Distribution and Summer Habitat Use of Bodie Bass in Lake Norman, NC

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Kelsey Roberts
Lawrence Dorsey
Powell Wheeler
Casey Joubert

North Carolina Wildlife Resources Commission
Inland Fisheries Division
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Abstract. Hybrid Striped Bass (*Morone chrysops x M. saxatilis*), or Bodie Bass as they are officially named in North Carolina, are a popular alternative to stocking Striped Bass (*M. saxatilis*) in reservoirs in North Carolina and across the Southeast due to their fast growth and higher temperature tolerance. Despite their popularity, little is known about their summer habitat use and seasonal distribution in NC reservoirs. In this study, Bodie Bass were implanted with depth and temperature-enabled Innovasea V9TP–2x coded acoustic transmitters and Lotek MCFT2–3FM coded radio transmitters in 2020 (n = 50) and 2021 (n = 64). Passive Innovasea VR-2KW receivers (n = 44) were used to continuously monitor fish locations, depth (m), and temperature (˚C) throughout Lake Norman, a cooling plant reservoir, from May 2020 to November 2022. Fish were manually located monthly during the fall, winter, and spring, and located weekly during peak summer stratification weeks (typically mid-July through August). Temperature and oxygen reservoir profile data and physical data recorded during manual tracking were used to determine

the temperature and dissolved oxygen tolerance range for this species in Lake Norman. Bodie Bass were in deeper water in the summer and winter months and shallower water in the fall and spring months. During the summer months, fish were widely distributed throughout the reservoir and were detected utilizing refuge areas, primarily in the mouth of the Catawba River in the upstream portion of the reservoir. The deep-water habitat located upstream of the dam was underutilized during the summer months. During the summer stratification period (July–August), fish were primarily detected using the epilimnion and avoided the metalimnion where a sub-set of fish exhibited diving behavior to access the hypolimnion. However, once oxygen in the hypolimnion fell below 1.5–2.0 mg/L, typically in July, detections in the hypolimnion decreased almost completely and fish sustained average weekly temperatures >27 ˚C September. The preferred temperature range of Bodie Bass in Lake Norman was estimated to be 21.1–24.5 °C. Bodie Bass appeared to prioritize preferred water temperatures in the early summer until dissolved oxygen became limiting. Bodie Bass then selected waters with dissolved oxygen concentrations >4.8 mg/L at the cost of higher water temperatures. In summary, high thermal tolerance and avoidance of the hypolimnion make Bodie Bass an excellent candidate for reservoirs where previous fish kills of Striped Bass or other top predators is a common occurrence.

Hybrid Striped Bass *Morone saxatilis* x *M. Chrysops*, officially named Bodie Bass in North Carolina, are a popular sportfish commonly stocked in reservoirs throughout the United States to provide unique opportunities for anglers. Bodie Bass have been stocked in North Carolina reservoirs since 1977 (NCWRC, personal communication) and are known to experience fast growth and thrive in warm, shallow, often eutrophic Southeastern reservoirs (Shultz et al. 2013). While Striped Bass *M. saxatilis* have historically been stocked more prevalently throughout the Southeast, Bodie Bass have become a popular alternative for management agencies due to their perceived robustness. Despite the popularity of Bodie Bass with anglers and fisheries managers alike, research has primarily focused on reservoir Striped Bass, and less is known about the habitat needs and seasonal distribution of Bodie Bass.

Landlocked Striped Bass are vulnerable to frequent fish kills in southeastern reservoirs due to their limited thermal tolerance, high metabolic needs, and feeding behavior. During summer, suitable habitat becomes limited when epilimnion water temperatures increase and cooler hypolimnion waters become hypoxic due to reservoir stratification. During stratification, Striped Bass seek refuge in the deeper, cooler, waters of the hypolimnion, which typically contains oxygenated water in early summer (Coutant 1985). As stratification intensifies the availability of cooler oxygenated water in the hypolimnion decreases as the metalimnion hinders mixing and fish passage. Trapped fish will continue to occupy this oxygen bubble in the hypolimnion as it slowly becomes hypoxic resulting in mortality or forced vertical movement into warm oxygenated waters (Coutant 1985; Rice et al. 2013). Consequently, Striped Bass populations in the Southeast often have poor growth or reduced body condition due to high metabolic needs (Thompson and Rice 2013), or suffer fish kills due to this well-documented "summertime oxygen squeeze" (Coutant 1985; Rice et al. 2013). Lake Norman, located in the Piedmont of North Carolina, was previously stocked with Striped Bass from the 1960s through 2012; however, due to poor growth and body conditions and frequent summer fish kills, the North Carolina Wildlife Resources Commission began stocking Bodie Bass in 2013. Since the introduction of Bodie Bass into Lake Norman there have been no Bodie Bass fish kills in the reservoir. In general, Bodie Bass stocked into the same system previously stocked with Striped Bass rarely suffer fish kills, yet the mechanism behind this avoidance is poorly understood.

The first potential mechanism is the higher thermal tolerance and preference of Bodie Bass. A higher thermal tolerance may allow Bodie Bass to physically avoid the summer oxygen squeeze in the hypolimnion by occupying warmer, more oxygenated water in the epilimnion. However, knowledge on the thermal tolerance and preferences of Bodie Bass is limited and varies widely (summarized in Table 1). Studies that have quantified vertical distribution of Bodie Bass in reservoirs during the summertime oxygen squeeze are even further limited (Kilpatrick and Ney 2013). In general, thermal selection appears to vary based on the geographical location of reservoirs as average summer temperatures occupied by Bodie Bass have ranged from 23.8 to 33.0 ˚C (Douglas and Jahn 1987, Kilpatrick and Ney 2013, Muncy et al. 1990, Piner 1993, Windham 1986). Overall, it is believed the preferred habitat for Bodie Bass in reservoirs includes temperatures ranging from 21.5 ˚C to 25.5 ˚C and dissolved oxygen (DO) greater than 4.5 mg/L (Kilpatrick 2003). In comparison, adult Striped Bass in reservoirs prefer temperatures less than 25.0 ˚C and DO concentrations above 4.0 mg/L (Coutant 1985; Coutant 2013; Table 2). While Striped Bass appear to select cooler waters during late summer stratification, Bodie Bass appear to prioritize water with higher DO content. This causes a vertical separation during summer stratification where Bodie Bass occupy shallower, warmer, and more oxygenated water compared to Striped Bass (Kilpatrick and Ney 2013). In previous studies, the average DO occupied by Bodie Bass in reservoirs during summer months ranged from 4.0–5.8 mg/L (Kilpatrick and Ney 2013; Windham 1986; Muncy et al. 1990; Piner 1993; Douglas and Jahn 1987). Though Striped Bass can occupy the oxycline (the area just above the thermocline) with minimal impacts to growth and survival (Thompson et al. 2010), Striped Bass may often be constrained to deeper water to satisfy thermal needs during late summer stratification. Thus, due to their stricter thermal needs, Striped Bass are at a higher risk of mortality during summer hypolimnetic hypoxia.

Summer horizontal distribution patterns may also contribute to the robustness of Bodie Bass, yet when compared to Striped Bass, very few studies on the distribution of Bodie Bass exist. Seasonal movement patterns of landlocked moronids are common as fish seek refuge during summer months, attempt spawning migrations, and exhibit seasonal feeding patterns. Primarily, during the summer Striped Bass and Bodie Bass in reservoirs have been shown to occupy deep cooler water, typically upstream of an impounded dam, or seek refuge areas near the mouths of creeks or tailraces during the summer (Douglas and Jahn 1987; Hoffman 2013; Kilpatrick and Ney 2013; Schaffler et al. 2002; Rabern 2022). Generally, Bodie Bass are present throughout the reservoir in spring and fall, occupying shallower water, and are closest to the dam during the summer months (Hoffman et al. 2013; Douglas and Jahn 1987; Kilpatrick and Ney 2013; Phalen et al. 1988; Rabern 2022). Bettinger (2015) found a similar pattern but found that Bodie Bass move into the lower reservoir later than Striped Bass. The higher thermal tolerance of Bodie Bass may affect their horizontal and temporal distribution patterns, allowing them to occupy refuge habitats that are not as suitable for Striped Bass during the summer.

Lastly, diet preferences may impact summer mortality events for moronids. The frequency of Striped Bass fish kills has increased in some reservoirs that have introduced clupeid populations such as Alewives (*Alosa pseudoharengus*) or Blueback Herring (*A. aestivalis*), collectively referred to as river herring. For example, in Lake Norman (the study site), Striped Bass fish kills became more common after river herring were introduced in the late 1990s. Prior to the introduction of river herring, Striped Bass fish kills were infrequent and small (i.e., <30 fish; Van Horn et al. 1996). Summer fish kills of Striped Bass in Lake Norman occurred annually from 2009 to 2012. In 2010, the fish kill resulted in almost 7,000 dead fish (McRae 2010). River herring concentrate in progressively deeper waters and in closer proximity to the intake of the McGuire Steam Station, located at the lower end of the reservoir, as summer stratification intensifies (Duke Energy, personal communication). When oxygen falls below 1.0 mg/L for a prolonged amount of time the river herring disappear from the hypolimnion (presumably from mortality or consumption) and Striped Bass utilizing them as a prey source get trapped in the diminishing oxygen bubble in the hypolimnion and suffer mortality (McRae 2010; Rice et al. 2013). Annual hydroacoustic fish surveys performed near the intake of Cowans Ford Dam on Lake Norman have documented the disappearance of prey species (presumably through mortality or consumption) when the hypolimnion becomes hypoxic (Duke Energy, personal communication). As Striped Bass have been shown to feed almost exclusively on clupeid species (when present) during summer months (Thompson et al. 2010), Striped Bass may prefer to follow clupeids deeper into the hypolimnion and become trapped when prey and oxygen disappear (McRae 2010; Rice et al. 2013). Alternatively, Bodie

Bass are more opportunistic feeders, consuming a wide variety of diet items throughout the year ranging from invertebrates to centrarchids, to gizzard shad (Olson et al. 2007). Yet, information on summer dietary and feeding behavioral differences between Bodie Bass and Striped Bass in reservoirs is lacking.

Overall, the technology used in previous research was limited to transmitters with temperature-only sensors resulting in estimated depth estimates. Current telemetry technology includes transmitters with depth and temperature sensors which will help to confirm and augment previous research on the horizontal and vertical seasonal distribution of Bodie Bass in reservoirs. The goals of this project were to: 1) evaluate seasonal horizontal and vertical distribution and 2) estimate the physical tolerances of Bodie Bass to aid in the management of stocked populations in North Carolina reservoirs.

Methods

Study site. Lake Norman is a 13,516–ha reservoir impounded on the mainstem of the Catawba River in 1963 in the Piedmont region of North Carolina. The reservoir is operated as a cooling impoundment for two Duke Energy Corporation (DEC) hydropower generating facilities (McGuire Nuclear Station and Marshall Steam Station) and receives heated effluent from those facilities. The reservoir is categorized as oligotrophic (DEQ 2023). Most of the shoreline is heavily developed with residential housing communities and piers, riprap, and bulkhead seawalls are the predominant shoreline structures. Aquatic cover such as woody debris and vegetation is limited. Lake Norman contains several other species of interest to anglers including Largemouth Bass Micropterus salmoides, Alabama Bass M. henshalli, Striped Bass *Morone saxatilis*, White Bass *M. chrysops*, Crappie *Pomoxis spp.*, Blue Catfish *Ictalurus furcatus*, Channel Catfish *I. punctatus*, and Flathead Catfish *Pylodictus olivaris*. Lake Norman is currently stocked with 325,000 Bodie Bass fingerlings, at a rate of 25 fish/ha. Bodie Bass in Lake Norman are managed by the state-wide Striped Bass and Bodie Bass regulation where 4 fish in combination over 508 mm (20 in) may be possessed.

For most analyses in this study, receivers were assigned to four large reservoir zones: Lower Forebay Zone, Upper Forebay Zone, Middle Zone, and Upper Zone, where each zone contained a varying number of receivers (Figure 1; Appendices A.1 and A.2). The Upper Zone begins at the mouth of the Catawba River and is comprised of shallow, flowing water and some undeveloped shoreline and extends to HWY 150. The Upper Zone also contains deeper water in the main river channel of the reservoir and several tributaries including Hicks Creek, Rocky Creek and Stumpy Creek. The Middle Zone is mostly comprised of the main river channel and contains several tributaries including Mountain Creek and McCrary Creek. The Middle Zone also receives heated effluent from the Marshall Steam Station. The Upper Forebay Zone includes Little and Davidson creeks. Finally, the Lower Forebay Zone includes the deepest portions of the reservoir near the dam as well as Ramsey Creek. The Lower Forebay receives heated effluent from the McGuire Nuclear Station. Trophic status and productivity decrease from the Upper Zone down toward the Lower Forebay Zone (Duke Energy 2023). As a result, Lake Norman exhibits a longitudinal trend where the relative abundance of sportfish and consequently angler catch rates decrease from the Upper Zone toward the Lower Forebay Zone (Siler et al. 1986).

For the distribution analyses, the zones were further divided into smaller reservoir areas that contained one or more receivers representing similar habitats or tributaries. As an example, the Lower Forebay Zone contains five reservoir areas. One of the reservoir areas, Ramsey Creek, contained three receivers (Appendices A1.1–1.2). In summary, the four reservoir zones were used for the depth, temperature, and DO analyses whereas the smaller reservoir areas within each zone were used to illustrate distribution patterns.

