

**BROOK TROUT MOVEMENT AND SURVIVAL IN THE WEST BRANCH OF THE  
WOLF RIVER, WISCONSIN**

By

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## ABSTRACT

A 21 km stretch of the West Branch of the Wolf River (WBWR), a tributary to the Wolf River, traversing the Menominee Indian Reservation in central Wisconsin is designated as a class I trout stream with naturally-reproducing brook trout *Salvelinus fontinalis*. Brook trout are the only stream trout (technically, a charr) native to Wisconsin. Because many anglers target brook trout, they are considered a highly sought-after sport fish and are intensively managed via harvest regulations and habitat improvement efforts.

Previous research on fish movement has focused largely on highly migratory and anadromous fish species, but fish in smaller stream systems can also exhibit extensive movements. Movement of brook trout throughout a system can affect management decisions. There are various factors affecting connectivity within a stream, the foremost factor being the construction or removal of dams. In 2015, the Menominee Indian Tribe removed two dams and constructed new channels with graded steps to promote upstream and downstream movement of fish in the WBWR. These changes may have affected brook trout movements by providing greater access to different portions of the river, including access to lacustrine habitats provided by Upper Bass Lake and the Neopit Mill Pond located at the upper and lower ends of the river segment. Little is known regarding movement of brook trout within this section of the WBWR and seasonal movements could have important implications for future management and stream restoration.

The objectives of my study were to determine if: 1) brook trout use multiple river segments during the year, including sections of the stream where two dams were removed and channel alterations occurred; 2) brook trout enter Upper Bass Lake and the Neopit Mill Pond as seasonal refuges, but eventually return to the WBWR; 3) a rapids located just upstream from the

Neopit Mill Pond acts as an upstream and downstream barrier to movement; 4) annual survival rates are comparable to other brook trout populations; and 5) relative abundance estimates are comparable to statewide Wisconsin trout streams.

Between 2016 and 2018, a total of 920 brook trout were captured using barge and backpack electroshocking at various locations throughout the WBWR. Brook trout  $\geq 120$  mm total length (TL) were implanted with 12-mm passive integrated transponder (PIT) tags and brook trout  $\geq 254$  mm were implanted with 23-mm PIT tags. Of the 920 captured brook trout, a total of 447 brook trout were implanted with PIT tags. In 2016 (13 October - 17 November), three paired stationary PIT antennas were deployed in the WBWR and during 2017 (April – 6 December) four antennas were installed in the stream. Locations for installation were based on ability to effectively address the project objectives and access to the river. Data were downloaded from these antenna installations on a weekly basis.

Upstream and downstream movement during the year was minimal, with the majority of brook trout remaining in the river sections they were tagged in. Use of Upper Bass Lake and the Mill Pond was also minimal, with  $< 5\%$  of tagged brook trout entering either of these habitats. Movement (both upstream and downstream) through the rapids located just before the Mill Pond was observed, with three fish moving downstream through the rapids and then returning upstream through the rapids into the WBWR. The low percentage of detections suggests that the brook trout within the WBWR display limited movement. Low occurrence of detections paired with low physical recaptures and an eight month survival rate of 0.27, suggests brook trout in the WBWR experience high mortality rates, which is consistent with previous assessments. Furthermore, average catch per unit effort (CPUE; fish/km) for all brook trout at all sampling stations was  $68 \pm 22$  brook trout per km (114 per mile) placing this section of the WBWR within

the 60<sup>th</sup> percentile of all statewide trout streams and within the 50<sup>th</sup> percentile for all statewide class I trout streams. Future research within this system should focus on determining if high mortality is a factor regulating brook trout abundance in the WBWR and whether exploitation (current harvest regulation is 20/day, 6-inch minimum) is a significant component of this mortality. Understanding these mortality components would help determine if the WBWR brook trout population would benefit by implementing more conservative harvest regulations.

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## INTRODUCTION

Understanding fish movements and habitat use is critical in determining the appropriate spatial scale for management actions (Curry et al. 2002; Fausch et al. 2002; Rodríguez 2002; Schrank and Rahel 2004). In general, movements of fish are related to life history, physiological needs, and habitat availability (Fausch et al. 2002; Hoffman and Dunham 2007; Schrank and Rahel 2004). Movement patterns of fish can also change over time in response to inherent environmental change (Isaak et al. 2010; Wenger et al. 2011) and human-induced alterations to aquatic systems, such as dam construction or removal (Gibson et al. 2005; Letcher et al. 2007; Warren and Pardew 1998). Dams prevent fish from accessing previously available habitat and this lack of connectivity have contributed to the decline of many riverine fish populations (Davis et al. 2015; Hoffman and Dunham 2007; Schrank and Rahel 2004). Moreover, dams may considerably alter available habitat (e.g., depth, flow, temperature) within impounded river reaches resulting in loss of certain habitats that can lead to declines or extirpation of some fluvial species (Letcher et al. 2007; Roghair and Dolloff 2005). Conversely, impoundment can create new habitat conditions (i.e., more lacustrine habitat, warmer water) that benefit other more lentic species (Nelms et al. 2012; Stanley et al. 2007).

The effects of dam construction on movements of highly migratory species in large river systems (e.g., lake sturgeon *Acipenser fulvescens*, paddlefish *Polyodon spathula*, and sauger *Sander canadensis*) and anadromous species (Pacific salmon *Oncorhynchus spp.*, Atlantic salmon *Salmo salar* and American shad *Alosa sapidissima*) have been well documented (Auer 1996; Baily et al. 2004; Raabe and Hightower 2014). Dams may also restrict movements of fish in smaller stream environments; these effects can also be extensive (Cooney and Kwak 2013; Gibson et al. 2005; Letcher et al. 2007) and may be necessary to meet life history requirements

(Hilderbrand and Kershner 2000; Mollenhauer et al. 2013; Schrank and Rahel 2004, 2006; Swanberg 1997). Swanberg (1997) reported that 8% of migratory bull trout *Salvelinus confluentus* in the Blackfoot River, Montana, moved downstream of a dam where the ability to move back upstream was not possible; this loss was significant as the bull trout population was estimated to be less than 500 individuals. In addition, Hilderbrand and Kershner (2000) demonstrated that establishing barriers to movement in streams located in the central and southern Rocky Mountain region, resulted in an insufficient amount of space to support sustainable populations of cutthroat trout *Oncorhynchus clarkii*. Consequently, construction and removal of dams could have substantial effects on the sustainability of stream fishes, especially if these fish make extensive movements throughout the year (Gibson et al. 2005; Hilderbrand and Kershner 2000; Letcher et al. 2007; Mollenhauer et al. 2013; Schrank and Rahel 2004, 2006; Swanberg 1997).

Brook trout *Salvelinus fontinalis* are the only stream trout (technically, a charr) native to inland streams east of the Rocky Mountains (Becker 1983; Clark and Rose 1997; Curry et al. 2002), although lake trout *Salvelinus namaycush* (another charr) can be found in some drainages in northern Canada or may enter streams or rivers on a seasonal basis (Loftus 1958; Snucins and Gunn 1995). Native brook trout can also be found in lakes or lake-stream complexes (Brasch et al. 1973) and have been stocked into many drainages where they did not previously occur. Because brook trout are native in many systems, relatively easy to catch, and their flesh considered firm and tasty, they are highly sought after by recreational anglers (Brasch et al. 1973; Mollenhauer et al. 2013; Studinski and Hartman 2014). Moreover, in many states and provinces, brook trout populations are intensively managed via harvest regulations (Nate et al. 2010) and a combination of habitat preservation and improvement (Davis et al. 2015; White et

al. 2011). Harvest regulations typically include establishing minimum length limits and harvest limits, and in some cases catch-and-release only guidelines. Habitat efforts may involve removal of dams or culverts to restore connectivity or stabilize eroding banks to reduce erosion and accumulation of fine sediment.

Ideal brook trout habitat consists of clear, cold groundwater-fed, a gravel stream bottom, a 1:1 riffle-pool ratio with slower moving, deep-water areas, and undercut banks to provide cover (Raleigh 1982). Brook trout tend to inhabit deeper pools (Cunjak and Power 1986; Kratzer and Warren 2013) with lower water velocities, but this preference can be greatly influenced by the habitat available and density of brook trout within the area (Anglin 2012). Groundwater is crucial for brook trout survival as it maintains warmer water in winter and colder water in summer (Brasch et al. 1973) and is essential for spawning in both lotic and lentic habitats because brook trout eggs require aeration combined with specific temperatures. Curry et al. (1995) observed temperatures at redd sites ranging from 2°C to 6.2°C and from 2.7°C to 8°C in Dickson and Meach lakes, Ontario, Canada. A redd is defined as the area in a stream excavated by a fish to deposit ova (Hobbs 1937; cited by Hawke 1978). Although brook trout typically inhabit streams, they are also capable of living and spawning in lakes and ponds. Their ideal lake habitat consists of cold, clear lakes and ponds, which are generally oligotrophic (Raleigh 1982). Brook trout also move to winter habitat that can include pools, lakes and larger tributaries (Cunjak 1996; Curry et al. 2002).

Movement of brook trout can have important implications for brook trout management (Armstrong et al. 1996; Hansbarger et al. 2010). Many factors influence brook trout movement, including: location and availability of spawning habitat (Curry et al. 2002; Kanno et al. 2013), water temperature and velocity (Petty et al. 2012), presence of non-native fish, and dam

construction or removal (Avery 1983, 2002; Kanno et al. 2013; Knudsen 1962; Stanley et al. 2007). Movement of brook trout can vary among drainages and individual streams based on habitat preferences and availability, which can also vary by season (Curry et al. 2002; Hoxmeier and Dieterman 2013; Josephson and Youngs 1996). Although brook trout may move extensively among seasons, they frequently occupy small home ranges within seasons (Gowan and Fausch 1996). For example, Riley et al. (1992) reported an average of 83% of brook trout tagged in small mountain streams in northern Colorado had a small home range of about 250 meters, but a large influx of untagged brook trout into the area between years suggested movement among seasons. Several studies have reported increased brook trout movement before, during, and after spawning, that occurs in fall (Curry et al. 2002; Mollenhauer 2013; Petty et al. 2005). Brook trout often move to upper headwater streams and tributaries to spawn and typically spawn in areas with groundwater seepage (Curry and Naokes 1995; Kanno 2011; Mollenhauer et al. 2013; Witzel and MacCrimmon 1983). Post-spawning movement of brook trout is often associated with trout migrating downstream immediately after spawning (Curry et al. 2002).

Previous studies have also reported substantial movements of brook trout during early and late summer (Kanno et al. 2013; Mollenhauer et al. 2013) that may reflect responses to reduced flows and increases in water temperature. Previous studies have indicated a variety of optimum and lethal temperature limits for brook trout, perhaps indicating local and regional adaptation (Raleigh 1982). Optimum temperature range for growth and survival of brook trout is 11-16°C, but they can tolerate temperatures between 0-24°C (Raleigh 1982). In Wisconsin, Brasch et al. (1973) reported a lethal limit of 25°C. Hitt et al. (2016) reported that when water temperatures exceed 20°C, brook trout rely on their ability to move to sections of a stream that provide thermal refugia. Movement by brook trout to areas with groundwater discharge is

necessary for spawning (Curry and Naokes 1995; Kanno 2011; Mollenhauer et al. 2013; Witzel and MacCrimmon 1983) as well as winter refugia because areas of streams with groundwater discharge are warmest during winter (Cunjak and Power 1986; Cunjak 1996). Moreover, Kanno et al. (2013) detected substantial movement of brook trout between West Brook, a stem of the Connecticut River, and two associated tributaries both in and around spawning (October-November) and in June. June movements coincided with decreased stream flow and increases in stream temperature (Kanno et al. 2013). Similarly, Petty et al. (2012) reported increased movement of brook trout in an Appalachian riverscape during summer, when water temperatures increased from 18°C to 25°C. The term riverscape refers to fish movement patterns relative to the spatial distribution of fish habitat within a drainage (Fausch et al. 2002; Schrank and Rahel 2004), which represents an important aspect to consider when examining movement (Schrank and Rahel 2004).

Preferred winter habitat for stream-dwelling brook trout is characterized by low flow with adequate cover consisting of woody structure and undercut banks (Chisholm et al. 1987; Cunjak 1996), similar to summer habitat preferences. When spawning in fall, adult brook trout tend to migrate upstream, but during winter months, move downstream to deeper waters (Hunt 1974; McFadden 1961). Mollenhauer et al. (2013) noticed a decline in brook trout activity in December when stream temperatures fell below 7°C. Chisholm et al. (1987) evaluated brook trout movement in a high elevation Wyoming stream during two consecutive winters and reported that most fish moved downstream from their release point in a high-gradient section of stream into low gradient pools or beaver ponds during the winter. Winter habitat may provide refuge from temperature changes and other abiotic factors (Chisholm et al. 1987; Cunjak 1996), but can also create new challenges such as predation and access to food (Cunjak 1996). Cunjak

(1996) ranked criteria for winter habitat selection by coldwater fishes in order of relative importance; access to suitable habitat or avoidance of changing physicochemical stream conditions (freezing water temperatures) ranked first in priority, while protection from predators and access to food ranked second and third, respectively. Declines in brook trout abundance could occur if fish enter winter habitat but are lost due to predation or other factors (i.e., an ecological “trap” or “sink”; Cunjak 1996). Larger fish such as northern pike *Esox lucius* may prey upon brook trout (Mirza and Chivers 2003) and the distribution of predatory fish can alter prey movement and habitat selection.

Habitat fragmentation by dams (both manmade and those constructed by beavers) and roads (i.e., culverts) can affect brook trout movement and habitat selection (Gibson et al. 2005; Letcher et al. 2007). Historically, beaver dam removal has been an important component of stream trout management in several states in the Upper Midwest (Avery 1983, 2002; Knudsen 1962). In general, beaver dams are considered a threat to wild trout management because they lead to changes in water temperature regimes, support populations of non-salmonid fish competing for food, and contribute to negative changes in stream channel characteristics (Avery 1983, 2002). A comprehensive study conducted by the Wisconsin Department of Natural Resources (DNR) on the Pemonee River flowing through Marinette County in northeastern Wisconsin showed a 67% increase in brook trout per mile within 18 years following beaver dam removals (Avery 2002). Conversely, provided that temperatures remain consistent with brook trout thermal limits, beaver dams may provide refuge during period of low flow as they create impounded stream reaches (Johnson-Bice et al. 2018).

Over the last two decades there has been increased interest in removal of manmade dams to increase stream connectivity and facilitate fish movements (Catalano et al. 2007; Kanehl et al.

1997; Stanley et al. 2007). The Boulder Creek drainage located in south-central Wisconsin consists of two tributaries that converge and flow into the Baraboo River, which support both brook and brown trout *Salmo trutta* (Catalano et al. 2007); in 2003, two dams were removed from each tributary. Shifts in fish assemblages were documented after dam removals at three of the four locations; these changes increased the index of biotic integrity (IBI) scores as more intolerant fish species were able to enter the system (Catalano et al. 2007). Despite changes in brook trout numbers (adults and juveniles) in some sections of the streams, dam removal seemed to have little effect on the brook trout population as a whole in the two years following removal (Stanley et al. 2007).

Presence of non-native fish such as brown trout and rainbow trout *Oncorhynchus mykiss* may also affect movement of brook trout (Clark and Rose 1997; Fausch and White 1981; Hitt et al. 2016; Hoxmeier and Dieterman 2013). Brown trout have been stocked into many North American streams where brook trout are present and have naturalized in many systems where they naturally reproduce (Davis et al. 2015; Hoxmeier and Dieterman 2013). Zimmerman and Vondracek (2007) suggest brown trout and brook trout have similar niches, resulting in interspecific competition. Brown trout can outcompete brook trout because they tolerate more degraded stream conditions (i.e., increased temperature and turbidity; Fausch and White 1981) and they are generally more piscivorous and aggressive than brook trout. In many cases, native brook trout are forced to relocate from their preferred position in the stream, often to smaller reaches, because of antagonistic relationships with brown trout (DeWald and Wilzback 1992; Fausch and White 1981; Waters 1983). Rainbow trout have also been introduced to many streams outside of their native range and have been shown to alter the distribution of native brook trout (Clark and Rose 1997; Larson and Moore 1985). Moreover, Larson and Moore

(1985) posited that encroachment of rainbow trout into brook trout streams of the southern Appalachian Mountains would result in a few small populations of brook trout with low genetic diversity. Many other biotic and abiotic factors may affect the interaction of these two species, but similar to brown trout, rainbow trout have a competitive advantage over brook trout due to increased size (Larson and Moore 1985).

Movement of fish can also be related to survival, especially among stream fishes that require specific habitats not only to survive, but also to grow and reproduce. Movement is potentially risky as it heightens the chance for predation and is energetically demanding (Sweka et al. 2017; White 2017), but movement may allow brook trout to reach better food sources or ideal spawning habitat (White 2017). Sweka et al. (2017) reported a survival rate of 0.66 ranging from mid-September through the end of October; the majority of brook trout mortality occurred prior to the end of October. Kanno et. al (2014) sampled two headwater streams in northwestern Connecticut and concluded that survival of brook trout was related to various habitat characteristics, especially the presence of pools within the system; a greater abundance of pools resulted in higher survival rates. Additional results indicated that water temperature did not have a significant effect on survival of adult brook trout within the two streams, which may have reflected the optimal temperature range for brook trout available within the streams. Conversely, Xu et al. (2010) reported increased stream temperature in summer reduced survival rates for brook trout in most size classes within four stream networks in western Massachusetts. Furthermore, survival among brook trout populations can be related to the presence or absence of naturalized, non-native trout such as brown trout and rainbow trout. Larson and Moore (1985) posited that encroachment of rainbow trout within the southern Appalachian Mountain streams would eventually reduce the native brook trout population to only a few inbred populations

located entirely within headwater streams. Conversely, Hoxmeier and Dieterman (2013) monitored seasonal growth and survival of brook trout in two southeastern Minnesota streams with the presence of brown trout and reported that survival did not vary in stream with differing brown trout densities.

