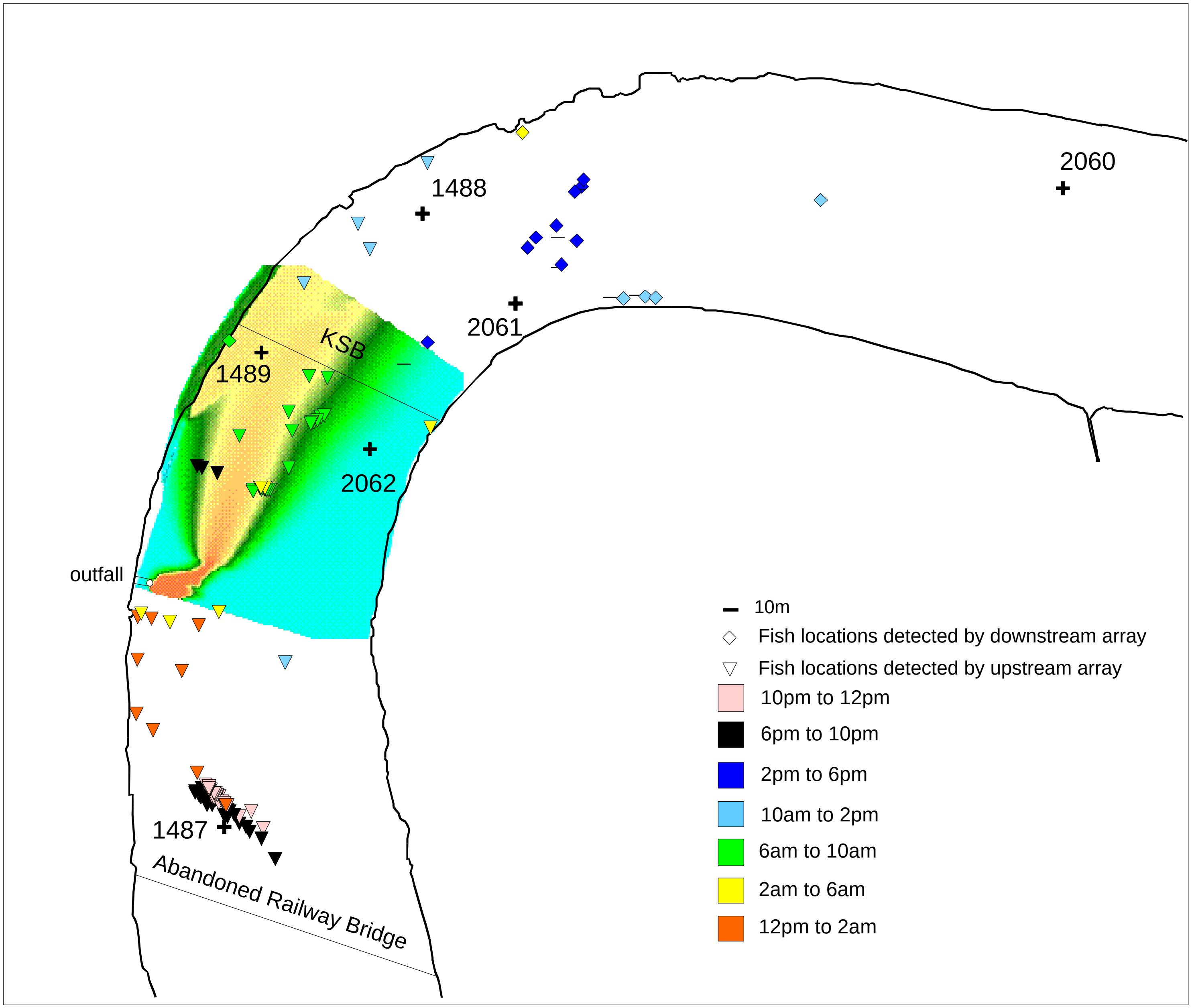

Figure 32. Positional data for Fish # 7963 in the vicinity of the NEWPCC plume, February 18, 2000.

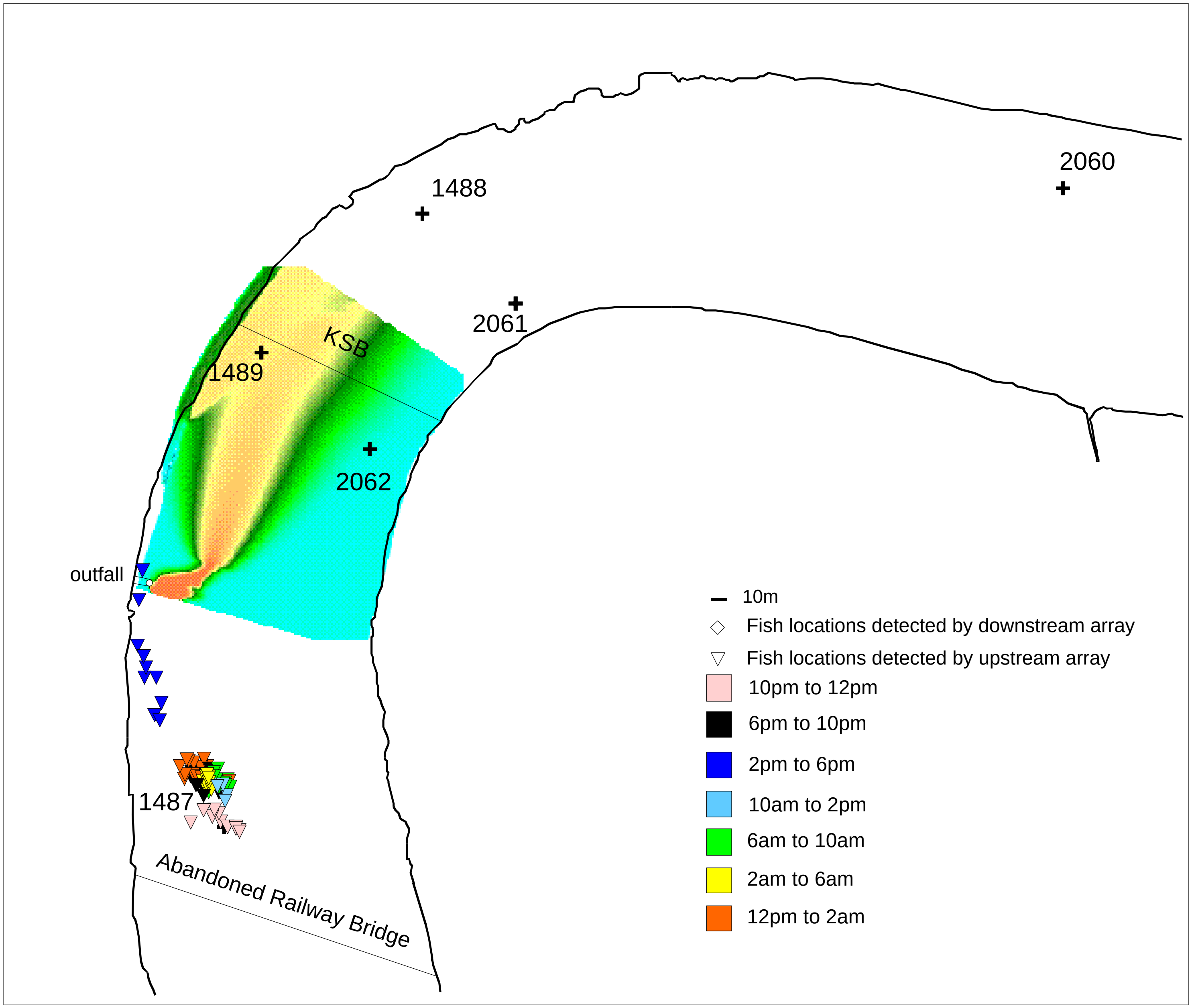

Figure 33. Positional data for Fish # 7963 in the vicinity of the NEWPCC plume, February 19, 2000.

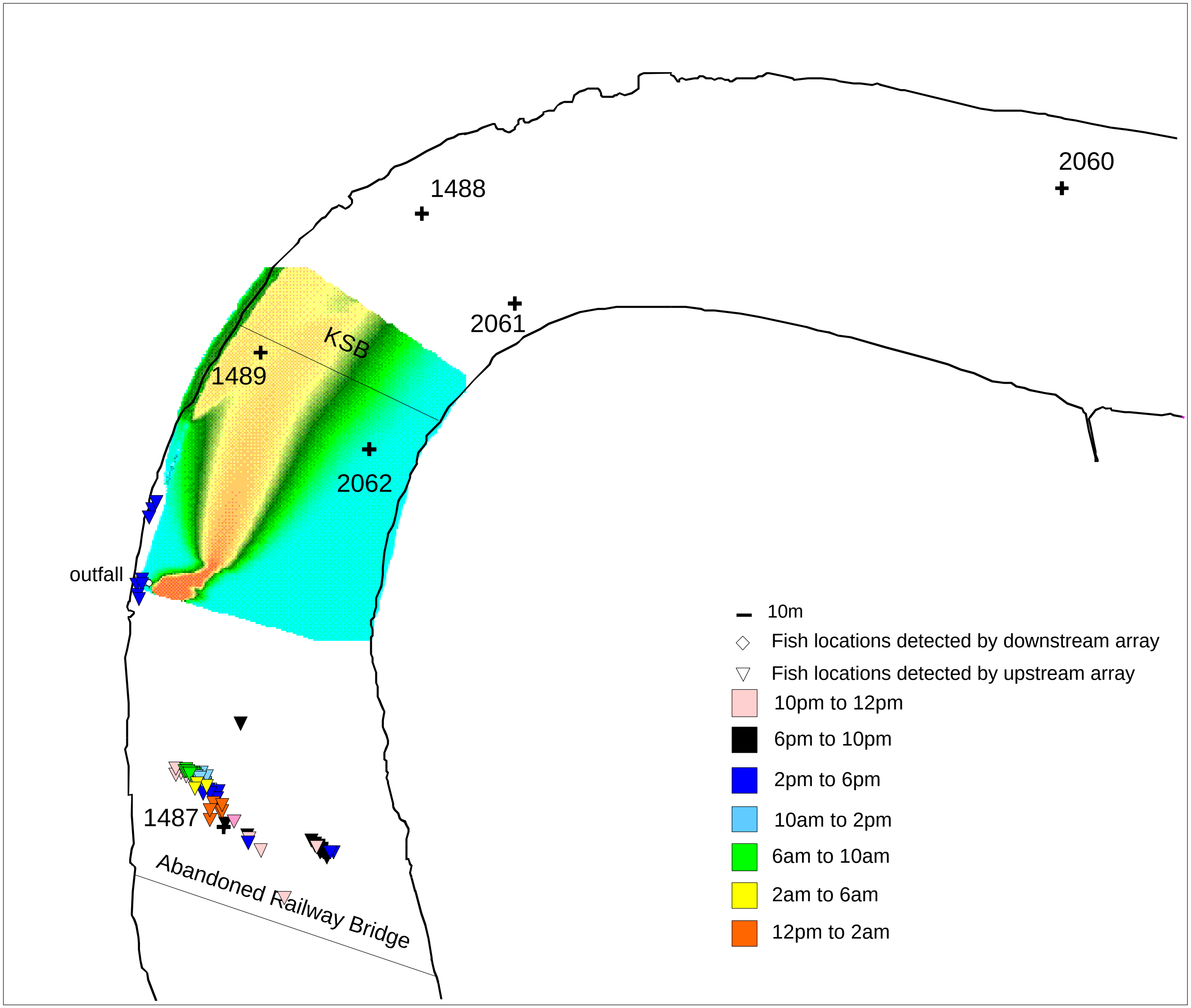

Figure 34. Positional data for Fish # 7963 in the vicinity of the NEWPCC plume, February 20, 2000.