Tagging. Bodie Bass were surgically implanted with Innovasea (Innovasea, Nova Scotia, Canada) coded acoustic V9TP–2x (9 x 31 mm; 4.9 g) and Lotek (Lotek, Newmarket, Canada) MCFT2–3FM coded radio telemetry transmitters (11 x 59 mm; 4.6 g) in May 2020 (n = 50) and May 2021 (n = 64). The acoustic tags relayed temperature (˚C) and depth (m) information with each detection. All fish were captured using hook and line and transferred via a livewell to the tagging and release location. Fish were first anesthetized using a "knock out" dosage of 40 mg/L of Aqui–s 20E and anesthetization was maintained using a dosage of 20 mg/L during surgery. All fish were weighed (g) and measured (mm) after anesthetization and before being placed on the surgery board. Then, following procedures outlined in Murray (2002), surgery was performed by first inserting the radio telemetry tag followed by the acoustic tag through an incision posterior just below the pelvic fins. Using a similar procedure as described in Owensby (2017), the radio tag antenna was threaded through the intracoelomic cavity and exited posterior of the incision of the fish using a stainless–steel catheter and needle. Incisions were closed using two or three 3–0 interrupted monofilament synthetic absorbable sutures with a 3/8 circle reverse cutting needle. The total tag weight did not exceed 2% of the fish's body weight. Lastly, an external Floy (Floy, Seattle, WA) T–bar tags labeled with contact information and "do not harvest" was inserted into the musculature below the dorsal fin using a tagging gun. Fish recovered in a live pen and were released once recovery was observed and fish were swimming upright. Fish were released from a single location in 2020 and multiple locations in 2021. Capture and release locations were not recorded for individual fish.

Water Quality. Dissolved oxygen (DO; mg/L) and temperature (˚C) reservoir profiles were obtained from Duke Energy and the North Carolina Department of Environmental Quality primarily during summer months at various standard locations throughout the reservoir from 2020–2022 (Figure 1; Appendix A.3). Dissolved oxygen and temperature were recorded at the surface and then at every meter beginning at approximately 1.0 m below the surface and continuing to 1.0 m above the bottom of the reservoir for each profile.

Fish Tracking. A combination of active and manual tracking was used to relocate fish. Radio transmitters allowed faster manual tracking whereas acoustic transmitters allowed continuous passive monitoring. From May 2020–November 2021 an array of passive Innovasea VR-2KW receivers (n = 44) were used to continuously locate fish (Figure 1). Two receivers were placed downstream of the Cowans Ford Dam to detect emigration. A receiver was also placed in the heated effluent release zones of the McGuire Nuclear Station and Marshall Steam Station. Receivers were maintained and downloaded at least monthly during the fall, winter, and spring and weekly during the summer months. Fish were manually located using a boat-mounted radio receiver while traveling along the shoreline and mid-channel habitats of the reservoir. When a tag was detected an Innovasea VR-165 omnidirectional hydrophone was used to determine the general location of the fish and transmitter depth (m), and temperature (˚C) were recorded. Exact locations were not determined due to time constraints and the high recreational use of the reservoir interfering with precise detections. Tagged fish were located monthly except during mid-July through August when weekly location efforts were conducted. During weekly tracking efforts, DO (mg/L) was also recorded at the depth fish were located. Monthly and weekly active tracking aided in finding fish that had died outside of the receiver ranges and in assigning individual fates of fish between months.

Data Analysis. Detections up to two weeks post-surgery were censored from data analysis to account for any surgery-related movement biases (Wilson et al. 2016). Fish that appeared to have died due to surgery or natural mortality (i.e., located on the bottom of the reservoir indefinitely) were censored from data analysis beginning one day after the assigned death date. In 2021, four acoustic tags used in 2020 that were retrieved after suffering natural or surgery–related mortalities were implanted into new fish in 2021. After censored fish were removed, depth and temperature recordings were paired. This was necessary as receivers recorded depth (m) and temperature (˚C) of individual acoustic tags at separate intervals. Thus, 1,196,565 depth observations and 1,197,400 temperature observations were stored in a data set with 2,393,965 rows. To synchronize depth and temperature recordings, an algorithm in the R programming language (R Core Team 2024) was created to convert the distinct observations into a data set of paired observations. The algorithm found the most synchronic temperature observation for each depth observation for each fish and produced a data set of paired observations. Any paired observations that were greater than 8 minutes apart or were detected on receivers that were $\geq$1,500 m apart were removed. If there was a tie for the most synchronic temperature observation, a match was chosen randomly. For example, if there was a temperature observation two minutes before and two minutes after the depth observation, the best match was chosen randomly.

To estimate DO concentrations at each location where a Bodie Bass was detected, a second algorithm matched the paired temperature and depth observations to DO observations from the water quality profiles. Paired temperature and depth observations that were recorded at the same receiver station were then matched with water quality measurements recorded within 1,500 m of the acoustic receiver and within 3 days of the paired observation. The best match was determined first by the proximity of the water quality profile to the acoustic receiver and secondly by synchronicity. Water quality profile observations were recorded at depth increments $\geq$1 m whereas the acoustic tags reported fish depth with sub-meter resolution, therefore a linear interpolation was used to estimate the DO concentration between water quality profile observations directly above and below the exact fish depth. Several key R packages were used during analyses including Geosphere (Hijmans R. 2024) for calculating distances between receivers, ggplot (Wickham 2016) to graph Figures 8–9, and NCIFD for data wrangling (Wheeler et al. 2023).

Paired detections were then used to estimate monthly and weekly average depth (m) and temperature (˚C) each year and for all years pooled. To evaluate differences between zones, some of these estimates were further subdivided into the four reservoir zones. Monthly quartiles for temperature (˚C) were used to estimate thermal tolerances. The two receivers at the heated effluent zones were excluded in this analysis to limit any biases associated with the higher temperatures in those areas. Lastly, paired detections that included dissolved oxygen data from the receivers in the lower three zones (Lower Forebay Zone, Upper Forebay Zone, Middle Zone) were used to calculate monthly average and quartile ranges of DO concentrations during summer months (June–August) annually. Due to missing data in some years, DO values from the Upper Zone were not used. In addition, monthly average DO was calculated from manual tracking data across the entire reservoir during summer months. Lastly, to evaluate distribution, the lake was divided into smaller reservoir areas and the weekly percentage of paired detections at each reservoir area was estimated for each year and for all years pooled. The function "weeknum" in Microsoft Excel was used to assign a week number to each detection date.

Results

Tagging and Fish Tracking. Fish tagged in 2020 (n = 50) weighed on average 1,526 g and had an average length of 491 mm. Fish tagged in 2021 (n = 64) weighed an average of 1,720 g and had an average length of 520 mm. The original capture locations of individual fish were not recorded. There were an estimated 13 (26%) surgery-related mortalities in 2020 and 13 (20%) in 2021. After censoring mortalities, 1,196,565 depth observations and 1,197,400 temperature observations resulted in a data set with 2,393,965 detections from May 2020 to November 2022. Syncing temperature and depth detections resulted in 1,022,813 paired detections. A minimum of 106 active tracking days were completed resulting in 754 re-locations of tagged fish. After censoring mortalities and incomplete records there were 348 re-locations recorded during June through August (2020 = 99; 2021 = 192; 2022 = 25). Only one fish emigrated out of Lake Norman through Cowans Ford Dam. Survival of the emigrated fish is unknown as it was detected on two receivers downstream of Cowans Ford Dam in March and April of 2022 before disappearing.

Water quality. A total of 44,711 paired depth and temperature detections from receivers were also paired with DO concentrations from reservoir profile data, 27,148 of which included DO data in the lower three zones during peak summer months (June–August). All water quality stations were used in pairing physical data with detections; however, station 1.0 (near the Cowans Ford Dam) was the only station consistently sampled for all three years of the study during summer months. Comparisons of DO between zones and stations was not possible due to the lack of consistent water profile data collected from the three upper zones. The onset of stratification in the Lower Forebay Zone varied interannually, but generally DO below the thermocline fell below 4.0 mg/L by early to mid–July. The Lower Forebay Zone did exhibit an oxygen bubble below the thermocline where DO concentrations increased and DO in this bubble typically fell below 1.0 mg/L in late July or August.

Horizontal Distribution. Overall, Bodie Bass used the entire reservoir, but some seasonal patterns were identified. Primarily, fish were detected in the Mouth of the Catawba reservoir area during weeks 15–20 (i.e., April to mid-May) in all three years (Figure 2). The percentage of total detections in the Upper Zone reservoir areas closest to the mouth of the Catawba River (i.e., Mouth of the Catawba, Upper Lake Channel, Upper Lake Creek) peaked during week 17 (i.e., late April) accounting for 59% of all detections (Figure 2). During calendar weeks 15–20, or early April through mid-May (i.e., the duration fish were detected in the Mouth of the Catawba reservoir area) average weekly transmitter temperatures pooled from 2021 and 2022 ranged between 15.2 ˚C (week 15) and 18.6 (week 20). Fish were minimally detected in the Mouth of the Catawba reservoir area after week 20 (i.e., detections in this area accounted for <1.0% of the total detections for that week).

During weeks 21–25 (i.e., late May to mid-June), tagged fish were detected throughout the entire reservoir; however, most detections occurred in the Davidson Creek (Upper Forebay Zone) and Mid Lake Channel (Upper Forebay and Middle Zone) reservoir areas (Figure 2–3). As summer progressed, detections in the Mouth of the Catawba reservoir area (Upper Zone) and in Ramsey Creek and Dam reservoir areas (Lower Forebay Zone) increased. The timing of increased detections between reservoir areas varied slightly occurring during weeks 26–34 (i.e., late June through August) in the Dam reservoir area, weeks 22–31 (i.e., mid-May through July) for the Ramsey Creek reservoir area, and weeks 25–39 (i.e., mid-June through September) for the Mouth of the Catawba reservoir area (Figures 2–3). Aside from the weeks above, detections in the Dam and Ramsey Creek reservoir areas within the Lower Forebay Zone were low, especially compared to other reservoir areas, and these areas appeared to only be utilized in the summer (Figures 2–3). During weeks 40–53 (i.e., October to December) and weeks 1–13 (i.e., January to March) fish were widespread and detections in the tributary creeks increased. For example, detections in the Mountain Creek reservoir area increased around week 40 (i.e., early October) and remained high through week 10 (i.e., early March; Figures 2–3).

Interannual variations in reservoir area use also occurred. For example, detections in the Davidson Creek reservoir area increased beginning in week 1 (i.e., January) and peaked during week 10 (i.e., early March) in 2022, just before the spawning run, but this pattern was not observed in 2021 (Figure 3). Detections in the Davidson Creek reservoir area accounted for 50% of all detections during week 10 in 2022. Overall detections in the Mountain Creek reservoir area were also higher in 2020 and 2021 compared to 2022. In general, the Davidson Creek and the Mid Lake Channel reservoir areas consistently had the highest percentage of detections overall. The use of the heated effluent areas was low (≤1% of total monthly detections) during all months at both stations.

Vertical Distribution. The average depth of detections varied monthly. The average monthly depth was shallower during the spring (March–May) and fall months (September–October) and deeper during the summer (June–August) and winter (December–February) months (Table 3; Figures 4–5). The average monthly depth of detections was the shallowest in April (2.2 m; SE = 0.01). As water temperatures warmed some fish were detected in deeper cooler water, yet most detections remained in the epilimnion (<10 m). The average depth of detections was the deepest in June (7.9 m; SE = 0.01) and July (7.9 m; SE = 0.01). By August, the average depth of detections decreased (6.2 m; SE = 0.01) and almost all detections occurred in the epilimnion. The average monthly transmitter depth and temperature also varied by zone, where fish detected in the Lower Forebay Zone were detected in deeper cooler water compared to other zones during the summer (Tables 3–4). In the Lower Forebay Zone, the average monthly depth was deepest in June (10.0 m; SE = 0.04) and July (10.8 m; SE = 0.04; Table 3), allowing fish to occupy colder water than the other three zones during those months (Table 4). The average monthly depth of detections varied slightly between years (Appendix A.4).

Because the vertical shift from peak depth usage to shallower water typically occurred mid-July, the weekly average depth of transmitters was also estimated. Peak weekly depth varied interannually occurring in-mid July during week 28 (9.7 m; SE = 0.06) in 2020, week 26

(9.5 m; SE = 0.03) in 2021, and week 27 (9.1 m; SE = 0.07) in 2022 (Figure 5). Peak average depth, and consequently transmitter temperature, also varied by reservoir zone. Mainly, fish were detected in deeper cooler water in the Lower Forebay Zone during the summer weeks (Figure 6). In the Lower Forebay Zone peak average weekly depth occurred during week 32, or early August, in 2020 (17.8 m; SE = 0.03), week 26, or late June, in 2021 (11.4 m; SE = 0.07), and week 27, or early July, in 2022 (12.5 m; SE = 0.12; Figure 6). As a result, transmitter temperatures from the Lower Forebay Zone were on average 8.9, 3.2, and 4.7 ˚C lower than detections in the remaining three zones during the weeks of peak depth in the Lower Forebay Zone in 2020, 2021, and 2022, respectively (Figure 7).

Hypolimnion use during summer, though limited, was most evident in the Lower Forebay Zone, but also occurred in the Upper Forebay and Middle Zones (Figures 8–9). To further assess the relationship between the vertical distribution of fish and DO during the summer, the depth of paired detections from the Dam and Lower Lake Channel reservoir areas within the Lower Forebay Zone were compared to DO data from Station 1.0 (the station closest to Cowans Ford Dam). Most Bodie Bass detections occurred in the epilimnion (>10 m of water), and fish generally avoided the metalimnion from June through August (i.e., during summer stratification; weeks 26–33; Figure 10). During this time, a subset of detections can be seen using the zone just below the metalimnion where oxygen increases (Figure 10). However, as stratification intensifies, and oxygen falls below 1.5 or 2.0 mg/L a shift occurs and detections in the hypolimnion greatly reduce (Figure 10). Hypolimnion use was more limited in 2021 and this shift is less pronounced. Fish also made quick dives into the hypolimnion (see Appendix A.6 for examples) during the early summer, a behavior that was also greatly reduced when DO concentrations in the hypolimnion fell below 1.5–2.0 mg/L. Fish that did not emigrate after this threshold was reached typically suffered mortality (see Appendix A.6 for an example). The frequency or duration of time spent at depth during these vertical migrations was not estimated.