With approximately 13,000 miles of inland trout streams, management of brook trout is particularly important in Wisconsin (WDNR 2016a). The distribution of Wisconsin brook trout streams is influenced by prevalence of groundwater flow to streams (Brasch et al. 1973; Kanno et al. 2011; Witzel and MacCrimmon 1983). Brook trout are predominantly found in the northern and central regions of the state, and in the Driftless Area in the southwestern portion of Wisconsin (Becker 1983). The Wisconsin DNR uses three classes to categorize trout streams throughout the state (WDNR 2016b). Class I streams (40%) have adequate natural reproduction and are able to sustain wild trout populations without supplementing trout numbers by stocking. Trout in these streams are usually smaller and demonstrate slower growth rates. Class II streams (46%) have some natural reproduction, but stocking is required to maintain the fishery. Compared to Class I streams, Class II streams usually contain larger trout. Class III streams (14%) have no natural reproduction, thus requiring annual stocking.

The Menominee Indian Reservation (hereafter referred to as “Reservation”) located in east-central Wisconsin contains 187 streams, including 586 km of Class I, II and III trout streams supporting native brook trout. The Wolf River, the main river running through the Reservation is one of the National Scenic Rivers in Wisconsin (Menominee Indian Tribe of Wisconsin 2004). Specifically, a 21 km stretch of the West Branch of the Wolf River (WBWR) that runs between Upper Bass Lake and the Mill Pond at Neopit, Wisconsin, is considered a Class I trout stream. The Environmental Services Department of the Menominee Indian Tribe manages fisheries,

wildlife, forests, and land and water use on the Reservation. In 2015, the Menominee Tribe removed two dams and constructed new channels with graded steps to promote upstream and downstream movements of fish in the WBWR upstream of the town of Neopit. These changes in stream connectivity may have affected brook trout movements by providing greater access to different portions of the river and the lacustrine habitats provided by Upper Bass Lake and the Mill Pond. Movement of brook trout through areas where dams were removed and channel alterations occurred is unknown. Furthermore, the percentages of brook trout that enter Upper Bass Lake or the Mill Pond at Neopit is unknown and these habitats may act as sinks for brook trout during winter or possibly during other portions of the year. Upper Bass Lake supports potential brook trout predators such as largemouth bass *Micropterus salmoides* as well as non-native competitors including rainbow trout, which may affect brook trout survival. The Neopit Mill Pond also contains predators such as northern pike and largemouth bass. The absence of brown trout in this segment of the WBWR also offers a rare opportunity to study the movement of brook trout without brown trout present.

Movement studies can be difficult, especially within stream systems that allow for movement in and out of the designated study area. Lotic systems also provide both physical and chemical variation longitudinally (Hoxmeier and Dieterman 2013) potentially altering fish behavior within various sections of a stream. Employing the use of a multistate mark-recapture study to determine transition (movement) probabilities between states or zones is a relatively new technique in fisheries; it was first suggested by Arnason (1972, 1973). A multistate model is particularly useful in systems where habitat is diverse, as it allows for a more complete understanding of habitat selection. Program MARK (White and Burnham 1999), a popular computer software program among ecologists, is often used to analyze various multistate models.

Modeling movement within a Bayesian framework has not been used frequently, but is becoming more popular among ecologists as information on how to utilize and interpret these models is becoming readily available (Doll and Jacquemin 2018). Furthermore, modeling within a Bayesian framework allows the researcher to calculate the probability of a hypothesis given the actual data, use prior knowledge of the system in the model (Doll and Jacquemin 2018) and may provide a simpler way to fit more complicated models (Clark 2005). Although the ability to utilize informative priors is useful within hierarchical modeling, there continues to be much debate on their reliability (Dennis 1996; McCarthy and Masters 2005).

The primary objectives of this study were to determine if: 1) brook trout use multiple river segments during the year, including sections of the stream where two dams were removed and channel alterations occurred; 2) brook trout enter Upper Bass Lake and the Neopit Mill Pond as seasonal refuges, but eventually return to the WBWR; 3) a rapids located just upstream from the Neopit Mill Pond acts as an upstream and downstream barrier to movement; 4) annual survival rates are comparable to other brook trout populations; and 5) relative abundance estimates are comparable to statewide Wisconsin trout streams. I addressed these primary objectives using paired stationary antenna arrays to detect passive integrated transponders (PIT) tags implanted into brook trout, which is a relatively new method for monitoring movements of individual fish and is especially useful in systems where fish are spatially constrained (i.e., small streams; Letcher et al. 2015). Additionally, using percentile classification, I compared catch rates and mean lengths of brook trout in the WBWR with similar metrics available for Wisconsin trout streams.

## METHODS

### *Study Area*

The WBWR is classified as a second order stream with a watershed size of 428 km<sup>2</sup> and flows for approximately 47 km through Menominee and Shawano counties in northeast Wisconsin with tributaries branching into Langlade County (Figure 1). A considerable amount of land bordering the WBWR in Langlade County has been cleared for pasture and agricultural use. The portion of the WBWR being studied for this project resides within Menominee County on the Menominee Indian Reservation and is approximately 21 km long, flowing downstream from Upper Bass Lake to the Mill Pond in Neopit, Wisconsin. Land cover surrounding this section of the stream is dominated by mixed-deciduous forest. This portion of the WBWR is classified as a Class I trout stream supporting a naturally-reproducing brook trout population. In 2015, the Lake Dam (Figure 2) located downstream of Upper Bass Lake and the Basswood Dam (Figure 3) located upstream of the Mill Pond in Neopit were removed from the WBWR. Exact dates of dam construction are unknown, but they were likely constructed between the 1920s and 1940s to facilitate driving logs to the mill. While no pre-removal information is available, the two dams likely affected movements of brook trout within the stream, but may not have served as complete barriers to movement. Furthermore, large-scale logging practices along brook trout streams reduced shade cover and instream habitat while also increasing finer sediment, negatively affecting brook trout survival and reproduction.

### *Fish Collection and Tagging*

Brook trout were captured using barge and backpack electroshocking at various transects located throughout the WBWR. Lengths of transects ranged from 0.15-1.15 km and depended on stream access and catch rates. Moreover, the selected transects allowed for a relatively even distribution of sampling effort throughout the stream. Latitude and longitude

were recorded at the beginning and end of each transect. Some transects exhibited higher catch rates of brook trout and were sampled multiple times in an attempt to tag additional brook trout and obtain recaptures for both supplementary movement information and to calculate tag shedding rates.

Brook trout were measured to the nearest mm (total length; TL). To monitor movements of individual fish, PIT tags were implanted into the body cavity and fish between 120 and 254 mm TL were tagged with a 12-mm half-duplex (12 mm × 2.12 mm; HDX) PIT tags (Oregon RFID<sup>®</sup>, Portland, OR). I choose 120 mm TL as the minimum length for implantation because a 12-mm PIT tag is 10% of the total length. A 23-mm (23 mm × 3.65 mm) HDX tag was used for larger fish ( $\geq 254$  mm) to enhance detection. A handheld tag reader (Biomark<sup>®</sup> model 601) was used to record the unique PIT tag identification number before tags were implanted into the fish. The 12-mm PIT tag was implanted via syringe posterior to the tips of the pectoral fins, but anterior to the anal fin (Figure 4). The insertion point was either to the right or left of the mid-ventral line with the needle pointing posterior as to avoid contact with vital organs (PIT Tag Steering Committee, subcommittee of Fish Passage Advisory Committee, 2014). When implanting the larger, 23-mm PIT tags, a small incision was made using a scalpel blade to insert the tag. Adipose fin clips were applied (Bateman et al. 2009) to  $\geq 100$  brook trout of different sizes to determine PIT tag retention rates over time. In each subsequent sampling event, brook trout were examined for the presence of an adipose fin clip and scanned for presence of a PIT tag. Locations of recaptured fish were recorded. Recapture of fish provided information on tag retention and additional information on movement within the stream.

### *Antenna Locations and Construction*

Paired antennas (one upstream, one downstream) for detecting PIT-tagged brook trout were deployed at three (fall 2016) and four (2017) strategic locations identified along the WBWR (Figure 5). Pairing the antennas at each location allowed me to determine direction of movement (upstream vs. downstream; Figure 6). Antenna site selection criteria included placing the antennas in locations that allowed me to address study objectives. In some cases, options for antenna deployment were limited due to access, suitable river width to install the antenna arrays and visibility of the array to the public. One set of paired antennas was deployed at a bridge located near the outlet of Upper Bass Lake (Figure 7) and provided information regarding brook trout immigration and emigration into the lake. The second set of paired antennas was located approximately 13 km downstream from Upper Bass Lake near a culvert complex on Big Jim Zoar Road (Figure 8). A third pair of antennas was placed an additional 4 km downstream from Upper Bass Lake and just upstream of the restored area of the stream where the Basswood Dam was removed in 2015 (Figure 9). The fourth pair of antennas was positioned between the Mill Pond in Neopit and the lowest dam removal site and provided information concerning brook trout movement into the Mill Pond and movement up and down the rapids located just upstream of the Mill Pond (Figure 10). During summer 2017, the antenna located at the outlet of Upper Bass Lake was moved 1.5 km downstream to avoid further vandalism that had occurred. In the fall, the antenna was deployed back at the bridge to ensure any brook trout entering Upper Bass Lake were detected.

Each paired antenna (Figure 11) was composed of 8-gauge audio cable connected to an ATC (auto tuner combiner) box (Oregon RFID<sup>®</sup>, Portland, Oregon; Figure 12) connected to an Oregon RFID<sup>®</sup> multi-antenna HDX reader box (Figure 13) via Belden<sup>®</sup> 9207 twinaxial cable.

Two 12-volt deep cycle marine batteries connected in parallel were used to power the antenna reader. To construct the arrays, lengths of 3/16-in polysynthetic rope were stretched across the entire width of the stream and tied off on available trees or to construction rebar stakes. These pieces of rope supported the top and bottom portions of the antenna loop or “gate”. Stream width at antenna locations ranged from 6.9 to 11.9 m with an average of 9.6 m. In some cases, the bottom rope was threaded through holes drilled into 3/4 inch PVC pipe which was driven into the bottom of the stream. In areas where the stream bottom was rocky, plastic tent stakes, cement weights, and cinder blocks were used as an alternative to PVC pipe for anchoring the bottom rope. Eight-gauge audio cable was tied to the top and bottom of the rope making a loop in the stream; the ends of the audio cable were then connected to the tuner box. In locations where stream flow was relatively high, cement weights and cinder blocks were tied onto the bottom cable to keep the cable from moving. Because of varying stream bottom types (e.g., sandy, rocky, mucky, etc.) and varying stream widths, some antenna arrays required construction rebar supports driven into the stream bed at other locations along the antenna to keep the cable in place. Inductance values on all loops were measured to be within the inductance range that the ATC box will effectively tune (24-102  $\mu$ H). The tuner box was positioned near the stream edge to easily connect to the audio cable and twinaxial cable which connects the tuner box and the antenna reader. The reader and batteries powering the reader were secured in a plastic tote (Figure 14). The antenna was tuned using a tuning indicator which adjusts the frequency resonated by the loop allowing for maximum read range (Oregon RFID 2009). To test the effectiveness of the antenna to detect a tag, a PIT tag was taped to the end of a PVC pipe. The pipe was then moved through the gate or loop at various locations and a piezoelectric buzzer, inserted into the antenna reader, was activated when a PIT tag was detected.

### *Data Collection and Downloading 2016 - 2017*

During 2016, the antennas were deployed from 13 October through 17 November (Table 1). The antennas were installed again in 2017 from April (antennas were deployed on different days in April depending on flow and water level) to 6 December (Table 2). The antennas were not maintained during the winter to avoid possible ice-related damage to the tuner boxes and readers and access became extremely limited with snow and ice accumulation. Additionally, mechanical issues with the radio frequency identification (RFID) equipment caused the antennas located at Upper Bass Lake and the culvert to need repairs and affected the ability to record detections during part of the summer in 2017 (June and July). Tag detections were downloaded from readers on a weekly basis using a personal digital assistant (PDA) installed with PTLogger software. The 12-volt batteries powering the antenna were also changed weekly to prevent power loss. Fish detections were uploaded from the PDA to a computer via PuTTY, an open-source software.

Water temperature (°C) was recorded hourly starting in October 2016 through the duration of the study. To record water temperature, we used two TidbiT<sup>®</sup> v2 Temp loggers (Onset Computer Corporation, Bourne, Massachusetts). One temperature logger was located at the bridge where the WBWR flows from Upper Bass Lake and the second located approximately 13 km downstream at a culvert complex. Temperature data from the loggers were downloaded after the antennas were removed from the stream in 2017 and at the completion of the study in summer 2018.

## *Data Analysis*

### Objective 1

To determine if brook trout were using multiple river segments during the year, I divided the WBWR into three zones based on antenna locations (Figure 5,6). Zone 1 included Upper Bass Lake and extended downstream to the culvert antenna. Zone 2 was downstream from the culvert antenna to the restored area antenna and zone 3 was downstream from the restored antenna, including the Neopit Mill Pond. Transition probabilities between and within the three zones were calculated using a multistate capture-recapture model within a Bayesian framework. The assumptions for this model are: 1) individuals are independent of each other; 2) individuals have the same probability of transition and being observed at a known time and state; 3) tags are not lost, and 4) individuals and states are recorded without error (Kéry and Schaub 2012). I used R2WinBUGS (Sturtz et al. 2005), a package in Program R, that allowed me to manipulate data in R and directly call up WinBUGS (a software package for performing Bayesian inference using Gibbs sampling; Gilks et al. 1994 and Lunn et al. 2000, 2009). WinBUGS uses MCMC (Markov chain Monte Carlo) sampling techniques to run through specified number of iterations where each new value is dependent on the previous value (Cowles 2013; Doll and Jacquemin 2018). The chains converge and generate a posterior distribution where the mean of the distribution is the probability of a parameter to occur. In Bayesian statistics, a parameter is considered random; the idea of random parameters differs from the classical or frequentist form of statistics where the parameter is fixed. Additionally, I did not conduct model selection because there is much debate on how to perform model selection for complex integrated models (Letcher et al. 2015), especially within Bayesian analysis.

Bayes theorem or rule is the underlying basis for any Bayesian analysis:

$$p(A|B) = \frac{p(B|A)p(A)}{p(B)}$$

which states the conditional probability of observing  $A$  (model) given that  $B$  (data) is true, is equal to the conditional probability of observing  $B$  given  $A$ , times the probability of  $A$ , divided by the probability of  $B$ . Furthermore, modeling within a Bayesian framework requires the use of either uninformative, which fits a likelihood to the data, or informative priors, which allows the researcher to incorporate prior knowledge. I used a multinomial logit function to specify a normal prior distribution for  $n-1$  transition parameters ( $\alpha$ ). Each ( $n-1$ ) parameter was calculated as:

$$\beta_j = \frac{\exp(\alpha_j)}{1 + \sum_{i=1}^{n-1} \exp(\alpha_i)}$$

where  $\alpha_j$  is prior distribution of the  $j^{\text{th}}$  parameter, (in this instance, the first two transition parameters),  $\alpha_i$  is the prior distribution of the  $i^{\text{th}}$  parameter and  $\beta_j$  is the probability estimate of the  $j^{\text{th}}$  parameter. Because only the first two transition probabilities can be calculated using the logit scale within a generalized linear model framework, the last parameter is calculated indirectly using the covariates from the initial two transitions (Kéry and Schaub 2012):

$$\beta_n = 1 - \sum_{i=1}^{n-1} \beta_i$$

where  $\beta_i$  is the probability of the first two ( $n-1$ ) parameters,  $\beta_n$  is the probability estimate of the last parameter.

Model inputs included capture histories of fish and the time period when the fish entered the system. Capture histories were coded based on antenna detections and physical recaptures during different sampling periods, such that 4 = fish was not detected or not yet in the system during sampling period  $i$ , 1 = fish was detected and was in zone 1 during sampling period  $i$ , 2 =

fish was detected and was in zone 2 during sampling period  $i$ , and 3 = fish was detected and was in zone 3 during sampling period  $i$ . Because the PIT antenna arrays were only running for a short period of time in 2016, capture histories were coded on a daily basis (12 October through 16 November). In 2017, monthly intervals were used to calculate transition probabilities (April through December). Additionally, to allow for comparison between years, daily encounters of brook trout were also used during 12 October through 16 November 2017.

A total of 15 parameters were calculated using the multistate model, these included transition probabilities between the three zones and apparent survival ( $\Phi$ ) and recapture ( $p$ ) probabilities within each zone. Each zone has three transition probabilities (Table 3). For example, a fish tagged in zone 1 can stay in zone 1 ( $\Psi_{AA}$ ), move to zone 2 ( $\Psi_{AB}$ ) or move to zone 3 ( $\Psi_{AC}$ ). I ran three MCMC chains with various numbers of iterations and burn-ins with a thinning of six and monitored convergence by visually inspecting the chains. The Brooks-Gelman-Rubin (BGR) convergence diagnostic,  $\hat{R}$ , was also used to assess convergence. Values near one indicate likely convergence, if values were  $> 1.1$ , convergence was likely not met and so I ran the model again increasing the number of iterations until convergence was achieved for all parameters (Brooks and Gelman 1998; Gelman et al. 2004; Gelman and Hill 2007). In addition to calculating  $\hat{R}$ , I plotted the posterior distributions for each parameter and determined if estimates were reasonably precise by visually assessing the distribution of the three chains.

Monthly data from 2017 lacked information for zone 3 transitions (few detections) so convergence was not met after multiple attempts to run the model with increasing iterations up to 500,000. To circumvent this issue, I utilized data augmentation (Tanner and Wong 1987) to increase my sample size by five times the original. Data augmentation refers to adding additional data (capture histories) to the original observations to make analysis easier,

convergence achievable and computation to proceed more quickly (Gelman 2004; Tanner and Wong 1987). I used the augmented data to generate specific priors to utilize for parameters that did not reach convergence with the original capture histories; the original capture histories were used when running the final model and generating probability estimates. Furthermore, the data had no instances of transitions upstream from zone 3 to zone 1, so I set a prior transition probability at zero; for zone 3 the model only predicted transition to zone 2 and the probability to stay within zone 3. I used the probabilities obtained from the augmented data to calculate specific priors to use in the model. These priors paired with 300,000 iterations and a 50,000 burn-in resulted in model convergence for all parameters.