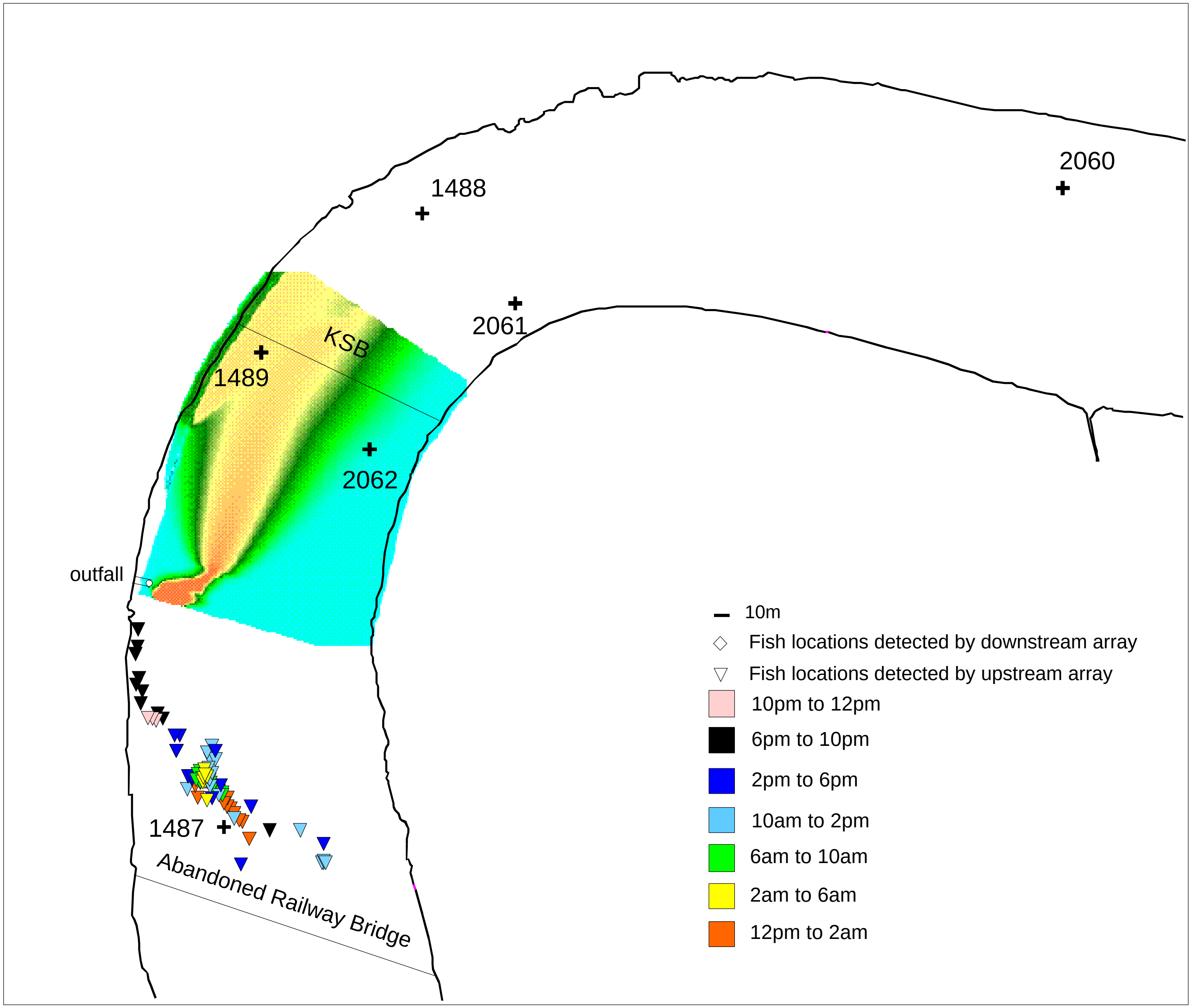

Figure 35. Positional data for Fish # 7963 in the vicinity of the NEWPCC plume, February 21, 2000.

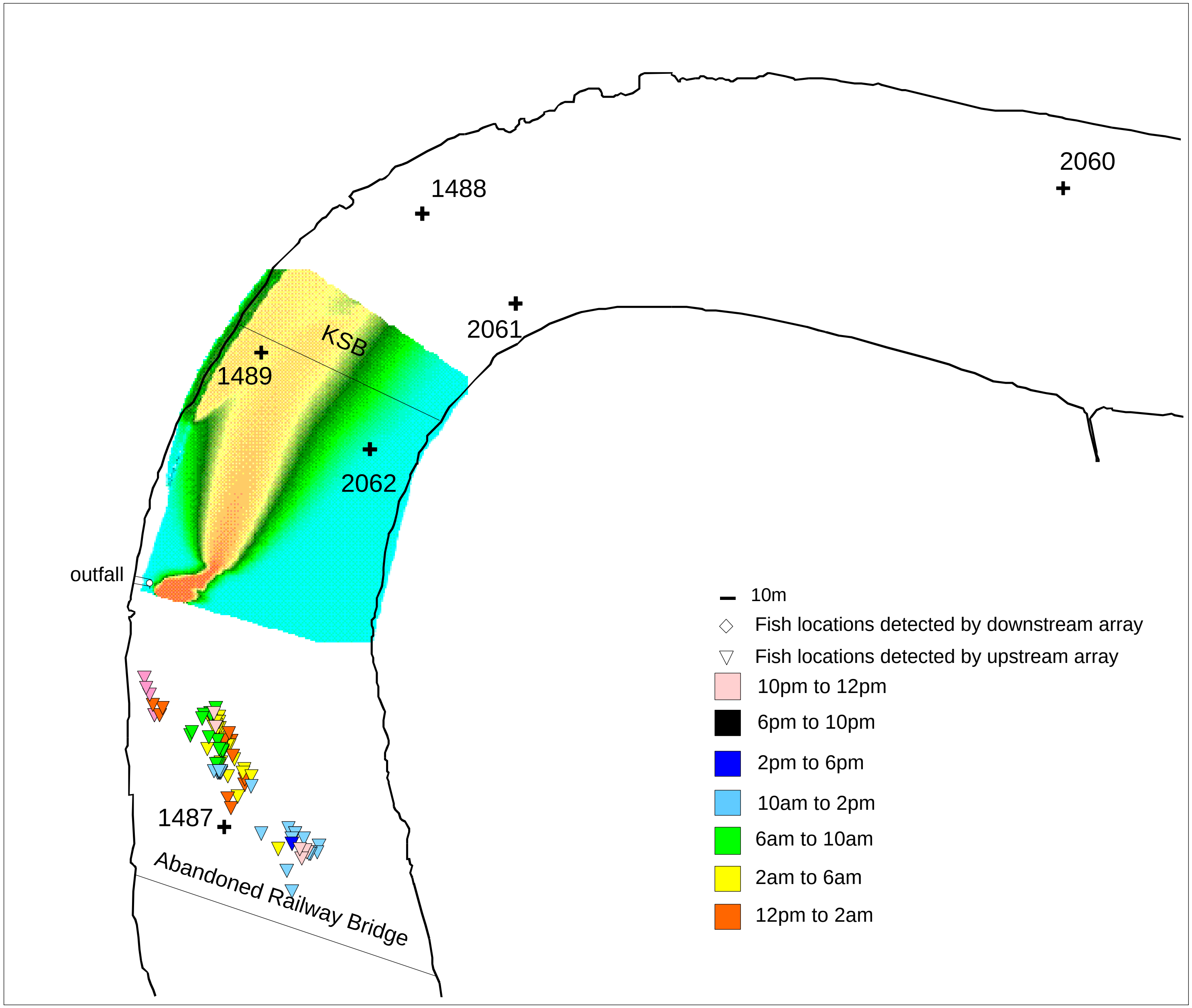

Figure 36. Positional data for Fish # 7963 in the vicinity of the NEWPCC plume, February 22, 2000.

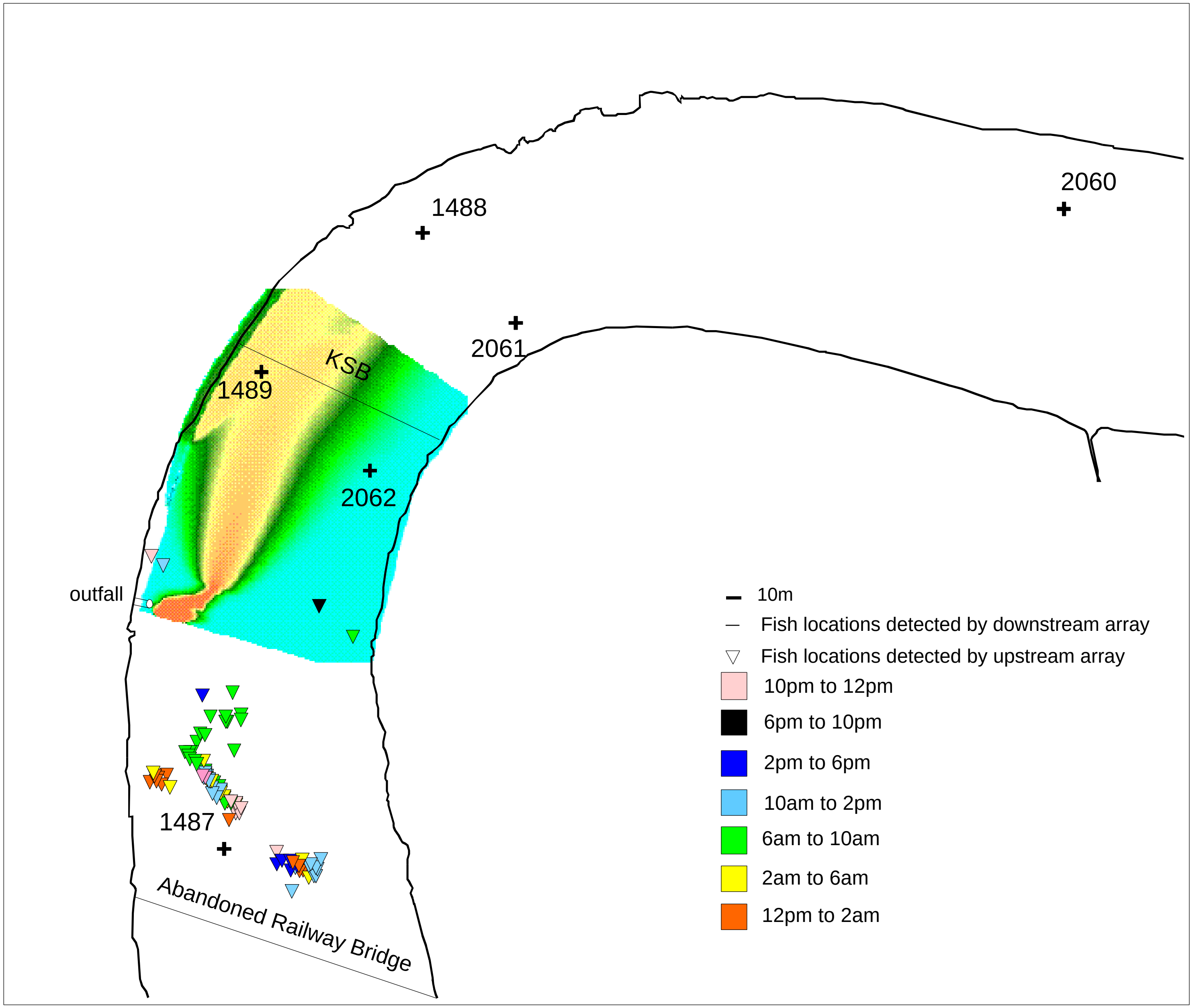

Figure 37. Positional data for Fish # 7963 in the vicinity of the NEWPCC plume, February 23, 2000.