Dissolved Oxygen and Temperature Tolerance. Pooled transmitter temperature data from all three years were used to determine temperature ranges during the summer months. The middle 50% of transmitter temperatures throughout the entire reservoir increased as summer progressed ranging from 21.1 to 24.5 ˚C in June (average = 22.5 ˚C; SE = 0.01), 25.6 to 28.1 ˚C in July (average = 26.1 ˚C; SE = 0.01), and 27.2 to 28.7 ˚C in August (average = 27.8 ˚C; SE = 0.01; Table 4). In August, 95% of detections were below 29.7 ˚C. Pooled average weekly transmitter temperatures peaked mid-August during week 33 in 2020 (27.5 ˚C; SE = 0.03), 2021 (28.2 ˚C; SE = 0.01), and in 2022 (29.0 ˚C; SE = 0.02; Figure 5). The average monthly transmitter temperatures varied by year and zone (Appendix A.5).

Paired detections with DO values from the lower three zones (Middle, Upper Forebay, Lower Forebay Zones; *n* = 27,148) were used to assess DO occupation during the summer months (June–August). Average DO from detections varied by zone, month, and year (Table 5). Fish in the lower three zones occupied the most oxygenated water in June (50^{th} quartile = 5.4–8.4 mg/L; average = 7.3 mg/L; SE = 0.06) and the least oxygenated water in July (50^{th} quartile = 2.0–5.3 mg/L; average = 3.7 mg/L; SE = 0.03; Figure 11). As fish utilized shallower water in late summer (August), the DO from detections increased (50^{th} quartile = 4.8–6.9 mg/L; average = 5.6 mg/L; SE = 0.01; Figure 11). The detections from the Lower Forebay Zone had the lowest average DO in July (50^{th} quartile = 1.9–3.1 mg/L; average = 2.9 mg/L; SE = 0.03) and DO in the

Lower Forebay Zone was lowest in July 2020 compared to 2021 and 2022 (Table 5). Most paired detections (95%) located on receivers in the lower three zones were recorded at DO concentrations greater than or equal to 1.3 mg/L in July and greater than or equal to 1.6 mg/L in August. Most fish (95%) located during active tracking in summer months (June–August) throughout the entire reservoir were detected at DO concentrations greater than 2.0 mg/L and the middle 50th quartile ranged from 4.5–6.4 mg/L. Average DO from active tracking re-locations was also lowest in July (4.9 mg/L; SE = 0.2).

Discussion

This is the first study to use transmitters with depth and temperature sensors to track the seasonal distribution of Bodie Bass in a Southeastern reservoir. Bodie Bass horizontal and vertical distribution exhibited seasonal patterns that varied interannually. Use of the Lower Forebay Zone (the reservoir zone closest to the dam) was low overall and only increased during the early summer. This is similar to other studies that have shown increased use of the lower zones in reservoirs during summer (Hoffman et al. 2013; Bettinger 2015); however, the extent of Bodie Bass use of the Lower Forebay Zone and deeper habitats appeared less pronounced in this study. Overall, their limited use of the Lower Forebay Zone in the summer in Lake Norman appears to be a key difference compared to the previous distribution patterns of Striped Bass in Lake Norman (Van Horn et al. 1996), and in other reservoirs (Bettinger 2015; Schaffler et al. 2002). Like Striped Bass (Bettinger 2015; Rabern 2022) and Bodie Bass (Bettinger 2015; Hoffman et al 2013) in previous studies, Bodie Bass in Lake Norman also appeared to seek refuge during late summer in major creeks, mainly the mouth of the Catawba River in Lake Norman. These refuge areas are likely popular due to flow, oxygen availability, or increased prey availability. Similar to observations of Striped Bass (Bettinger 2015) and Bodie Bass (Hoffman et al. 2013) in previous studies, Bodie Bass in Lake Norman used the mouths of creeks more frequently in the spring and fall. Increased detections in the Mouth of Catawba River reservoir area during the spring were likely a result of attempted spawning runs, which have been documented in previous studies (Phalen et al. 1988; Kilpatrick 2003). The transmitter temperature range during the estimated “spawning run” (15.2–18.6 ˚C) provides insight into when spawning migrations may occur for Bodie Bass, which is information currently lacking in the literature. Overall, results from this study suggest that while some seasonal horizontal distribution patterns of Bodie Bass are similar to Striped Bass; distribution patterns likely vary based on reservoir-specific factors, such as depth, prey availability, refuge availability, and interannual variations in weather and limnological patterns.

While Bodie Bass and Striped Bass may exhibit similar horizontal distribution patterns, differences in vertical distribution, especially during summer months, between the two species may be a key mechanism responsible for the increased survival of Bodie Bass. Seasonal vertical distribution patterns were observed in this study, primarily a major vertical shift toward shallower water occurred mid-to late-summer. Water temperatures appeared to drive early summer vertical distribution whereas DO appeared to drive late summer vertical distribution for tagged Bodie Bass. In June, fish actively sought deeper, cooler water and the middle 50% of detections (21.1–24.5 °C) were within the preferred temperature range of Kilpatrick and Ney (21.5–25.5 °C; 2013). Thus, when DO was not a limiting factor (i.e., >4.5 mg/L) Bodie Bass selected cooler water within their preferred temperature range. By July, fish occupied water with less than preferred DO concentrations to continue to select for cooler water. For example, in July the middle 50% of detections had DO concentrations of 2.0–5.3 mg/L and an average DO concentration of 3.7 mg/L which is lower than the previously estimated preferred dissolve oxygen concentration (>4.5 mg/L; Kilpatrick and Ney 2013; Windham 1986; Muncy et al. 1990; Piner 1993; Douglas and Jahn 1987). Though the average temperature of detections in July (26.1 °C) exceeded the preferred temperature range, fish in the Lower Forebay Zone achieved an average water temperature (23.3 °C) within the preferred range. However, typically during late-July or early-August, when the DO in the hypolimnion fell below a threshold, tagged fish selected for warmer water outside of their preferred range for more oxygenated water. For example, in August, the average temperature of all detections (27.8 °C) and detections only within the Lower Forebay Zone (27.2 °C) exceeded their maximum preferred temperature. Whereas the middle 50% of detections had DO concentrations (4.8–6.9 mg/L) were well within the preferred range of >4.5 mg/L. In comparison, Striped Bass have been shown to have <1 month survival at temperatures >27.0 °C (Table 2) and Bodie Bass in this study occupied temperatures greater than 26 °C (i.e., warmer than the preferred temperature range of Striped Bass) during late July through September. This increased thermal tolerance allows Bodie Bass to vertically separate from Striped Bass, as seen by Kilpatrick and Ney (2013), and avoid fish kills during the critical summertime oxygen squeeze.

Another driver of vertical distribution patterns is prey availability and preference. In one eutrophic reservoir when oxygen in the hypolimnion became hypoxic, Striped Bass occupied the oxycline (or the area just above the thermocline) with minimal impacts to growth and survival (Thompson et al. 2010). Thompson et al. (2010) also found that Striped Bass fed almost exclusively on pelagic clupeid species during the summer, despite other prey availability. In an oligotrophic system like Lake Norman, the diet preferences of Striped Bass and limited prey availability may impact the feeding behavior of Striped Bass by forcing them to follow prey into the hypolimnion when conditions are not ideal. Bodie Bass are more opportunistic feeders and likely only opportunistically forage on clupeids in the hypolimnion during the summer as their diving behavior ceased when the prey species occupying the hypolimnion were no longer detected on hydroacoustic surveys. In contrast, Striped Bass have been shown to "porpoise" in the opposite direction, making quick trips to the lower epilimnion for relief from the limited oxygen in the hypolimnion (Rabern 2022). The increased thermal tolerance, opportunistic diets, and diving behavior allow Bodie Bass to make vertical shifts before prey and oxygen become unavailable in the hypolimnion and reduce prolonged exposure to the hypoxic water in the hypolimnion. Future bioenergetic studies focusing on the differences and changes in diet of both species during critical summer weeks would help to further understand how diet preferences contribute to increased survival of Bodie Bass in the summer.

In this study, we also identified general habitat preferences and physical tolerance ranges for Bodie Bass. In June, when DO was not a limiting factor in the hypolimnion (i.e., <4.5 mg/L), the preferred temperature range of Bodie Bass in Lake Norman was 21.1–24.5 °C which was almost identical to the range reported in Kilpatrick and Ney (2013) of 21.5–25.5 ˚C and also aligned with ranges determined in other studies (summarized in Table 1). The suggested preferred temperature range found in this study is higher than the preferred temperature range of Striped Bass (summarized in Table 2). Like Kilpatrick and Ney (2013), in late July and

August when DO concentrations were a limiting factor in the hypolimnion (i.e., below 1.5–2.0 mg/L), Bodie Bass occupied water temperatures greater than 26 ˚C. The upper thermal tolerance of these fish appeared to be between 29.2 and 29.6 ˚C (the temperature at which 95% of detections were observed in July and August), which is in the range of the thermal maximums found by Piner (1993; 27.1–32.0 ˚C). When selecting water with higher DO concentrations in August, the preferred DO range was 4.8–6.9 mg/L which supports previous findings that DO concentrations >4.5 mg/L are preferred by Bodie Bass (Table 1). Not unlike Striped Bass, DO concentrations below 2.0 were largely avoided (Kilpatrick and Ney 2013). However, this study indicates that Bodie Bass might be more tolerant of minimum DO levels than previously thought. Our findings suggest that the DO threshold for Bodie Bass in Lake Norman is likely between 1.3 and 1.6 mg/L as 95% of detections were observed above these DO concentrations of in July and August, respectively. While the oxygen demands for both species are thought to be similar, Bodie Bass in this study appear to utilize and survive in water with less than 2.0 mg/L of DO. However, the extent of the use of low-oxygenated water was not analyzed in this study and the length of time spent at depths with low oxygen is not known.

Though the data collected in this study was substantial and produced an impressive and robust dataset, there were a few limitations. First, the reservoir profile data was limited and varied in frequency based on station location and year. This reduced the number of detections capable of being paired with physical data. Ultimately, the thermal and DO tolerance estimates could be improved in future studies by conducting weekly reservoir profiles at fixed stations throughout the entire reservoir during summer months. Also, active tracking was mainly useful in identifying and locating mortalities, and recovering transmitters, but could have been improved by recording temperature and DO profiles at observed fish locations or at receiver stations. This would have allowed us to determine available habitat and habitat selection during the summer. Secondly, site affinity or differences in distribution and habitat use could have been distinguished if the capture location of each fish was originally recorded. Previous research has documented high angler catch rates near the Marshal Steam Station in Lake Norman (Commission, unpublished data), yet this study revealed little use of that area in any season. This difference may be due to the capture and release locations of tagged fish as differences in habitat selection based on capture location for Striped Bass have been found (Bettinger 2015; Jackson and Hightower 2001).

Overall, it appears that differences in fish physiology (i.e., thermal preferences), feeding behavior, and diet preferences all contribute to the differences observed between Striped Bass and Bodie Bass summer survival in Lake Norman. This study provided vertical and horizontal distribution data for Bodie Bass over three summers and demonstrated that Bodie Bass are an excellent candidate for biologists wanting to stock temperate bass species when suitable habitat is limited for Striped Bass. Their high thermal tolerance and behavioral advantages, allow managers ample options for stocking. Where it was previously believed Bodie Bass had similar physical habitat requirements as Striped Bass, this study demonstrates that Bodie Bass can generally survive and even thrive in shallower warmer water for prolonged periods, and are thus, not as limited by suitable summer habitat availability.

Management Recommendations

1. Continue to stock Bodie Bass in Lake Norman at the current rate of 25 fish/ha. Monitor changes in the population every 3–5 years.
2. Maintain the current regulation on Lake Norman and consider a no–culling regulation to reduce summer mortality.
3. Use telemetry data to estimate monthly mortality, quantify vertical movement patterns, and build a model to test for significant differences in vertical and temporal distribution patterns.

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This project was no simple task and required long hours and devotion from many NCWRC employees including but not limited to Lawrence Dorsey, Corey Oakley, Casey Joubert, Rick Bradford, Troy Thompson, Seth Mycko, David Belkoski, and Carson Pope. We would not have been able to capture and tag fish as easily as we did without the help of Kim Baker and his selfless dedication to this project. A special thanks to Duke Energy for purchasing the radio tags which allowed biologists to locate individual fish more easily.

References

Bettinger, J. M. 2015. Striped Bass distribution and habitat use in J. Strom Thurmond Reservoir, South Carolina – Georgia, South Carolina Department of Natural Resources, Federal Aid in Sport Fish Restoration, Final Report, Columbia, South Carolina.

DEQ. 2023. Lake and reservoir assessments; Catawba River Basin. Division of Environmental Quality, Monitoring Report, Raleigh, North Carolina.

Coutant, C. C. 1985. Striped Bass temperature and dissolved oxygen: a speculative hypothesis for environment risk. Transactions of the American Fisheries Society 114:31–61.

Douglas, D. R., and L. A. Jahn. 1987. Radiotracking hybrid Striped Bass in Spring Lake, Illinois, to determine temperature and oxygen preferences. North American Journal of Fisheries Management 7:531–534.

Duke Energy. 2023. Lake Norman maintenance monitoring program: 2021 summary. Duke Energy Corporation, Charlotte, NC.

Hijmans, R. (2024). _geosphere: Spherical Trigonometry_. R package version 1.5-20, <https://CRAN.R-project.org/package=geosphere>

Hoffman, K. J., D. S. Kittaka, and B. M. Schoenung. 2013. Evaluation and management of hybrid Striped Bass in Monroe Lake, Indiana. Pages 313–312 *in* J. S. Bulak, C. C. Coutant, and J. A. Rice, editors. Biology and management of inland Striped Bass and hybrid Striped Bass. American Fisheries Society Symposium, 80, Bethesda, Maryland.