Daily movement data from 2016 and 2017 posed similar convergence issues. To address these issues for daily transitions in 2016, I used informative priors for parameters that did not initially reach convergence or if posterior density plots did not appear to be predicting precise estimates (i.e. chains did not follow a normal distribution). Although there were occurrences of brook trout transitioning from zone 3 to 1, they represented less than 1% of the transitions so I set the transition to zero. Setting this transition to zero aided with convergence in parameters to transition from zone 3 to zone 2 and to stay in zone 3. The daily capture histories from 2017 posed similar issues which were addressed by using informative priors for parameters not reaching convergence.

### Objective 2 & 3

Movements into both Upper Bass Lake and the Neopit Mill Pond were defined using detections on the antennas nearest to these areas. If a fish was detected at antenna 1U (Figure 6) I assumed the fish entered Upper Bass Lake. Similarly, if a fish was detected at antenna 4D (Figure 6) I assumed the fish entered the Mill Pond. Conversely, leaving the lacustrine habitats

was defined as a fish detected at antenna 1D (Figure 6) and a fish detected at antenna 4U (Figure 6); these fish were presumed to have left the lacustrine habitat and reentered the WBWR.

Movement through the rapids (both up and down) was defined by a fish detected at antenna 4U or 4D (Figure 6) and at a later date detected at an upstream antenna (e.g., 3D, 3U, etc.).

#### Objective 4

I calculated apparent survival ( $\Phi$ ) and recapture ( $p$ ) probabilities using the Cormack-Jolly-Seber (CJS) modeling approach (Cormack 1964; Jolly 1965; Seber 1965) within a Bayesian framework. I did not use the apparent survival or recapture probabilities from the multistate model; when running the multistate models, I only used fish that were detected at least once, thus survival and recapture estimates would be biased. One assumption of the CJS model is that tags are not lost among individuals. Using the CJS approach for estimating survival and recapture probabilities allowed me to correct for tag loss within the system by removing the appropriate number of fish that had been tagged, but were not observed again. I removed the correct number of fish by randomly removing the capture history of fish that were tagged, but never seen again. I did this by multiplying the instantaneous rate of shedding by the number of days the tagged fish were in the system. This calculation provided an estimate of the number of the number of fish that potentially lost their tags during the specified number of tags post tagging.

Total shedding rate ( $\phi$ ) of PIT tags was calculated as:

$$\phi = 1 - (r_c / (r_t + r_c))$$

where  $r_t$  is the number of recaptured fish with adipose clips but no PIT tags and  $r_c$  is the number of recaptured brook trout with PIT tags and adipose fin clips. The majority of brook trout were

recaptured within five months after tagging; therefore,  $\phi_{\text{total}}$  was calculated for a five-month period. To facilitate making these corrections, I calculated an instantaneous tag loss rate ( $\Omega$ ):

$$\Omega = -\ln(1 - \phi)$$

Because instantaneous rates are additive (Miranda and Bettoli 2007), I was able to calculate a daily tag loss rate ( $\Omega_{\text{daily}}$ ) by dividing  $\Omega$  by 150 which allowed me to estimate the number of tagged fish at large in the system during various times of the study. I used the instantaneous tag loss rate to determine the correct number of fish to remove from each capture history for each model. Similar to the multistate model, model input included capture histories of fish and the time in which the fish entered the system. Unlike the multistate model, capture histories were coded such that 1 = fish detected during sampling period  $i$  and 0 = fish was not detected during month  $i$ . I used non-informative priors with uniform distributions ranging from 0 - 1 for all models. These survival and recapture estimates are for the entire tagged population of brook trout ranging from April – December 2017.

#### Objective 5

I calculated relative abundance as catch per unit effort (CPUE; fish/km) for total number of brook trout and number of brook trout  $\geq 152$  mm (i.e., minimum length limit for harvest in the WBWR) captured during individual electrofishing runs. These estimates were compared to other statewide trout streams using statewide percentiles provided by the Wisconsin Department of Natural Resources (J. Griffin, Wisconsin Department of Natural Resources, personal communication).

## RESULTS

### *Objective 1*

#### 2016

During the entire study period (2016-2018), I captured 920 brook trout (Figure 15); 447 of these fish were implanted with either 12- or 23-mm PIT tags (Figure 16). During fall 2016, 129 tagged fish were at large in the WBWR. Twenty-eight percent of the fish were tagged in zone 1, 62% in zone 2 and 10% in zone 3 and 30.2% of these fish were detected at one or more antennas or were recaptured in subsequent electrofishing runs. For the duration of fall data collection (13 October through 16 November), upstream movement was displayed by 35.9% of detected fish, while 7.7% of brook trout exhibited downstream movement. The remaining 56.4% of detected fish remained in the zone in which they were tagged. With the exception of zone 1 where the probability to transition downstream was higher, multistate model output from daily capture histories in fall 2016 indicated the probability of a fish remaining in the zone of tagging to be higher than the probability of transitioning to a different zone (Figure 17). Posterior distribution density plots indicated precise parameter estimates with the three chains following a normal distribution (Figure 18). Convergence was visually assessed and values of the BGR convergence diagnostic,  $\hat{R}$ , indicated convergence for all parameters (Figure 19).

#### 2017

During 2017 (April - 6 December), an additional 318 brook trout were tagged within the WBWR and 27.2% were detected at one or more antennas or physically recaptured. Twenty-nine percent were tagged in zone 1, 71% in zone 2 and 0% in zone 3. Of fish that were detected 18.8% moved upstream, 10.7% downstream and 70.5% remained in the same zone where they were tagged. Additionally, only 10 fish tagged in 2016 were detected or recaptured during 2017.

Transition probabilities from monthly capture histories in 2017 indicated fish were more likely to remain in the tagging zone than transition upstream or downstream into a different zone (Figure 20). Convergence was visually assessed and values of  $\hat{R}$  indicated convergence for all parameters (Figure 19) and posterior distribution density plots for each parameter indicated precise estimates with the chains and iterations following a normal distribution (Figure 21). The percentage of tagged brook trout within each zone during the months in which the antennas were deployed was also calculated to make comparisons and strengthen results from the multistate model estimates (Figure 22). These percentages showed that most fish reside in zone 2 with very few transitions between months. I also plotted three different fish movement patterns, movement upstream, downstream, and remaining within the same zone (Figure 23) and number of individual brook trout detected at each antenna during each month the antennas were deployed in 2017 (Figure 24).

Unlike parameter estimates from the 2016 model, daily transition parameters from the daily capture histories in 2017 indicated higher probabilities of fish moving to an upstream zone than remaining within the zone where they were tagged (Figure 25). Furthermore, the probability of fish to remain in zone 1 was higher in 2017 ( $0.96 \pm 0.009$ ) than in 2016 ( $0.44 \pm 0.16$ ). Convergence was visually assessed and  $\hat{R}$  indicated convergence for all parameters (Figure 19). Posterior distribution density plots for each parameter indicated precise parameter estimates (Figure 26).

### *Objectives 2 & 3*

During 2016, approximately 5% of tagged fish ( $N = 7$ ) were detected at the Upper Bass Lake antenna while only four demonstrated movement into Upper Bass Lake and two fish remained in the lake. Of these seven fish, six were tagged in zone 1 and one was tagged in zone

2. These two fish were last detected as moving into the lake on 26 October 2016 and 16 November 2016. In 2017, approximately 3% of tagged fish (N = 11) were detected at Upper Bass Lake and only four fish indicated movement into the lake and one remained in the lake. Of these 11 fish, nine were tagged in zone 1 and two were tagged in zone 2. Most detections at the Upper Bass Lake antenna occurred during the fall (September-November). Moreover, during March 2018, one tagged brook trout was caught by an angler through the ice in Upper Bass Lake. This fish was previously detected at the Upper Bass Lake antenna in November, but did not indicate movement into the lake. Finally, two fish were detected at the Upper Bass Lake antenna in April when the antenna was first deployed; both fish had been tagged in 2016. These fish were detected at the downstream antenna entering the WBWR. One of these fish had been detected at the antenna in 2016, but had not indicated movement into the lake and the other fish was not detected in 2016. These fish were likely missed detections into the lake either prior to removal of the antennas or more likely entered the lake later in the fall or winter when the antennas were not deployed.

Temperature at the temperature logger located by antenna 2D (Figure 27) never exceeded the lethal limit of 25°C, but temperature  $\geq 25^\circ\text{C}$  were recorded at the entrance to Upper Bass Lake located by antenna 1D (Figure 28) for approximately 5.5 days with 4.5 days of exceedance during July. Furthermore, exceedance of 20°C, the temperature reported by Hitt et al. (2016) where brook trout rely on their ability to move and find more suitable temperature, was recorded for 81.5 days at the upstream temperature logger (14.7% of total recorded days) and 24.5 days at the downstream temperature logger (4.4% of total recorded days). Raleigh (1982) reported an optimum temperature range for growth and survival of brook trout to be 11-16°C, the upstream

logger reported 46 days (8% of total recorded days) within the optimum temperature range and the downstream logger recorded 67 days (12% of total recorded days).

In 2017, approximately 2% of tagged fish ( $N = 9$ ) were detected at the Mill Pond antenna (furthest downstream) with six fish remaining in the Mill Pond. The other three fish were detected as moving back upstream through the rapids. Eight of the detected fish were tagged in zone 2, while one was tagged in zone 1. There did not seem to be any pattern to when fish moved into the Mill Pond; detections ranged from April-November. The three occurrences of fish moving up through the rapids occurred in June, July, and August and the fish ranged in size from 136 mm to 156 mm TL.

#### *Objective 4*

During all sampling events, 33 brook trout with adipose fin clips were recaptured; four fish were recaptured twice and six fish indicated tag loss. During 2016, four fish were recaptured in which no tag loss was observed. During 2017, 25 fish were recaptured with four fish exhibiting tag loss. During 2018, four fish were recaptured and two displayed tag loss. Over a five month period,  $\phi = 0.214$  and  $\Omega = 0.241$ , thus  $\Omega_{\text{daily}} = 0.241/150 \text{ days} = 0.001607$ . I estimated the number of tags at large in the system against days post tagging using my estimate of  $\Omega_{\text{daily}}$ . These estimates only included fish that were recaptured during the five-month time period, which consisted of 22 brook trout recaptured with an adipose clip and a PIT tag and 6 fish recaptured with an adipose clip but no PIT tag. Using  $\Omega_{\text{daily}} = 0.001607$ , I estimated the number of tags at large in the system at each day post-tagging (Figure 29). Monthly capture histories in 2017 (April – December) indicated a monthly apparent survival estimate of  $0.85 \pm 0.05$  and a recapture estimate of  $0.13 \pm 0.02$  and density plots indicated precise estimates for all parameters by visual assessing the distribution around the three chains (Figure 30). Convergence

was visually assessed and values of the BGR convergence diagnostic,  $\hat{R}$ , indicated convergence for all parameter estimates (Figure 31).

#### *Objective 5*

The average CPUE (Table 4) for all brook trout at all sampling stations was  $68 \pm 22$  brook trout per km (114 per mile) placing this section of the WBWR within the 60<sup>th</sup> percentile of all statewide trout streams and within the 50<sup>th</sup> percentile for all statewide class I trout streams. The average CPUE for brook trout  $\geq 152$  mm TL at all sampling stations was  $29 \pm 7$  per km (37 per mile) placing this section of the WBWR within the 55<sup>th</sup> percentile for all statewide trout streams and within the 45<sup>th</sup> percentile for all statewide class I trout streams.

## **DISCUSSION**

#### *Movement*

Various results indicate the majority of brook trout in the WBWR remained in the same zone in which they were tagged. Additionally, the small percentage of brook trout detected at any of the antennas (33%) suggests that most brook trout in the WBWR display limited movement. These assertions are supported by the fact that all but one brook trout recaptured by electrofishing was collected in the same transect where initially captured. Limited movement between zones suggests that ideal brook trout habitat is present within each zone. Petty et al. (2012) suggested that brook trout populations residing in smaller tributaries tend to be more sedentary than populations located within larger main stem rivers. Furthermore, Hoxmeier and Dieterman (2013) described seasonal patterns in movement of brook trout in two southeastern Minnesota streams and found that over half of the brook trout showed limited movement; 74% of the recaptured fish were captured  $< 50$  meters from previous capture locations. Similarly, Carlson and Letcher (2003) reported study site movement rates to be low (5%) among brook

trout and brown trout within the West Brook, a stream within the Connecticut River Basin in western Massachusetts.

During the time the antennas were deployed, no seasonal period appeared to display peak brook trout movement within the WBWR. Based on previous studies and brook trout life history, I expected to see increased movement upstream during the spawning period (October – November) as several studies have reported increased movement upstream to headwater streams and tributaries to spawn (Curry and Naokes 1995; Kanno 2011; Mollenhauer et al. 2013; Witzel and MacCrimmon 1983). I did observe this trend during 2017 when I observed increased upstream movement from zone 2 to zone 1. However, this transitional peak may have been an artifact of releasing tagged brook trout on the border of zone 1 and 2 on 11 October 2017, as many fish tagged in zone 2 moved upstream to zone 1 immediately after tagging. Limited pre-spawning movement suggests that ideal spawning habitat is available in all three zones. Additionally, limited movement also suggests that overwintering habitat (i.e., deep pools and undercut banks) is available in all zones. Although I removed the antennas in mid-November (2016) and early December (2017), I do not believe I missed any movement to overwintering habitat as this movement tends to occur immediately after the spawn (Curry et al. 2002).

While my study design accounted for transitional movements among zones, I could not determine movements within zones. For example, brook trout could move several kilometers within zone 1, but these movements would not be accounted for due to my antenna placement. However, deployment of additional antennas that would allow for more detailed assessment of movements was not feasible based on river access, logistics of maintaining antennas, and cost. Brook trout could also enter Menominee Creek, a tributary to the WBWR located in zone 1, or

other smaller tributaries connected to zone 1, during the spawning period or other portions of the year.

I did observe upstream movement of brook trout in the summer, specifically fish moving from zone 2 to zone 1 (7 fish; 5%). Upstream movement in summer was not likely related to increasing water temperature, as temperatures never exceeded the lethal limit of 25°C (Figure 32; Brasch et al. 1973) at the downstream temperature logger located by antenna 2D (Figure 6). To strengthen the claim that upstream movement was not temperature related, 63% of recorded days over 20°C at the downstream logger occurred in July and only six fish were detected in July and none of these fish exhibited upstream movement.

#### *Apparent Survival and Recapture Estimates*

The apparent survival estimate (0.27 over 8 months), corrected for tag loss using the Cormack-Jolly-Seber method based on monthly 2017 capture histories, was comparable to other survival estimates (Carlson and Letcher 2003; Hoxmeier and Dieterman 2003). In general, apparent survival underestimates true survival because the model cannot determine the difference between death and immigration or emigration from the system. Hoxmeier and Dieterman (2003) reported a 3-month brook trout survival rate in southeastern Minnesota streams ranging from 41 – 100% with the lowest survival reported during the winter. Conversely, Carlson and Letcher (2003) reported a survival rate of 0.35 for both brook trout and brown trout age-1+ during the fall and a summer survival rate of 0.44.

The low recapture (detection) probability for the Cormack-Jolly-Seber model may be an artifact of the equipment used to detect the tagged fish. If more than three (2016) or four (2017) stationary PIT antenna arrays were deployed in the WBWR, which was not feasible, recapture probability would most likely be increased as there would be a greater chance of a fish to be

detected by one or more antenna. Moreover, although the recapture estimates were not divided by zone, recapture probabilities likely differed between zones, as zone 1 was much larger in distance compared to the other zones. Much of the capture history data included periods where a fish was not detected by any antenna resulting in overall lower recapture probabilities. For a fish to be detected, the fish: 1) had to retain its tag, 2) swim through the stationary antenna array, and 3) the array had to detect the fish. If all these measures were not met, then the fish was not detected and a relative location could not be assigned for that sampling period. Furthermore, Gowan et al. (1994) emphasized the fact that in many studies low recapture rates are typically ignored or even unreported, but low recapture rates, especially among salmonids is expected because of the already high mortality rates among stream salmonids.

#### *Detection Efficiency & Technical Issues*

The performance of stationary PIT antenna arrays for detecting PIT-tagged fish is a function of various factors, including PIT tag size, antenna width and construction of the system (i.e., single or multiplexor). Baker et al. (2017) tested the efficacy of 12-mm PIT tags used to monitor fish; results indicated that with appropriate antenna design, the detection efficiency ranged from 89% to 100% with no significant difference between tag size in detection efficiency, but the 23-mm tag had a significantly larger read range than the 12-mm tag. I attempted to quantify detection efficiency of the stationary PIT antennas under various environmental conditions (e.g., stream flow, water temperature and air temperature), battery voltage and tag sizes. In April and May of 2017, I conducted a series of these assessments in which results indicated technical issues with the equipment. Due to increased issues with the equipment at two of the antenna sites, I was not able to conduct further assessments. Moreover, there was a period of time in 2017, (April-June) when the antennas located at Upper Bass Lake and the culvert were

not functioning properly. Technical issues with equipment affected read-range of the antennas decreasing it to where antennas only detected fish swimming directly over the cables. An example of a missed detection was the tagged brook trout caught through the ice in March 2017. This fish was only detected at the downstream cable at Upper Bass Lake in November, but was never detected as entering the lake, indicating a probable missed detection. Although, it is possible that the fish did not enter Upper Bass Lake until after the antennas were removed in December. Furthermore, vandalism occurred during the summer of 2017 on the Upper Bass Lake antenna; the antenna was moved downstream 1.5 km in July where it continued to operate until September when it was moved back upstream to the bridge to detect any brook trout entering Upper Bass Lake as possible overwintering habitat. Technical issues with the equipment were fixed and all four antennas were working properly for the remainder of 2017.

#### *Tag Shedding*

The PIT shedding rate for this study (five-month rate was 0.241) was higher than observed in some previous studies (Dieterman and Hoxmeier 2009; Ombredane et al. 1998), but lower than observed in other studies focused on PIT tag retention rates (Bateman et al. 2009; Meyer et al. 2011). Bateman et al. (2009) observed retention rates ranging from 62-80% in wild cutthroat trout *Oncorhynchus clarkii* while Ombredane et al. (1998) observed an average PIT tag loss rate of 3.38% seven months after implantation. Moreover, Dieterman and Hoxmeier (2009) conducted a study with results showing 70% retention rate by brook trout when the PIT tag was implanted into the body cavity compared to 100% when the PIT tag was implanted into the dorsal musculature. Dieterman and Hoxmeier (2009) mention that compared to other studies analyzing tag retention their results showed lower retention rates when the tag was inserted into the body cavity. This may have been due to environmental conditions or the tagging methods

used. Meyer et al. (2001) observed a significant difference in retention rates of mature male and female rainbow trout, suggesting that egg expulsion may cause tag loss in salmonids which has also been reported in other studies (Bateman et al. 2009; Prentice et al. 1990). The majority of recaptured fish in my study were recaptured < five months after tagging, therefore, I calculated the tag shedding rate for my study over a five month period. Dare (2003) reported that the majority of PIT tags implanted into juvenile chinook salmon *Oncorhynchus tshawytscha* were shed within the first two days after tagging. Foldvik (2018) reported similar results in Atlantic salmon with the lowest retention rate during the first period of tagging (days 0-49), although tag retention rate did decrease again during later sampling.