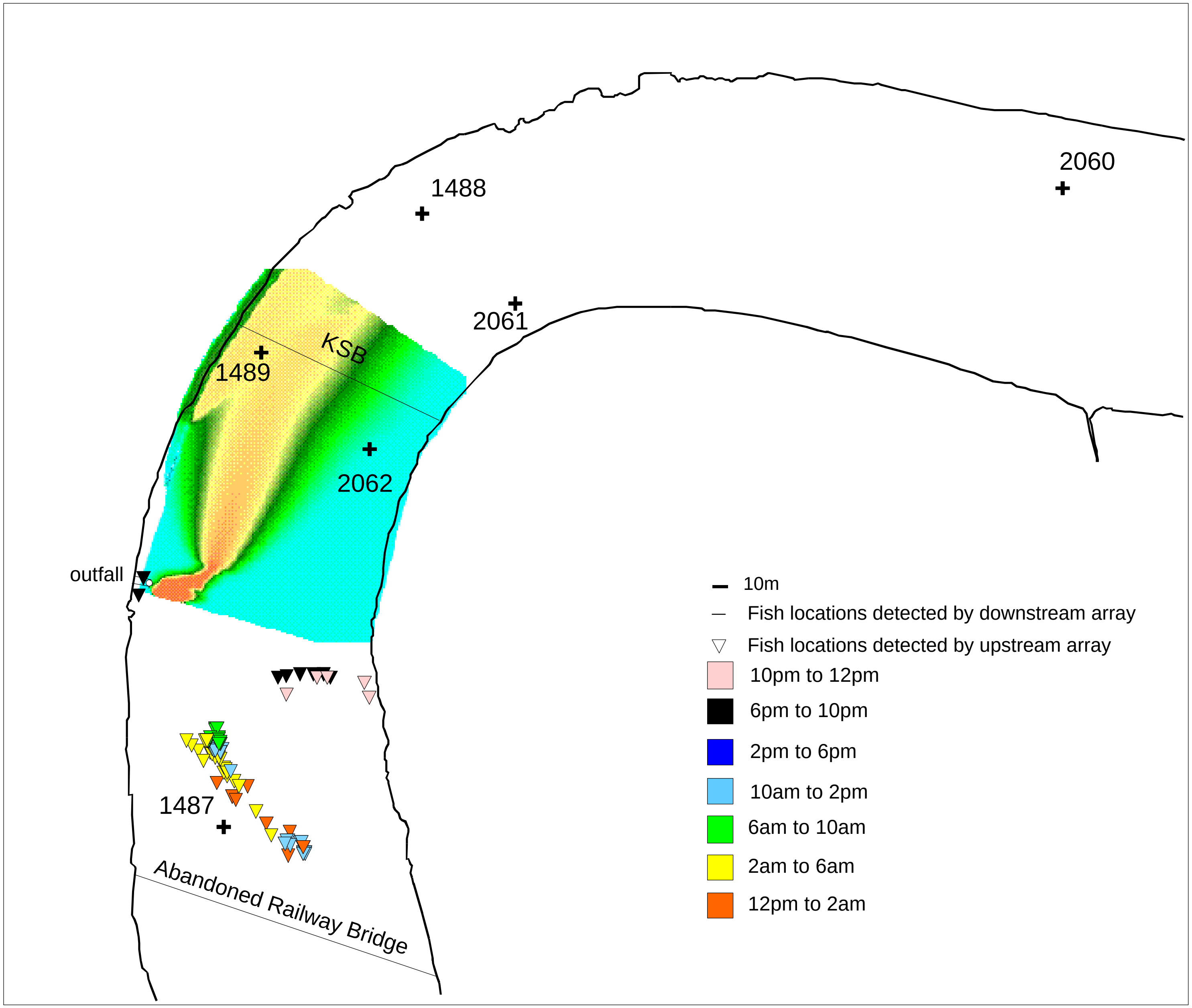

Figure 38. Positional data for Fish # 7963 in the vicinity of the NEWPCC plume, February 24, 2000.

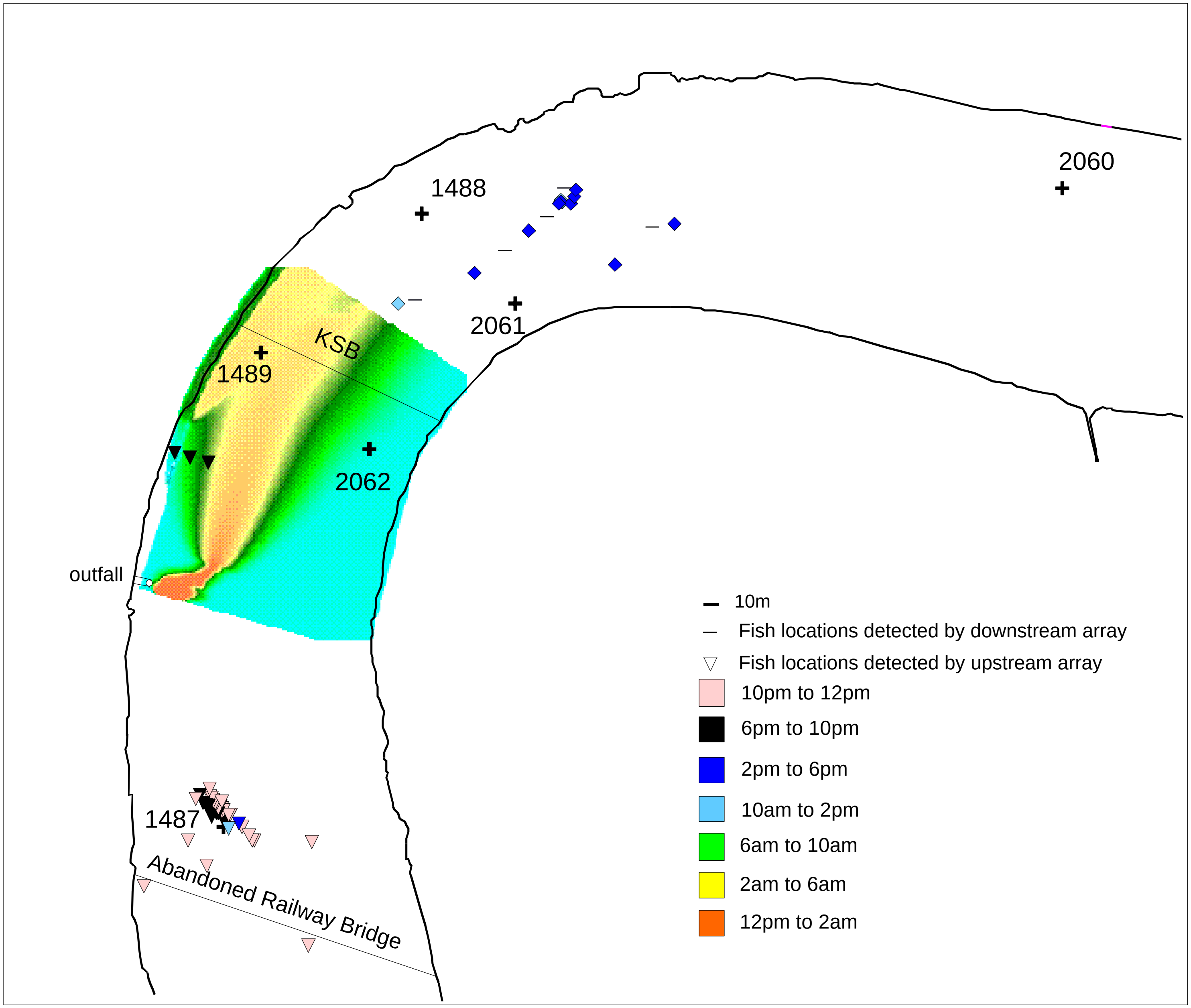

Figure 39. Positional data for Fish # 7964 in the vicinity of the NEWPCC plume, February 18, 2000.

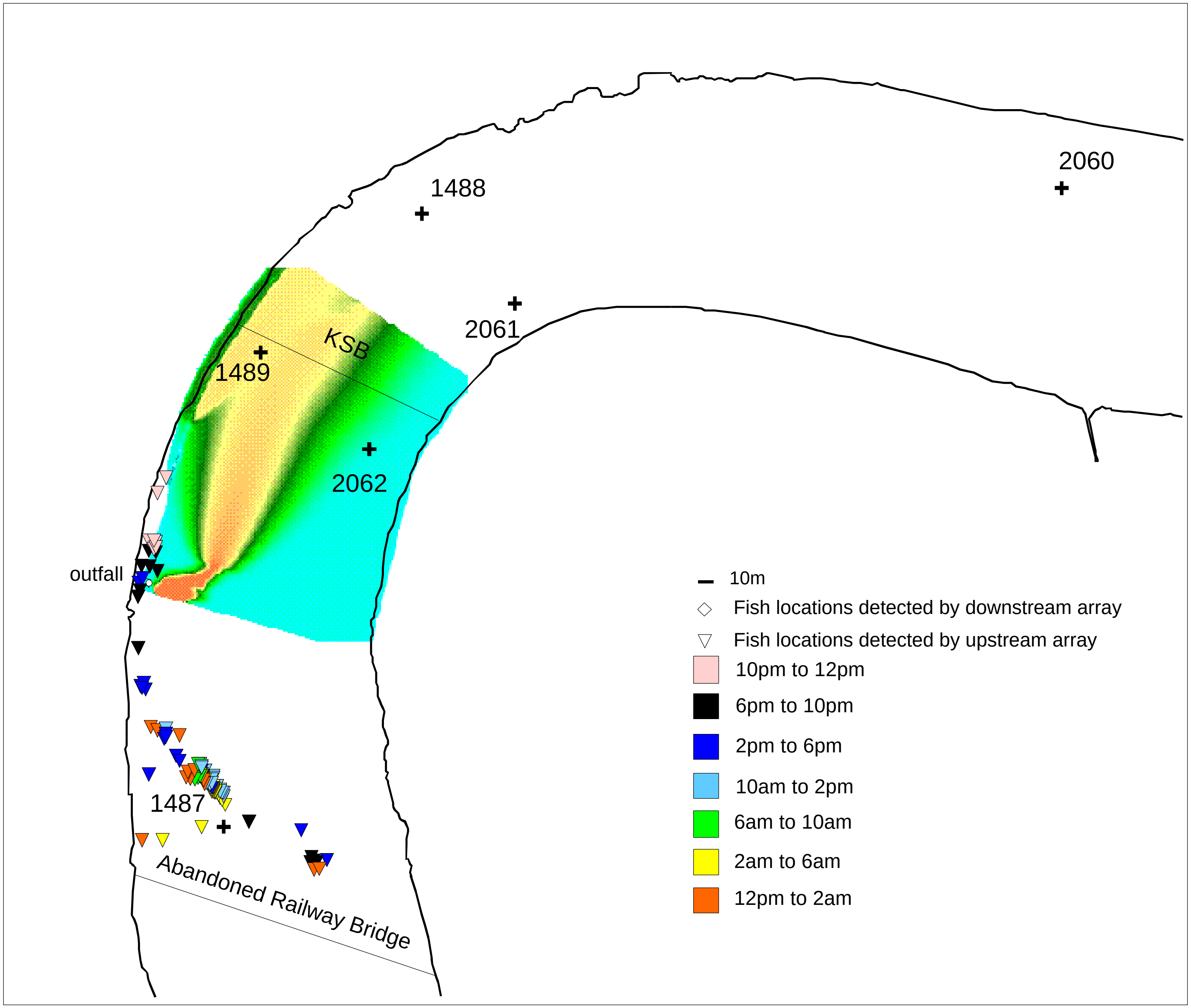

Figure 40. Positional data for Fish # 7964 in the vicinity of the NEWPCC plume, February 19, 2000.