Jackson, J. R., and J. E. Hightower. 2001. Reservoir Striped Bass movements and site fidelity in relation to seasonal patterns in habitat quality. North American Journal of Fisheries Management 21:34–45.

Jones, M. S., and K. B. Rogers. 1998. Palmetto Bass movements and habitat use in a fluctuating Colorado irrigation reservoir. North American Journal of Fisheries Management 18:640–648.

Kilpatrick, J. M. 2003. Habitat use, movements, and exploitation of Striped Bass and hybrid Striped Bass in Claytor Lake, Virginia. Master's Thesis. Virginia Polytechnic Institute and State University, Blacksburg, Virginia.

Kilpatrick, J. M., and J. J. Ney. 2013. Temperature and dissolved oxygen habitat use by Striped Bass and hybrid Striped Bass in Claytor Lake, Virginia. Pages 147–159 *in* J. S. Bulak, C. C. Coutant, and J. A. Rice, editors. Biology and management of inland Striped Bass and hybrid Striped Bass. American Fisheries Society Symposium, 80, Bethesda, Maryland.

McRae, B. 2010. Lake Norman Striped Bass mortality event. North Carolina Wildlife Resources Commission, Federal Aid in Sport Fish Restoration, Project F–68–04, Summary Report, Raleigh.

Muncy, R. J., R. A. DeMauro, L. E. Miranda, and P. S. Phalen. 1990. Habitats used by radio–tagged adult hybrids in Ross Barnett Reservoir. Mississippi Cooperative Fish and Wildlife Research Unit, Completion Report, Federal Aid to Fisheries Project F–82–1, Mississippi State.

Olson, N. W., C. S. Guy, K.D. Koupal. 2007. Interactions among Three Top-Level Predators in a Polymictic Great Plains Reservoir. North American Journal of Fisheries Management 27:268–278.

Owensby, D. P., J. A. Rice, D. D. Aday. 2017. Mortality, dispersal, and habitat use of stocked juvenile Muskellunge in two western North Carolina rivers. North American Journal of Fisheries Management 37:108–121.

Phalen, P. S., R. J. Muncy, T. K. Cross. 1988. Hybrid Striped Bass movements and habitat in Ross Barnett Reservoir, Mississippi. Proceedings of the Annual Conference of Southeastern Association of Fish and Wildlife Agencies 42:35–43.

Piner, K. R. 1993. Seasonal distribution of hybrid Striped Bass in a power–plant reservoir and a comparison to Red Drum. Master's thesis. Texas A&M University, Galveston, Texas.

R Core Team (2024). _R: A Language and Environment for Statistical Computing_. R Foundation for Statistical Computing, Vienna, Austria. <https://www.R-project.org/>.

Rabern, A. 2022. Georgia Department of Natural Resources, Federal Aid in Sport Fish Restoration, Final Report, Social Circle, Georgia.

Rice, J. A., J. S. Thompson, J. A. Sykes, C. T. Waters. 2013. The role of metalimnetic hypoxia in Striped Bass Summer Kills: consequences and management implications. Pages 121–145 i*n* J. S. Bulak, C. C. Coutant, and J. A. Rice, editors. Biology and management of inland Striped Bass and hybrid Striped Bass. American Fisheries Society Symposium, 80, Bethesda, Maryland.

Shultz, R. D., J. M. Goeckler, M. C. Quist. 2013. Comparisons of growth for hybrid Striped Bass in North America. 2013. Pages 219–227 *in* J. S. Bulak, C. C. Coutant, and J. A. Rice, editors. Biology and management of inland Striped Bass and hybrid Striped Bass. American Fisheries Society Symposium, 80, Bethesda, Maryland.

Siler, J. R., W. J. Foris, and M. C. McInerny. 1986. Spatial heterogeneity in fish parameters within a reservoir. Pages 122-136 *in* G. E. Hall and M. J. Van Den Avyle, editors. Reservoir Fisheries

Management: Strategies for the 80's. American Fisheries Society, Reservoir Committee, Southern Division, Bethesda, Maryland.
Thompson, J. S., and J. A. Rice. 2013. The relative influence of thermal experience and forage availability on growth of age 1–5 Striped Bass in two southern reservoirs. Pages 93–120 *in* J. S. Bulak, C. C. Coutant, and J. A. Rice, editors. Biology and management of inland Striped Bass and hybrid Striped Bass. American Fisheries Society Symposium, 80, Bethesda, Maryland.
Thompson, J. S., J. A. Rice, and D. Scott Waters. 2010. Striped Bass habitat selection rules in reservoirs without suitable summer habitat offer insight into consequences for growth. Transactions of the American Fisheries Society 139: 1450–1464.
VanHorn, S. L., J. R. Finke, D. Degan. 1996. Summer habitat selection of Striped Bass in Lake Norman. Proceedings of the Annual Conference of Southeastern Association of Fish and Wildlife Agencies 50:91–97.
Wheeler, A. P., K. T. Rachels, and K. J. Dockendorf. 2023. NCIFD — an internal R package for a fisheries agency. Fisheries 48(10):411–417.
Wickham, H. ggplot2: Elegant Graphics for Data Analysis. Springer-Verlag New York, 2016.
Wilson, A. D. M., T. A. Hayden, C. S. Vandergoot, R. T. Kraus, J. M. Dettmers, S. J. Cooke, C. C. Krueger. 2016. Do intracoelomic telemetry transmitters alter the post-release behavior of migratory fish? Ecology of Freshwater Fish 26:292–300.
Windham, W. T. 1986. Summer temperature selection of Striped Bass x White Bass hybrids in a southeastern reservoir. Master's thesis. University of Georgia, Athens.

TABLE 1. General reservoir summer habitat suitability categories for adult Bodie Bass using temperature and dissolved oxygen combinations (DO). Bodie Bass will occupy “Preferred” habitat if it is available, “Good” habitat is adequate for survival of Bodie Bass, and “No Habitat” is outside of the habitat requirements for Bodie Bass. These values were synthesized from references in Coutant (2013) and Kilpatrick and Ney (2013). Some generalizations were made to categorize and assign research to categories for this table.

DO (mg/L)	Temperature (°C)			
	<21.0	21.0–27.0	27.1–32.0	>32.0
>=4.5	**Good**	**Preferred** Windham (1986) Douglas and Jahn (1987) Muncy et al. (1990) Kilpatrick and Ney (2013)	**Good** Piner (1993)	**No Habitat**
2.0–4.4	**Good**	**Good**	**Good**	
<2.0	**No Habitat**			**No Habitat**

TABLE 2. General reservoir summer habitat categories for adult (>=270 mm TL) Striped Bass using temperature and dissolved oxygen (DO) combinations. Striped Bass will occupy “Preferred” habitat if it is available, “Good” habitat is adequate for survival of Striped Bass, “<1 Month Survival” conditions may be fatal after a duration of one month, and “No Habitat” is outside of the habitat requirements for Striped Bass. These values were synthesized from references in chapters in Bulak, J. S., et al. editors (2013). Some generalizations were made to categorize and assign research to categories for this table.

<table>
<tr><td>DO (mg/L)</td><td colspan="5">Temperature (°C)</td></tr>
<tr><td></td><td><18.0</td><td>18.0–24.9</td><td>25.0–26.9</td><td>27.0–29.0</td><td>>29.0</td></tr>
<tr><td>>=4.0</td><td>Good
Bettoli (2005)</td><td>Preferred
Coutant (1978)
Lewis et al. (1979)
Cheek et al. (1985)
Coutant (1985)
Lewis (1985)
Schaffler et al. (2002)
Young and Isely (2002)
Bettoli (2005)</td><td>Good
Lewis et al. (1979)
Lewis (1985)
Moss (1985)
Young and Isely (2002)</td><td rowspan="2"><1 Month Survival
Matthews et al. (1989)
Zale et al. (1990)
Jackson and Hightower (2001)</td><td rowspan="2">No Habitat</td></tr>
<tr><td>2.0–3.9</td><td>Good
Schaffler et al. (2002)</td><td>Good
Coutant (1978)
Lewis et al. (1979)
Lewis (1985)
Young and Isely (2002)</td><td>Good
Lewis et al. (1979)
Lewis (1985)
Young and Isely (2002)</td></tr>
<tr><td><=2.0</td><td colspan="4">No Habitat</td><td>No Habitat</td></tr>
</table>

TABLE 3. Pooled average monthly depth (m) of fish detected on all receivers by reservoir zone from May 2020 to November 2022.

	Lower Forebay		Upper Forebay		Middle		Upper		Grand Total	
	Avg.	SE	Avg.	SE	Avg.	SE	Avg.	SE	Avg.	SE
January	8.2	0.16	7.1	0.0	5.6	0.0	3.9	0.0	5.7	0.01
February	4.6	0.08	7.2	0.0	6.7	0.0	3.9	0.0	6.3	0.01
March	5.0	0.11	3.4	0.0	5.1	0.0	2.1	0.0	3.6	0.01
April	4.8	0.12	3.0	0.0	2.3	0.0	1.7	0.0	2.2	0.01
May	5.7	0.08	4.1	0.0	4.5	0.0	4.3	0.0	4.3	0.01
June	10.0	0.04	8.5	0.0	7.5	0.0	6.5	0.0	7.9	0.01
July	10.8	0.04	8.4	0.0	7.5	0.0	5.6	0.0	7.9	0.01
August	7.9	0.04	6.8	0.0	6.9	0.0	4.4	0.0	6.2	0.01
September	6.4	0.05	5.3	0.0	6.0	0.0	3.4	0.0	4.9	0.01
October	3.6	0.11	2.2	0.0	6.6	0.0	4.9	0.0	4.7	0.02
November	4.0	0.12	4.1	0.0	5.0	0.0	3.4	0.0	4.4	0.01
December	3.8	0.13	7.6	0.0	4.7	0.0	3.7	0.0	5.2	0.01
Grand Total	8.4	0.02	6.0	0.0	6.0	0.0	4.0	0.0	5.6	0.00

TABLE 4. Pooled average monthly temperature (˚C) of fish detected on all receivers by reservoir zone from May 2020 to November 2022.

	Lower Forebay		Upper Forebay		Middle		Upper		Grand Total	
	Avg.	SE	Avg.	SE	Avg.	SE	Avg.	SE	Avg.	SE
January	11.1	0.0	10.8	0.0	10.5	0.0	9.4	0.0	10.3	0.01
February	11.7	0.1	9.3	0.0	8.5	0.0	7.6	0.0	8.7	0.00
March	14.0	0.1	12.6	0.0	12.0	0.0	12.9	0.0	12.5	0.01
April	16.3	0.1	16.7	0.0	16.9	0.0	16.4	0.0	16.6	0.01
May	21.2	0.0	21.9	0.0	21.7	0.0	20.9	0.0	21.6	0.01
June	20.5	0.0	21.7	0.0	23.1	0.0	23.8	0.0	22.5	0.01
July	23.2	0.0	26.5	0.0	26.7	0.0	27.2	0.0	26.1	0.01
August	27.2	0.0	28.5	0.0	28.1	0.0	27.2	0.0	27.8	0.01
September	26.2	0.0	26.8	0.0	26.6	0.0	26.0	0.0	26.4	0.00
October	23.6	0.0	22.9	0.0	22.6	0.0	21.8	0.0	22.4	0.01
November	19.3	0.1	16.8	0.0	17.1	0.0	16.1	0.0	16.8	0.01
December	14.7	0.1	13.3	0.0	12.8	0.0	12.3	0.0	12.8	0.00
Grand Total	22.9	0.0	19.2	0.0	18.4	0.0	20.1	0.0	19.3	0.01

TABLE 5. Dissolved oxygen concentrations (mg/L) from paired detection data in the lower three zones (Lower Forebay Zone, Upper Forebay Zone, Middle Zone).