### *Management Implications*

My results will help Menominee Tribal biologists to determine if additional habitat alterations or other management actions could be implemented to benefit the brook trout population in the WBWR and other streams on the Menominee Indian Reservation. For example, a third dam is located at the point where the Neopit Mill Pond flows into the downstream 26 km stretch of the WBWR. If a large percentage of brook trout were entering the Mill Pond and not able to return back up through the rapids, removing or altering this dam to create passage could create additional habitat for brook trout to survive and reproduce. Results from this project indicate that only a small percentage of the brook trout population are entering lacustrine habitat provided by Upper Bass Lake and the Mill Pond, suggesting that these habitats are not acting as sinks. Furthermore, based on detections of tagged brook trout, movement back upstream through the rapids to the WBWR is possible. These results suggest that creating passage for brook trout to access the downstream 26 km stretch of the WBWR would probably

not substantially benefit the current brook trout population but could expand the brook trout range and availability of habitat within the WBWR.

Limited movement into lake habitats paired with a small percent of recaptured or detected fish between and among years suggests high mortality of brook trout in the WBWR. High mortality may be due to extensive fishing pressure paired with liberal fishing regulations (20 fish per day, 152-mm minimum total length limit) or may be a function of brook trout life history. In general, brook trout are not a long-lived fish. According to Brasch et al. (1958), high mortality among brook trout in Wisconsin leads to rare cases of fish living past the age of four. In Lawrence Creek, Wisconsin, the average length of age four brook trout in September was 353 mm (Brasch et al. 1958). Although we did not conduct any age or growth analysis for the brook trout in the WBWR, based on length data, I am confident in saying a large percentage of brook trout within the WBWR are not living longer than four years, as only one captured brook trout was greater than 353 mm. There is little consensus on what limits survival of stream salmonids. Many studies suggest winter (decreased water temperature and ice formation; Brown et al. 2011) to be a time for poor survival while others suggest increased summer temperatures result in lower survival rates among stream trout (Xu et al. 2010). Furthermore, flooding events have also been reported to alter survival of brook trout within streams (Carline and McCollough 2003; Hoxmeier and Dieterman 2013). Hoxmeier and Dieterman (2013) reported that in two southeastern Minnesota streams, survival of brook trout may not be dependent on season, but regulated by conditions within each season. High mortality within the brook trout population in the WBWR is likely related to a variety of factors. The fact that approximately 8% of the fish tagged in 2016 were detected or physically recaptured in 2017 may suggest winter survival is low, but because the antennas were not deployed during the winter months this in only an

assumption. However, the downstream temperature logger, located by antenna 2D (Figure 6), did record temperatures below 0°C for a total of 27 days (4.8%) and at or below 1°C for 208 days (37.3%). Although the upstream temperature logger, located by antenna 1D (Figure 6) did not record temperatures at 0°C or below, it did record temperatures at or below 1°C for 142 days (25.5%). Temperatures < 0°C are below the optimum temperature range for brook trout (Raleigh 1982), thus may affect brook trout survival.

An important aspect of managing a sport fishery is understanding mortality rates and if exploitation is having negative effects on the fishery (e.g., additive mortality; Allen et al. 2008). Exploitation of brook trout within the WBWR is unknown, but may be attributing to high mortality within the brook trout population. To better manage the brook trout fishery within the WBWR, it would be beneficial to estimate annual exploitation. Exploitation can be calculated from harvest estimates based on creel survey data (Deroba et al. 2005) if a population estimate is also available, but currently, both creel information and a brook trout population estimate are not available for the WBWR. Another method for estimating exploitation is to utilize a tag-return study in which the ratio of fish tagged and caught in one year is divided by the total number of fish tagged within the year (Miranda and Bettoli 2007). Utilizing a tag-return study can both underestimate (non-reporting) or overestimate (increase angler effort if a reward is offered) mortality. However, evaluation of mortality from angling is an extremely important assessment of any exploited population (Pope et al. 2010), as it can be a limiting factor for brook trout (Hunt et al. 1962) as well as other stream-dwelling salmonids. If exploitation proves to be a significant factor leading to high mortality of brook trout within the WBWR, establishing more conservative regulations by decreasing the bag limit or implementing a minimum length limit may be beneficial to the brook trout population in the WBWR.

### *Future Research*

Results from my study suggest that mortality of brook trout in the WBWR is high. These indicators include, 1) low number of recaptures, 2) low percentage of detected fish, and 3) limited movement into lake habitat. The low percent of detected fish could be due to the limited movement of brook trout within the system, but if the fish are not moving to a great degree, I would expect to see a higher number of recaptures. During 2017, I sampled extensively and only recaptured 25 fish, all recaptures occurred within zone 2 and 52% (13 of 25) occurred during one sampling event in October. Based on these results, I believe additional research should focus on better understanding natural mortality and exploitation within the WBWR. This may be done by designing an effective creel survey and estimating population size or by implementing a tag-return study.

During sampling events conducted for this study, four rainbow trout were captured 1.5 km downstream from Upper Bass Lake in the fall of 2017 and six were captured in the summer of 2018. Downstream movement by rainbow trout from Upper Bass Lake may be a concern. Rainbow trout tend to be larger than brook trout likely giving them a competitive advantage in habitat preference over brook trout. It is known that a large number of juvenile rainbow trout reside in Drew Creek (connected to Florence Lake and Upper Bass Lake via a channel connecting the two lakes), but movement into the WBWR had not been observed prior to my sampling in 2017. The removal of both the Lake and Basswood dams in 2015 did increase stream access for the native brook trout population, but may have also increased access to the WBWR for non-native rainbow trout. Increased numbers of non-native rainbow trout within the WBWR may alter the distribution of the native brook trout (Larson and Moore 1985; Clark and Rose 1997) and even decrease the current population (Larson and Moore 1985). Moving

forward, future sampling for the presence of rainbow trout in the WBWR should be considered to ensure that the rainbow trout are not moving further downstream into the WBWR.

Lastly, creating greater stream connectivity by removing the Neopit Mill Pond Dam could also benefit the brook trout population in the WBWR. Removing the Mill Pond Dam would create passage and access for brook trout residing in the 26 km downstream portion of the WBWR to enter the upstream portion and also create additional habitat for brook trout currently residing in the 21 km study section. Access may increase spawning potential and possibly increase the population of brook trout within the upper 21 km stretch. Furthermore, Menominee Creek and other smaller tributaries may also encompass a portion of the brook trout population, protecting these smaller tributaries should be a priority in order to preserve existing coldwater sources as the climate continues to change.

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Table 1. Dates and locations (given names and river km [rkm]) of PIT antenna arrays deployed in the West Branch of the Wolf River during 2016 along with the number of brook trout detected at each location.

Date set	Date pulled	Location	River km	Fish detected
10/12/2016	11/16/2016	Upper Bass Lake	44.084918	7
10/12/2016	11/16/2016	Culvert	29.834918	21
10/12/2016	11/16/2016	Restored Area	26.214918	12

Table 2. Dates and locations (given names and river km [rkm]) of installation of the PIT antenna arrays deployed in the West Branch of the Wolf River during 2017 along with the number of brook trout detected at each location.

Date set	Date pulled	Location	River km	Fish detected
04/03/17	12/06/17	Upper Bass Lake	44.08	11
04/13/17	12/06/17	Culvert	29.83	79
04/24/17	12/06/17	Restored Area	26.21	24
04/24/17	12/06/17	Mill Pond	25.31	9

Table 3. The state transition matrix defining the probability of a brook trout being in a specific zone within the West Branch of the Wolf River at a specific time. Parameters include site-specific survival  $\emptyset$  and movement probabilities  $\Psi$ .

	Site A	Site B	Site C	Dead
Site A	$\emptyset_A(1 - \Psi_{AB} - \Psi_{AC})$	$\emptyset_A \Psi_{AB}$	$\emptyset_A \Psi_{AB}$	$1 - \emptyset_A$
Site B	$\emptyset_B \Psi_{BA}$	$\emptyset_B(1 - \Psi_{BA} - \Psi_{BC})$	$\emptyset_B \Psi_{BC}$	$1 - \emptyset_B$
Site C	$\emptyset_C \Psi_{CA}$	$\emptyset_C \Psi_{CB}$	$\emptyset_C(1 - \Psi_{CA} - \Psi_{CB})$	$1 - \emptyset_C$
Dead	0	0	0	1

Table 4. Relative abundance estimates (catch per km) for each sampling run on the West Branch of the Wolf River, Wisconsin from 2016 – 2018.

Station	Date	Sampling type	Station length (km)	Number	Average Length (mm)	Length Range	CPUE (No. per km)	
							CPUE (km)	CPUE $\geq$ 152 mm (km)
1	10/12/2016	Barge	0.69	145	130	74-286	210	65
1	11/4/2016	Barge	0.76	49	124	80-205	65	15
1	6/1/2017	Barge	1.16	73	173	119-276	63	39
1	8/3/2017	Barge	0.89	105	132	54-295	119	46
1	10/11/2017	Barge	0.82	125	129	69-282	152	51
1	5/8/2018	Barge	1.00	70	143	85-295	70	18
2	10/19/2016	Barge	0.48	23	118	72-200	48	17
2	6/7/2017	Barge	0.48	23	159	125-236	48	27
2	8/3/2017	Barge	0.48	38	163	61-292	79	46
2	10/11/2017	Barge	0.48	51	138	65-264	106	41
2	5/8/2018	Barge	0.48	20	118	92-197	42	2
3	10/19/2016	Barge	0.42	22	154	98-195	53	29
3	10/18/2017	Backpack	0.21	9	176	101-207	43	38
4	11/10/2016	Barge	0.68	22	175	95-355	33	22
4	6/2/2017	Barge	0.64	26	175	117-267	40	26
4	8/9/2017	Barge	0.39	10	188	157-224	26	26
5	7/27/2017	Backpack	0.79	27	160	66-291	34	20
5	10/18/2017	Backpack	0.64	28	128	75-254	43	9
6	6/7/2017	Barge	0.19	12	149	126-181	62	26
7	5/24/2018	Backpack	1.22	38	156	110-229	31	12
Total and overall means			12.90	916	149 $\pm$ 10		68 $\pm$ 22	29 $\pm$ 7

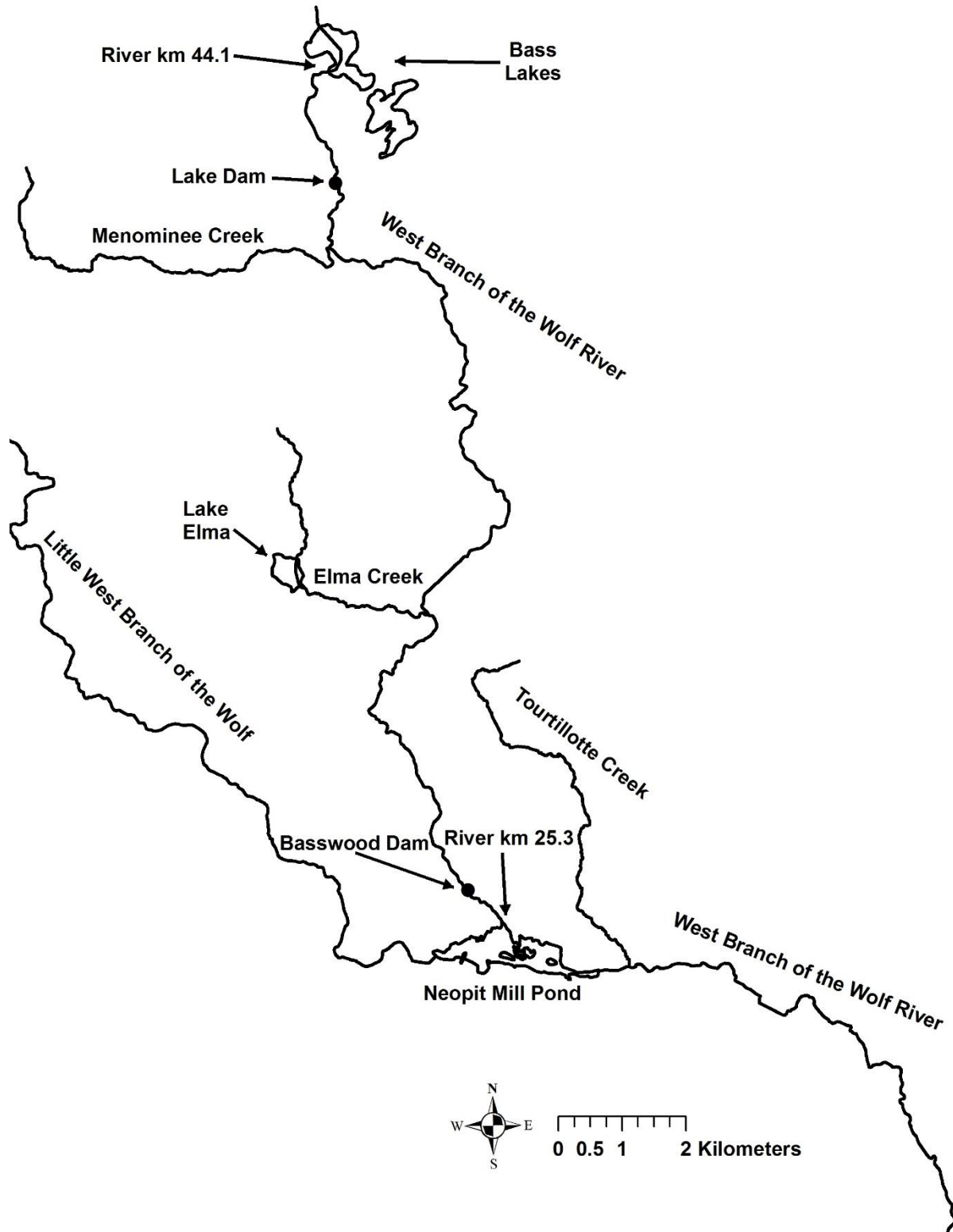


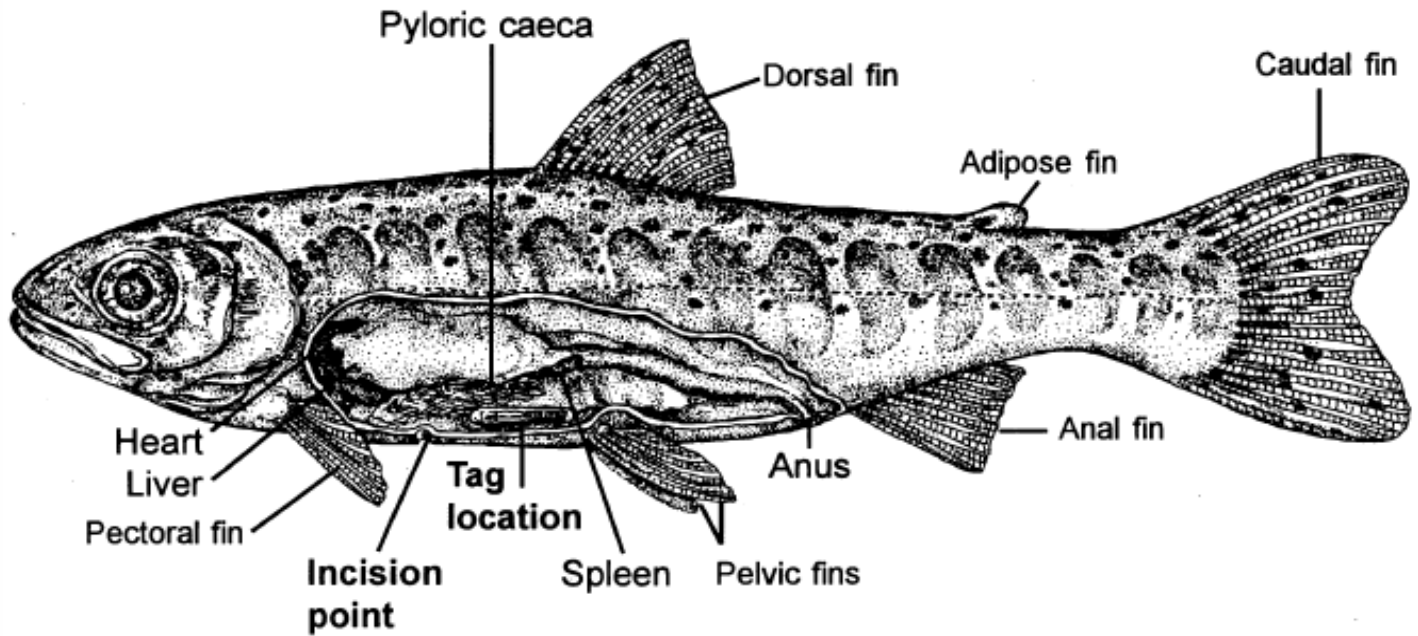
Figure 1. Map of the West Branch of the Wolf River, Wisconsin, depicting important tributaries, Upper Bass Lake, and the Neopit Mill Pond. River kilometers [rkm] and the location of removed dams are denoted.



Figure 2. Upstream photograph of the Lake Dam located approximately two km downstream of the entrance into Upper Bass Lake on the West Branch of the Wolf River, Menominee Indian Reservation, Menominee County, Wisconsin.



Figure 3. The Basswood Dam located on the West Branch of the Wolf River, Menominee Indian Reservation approximately one km upstream of the Mill Pond in Neopit, Wisconsin.



**This illustration is based on a fish specimen of 150 mm fork length.**

Figure 4. Placement of the PIT tag in fish. Adapted from “PIT tag marking procedure manual” by PIT Tag Steering Committee subcommittee of Fish Passage Advisory Committee, 2014. pp. 17.