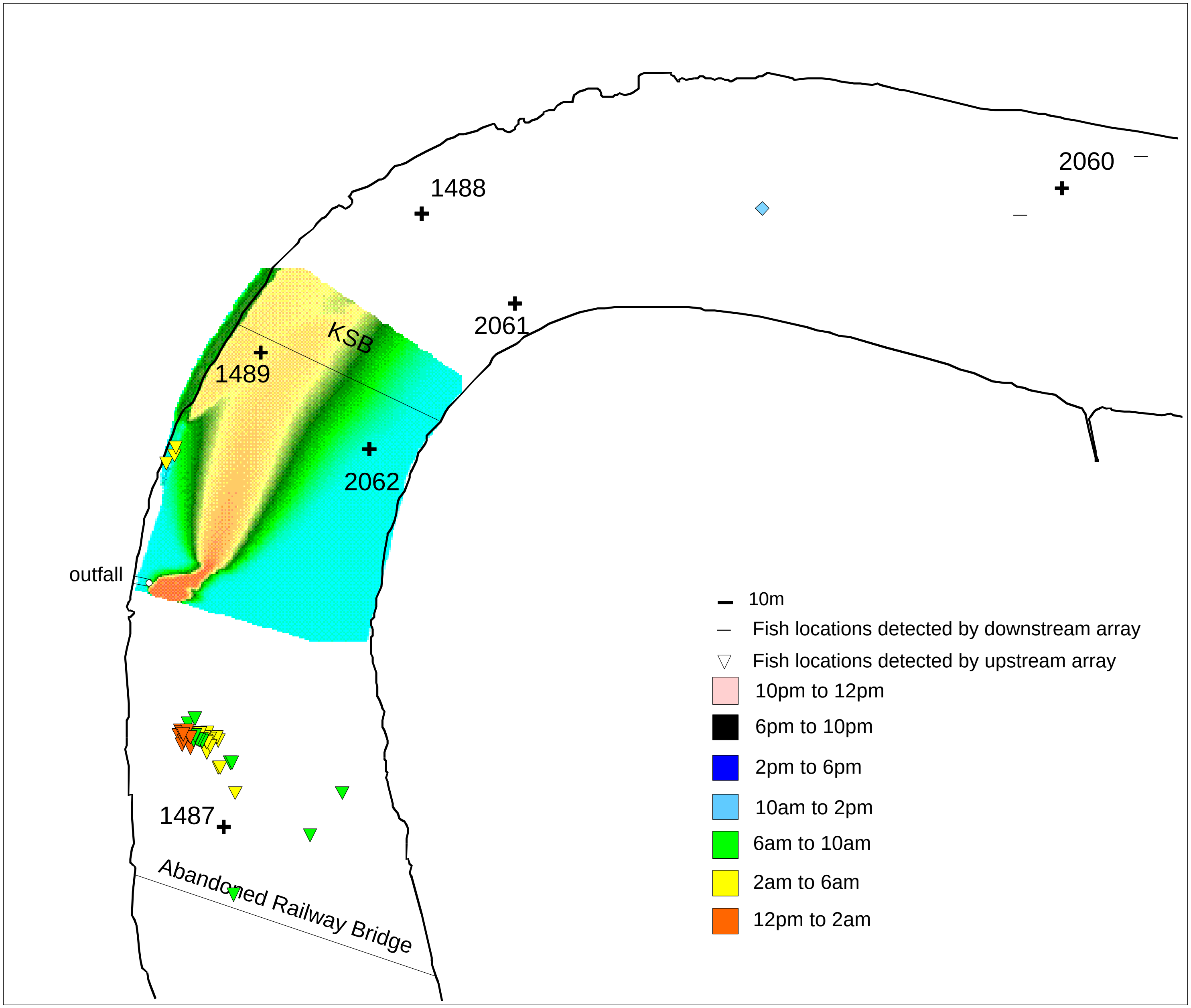

Figure 41. Positional data for Fish # 7964 in the vicinity of the NEWPCC plume, February 20, 2000.

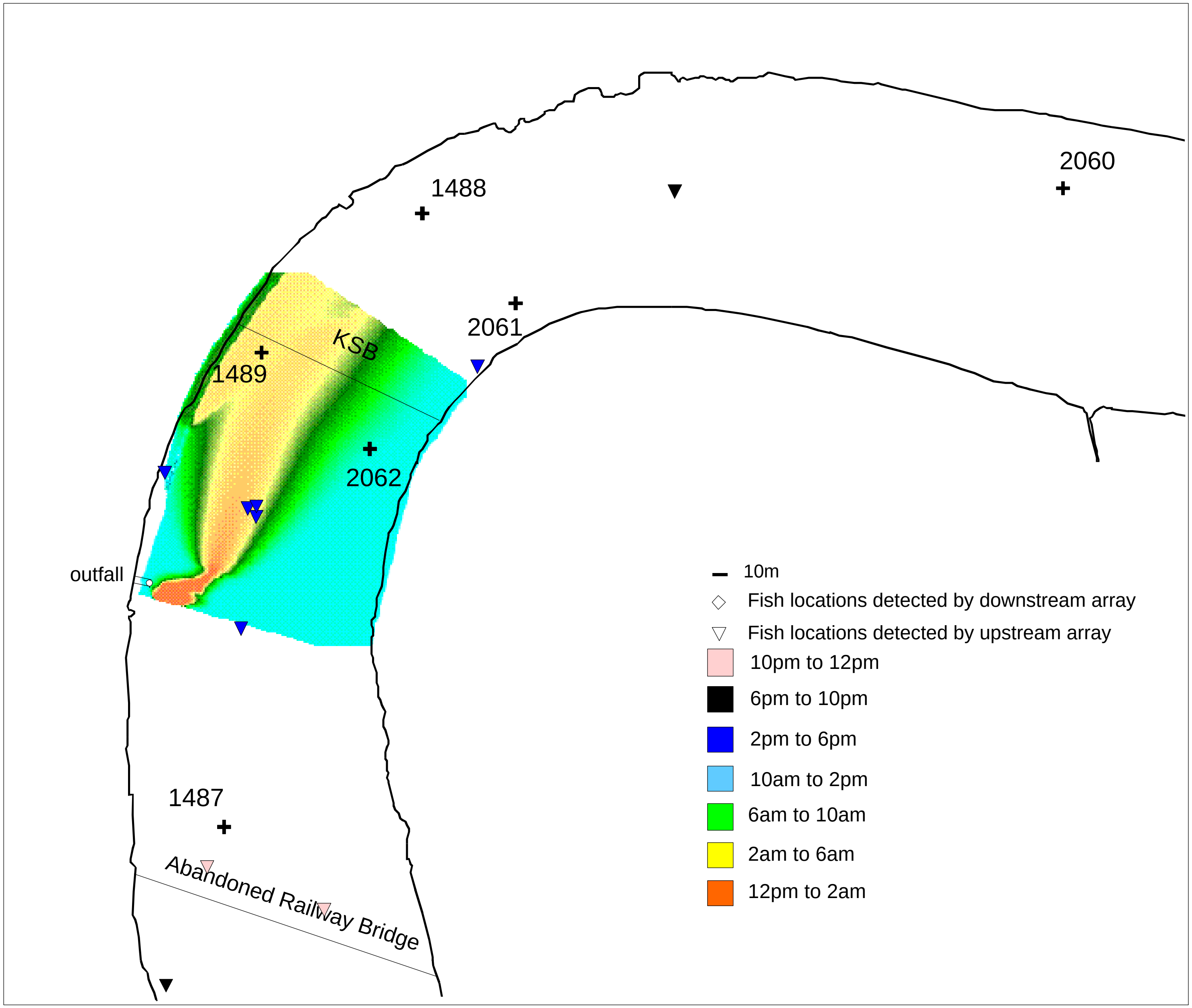

Figure 42. Positional data for Fish # 7965 in the vicinity of the NEWPCC plume, February 17, 2000.

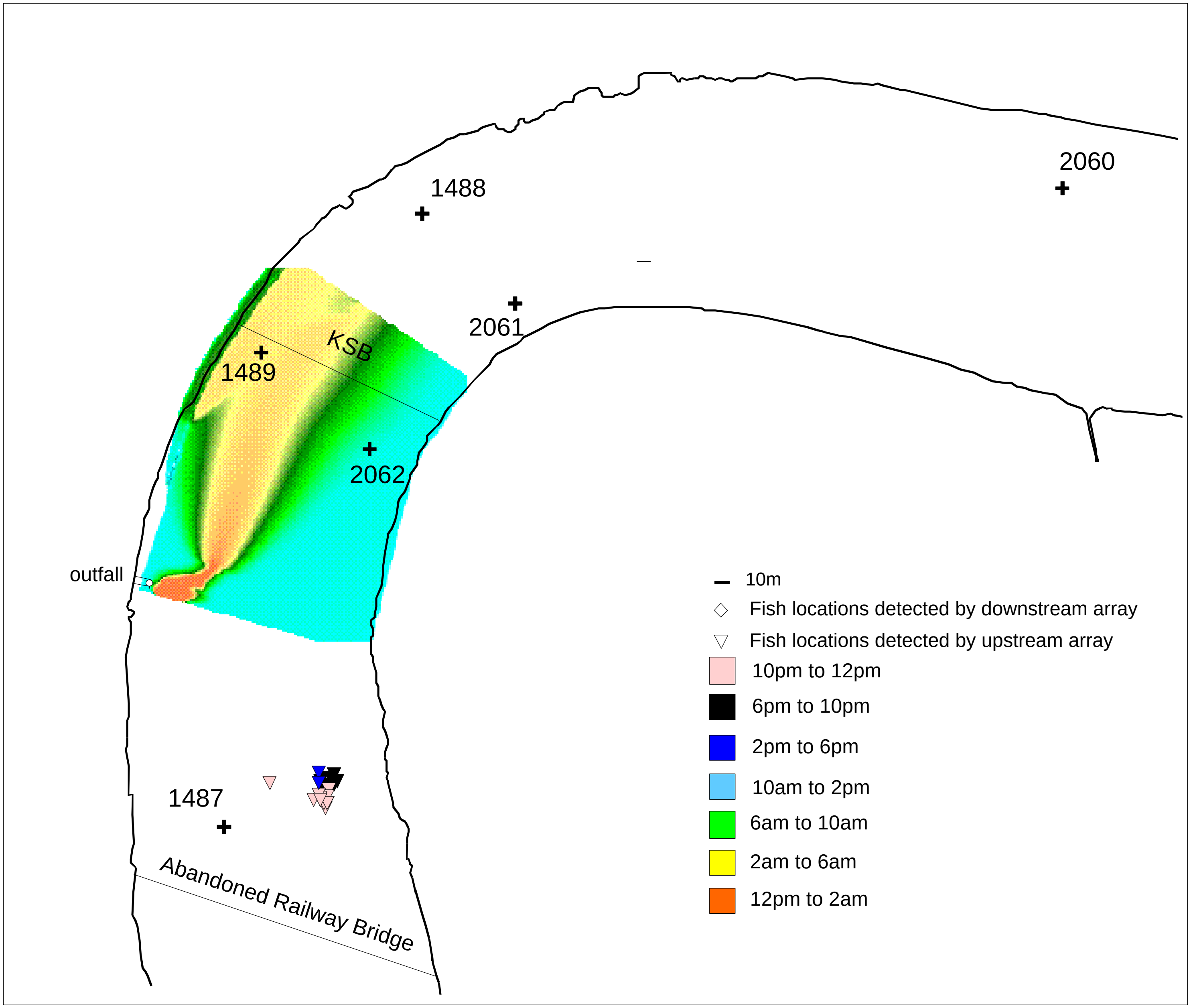

Figure 43. Positional data for Fish # 7965 in the vicinity of the NEWPCC plume, February 18, 2000.