		2020		2021		2022		Total	
		Avg.	SE	Avg.	SE	Avg.	SE	Avg.	SE
Lower Forebay	June	7.9	0.1	-	-	5.9	0.1	7.5	0.1
	July	2.4	0.0	4.1	0.1	3.5	0.1	2.9	0.0
	August	3.0	0.1	6.3	0.0	4.1	0.1	5.5	0.0
Upper Forebay	June	-	-	-	-	5.9	0.2	5.9	0.2
	July	-	-	-	-	6.6	0.1	6.6	0.1
	August	6.2	0.0	6.1	0.0	6.0	0.1	6.1	0.0
Middle	June	-	-	-	-	7.8	0.2	7.8	0.2
	July	4.2	0.1	4.4	0.1	5.1	0.1	4.5	0.0
	August	4.3	0.0	5.8	0.0	5.5	0.1	5.5	0.0
All lower zones	June	7.9	0.06	-	-	6.3	0.10	7.3	0.06
	July	2.8	0.04	4.4	0.05	4.3	0.06	3.7	0.03
	August	4.3	0.03	6.0	0.01	5.3	0.05	5.6	0.01

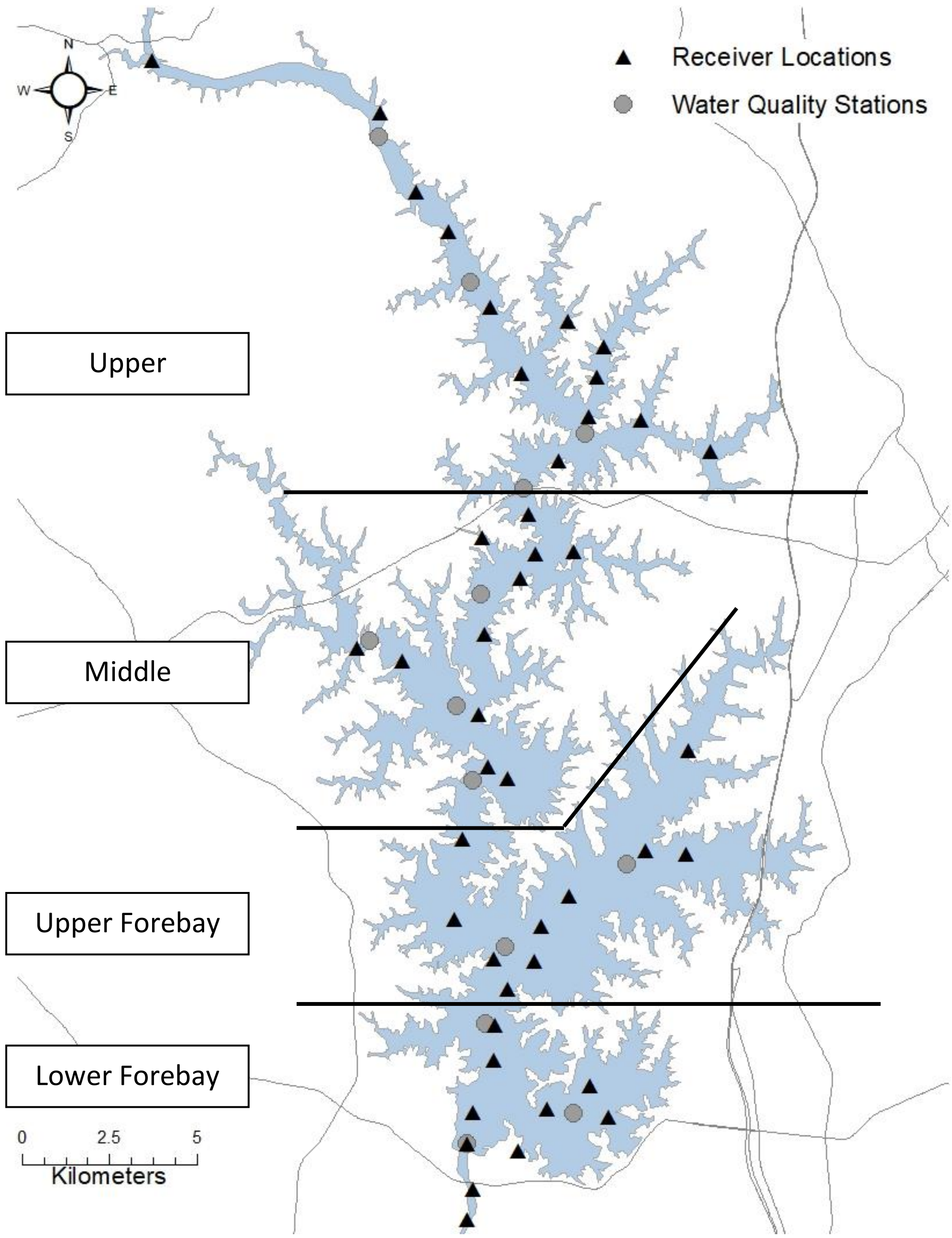


FIGURE 1. Receiver, water quality station locations, and the delineation of the four reservoir zones in Lake Norman (Lower Forebay Zone, Upper Forebay Zone, Middle Zone, and Upper Zone).

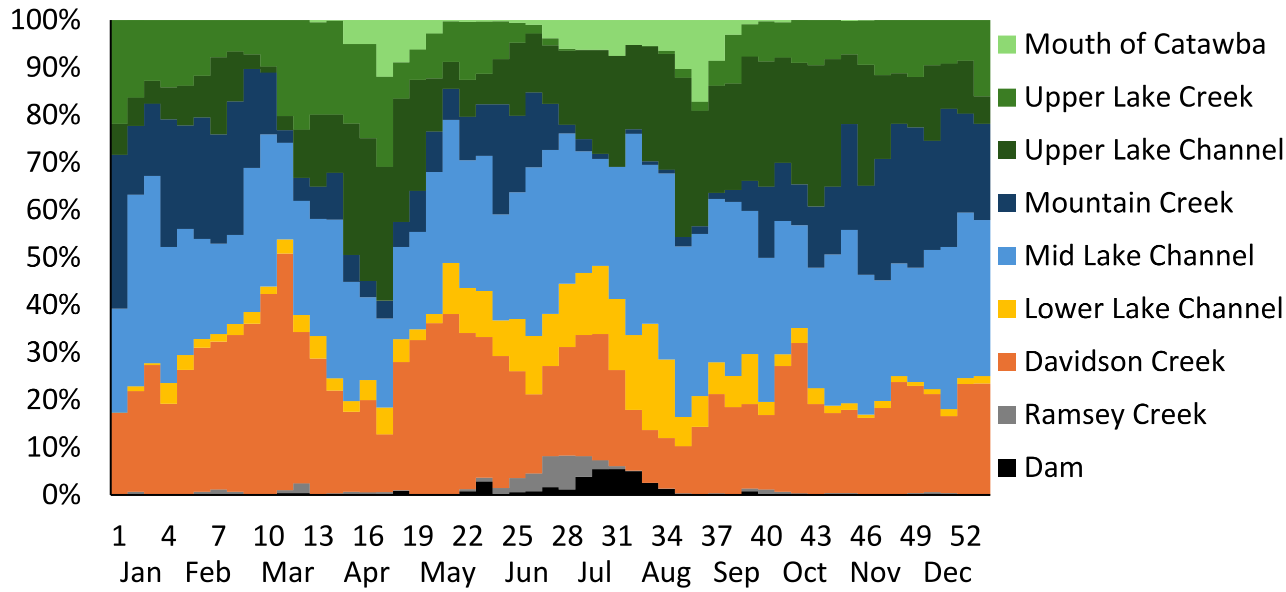


FIGURE 2. Percentage of receiver fish detections by week and reservoir area from 2020, 2021, and 2022 combined. The approximate month is also included for reference.

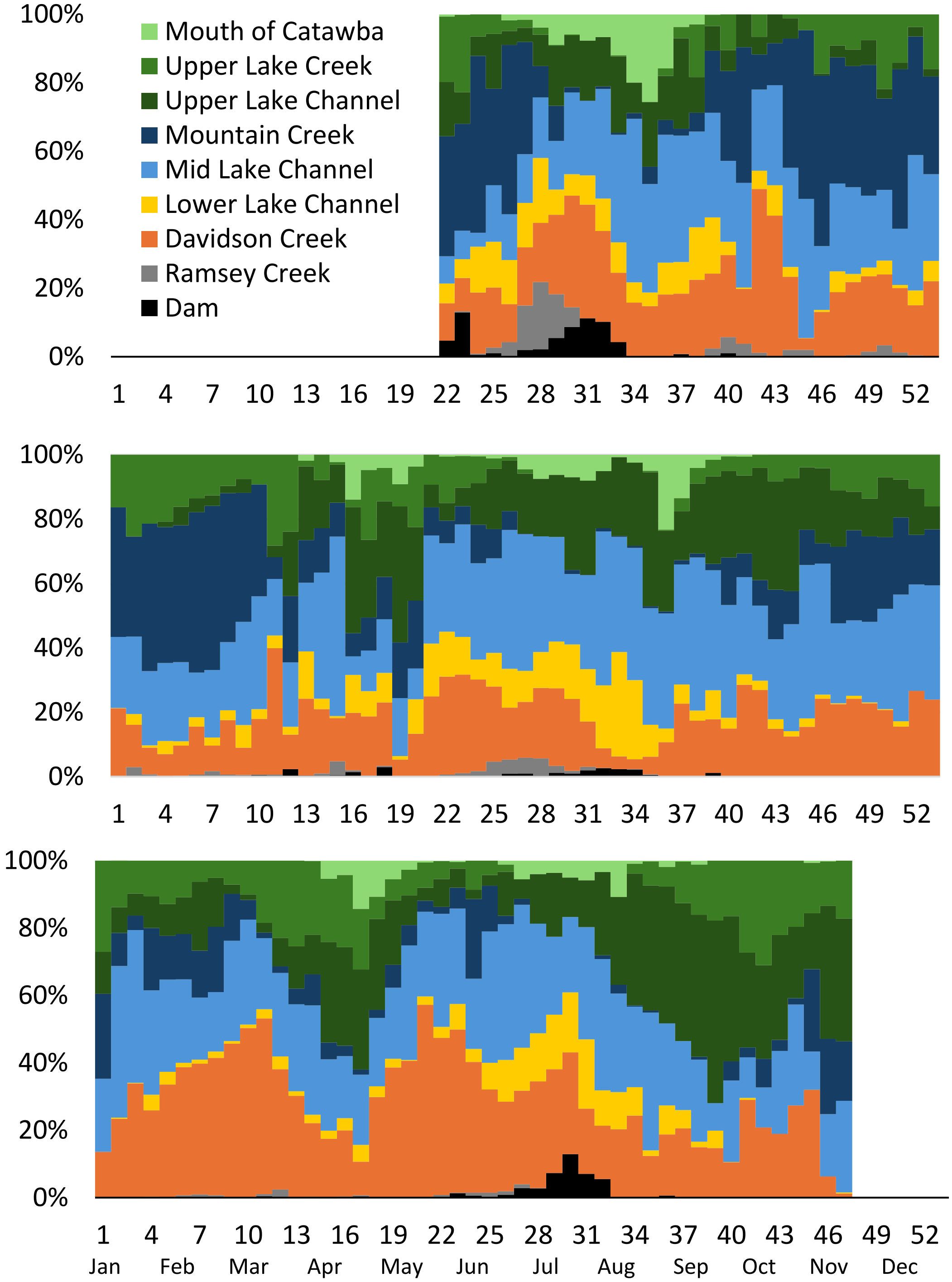


FIGURE 3. Percentage of receiver detections by week and reservoir area in 2020 (top), 2021 (middle), and 2022 (bottom). The approximate month is also included for reference.

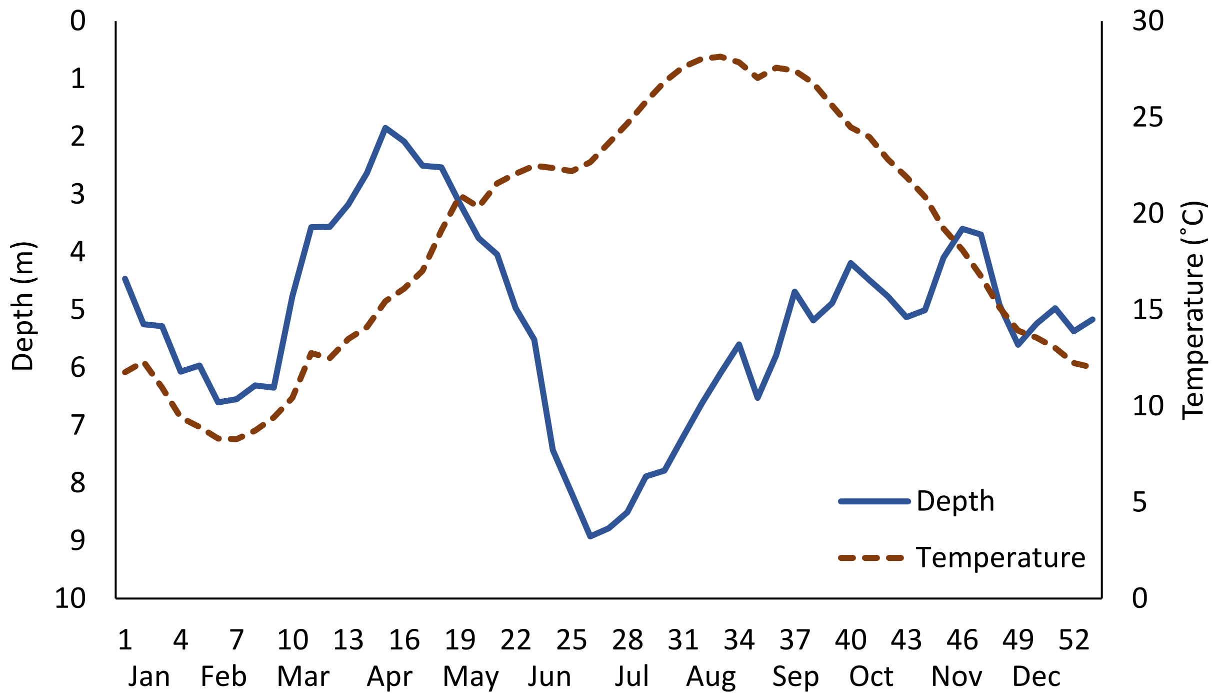


FIGURE 4. Weekly pooled average depth (m) and temperature (˚C) of fish detected on receivers from 2020, 2021, and 2022.