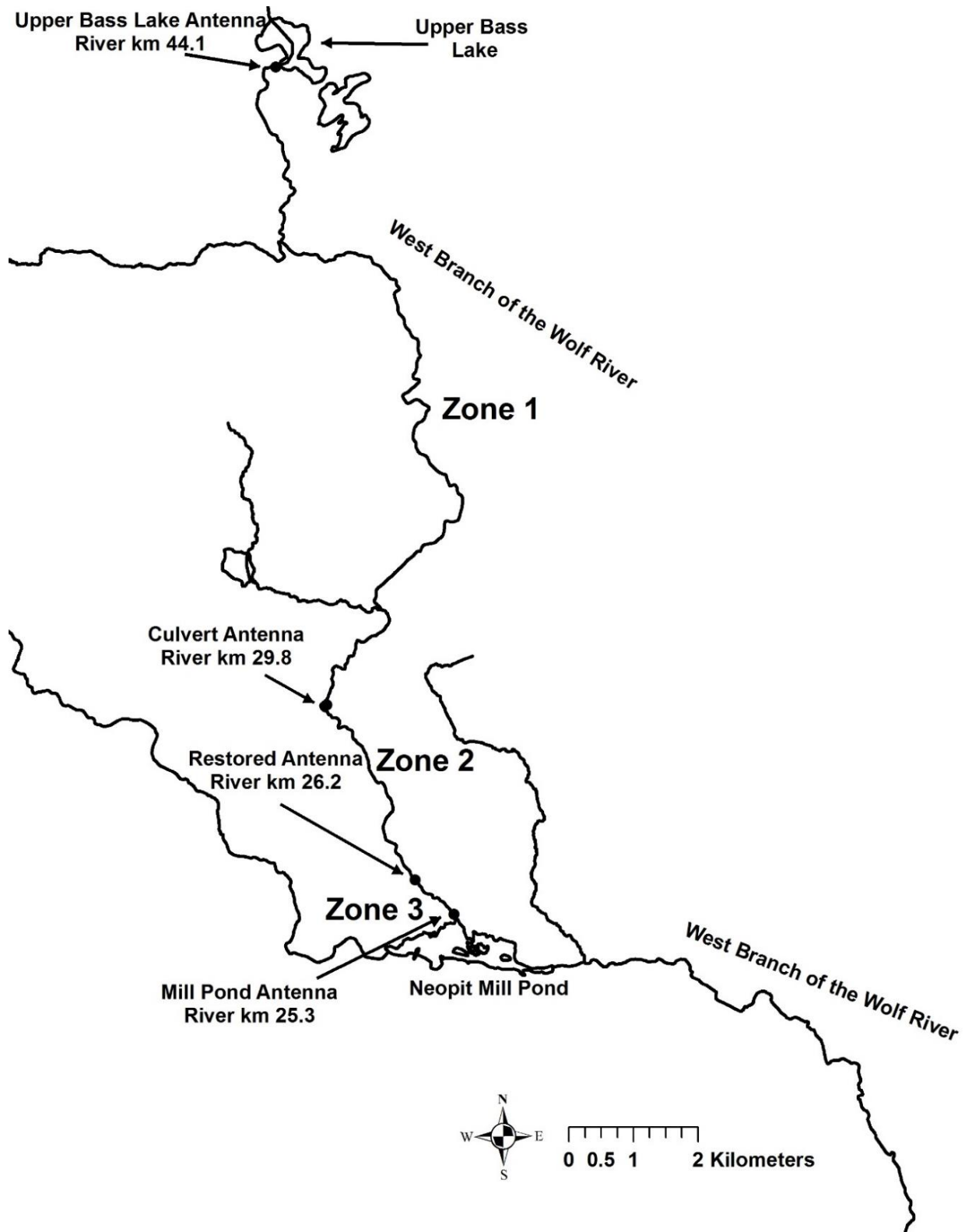


Figure 5. Map of the West Branch of the Wolf River, Wisconsin, depicting locations of the four stationary PIT antenna arrays and three zones dividing the stream. The zones are divided based on locations of the antennas in the stream.

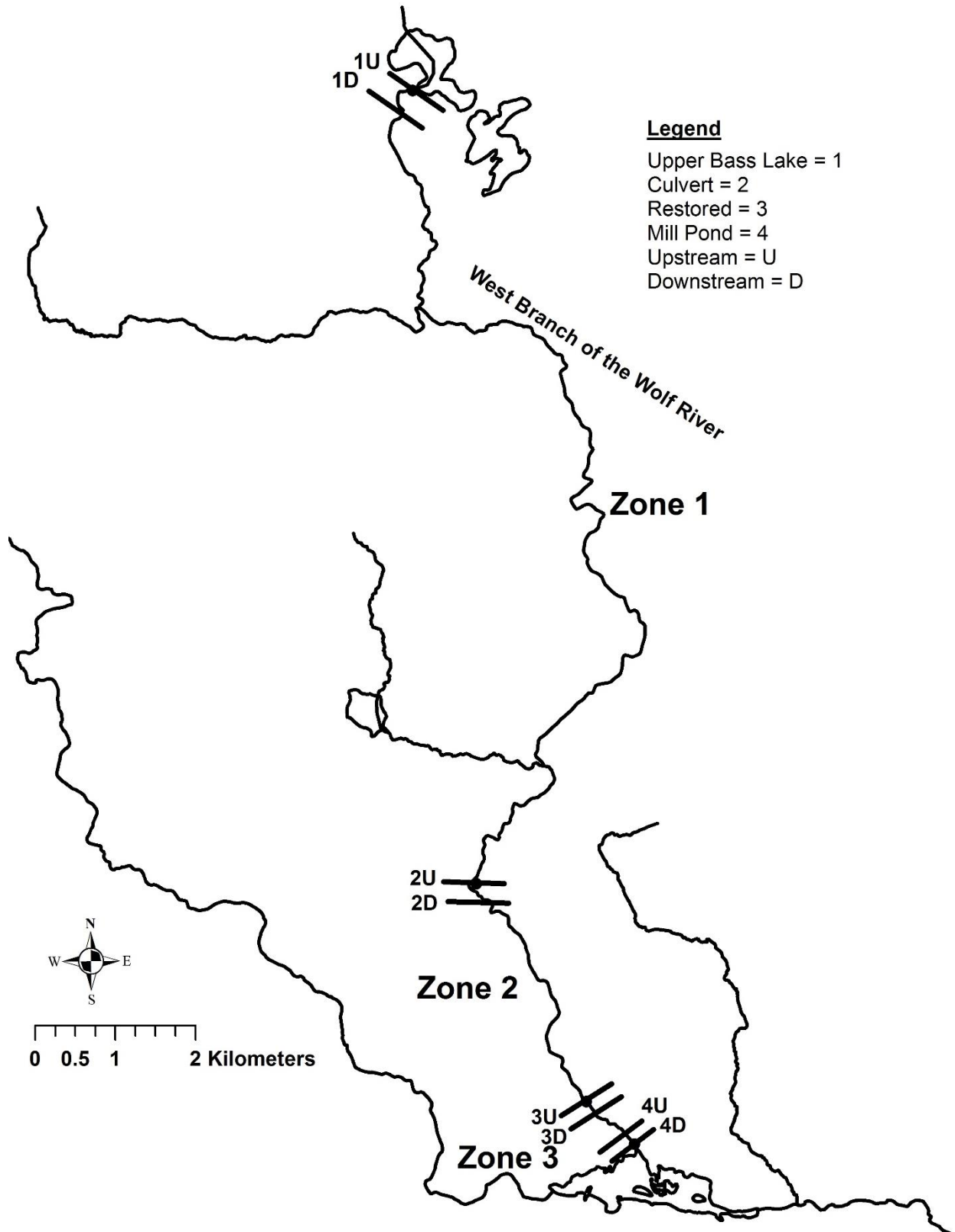


Figure 6. Map of the West Branch of the Wolf River, Wisconsin, depicting paired antenna arrays (one upstream; one downstream) for each of the four antennas denoted as solid black lines.



Figure 7. Upper Bass Lake antenna (1D) positioned under the bridge leading into Upper Bass Lake on the West Branch of the Wolf River, Menominee Indian Reservation, Menominee County, Wisconsin. Antenna locations are shown on the map in Figure 6.



Figure 8. Culvert antenna (2U) positioned at the culvert complex on the West Branch of the Wolf River, Menominee Indian Reservation, Menominee County, Wisconsin. Antenna locations are shown on the map in Figure 6.



Figure 9. Restored antenna array (antennas 3U and 3D) positioned at the restored section of stream on the West Branch of the Wolf River, Menominee Indian Reservation, Menominee County, Wisconsin. Antenna locations are shown on the map in Figure 6.



Figure 10. Rapids antenna (4U) positioned downstream from a rapids and upstream from the Mill Pond on the West Branch of the Wolf River, Menominee Indian Reservation, Menominee County, Wisconsin. Antenna locations are shown on the map in Figure 6.

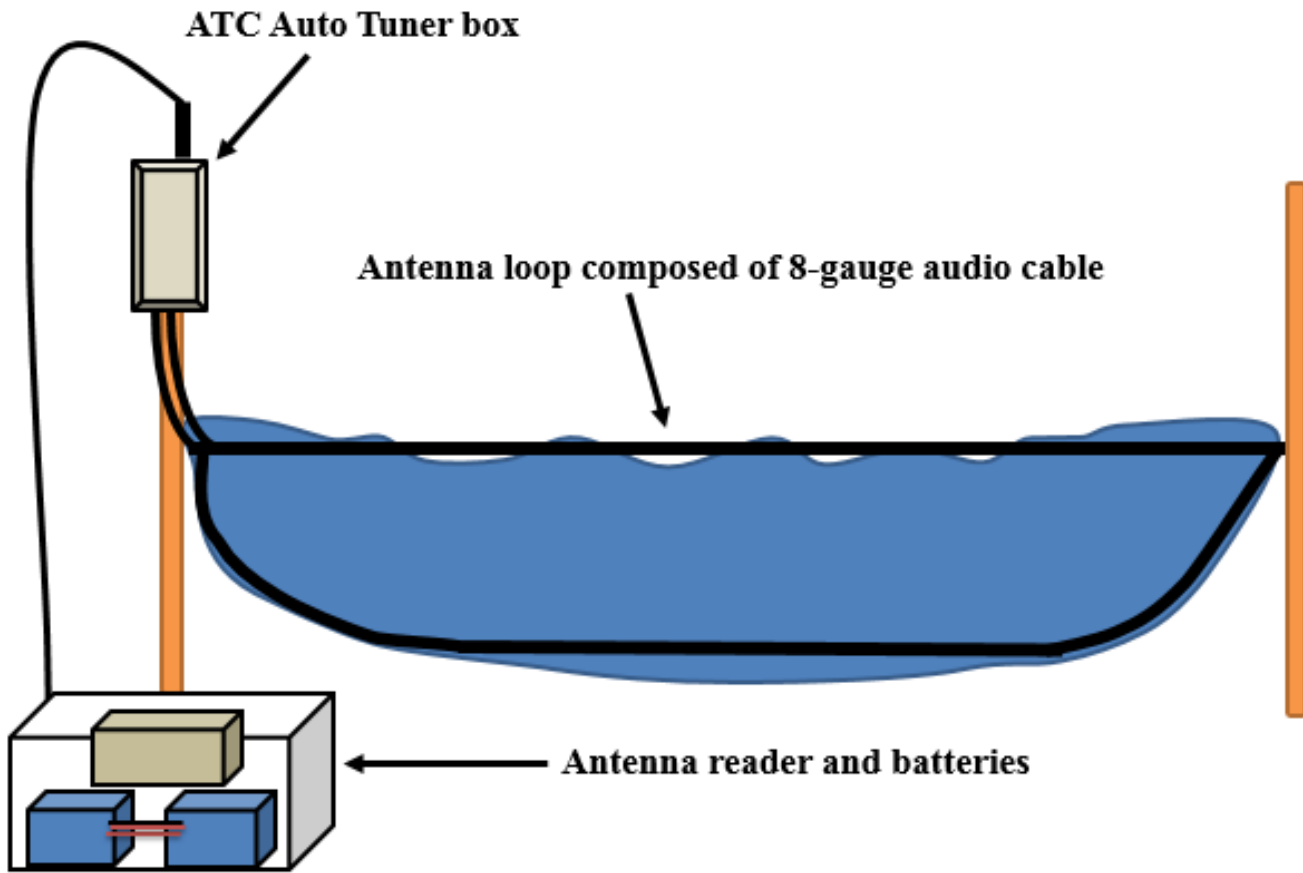


Figure 11. Schematic of antenna array positioned in stream.



Figure 12. Oregon RFID® (Portland, OR) tuner box connected to the multi-antenna HDX reader box via Belden® 9207 twinaxial cable.



Figure 13. Oregon RFID® multi-antenna HDX reader box powered by two 12-volt deep cycle marine batteries connected in parallel.



Figure 14. Plastic tote protecting Oregon RFID®, Portland, OR multi-antenna HDX reader box powered by two 12-volt deep cycle marine batteries connected in parallel.

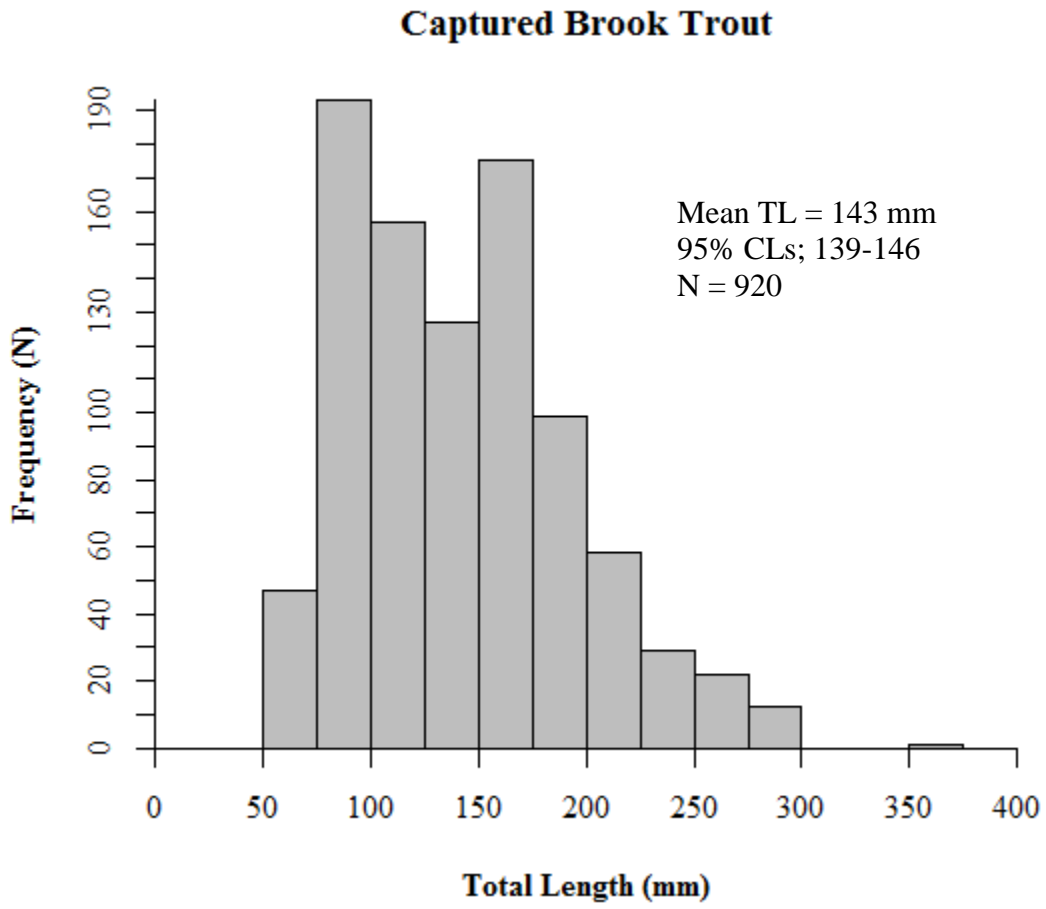


Figure 15. Length-frequency distribution of captured brook trout in the West Branch of the Wolf River, Wisconsin, from 2016 - 2018.

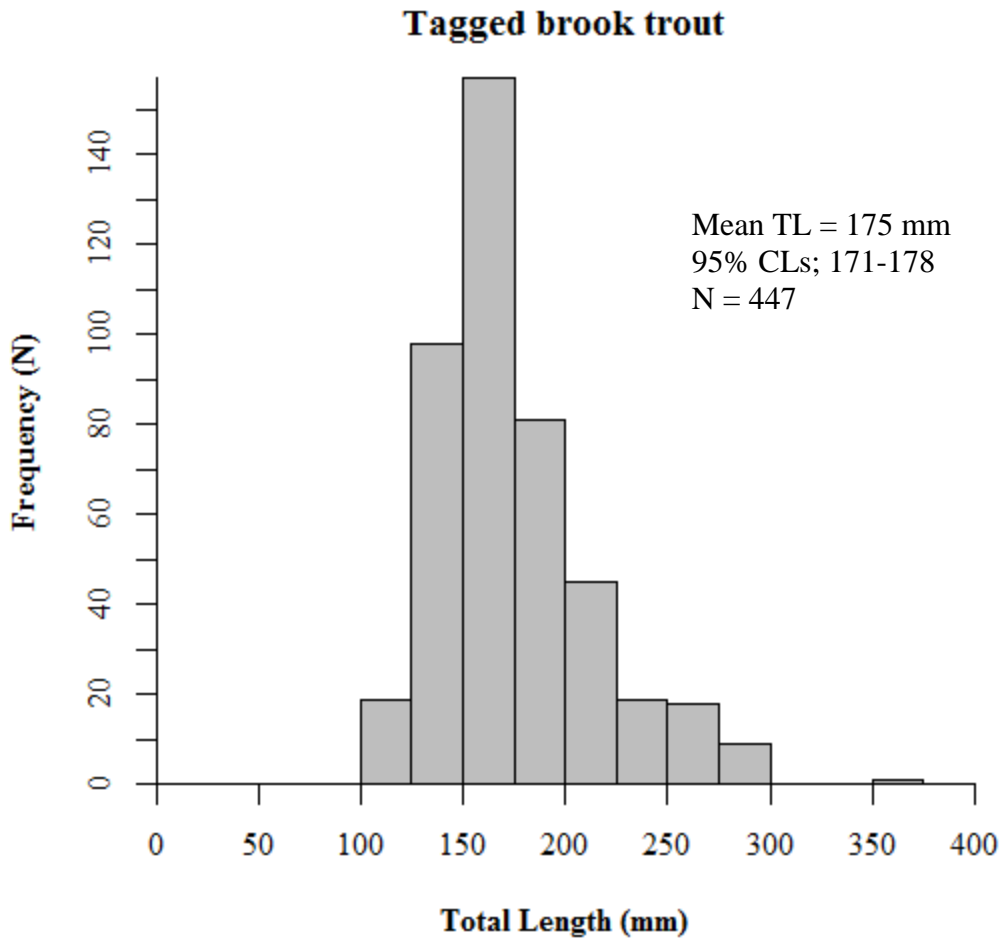


Figure 16. Length-frequency distribution of tagged brook trout in the West Branch of the Wolf River, Wisconsin, from 2016 and 2017 sampling.