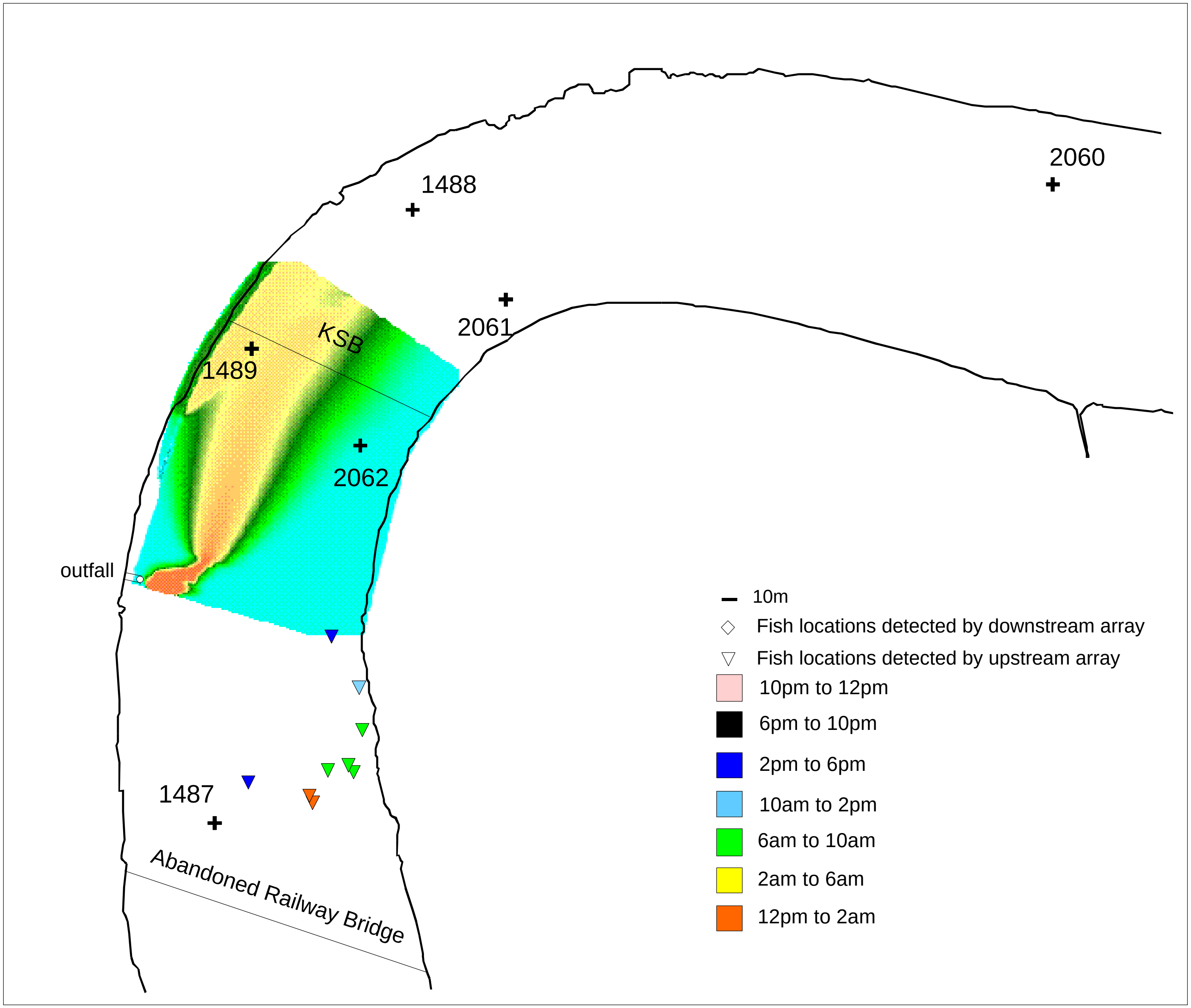

Figure 44. Positional data for Fish # 7965 in the vicinity of the NEWPCC plume, February 19, 2000.

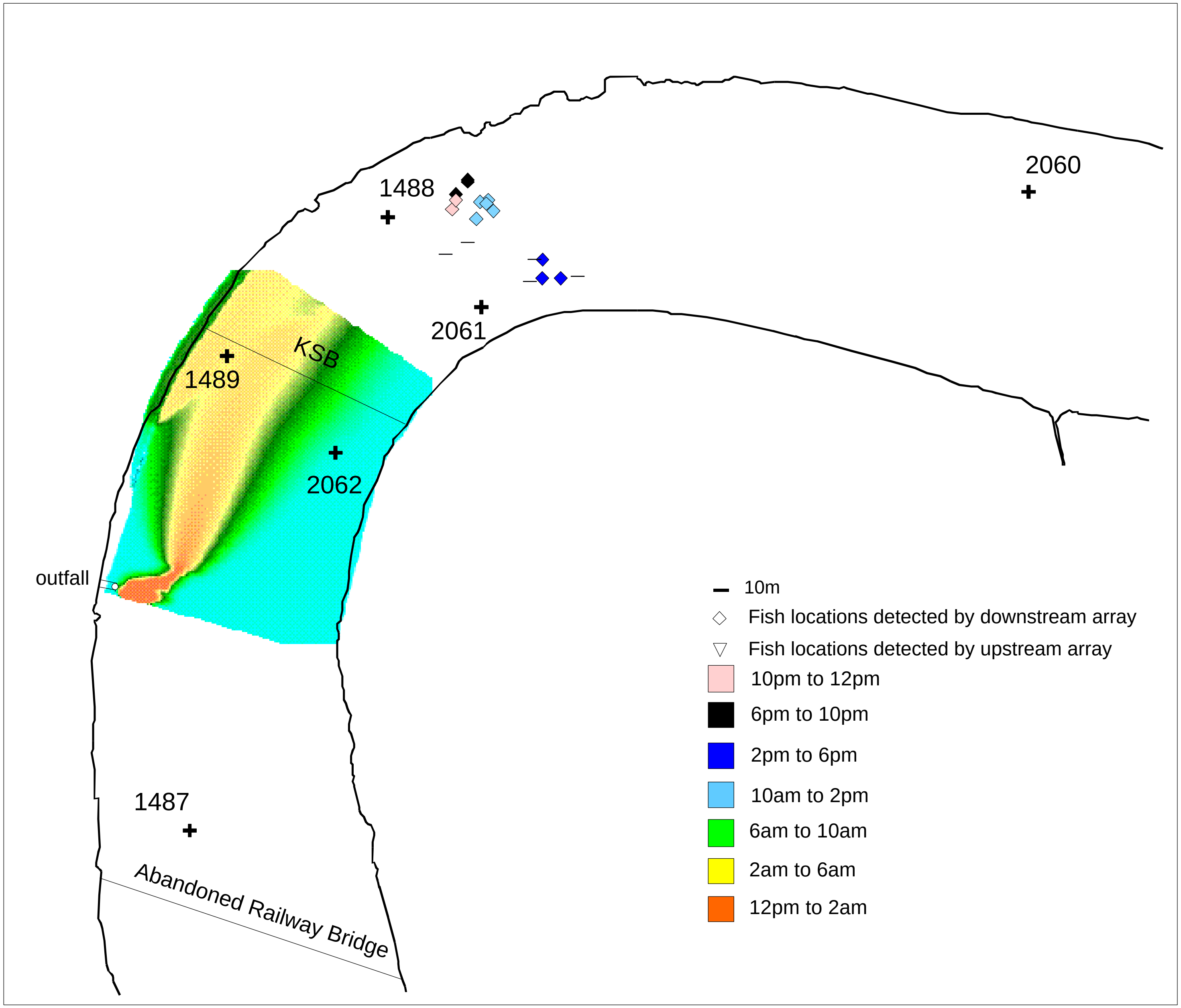

Figure 45. Positional data for Fish # 7966 in the vicinity of the NEWPCC plume, February 18, 2000.

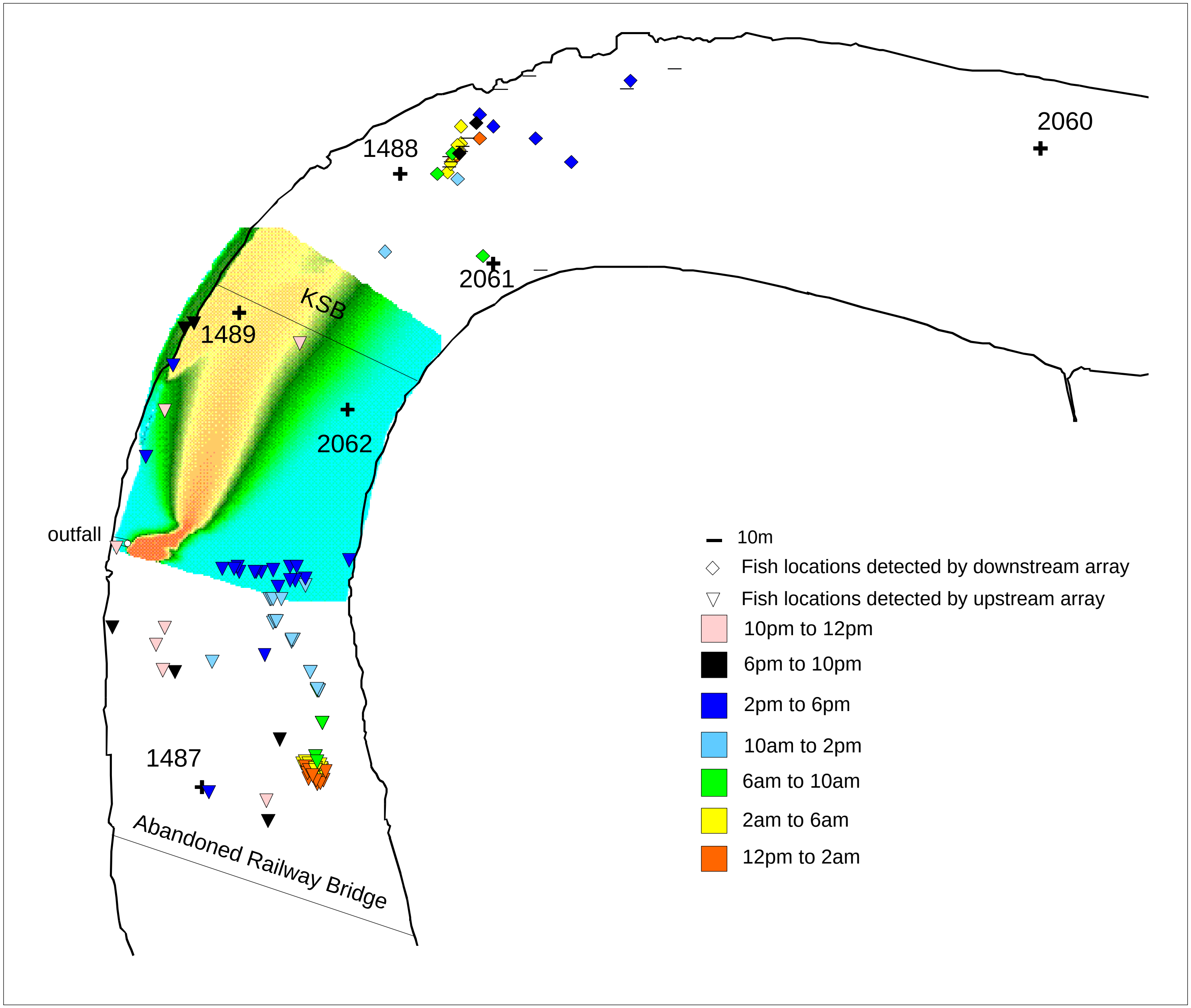

Figure 46. Positional data for Fish # 7966 in the vicinity of the NEWPCC plume, February 19, 2000.