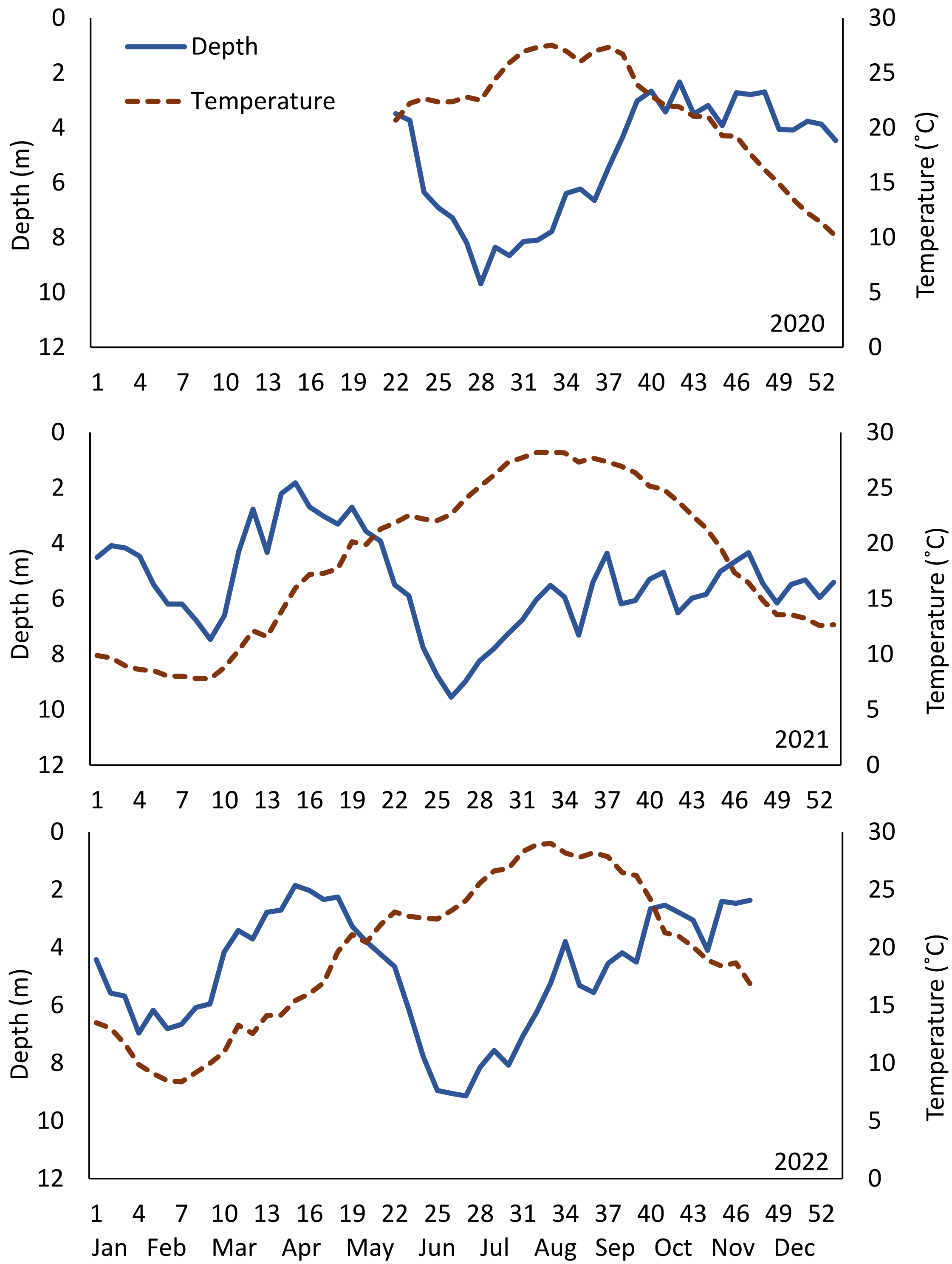


FIGURE 5. Weekly average depth (m) and temperature (˚C) for fish detected on receivers in 2020 (top), 2021 (middle), and 2022 (bottom).

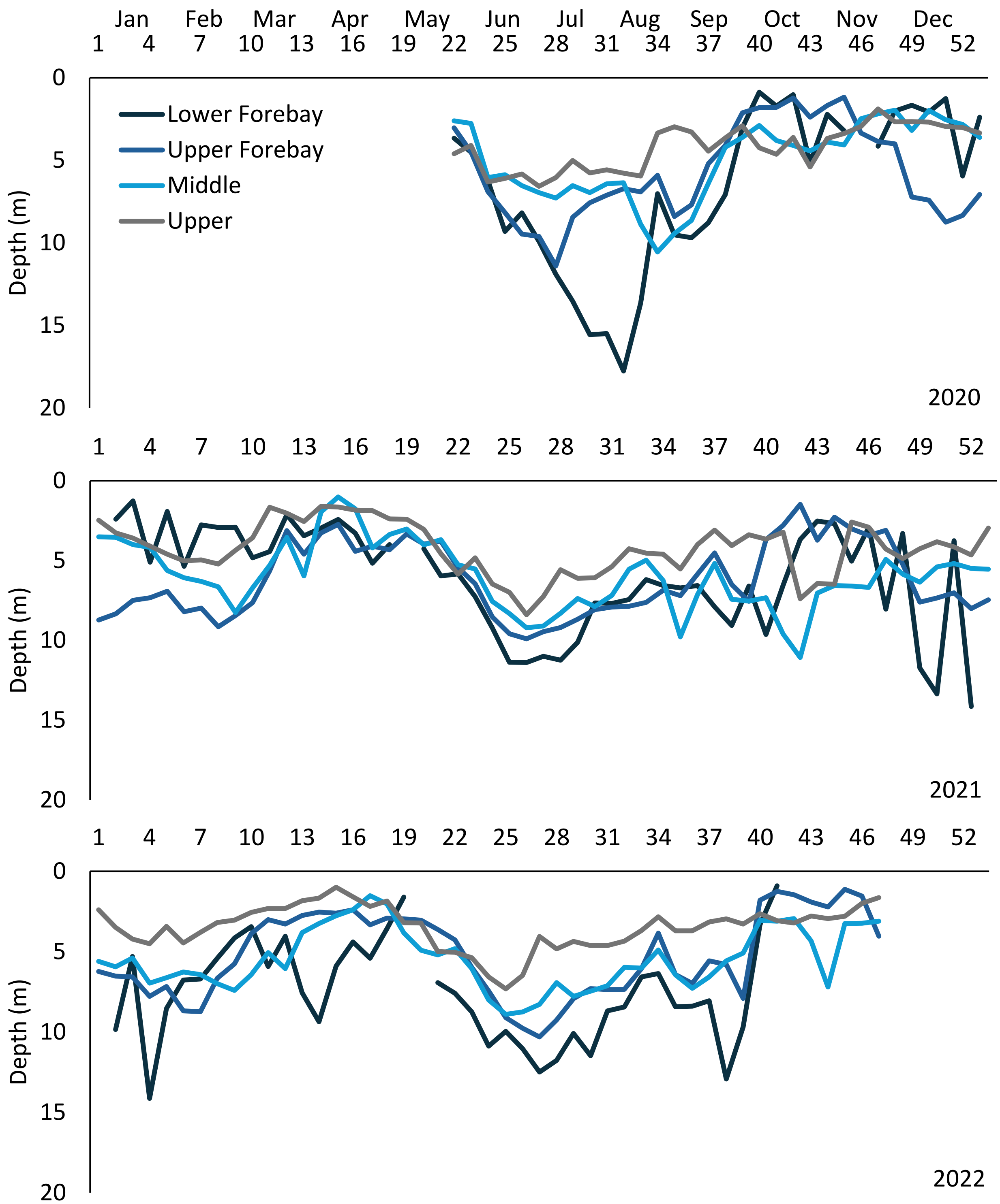


FIGURE 6. Weekly average depth (m) by zone for 2020, 2021, and 2022.

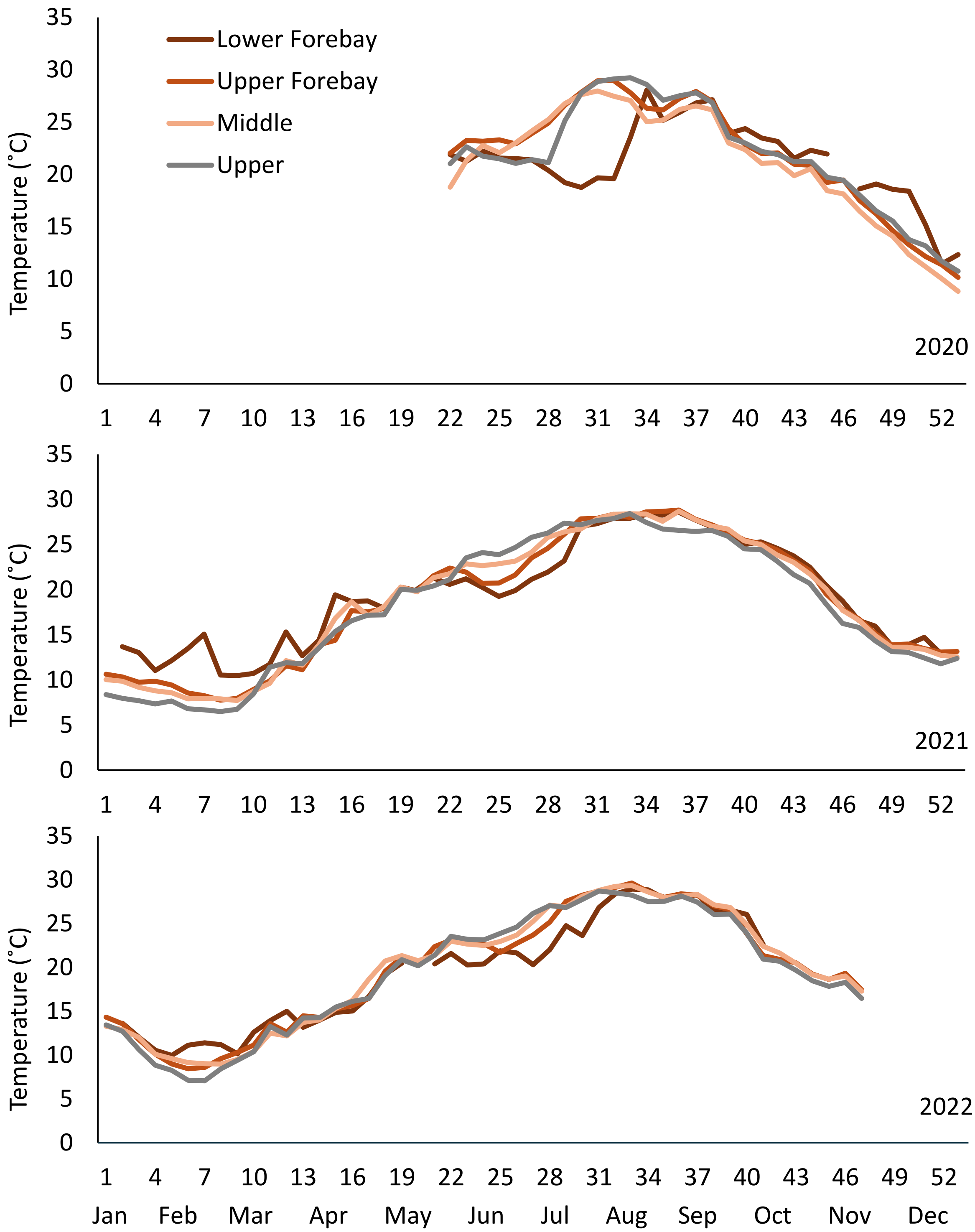


FIGURE 7. Weekly average temperature (˚C) by zone for 2020 (top), 2021 (middle), and 2022 (bottom).

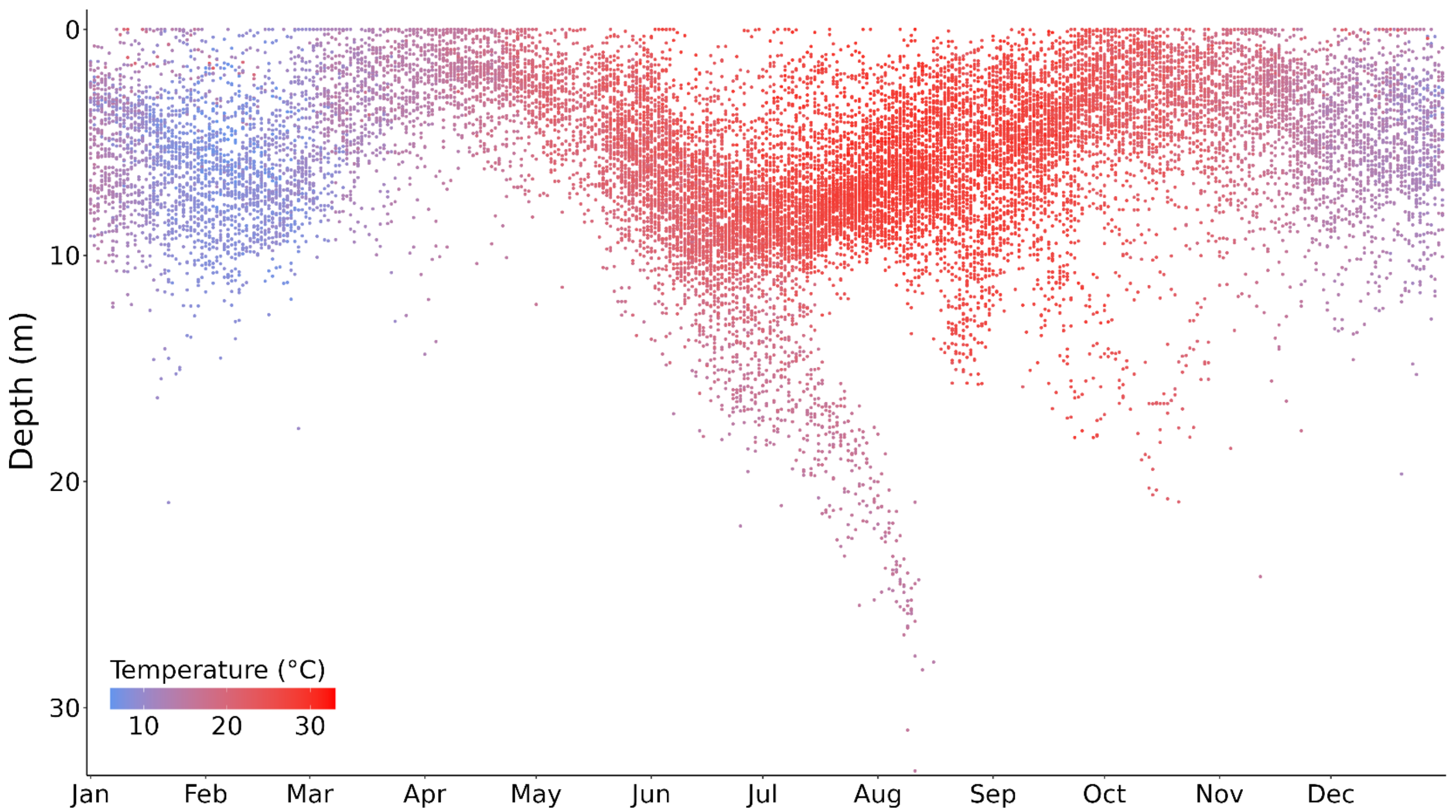


FIGURE 8. Average daily temperature (˚C) and depth (m) of individual fish from January through December in 2020–2022.