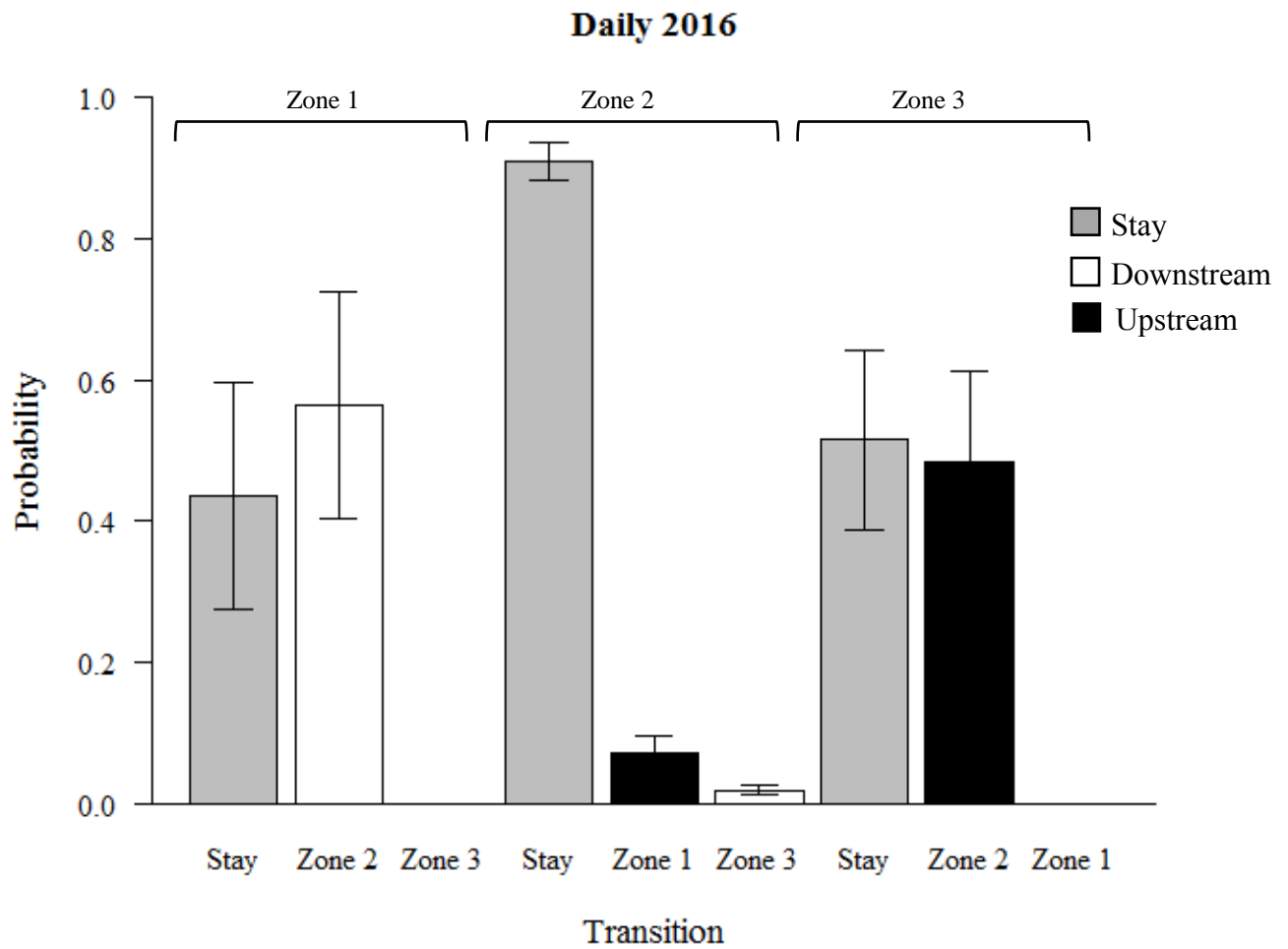


Figure 17. Daily transition probabilities between zones from 13 October - 16 November 2016 for brook trout in the West Branch of the Wolf River, Wisconsin.

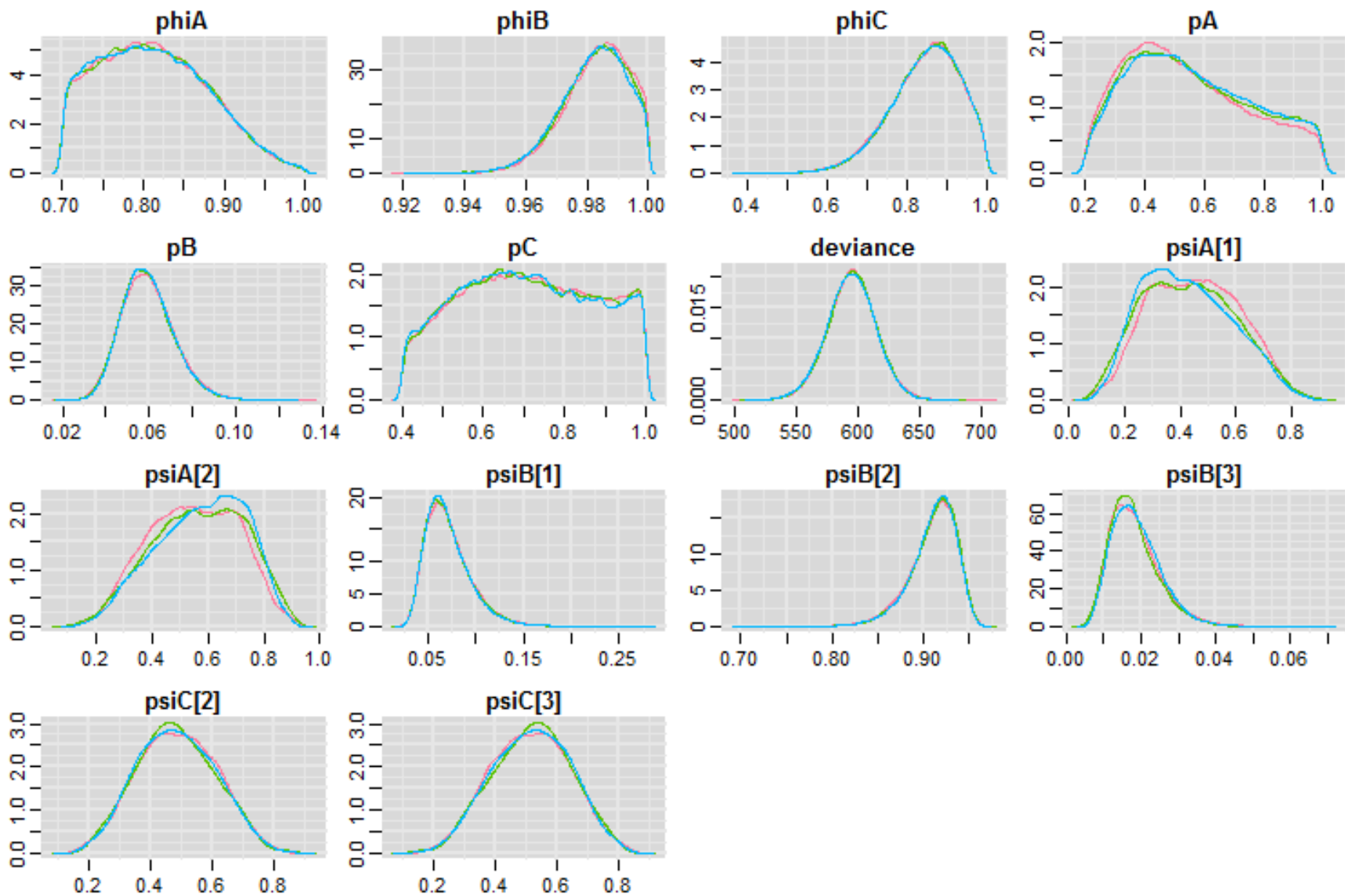
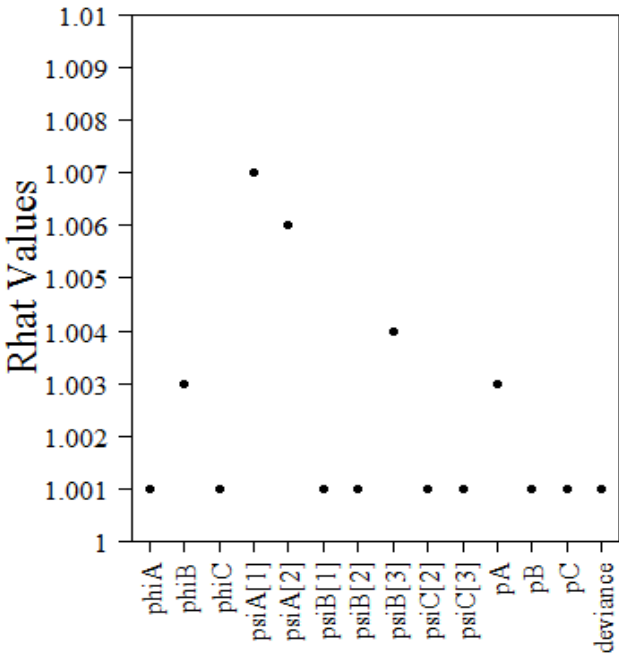
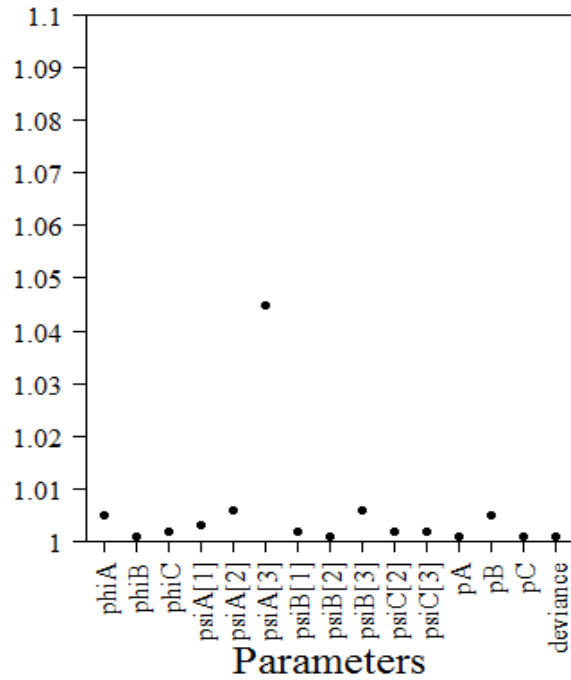


Figure 18. Posterior distribution plots for all parameters from capture histories ranging from 13 October – 16 November 2016 for brook trout in the West Branch of the Wolf River, Wisconsin.

**Daily 2016**



**Daily 2017**



**Monthly 2017**

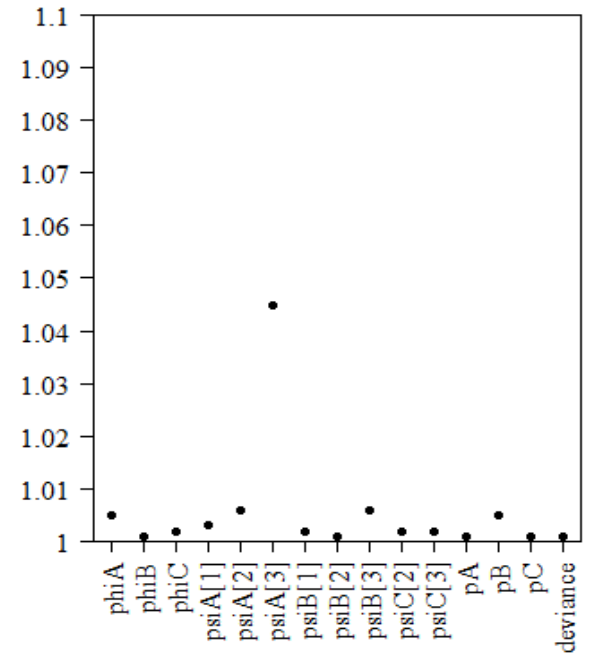


Figure 19. The Brooks-Gelman-Rubin (BGR) convergence diagnostic,  $\hat{R}$ , output for all multistate model parameters depicting brook trout transition between three zones on the West Branch of the Wolf River, Wisconsin. Values close to one suggest convergence, while values  $>1.1$  suggest convergence was not met.

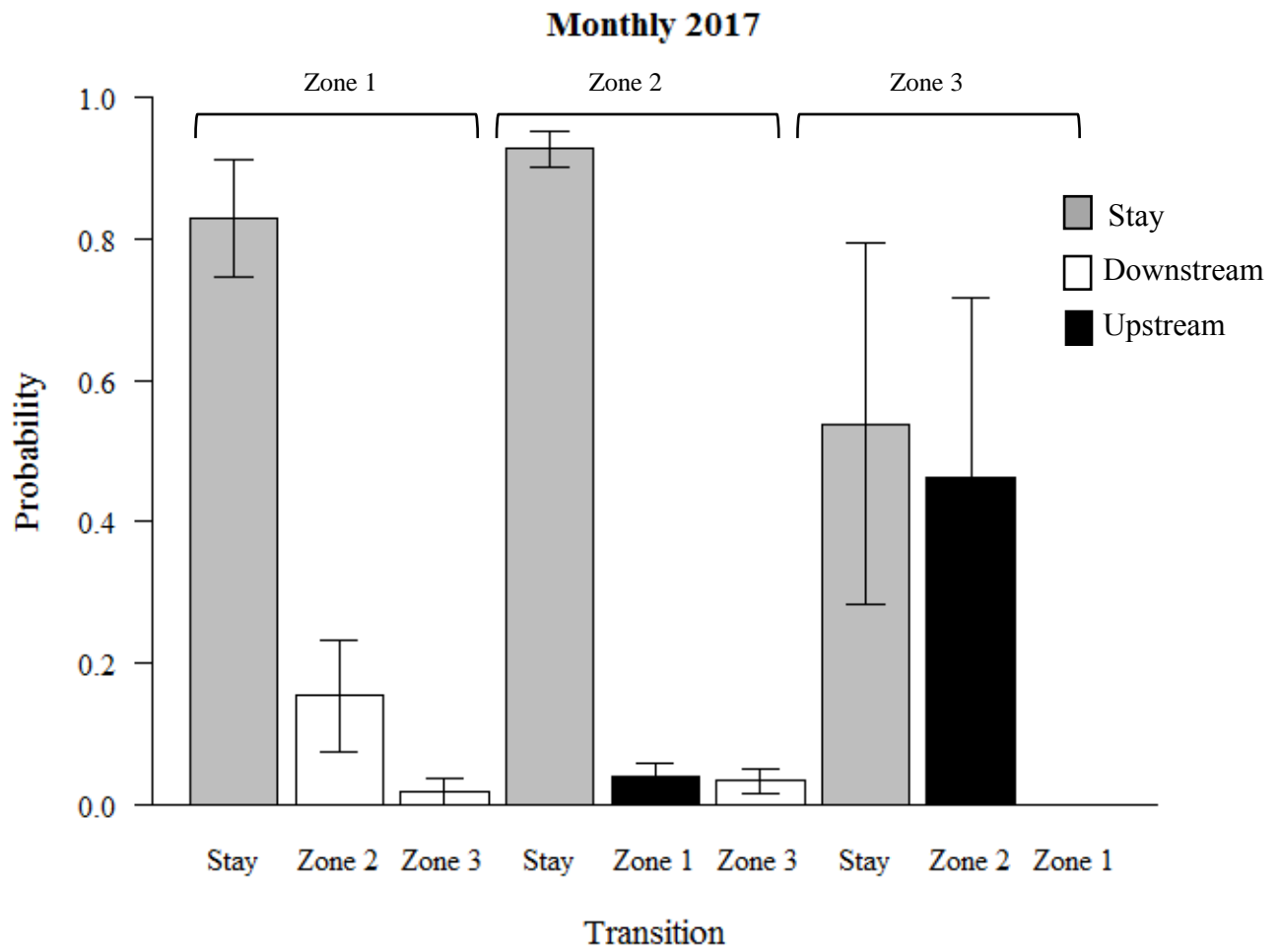


Figure 20. Monthly transition probabilities between zones from April – 6 December 2017 for brook trout in the West Branch of the Wolf River, Wisconsin.