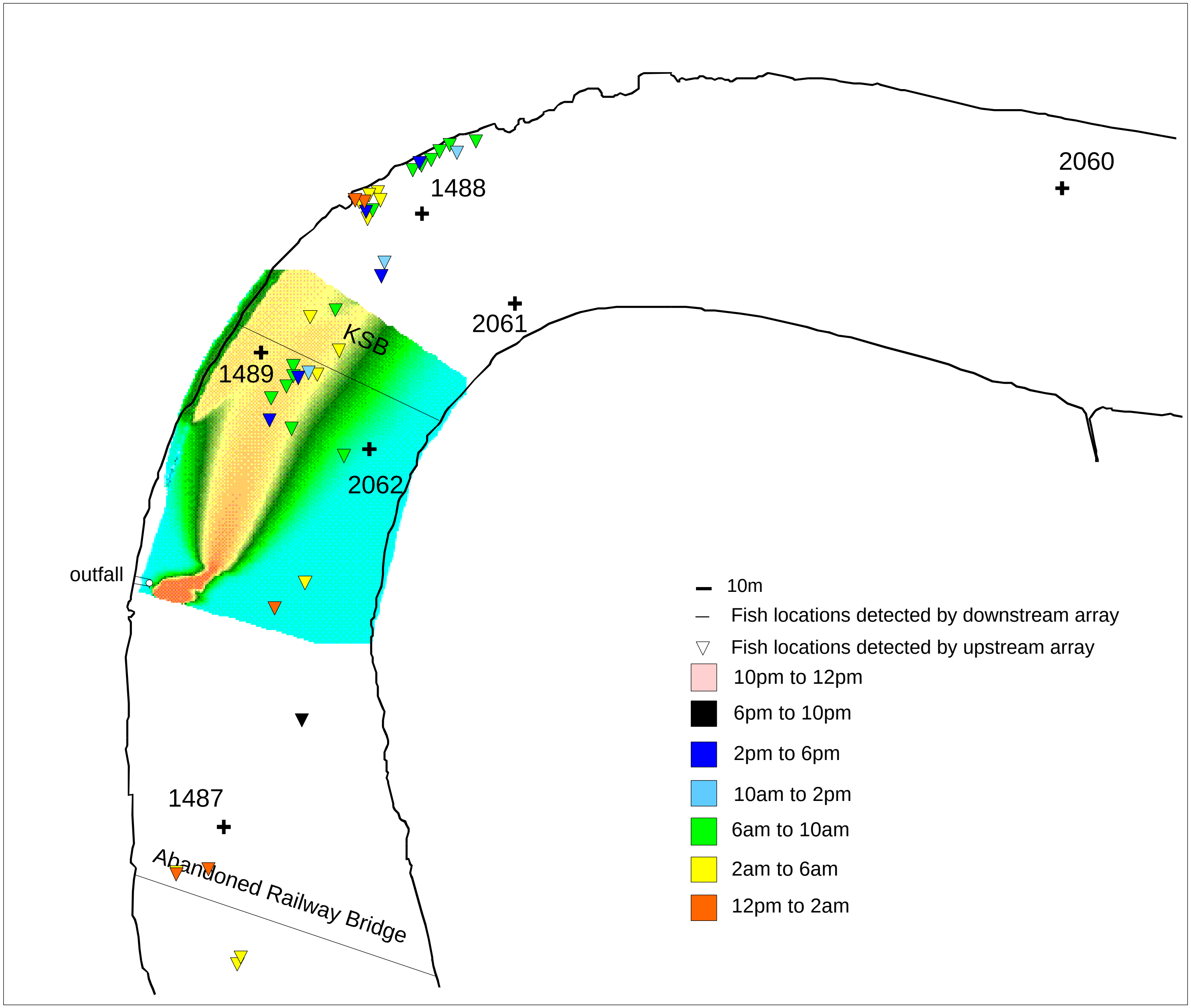

Figure 47. Positional data for Fish # 7966 in the vicinity of the NEWPCC plume, February 20, 2000.

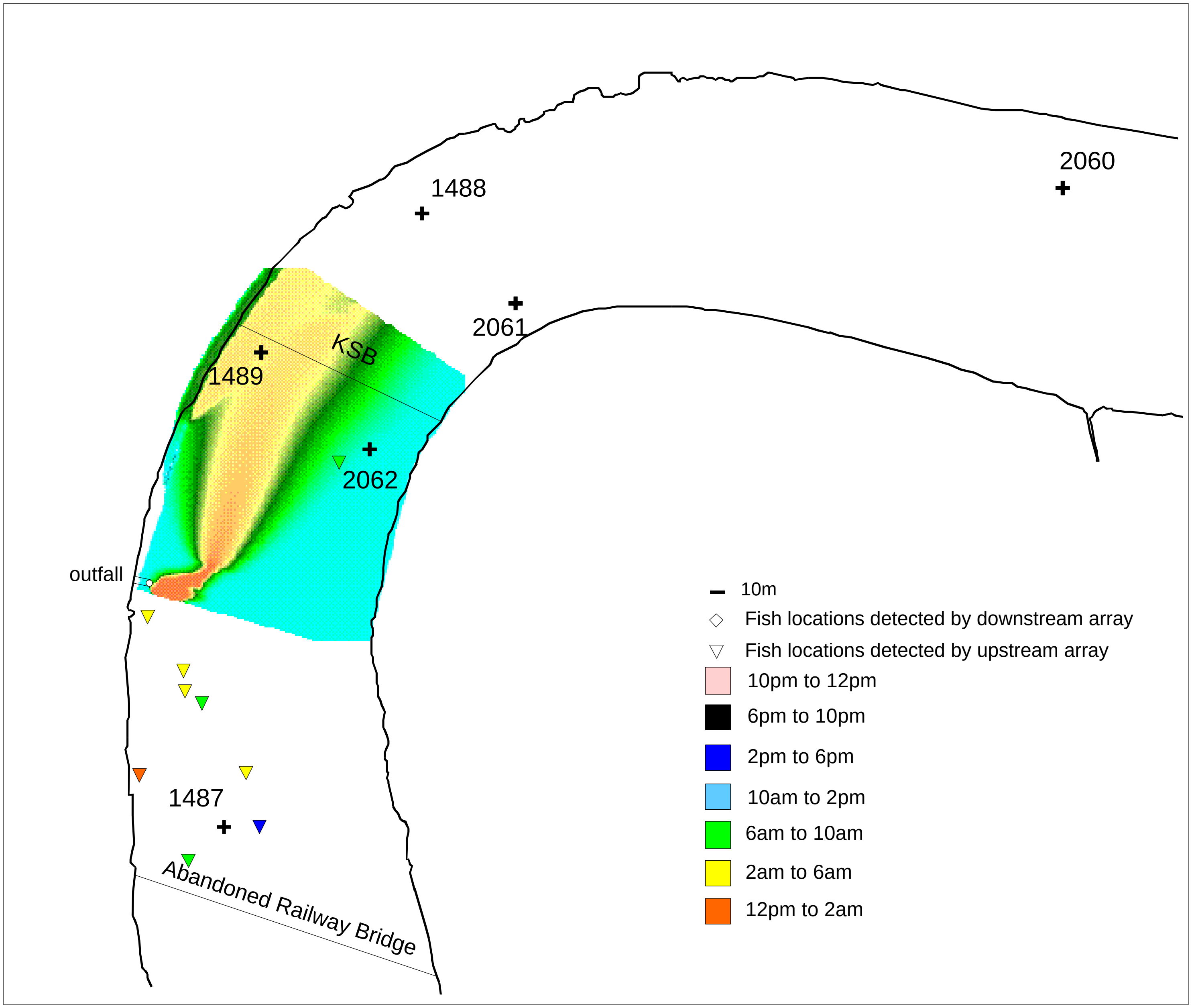

Figure 48. Positional data for Fish # 7966 in the vicinity of the NEWPCC plume,February 21, 2000.

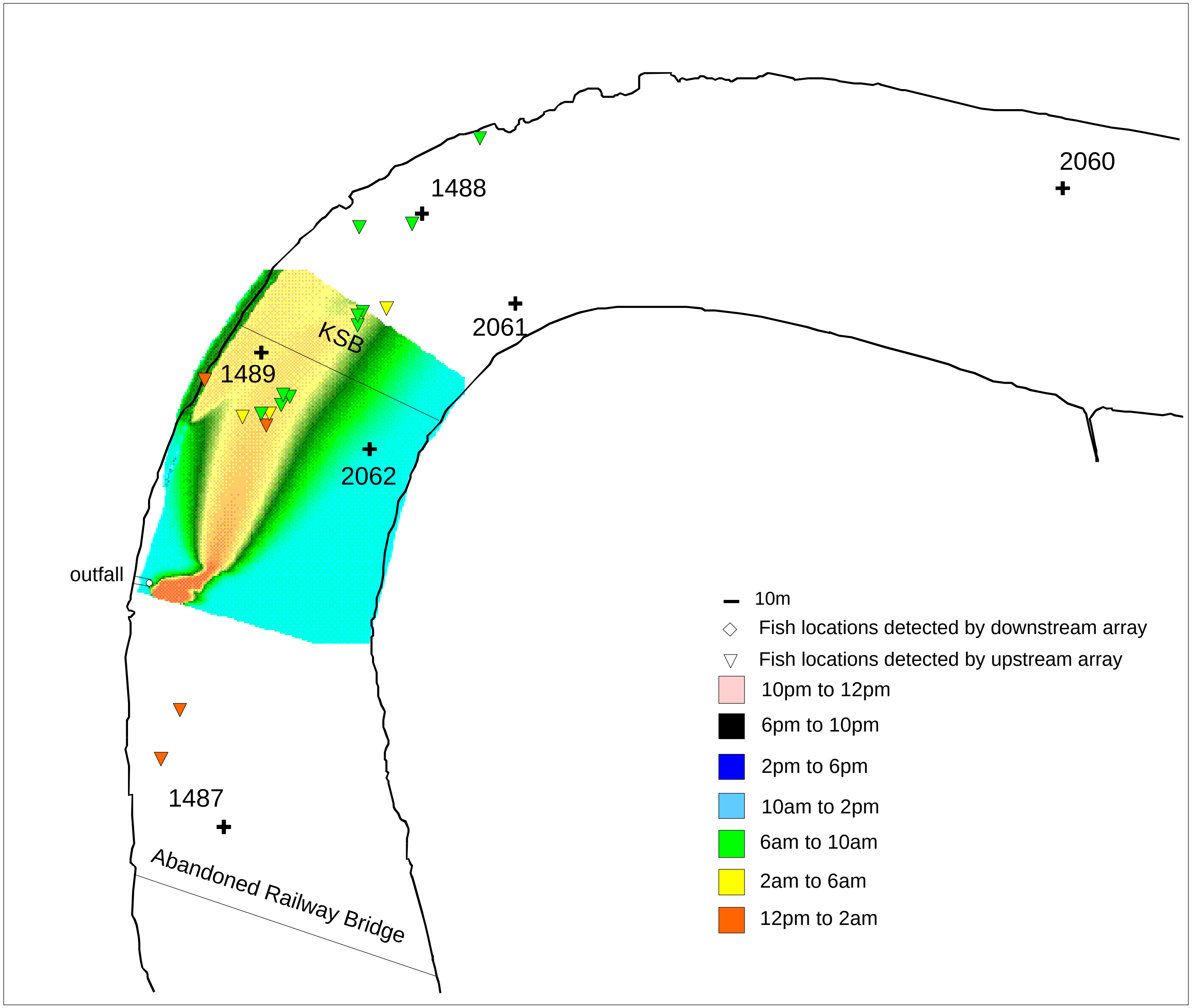

Figure 49. Positional data for Fish # 7966 in the vicinity of the NEWPCC plume, February 22, 2000.