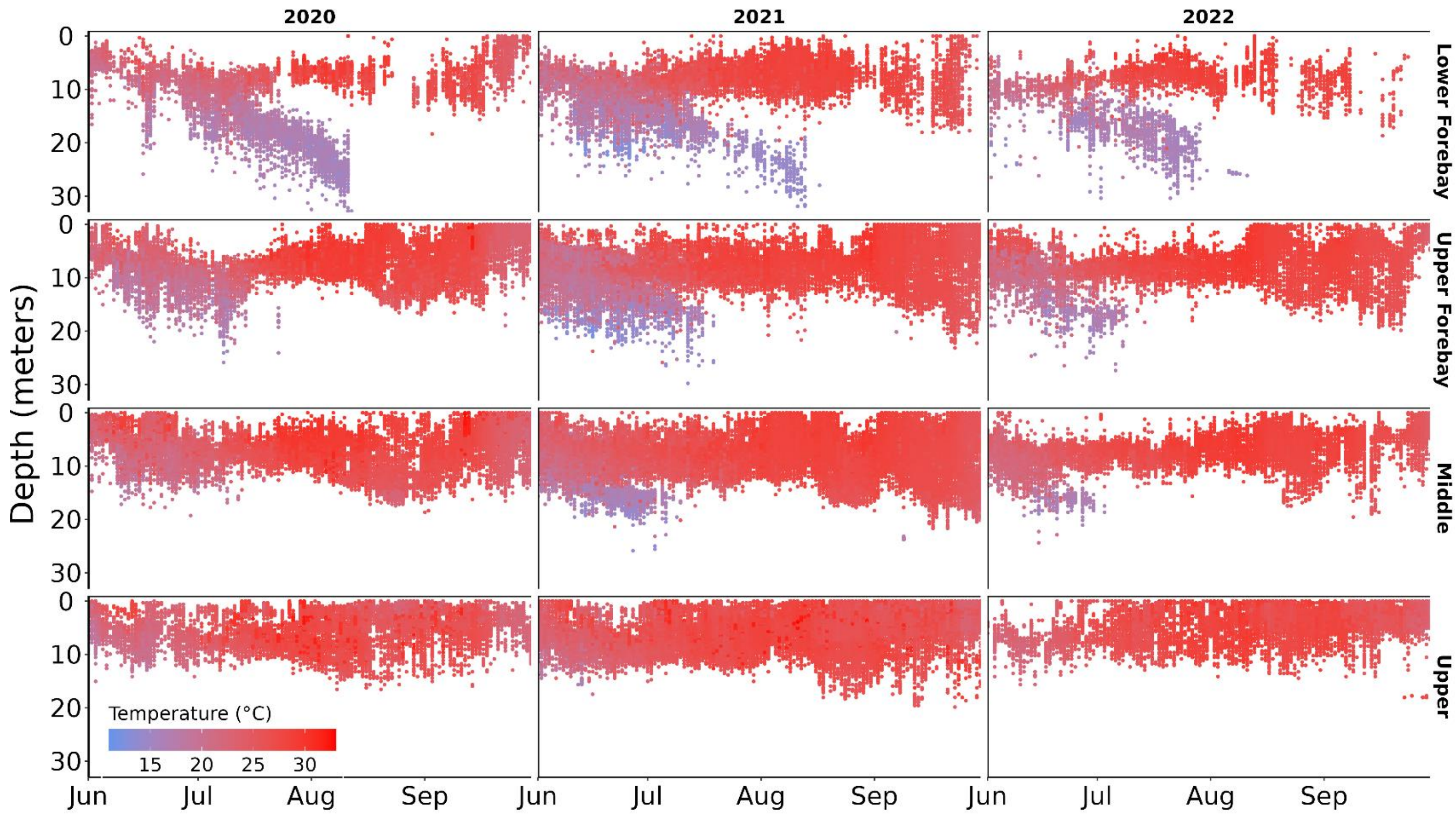


FIGURE 9. Temperature (˚C) and depth (m) detections of individual fish by zone from 2020–2022.

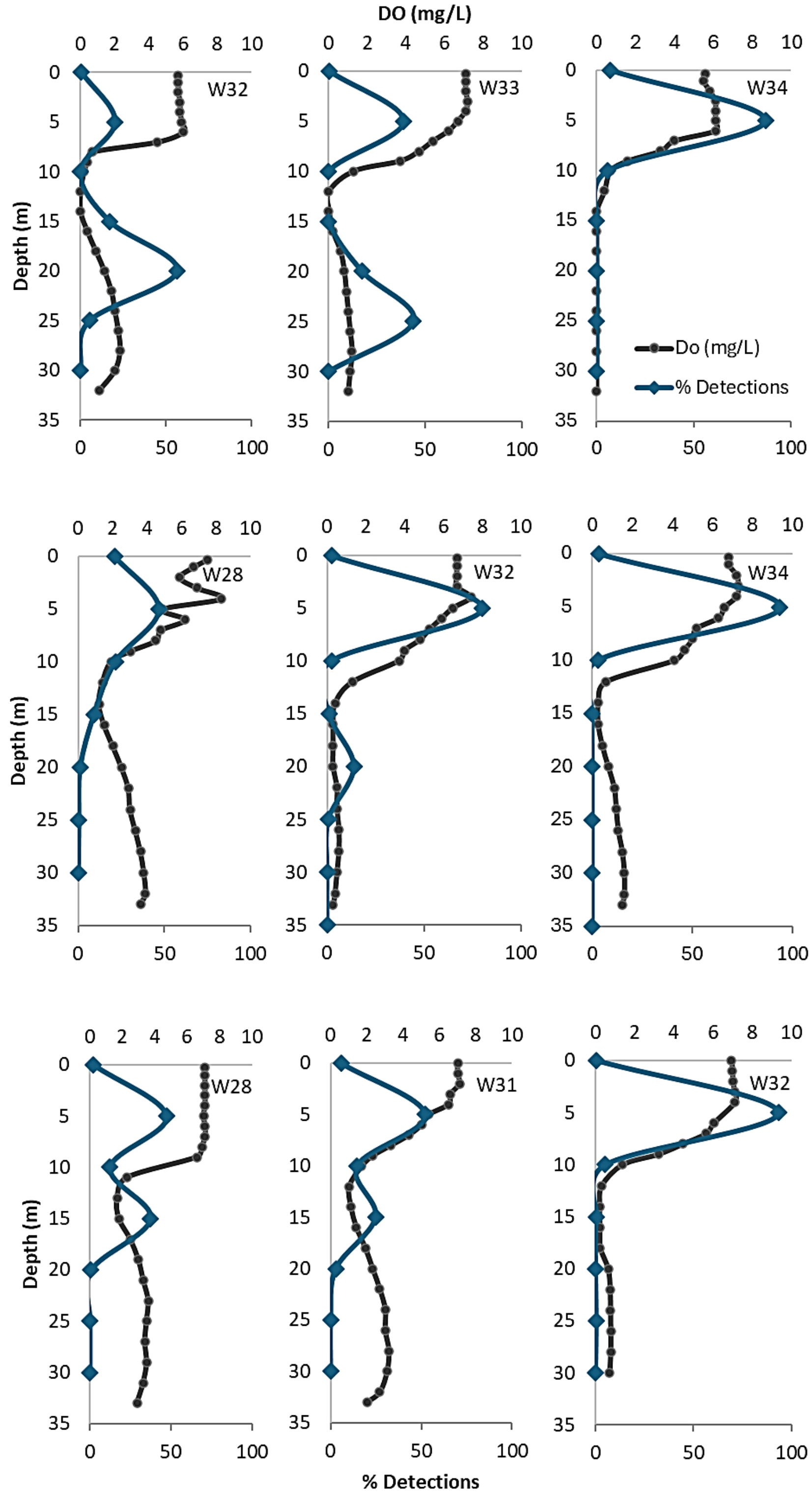


FIGURE 10. Dissolved Oxygen profiles of Duke Energy Water Quality Station 1.0 in 2020 (top), 2021 (middle), and 2022 (bottom) during progressive weeks in late summer. The percentage of fish detected on receivers WQ1, 1, 1A, and 2A 5 m intervals is also shown.

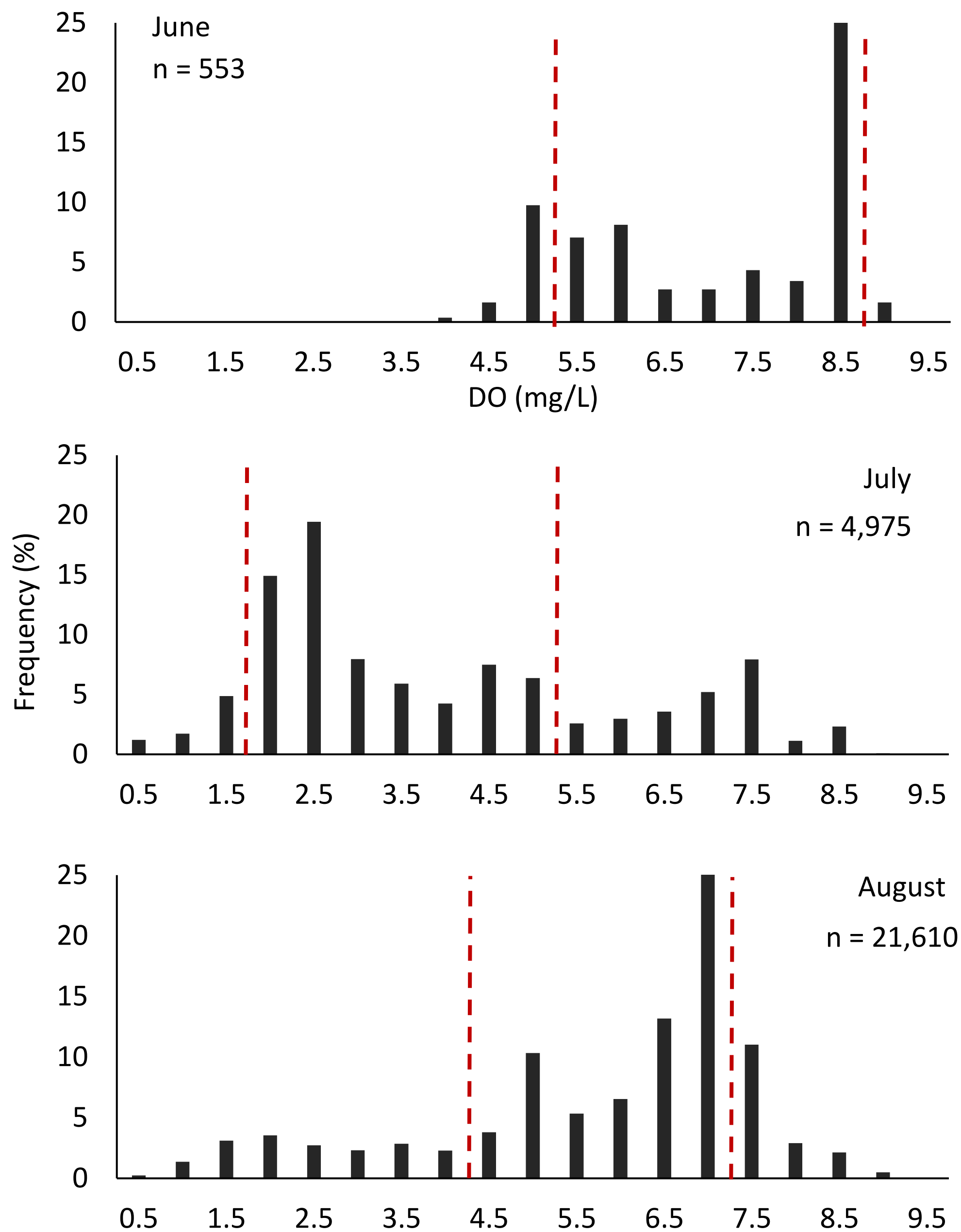


FIGURE 11. Frequency distribution of fish detections in the Lower Forebay Zone, Upper Forebay Zone, and Middle Zone at varying dissolved oxygen (DO) concentrations for June (top), July (middle), and August (bottom). The middle 50^{th} quartile of data is contained within the dotted red lines.