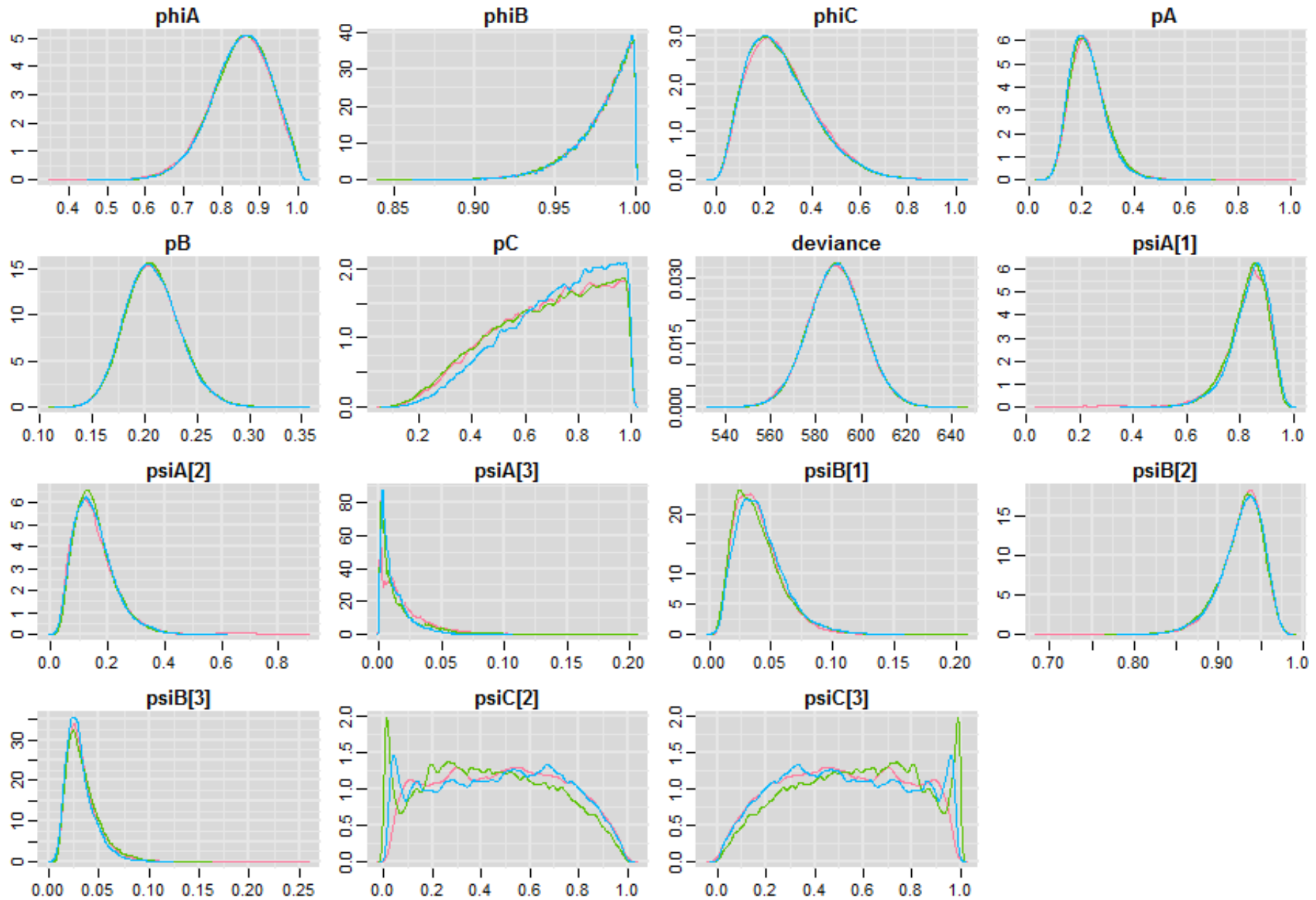


Figure 21. Posterior distribution plots for all parameters from capture histories ranging from April – 6 December 2017 for brook trout in the West Branch of the Wolf River, Wisconsin.

### Percent of brook trout within each zone

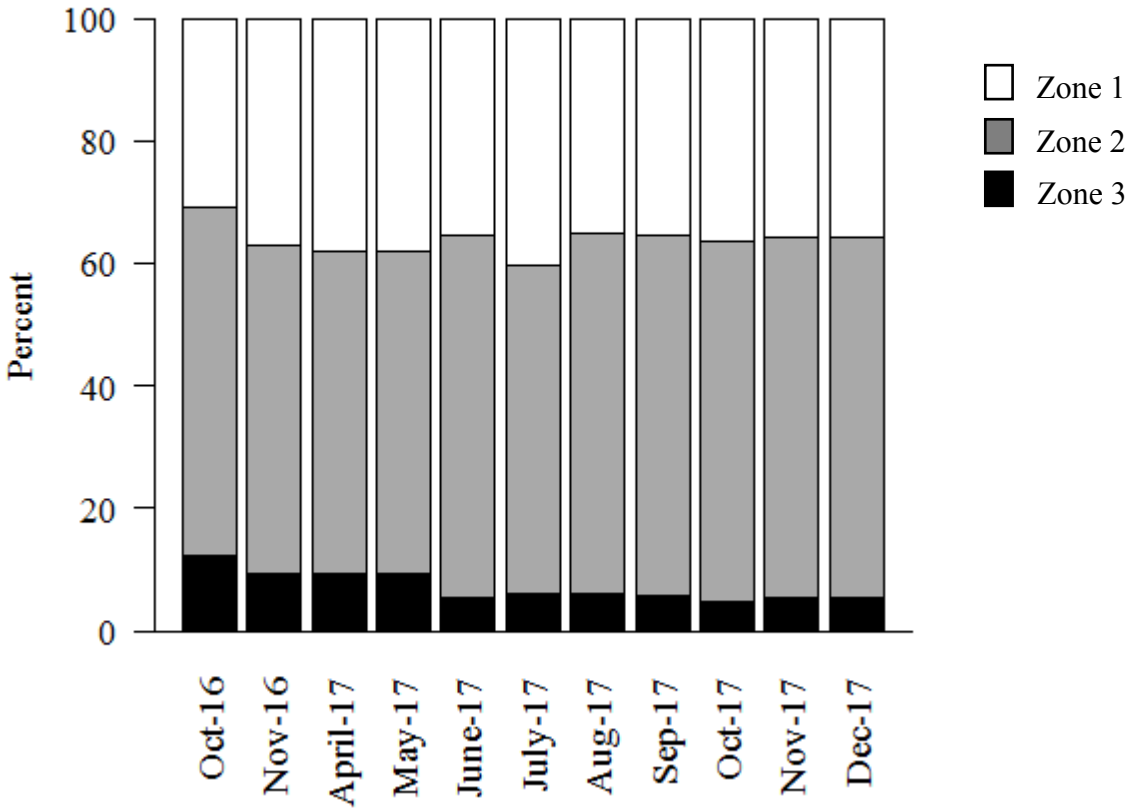


Figure 22. Percent of tagged brook trout in the West Branch of the Wolf River, Wisconsin, within each zone for each month the antennas were deployed (October 2016 - December 2017).

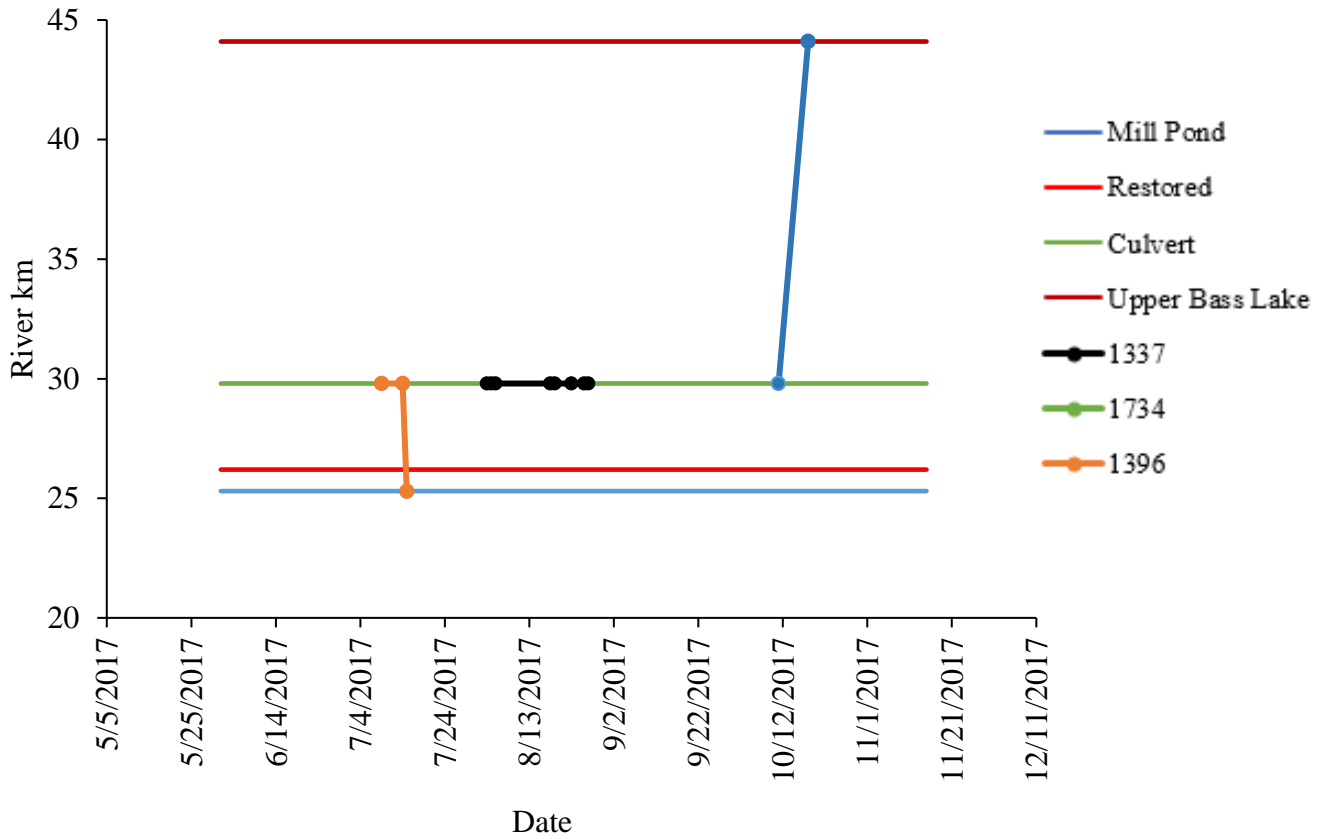


Figure 23. Individual movements of three tagged brook trout in the WBWR. The y-axis represents river km (rkm) and the x-axis displays the dates of detections. Horizontal lines represent the locations of the four stationary PIT antennas along the stream and the dotted lines represent the detections and movement of three brook trout.

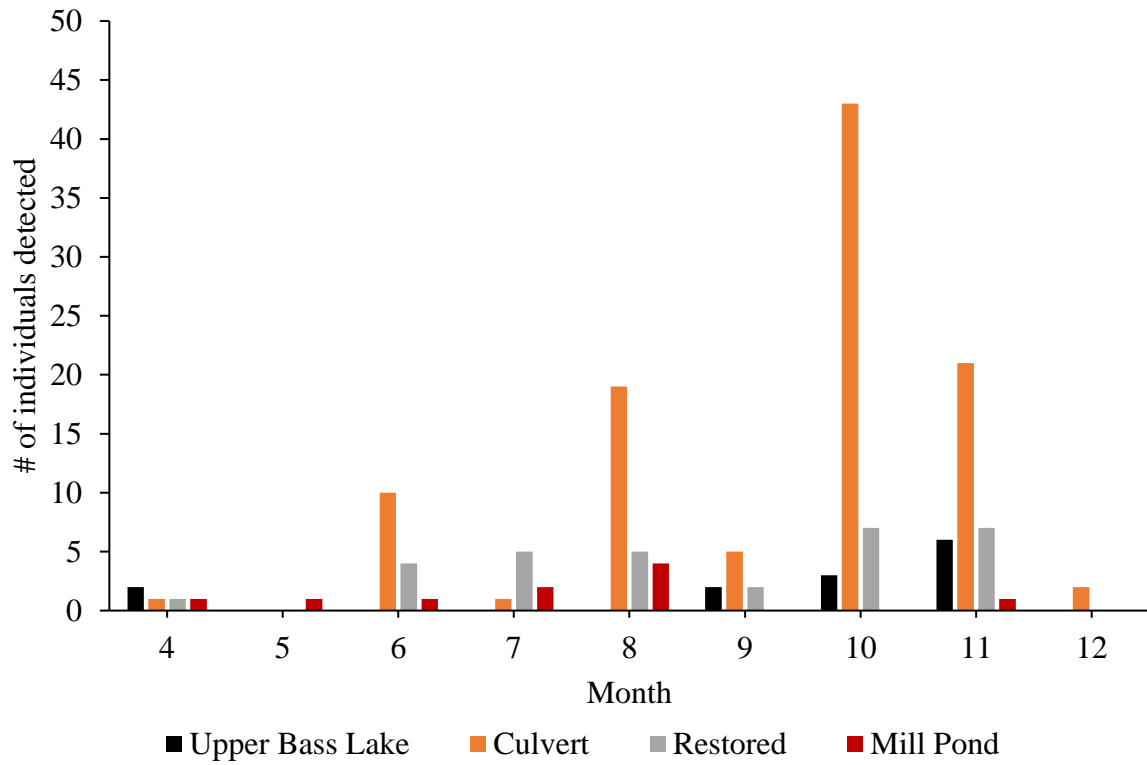


Figure 24. Number of individual brook trout detected at each antenna during each month the antennas were deployed in 2017.

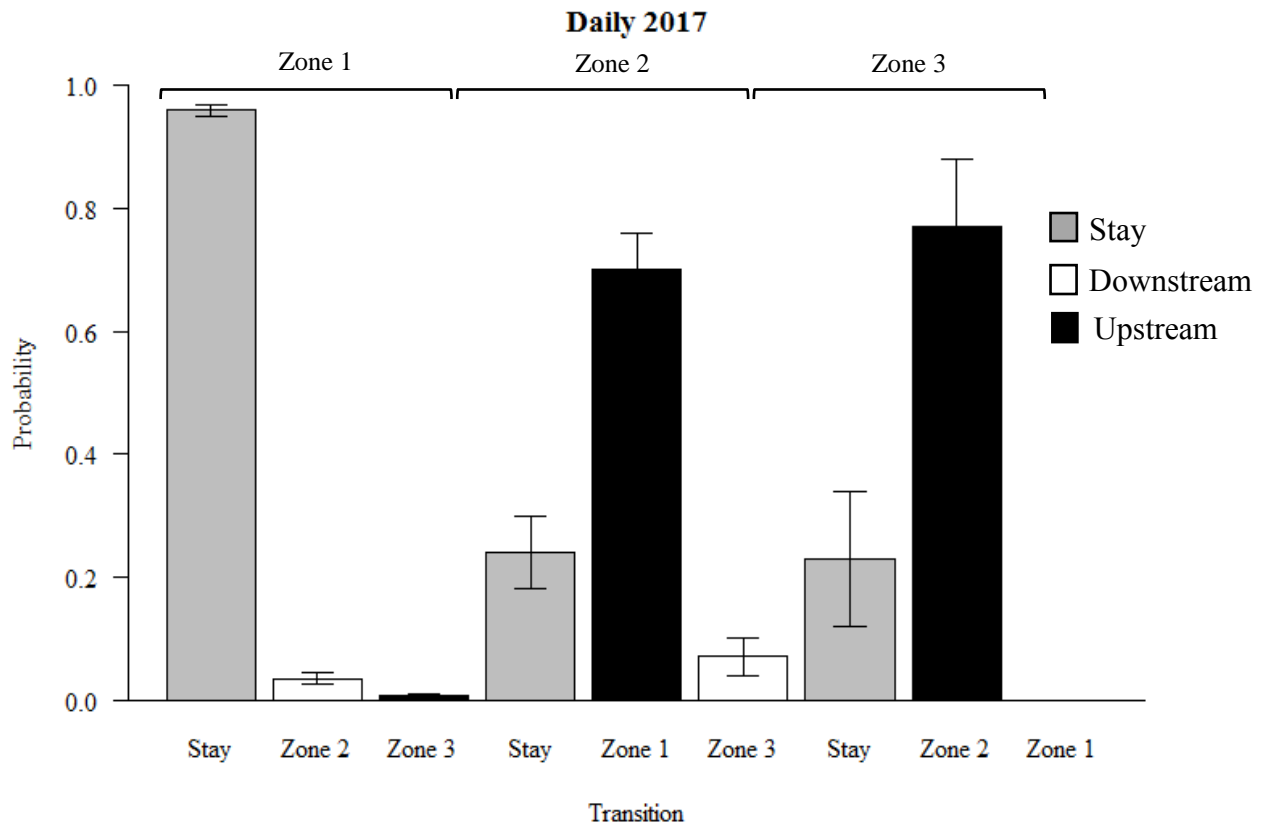


Figure 25. Daily transition probabilities between zones from 13 October – 16 November 2017 for brook trout in the West Branch of the Wolf River, Wisconsin.

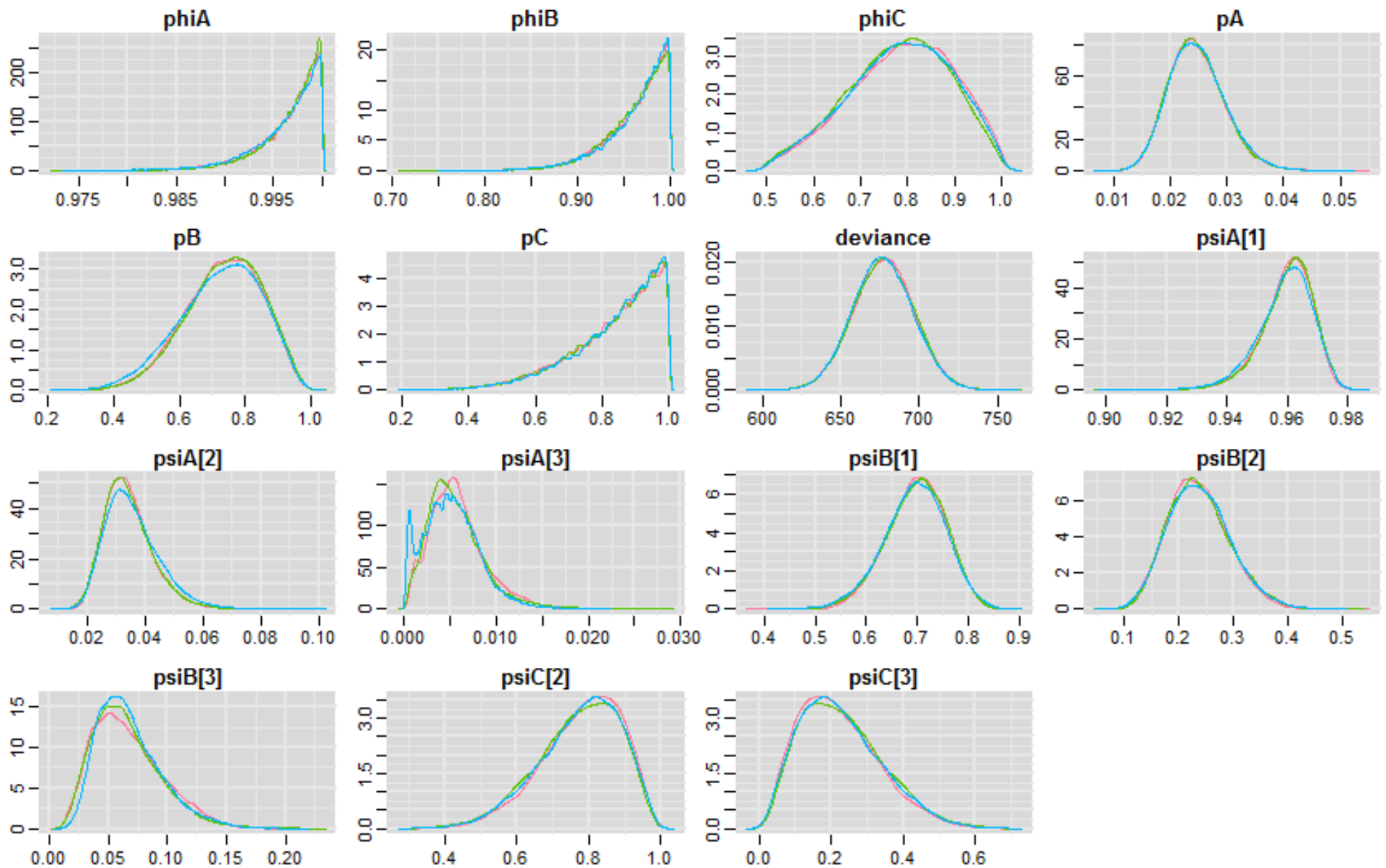


Figure 26. Posterior distribution plots for all parameters from capture histories ranging 13 October – 16 November 2017 for brook trout in the West Branch of the Wolf River, Wisconsin.