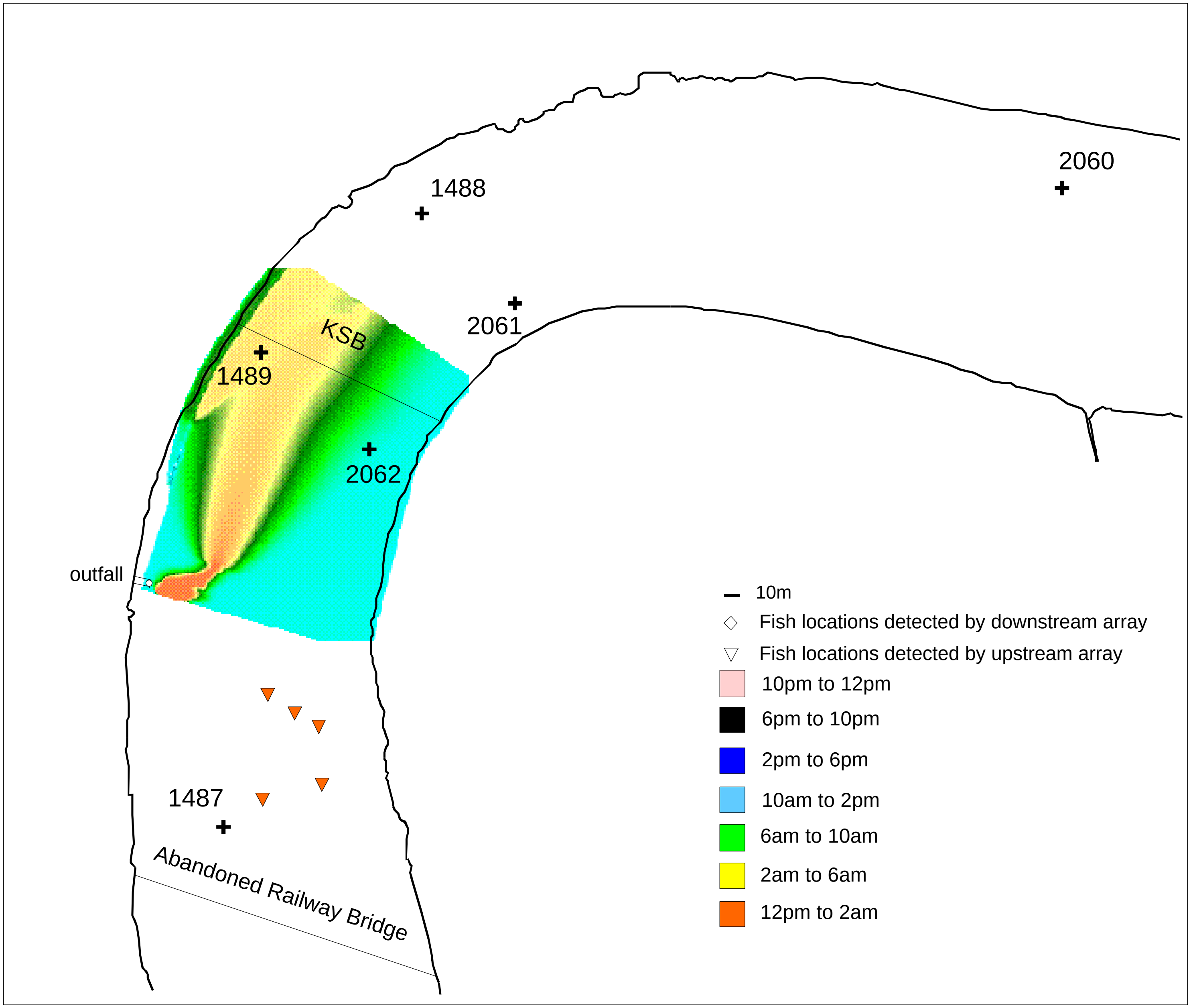

Figure 50. Positional data for Fish # 7966 in the vicinity of the NEWPCC plume, February 23, 2000.

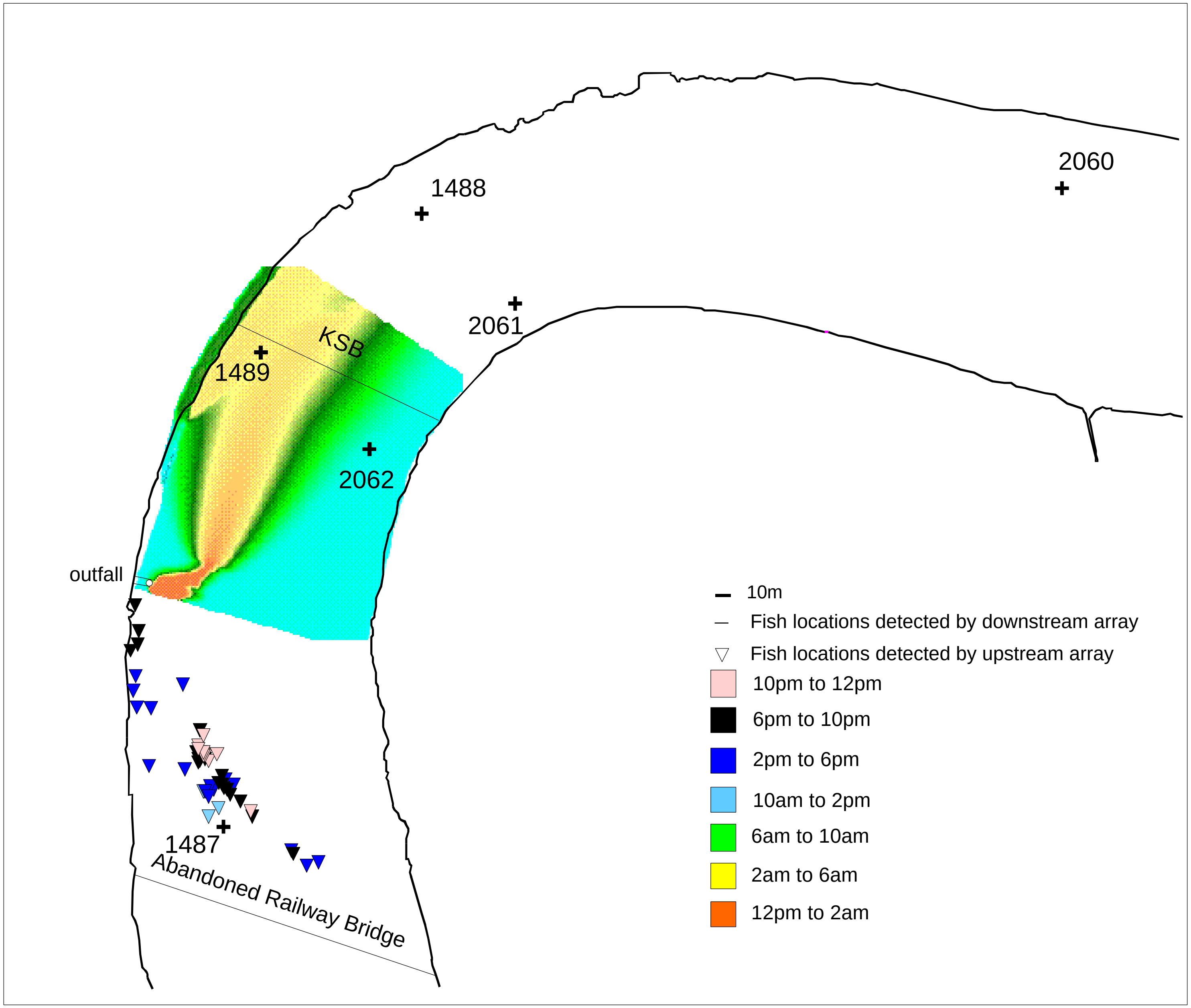

Figure 51. Positional data for Fish # 7967 in the vicinity of the NEWPCC plume, February 19, 2000.

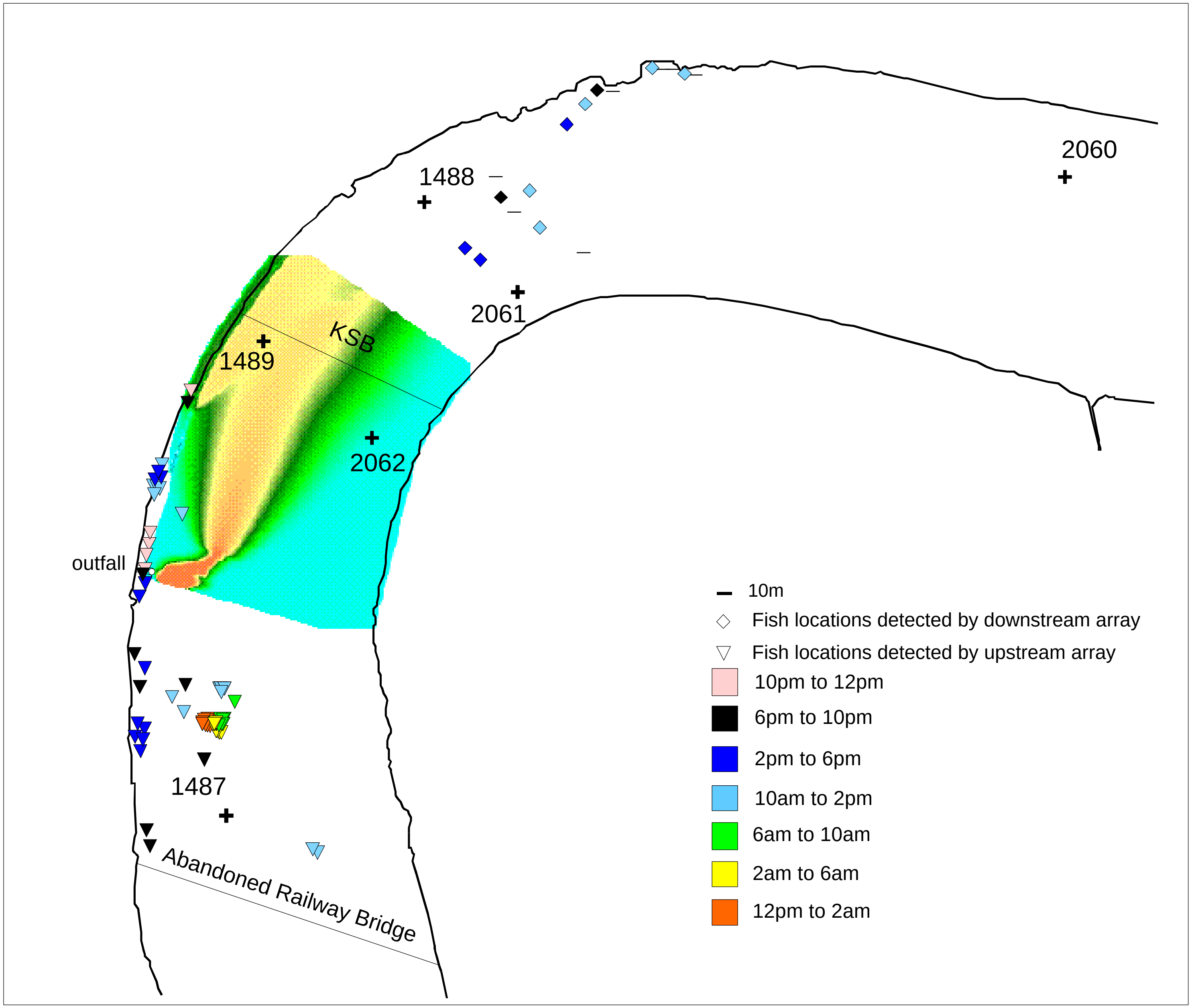

Figure 52. Positional data for Fish # 7967 in the vicinity of the NEWPCC plume, February 20, 2000.

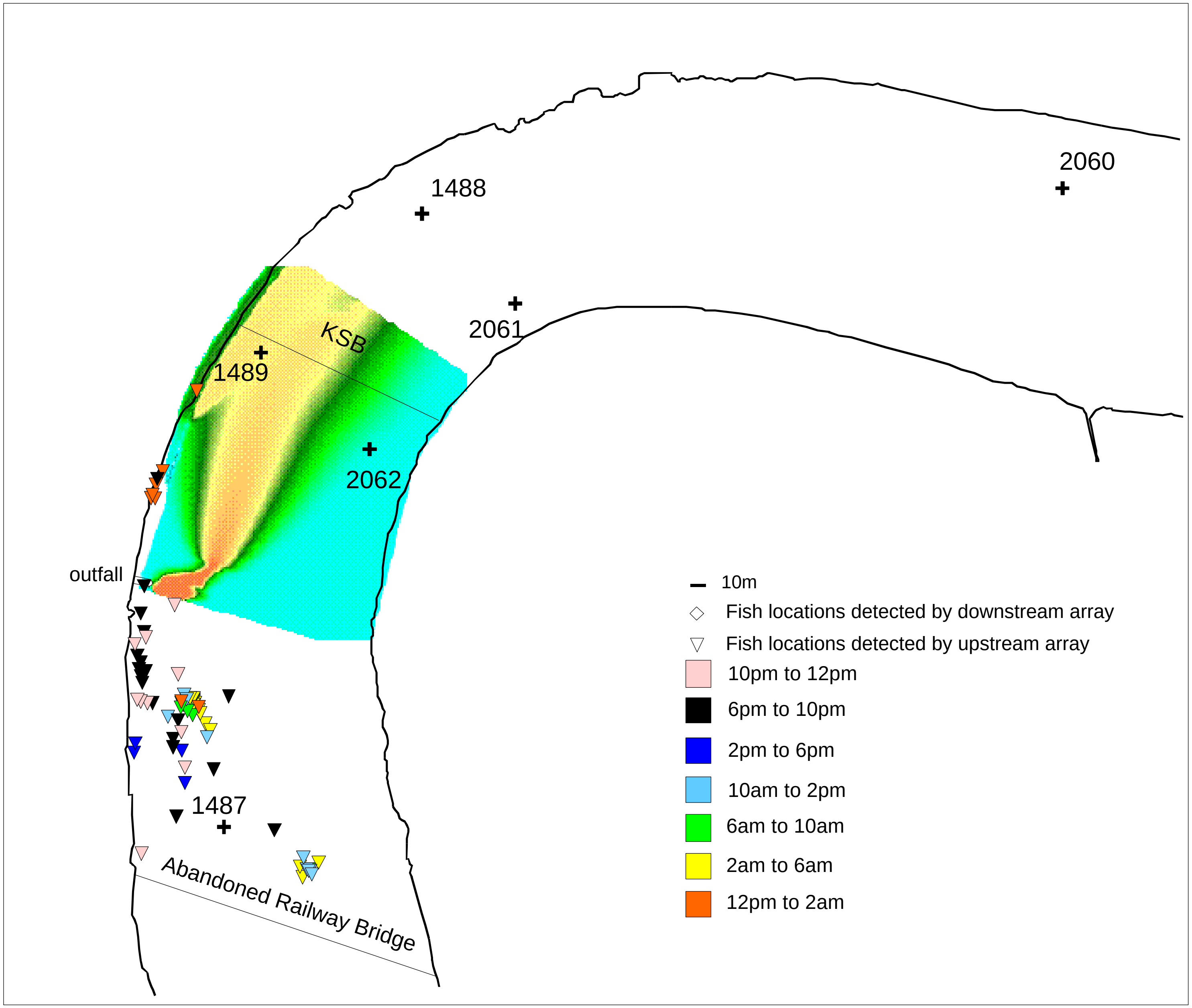

Figure 53. Positional data for Fish # 7967 in the vicinity of the NEWPCC plume, February 21, 2000.

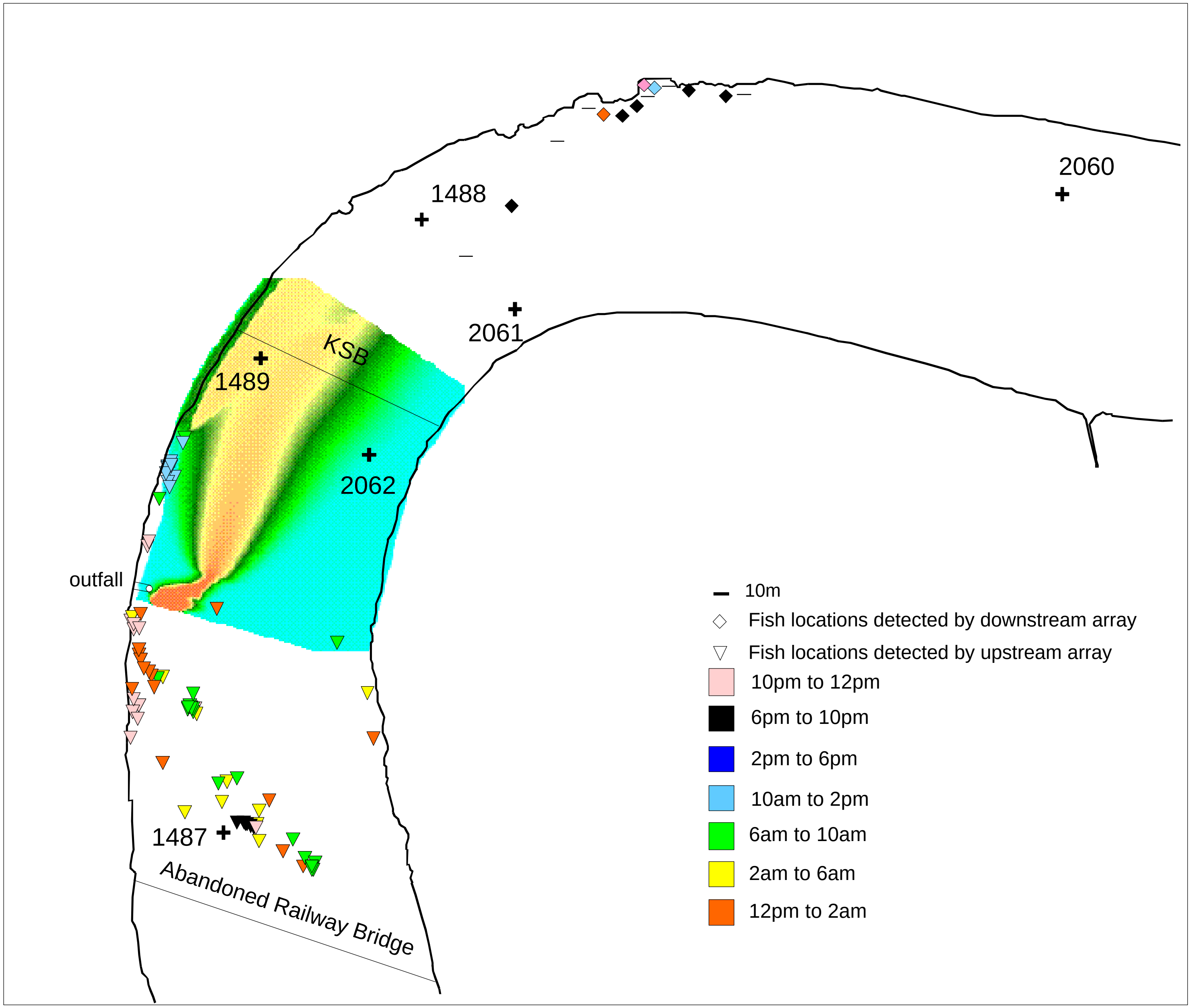

Figure 54. Positional data for Fish # 7967 in the vicinity of the NEWPCC plume, February 22, 2000.

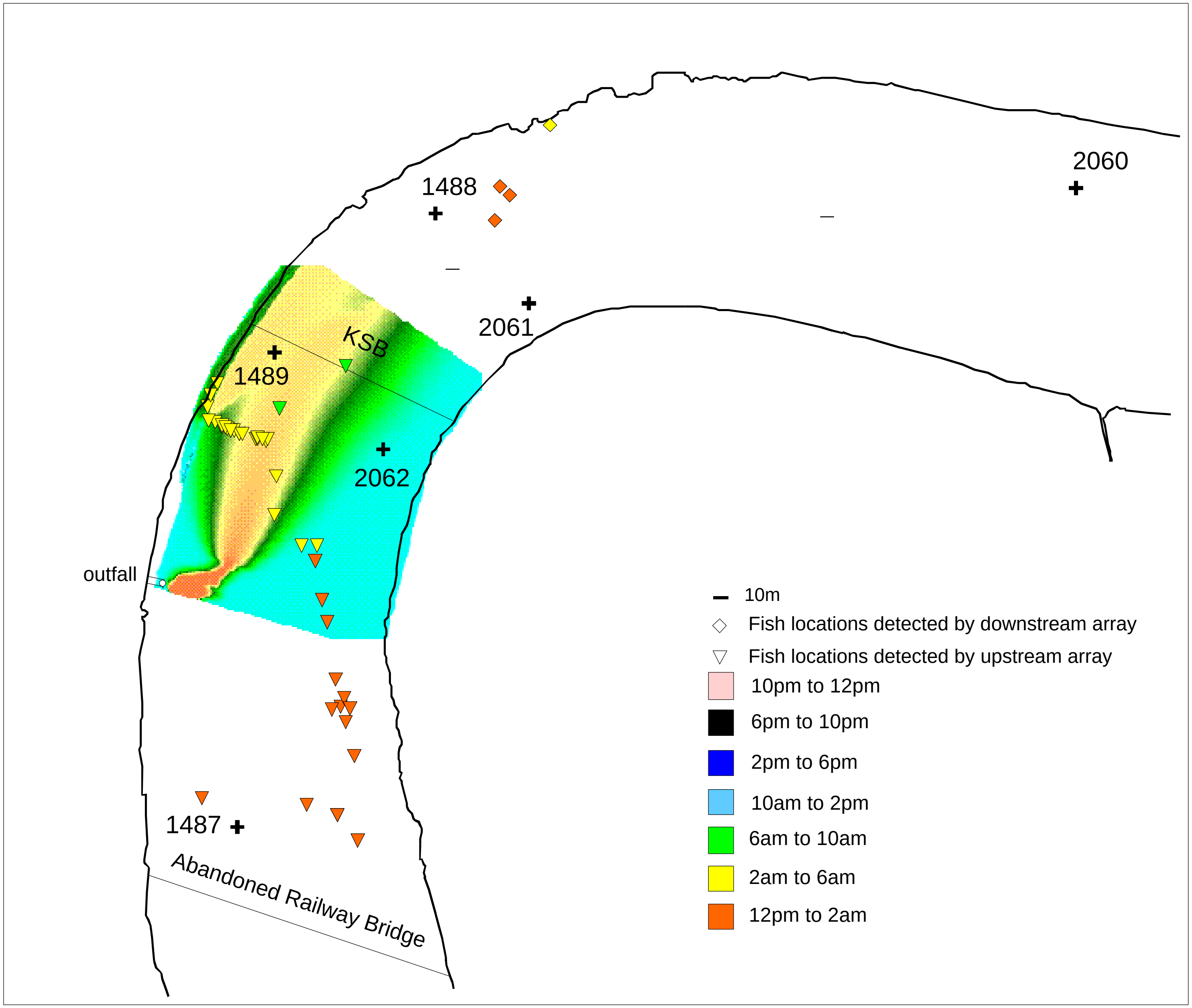

Figure 55. Positional data for Fish # 7967 in the vicinity of the NEWPCC plume, February 23, 2000.