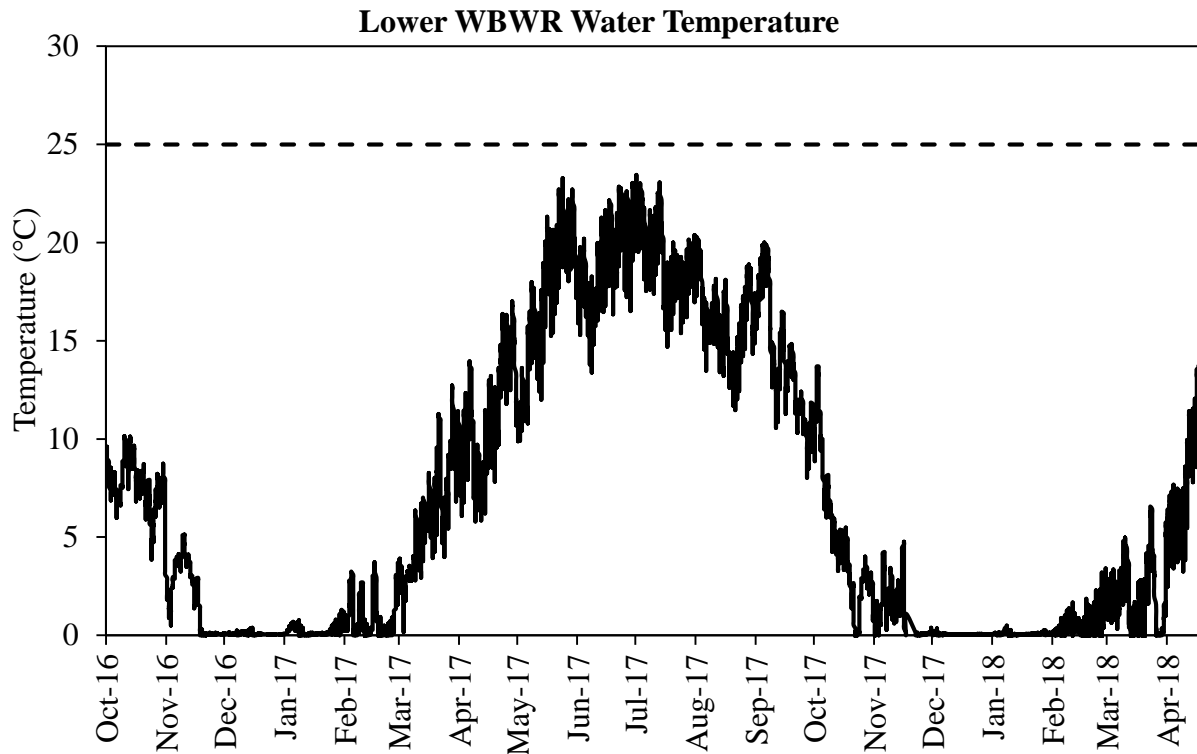


Figure 27. Water temperature readings from October 2016 - May 2018. The temperature logger was located at antenna 2D (Figure 6) in the West Branch of the Wolf River, Wisconsin. The dotted line defines the lethal limit for brook trout reported by Brasch et al. (1973).

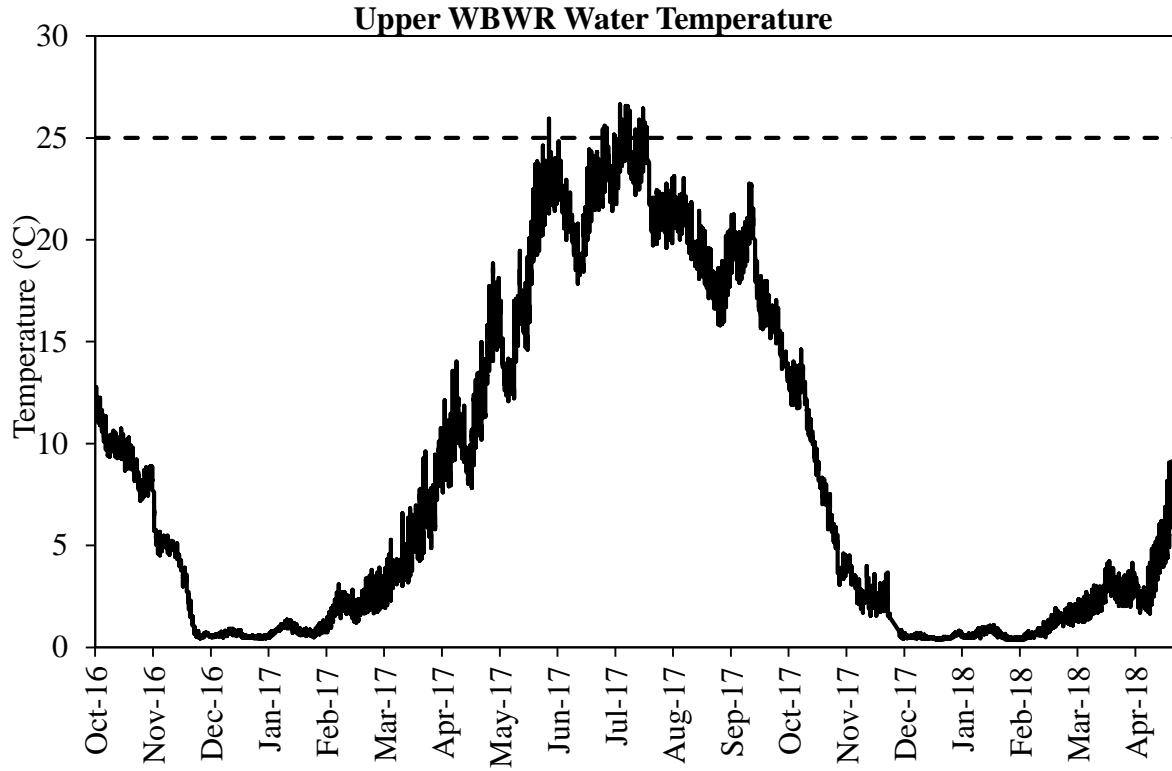


Figure 28. Water temperature readings from October 2016 - May 2018. The temperature logger was located at the antenna 1D (Figure 6) in the West Branch of the Wolf River, Wisconsin. The dotted line defines the lethal limit for brook trout reported by Brasch et al. (1973).

### Model of tag loss rate

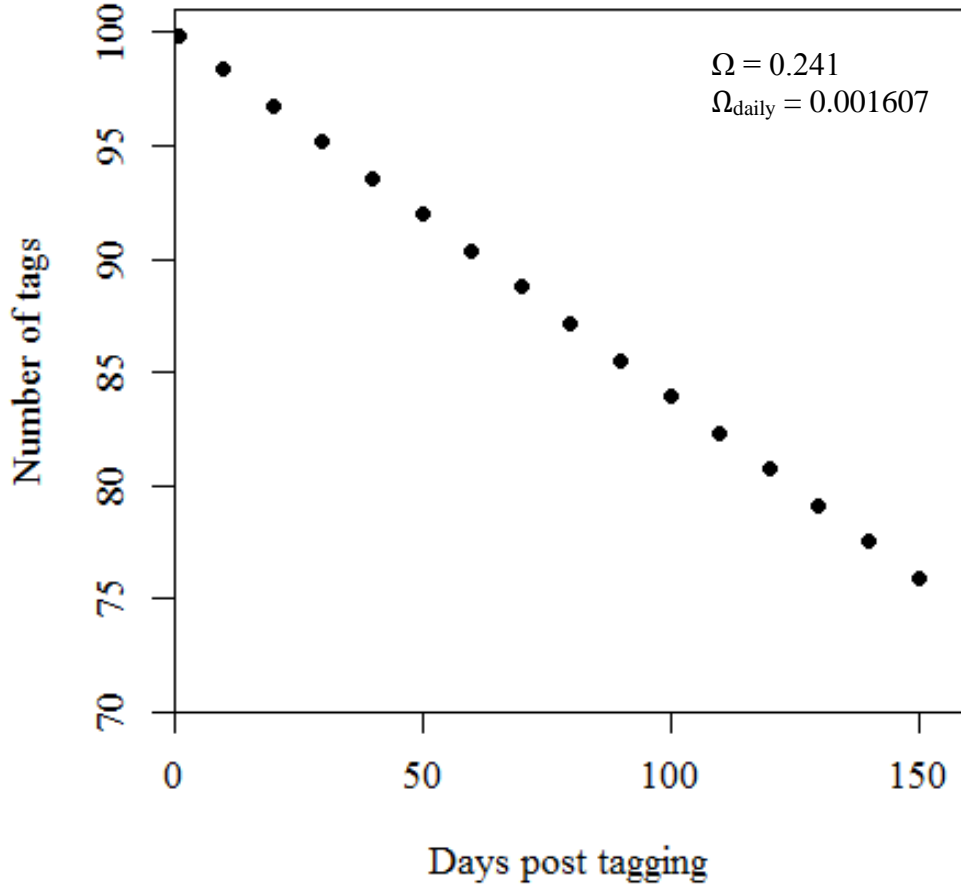


Figure 29. Model of tag loss rate over five months,  $\Omega = 0.241$ , for brook trout in the West Branch of the Wolf River, Wisconsin.

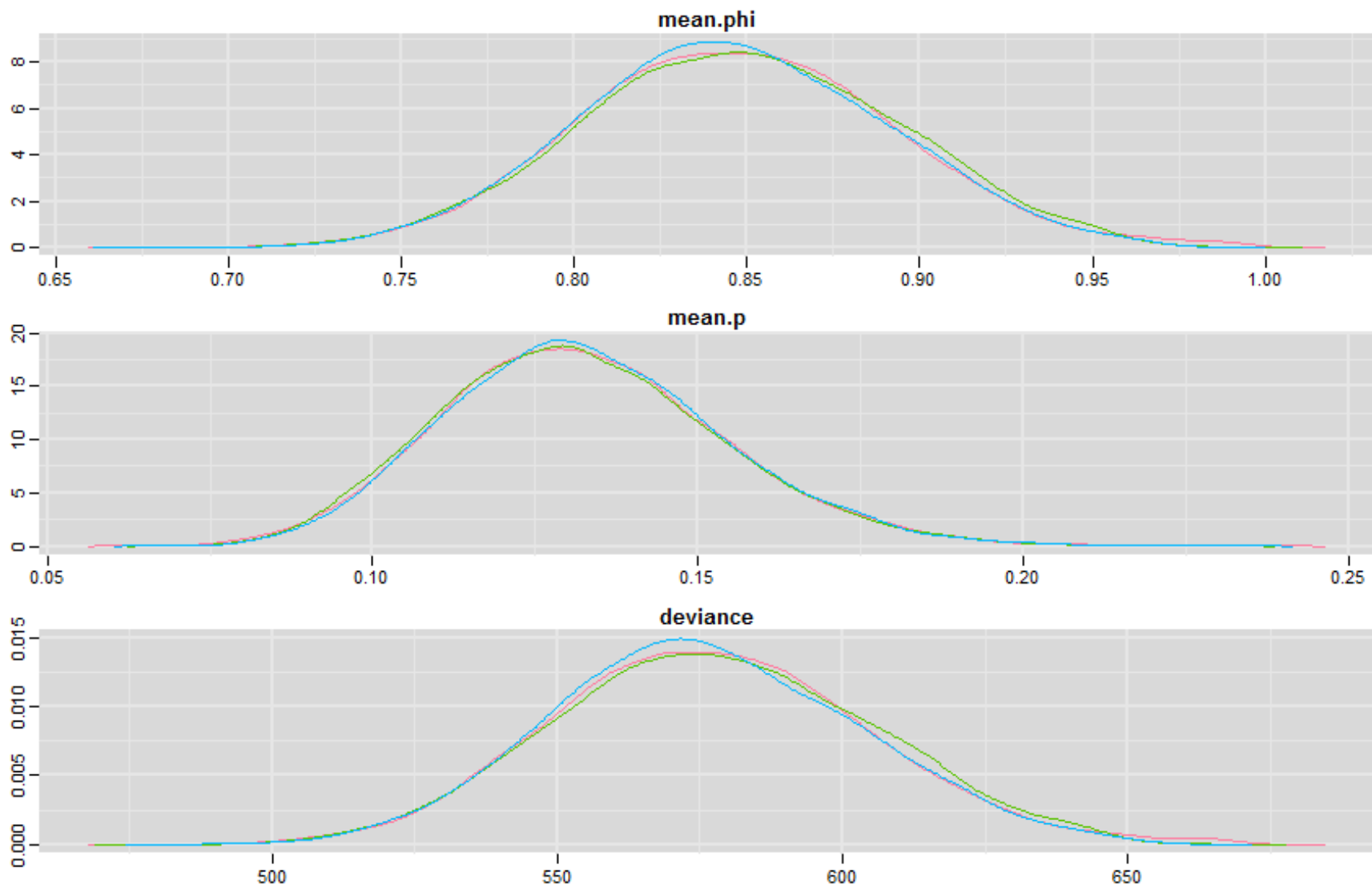


Figure 30. Posterior distribution plots for all parameters from 2017 monthly capture histories (April-December) using the Cormack-Jolly-Seber method for brook trout in the West Branch of the Wolf River, Wisconsin.

### Monthly 2017

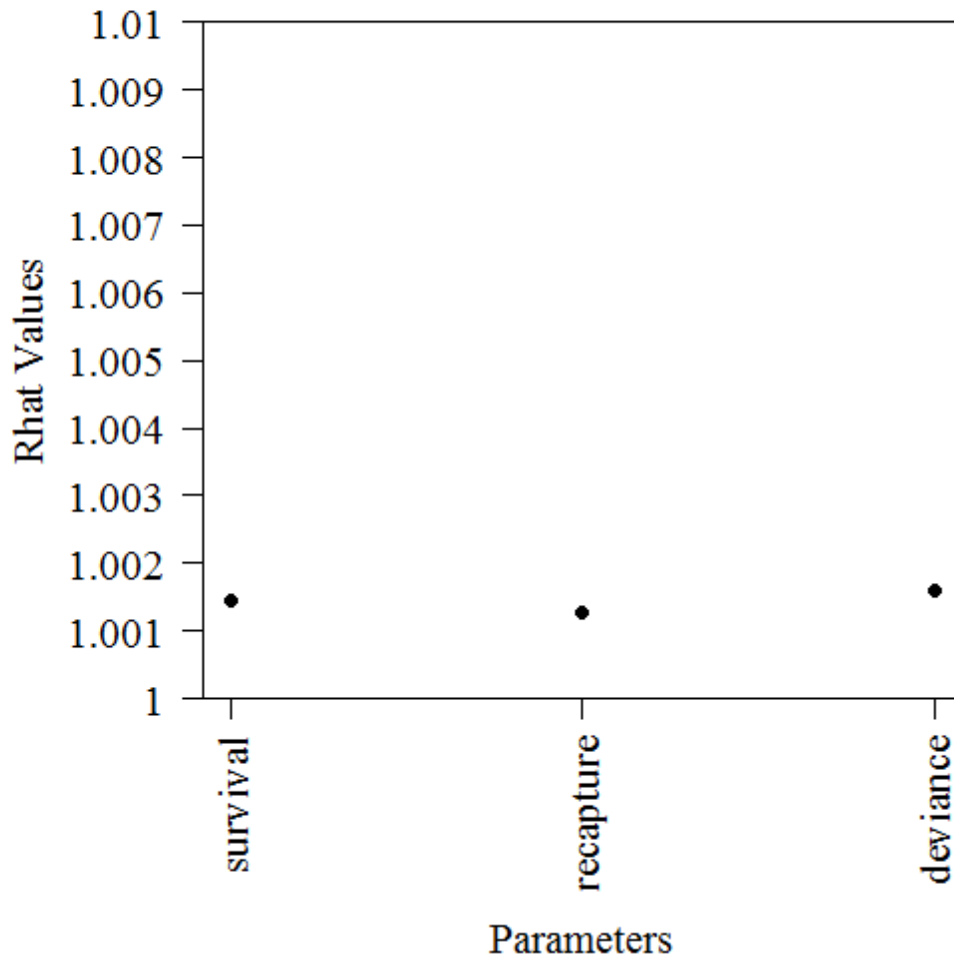


Figure 31. The Brooks-Gelman-Rubin (BGR) convergence diagnostic,  $\hat{R}$ , output for monthly 2017 Cormack-Jolly-Seber model parameters depicting brook trout survival and recapture probabilities within the West Branch of the Wolf River, Wisconsin. Values close to one suggest convergence, while values  $>1.1$  suggest convergence was not met.