Appendices

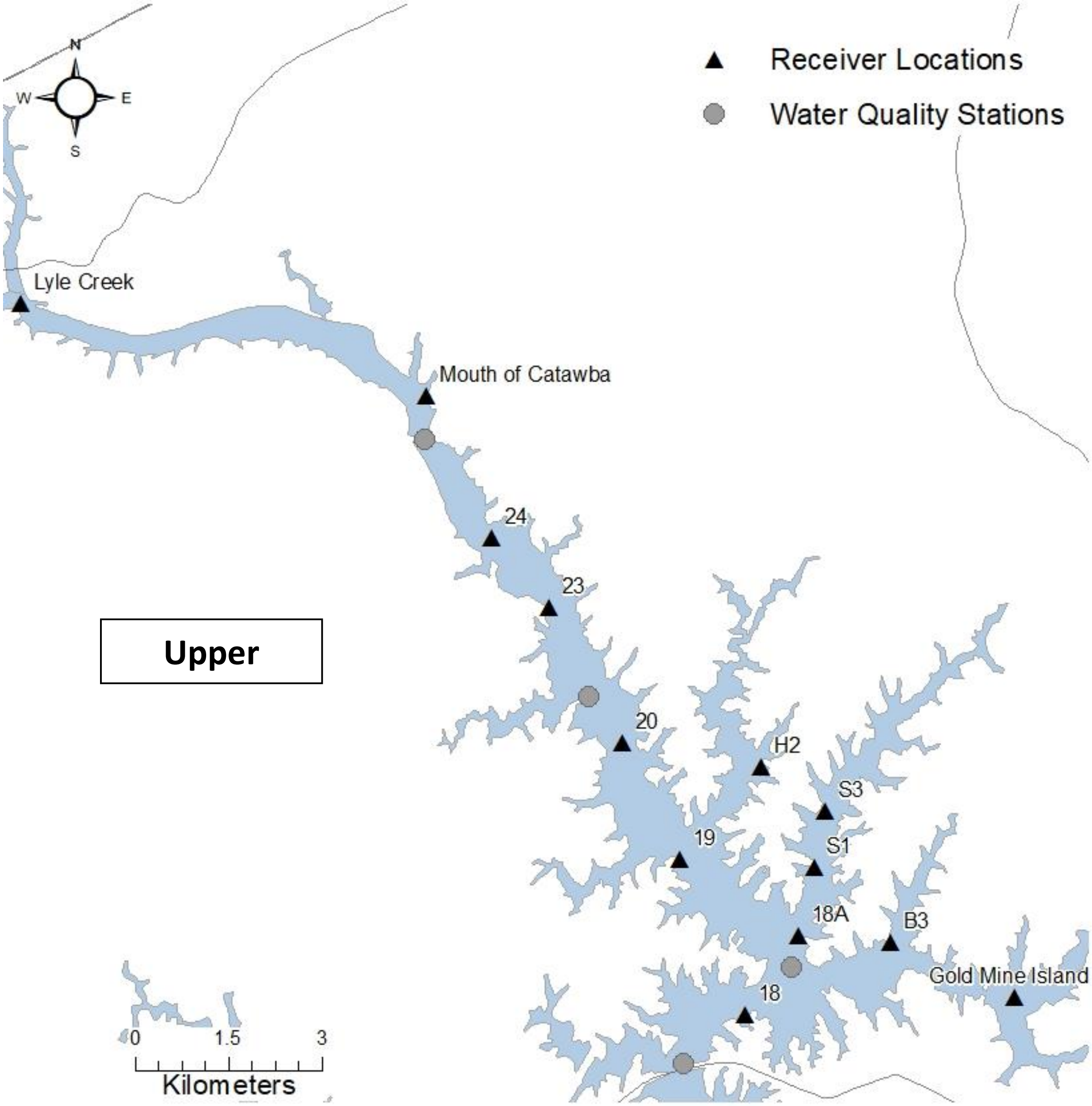
Appendix A.1–Station ID, Reservoir Zone, Reservoir Area, and GPS coordinates for receivers.

Station ID	Reservoir Zone	Reservoir Area	Latitude	Longitude
MIL1	Downstream of Dam	Downstream of Dam	35.4260	–80.9551
MIL2	Downstream of Dam	Downstream of Dam	35.4182	–80.9568
WQ1	Lower Forebay	Dam	35.4376	–80.9571
1	Lower Forebay	Dam	35.4455	–80.9555
MNS Discharge	Lower Forebay	MNS Discharge	35.4359	–80.9409
R2	Lower Forebay	Ramsey Creek	35.4467	–80.9321
R3	Lower Forebay	Ramsey Creek	35.4531	–80.9187
R4	Lower Forebay	Ramsey Creek	35.4450	–80.9129
1A	Lower Forebay	Lower Lake Channel	35.4590	–80.9493
L1	Lower Forebay	Little Creek	35.4640	–80.9743
2	Lower Forebay	Lower Lake Channel	35.4681	–80.9492
2A	Lower Forebay	Lower Lake Channel	35.4774	–80.9455
T3	Upper Forebay	Davidson Creek	35.5129	–80.8901
D2	Upper Forebay	Davidson Creek	35.4640	–80.9743
D3	Upper Forebay	Davidson Creek	35.4935	–80.9351
D5	Upper Forebay	Davidson Creek	35.5014	–80.9266
D8	Upper Forebay	Davidson Creek	35.5136	–80.9029
D10	Upper Forebay	Davidson Creek	35.5393	–80.8899
3	Upper Forebay	Lower Lake Channel	35.4850	–80.9498
5	Upper Forebay	Mid Lake Channel	35.4949	–80.9626
7	Upper Forebay	Mid Lake Channel	35.5157	–80.9605
NML	Middle	Mid Lake Channel	35.5314	–80.9468
10	Middle	Mid Lake Channel	35.5342	–80.9528
12	Middle	Mid Lake Channel	35.5475	–80.9562
M3	Middle	Mountain Creek	35.5608	–80.9807
M5	Middle	Mountain Creek	35.5641	–80.9948
14	Middle	Mid Lake Channel	35.5682	–80.9548
16	Middle	Mid Lake Channel	35.5826	–80.9439
15A	Middle	Mid Lake Channel	35.5891	–80.9392
MSS Discharge	Middle	MSS Discharge	35.5930	–80.9562
MC1	Middle	Mid Lake Channel	35.5899	–80.9274
17A	Middle	Mid Lake Channel	35.5991	–80.9417

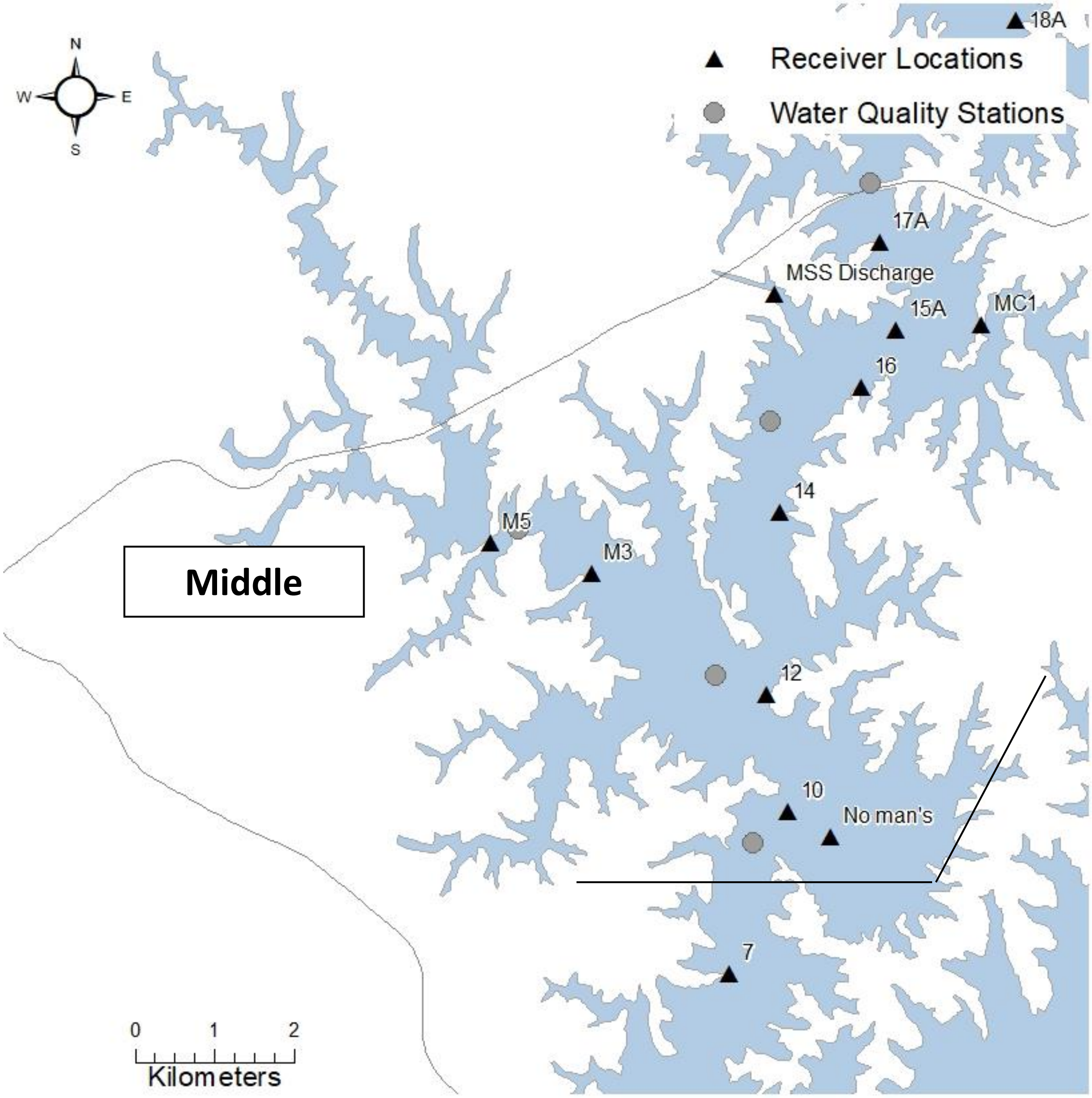
Appendix A.1– Station ID, Reservoir Zone, Reservoir Area, and GPS coordinates for receivers.

Station ID	Reservoir Zone	Reservoir Area	Latitude	Longitude
18	Upper	Upper Lake Channel	35.6131	–80.9324
B3	Upper	Upper Lake Creek	35.6239	–80.9069
Gold Mine Island (GMI)	Upper	Upper Lake Creek	35.6163	–80.8847
S1	Upper	Upper Lake Creek	35.6346	–80.9208
S3	Upper	Upper Lake Creek	35.6426	–80.9189
18A	Upper	Upper Lake Channel	35.6246	–80.9233
H2	Upper	Upper Lake Creek	35.6489	–80.9305
19	Upper	Upper Lake Channel	35.6353	–80.9446
20	Upper	Upper Lake Channel	35.6520	–80.9551
23	Upper	Upper Lake Channel	35.6712	–80.9686
24	Upper	Upper Lake Channel	35.6811	–80.9790
Mouth of Catawba (MOC)	Upper	Mouth of Catawba	35.7014	–80.9911
Lyle Creek (LC)	Upper	Mouth of Catawba	35.7135	–81.0635

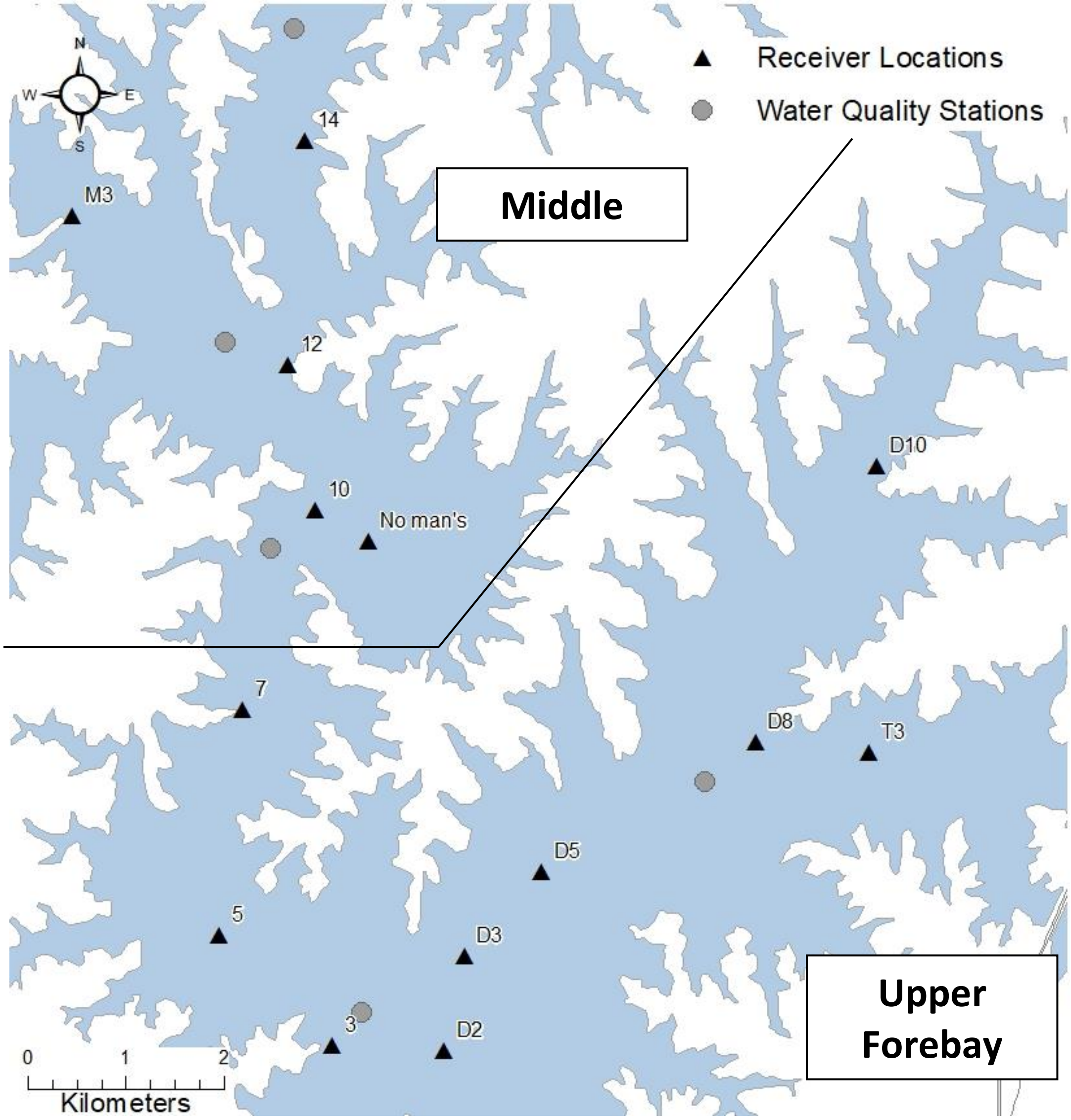
Appendix A.2–Receiver Station ID's by zone.



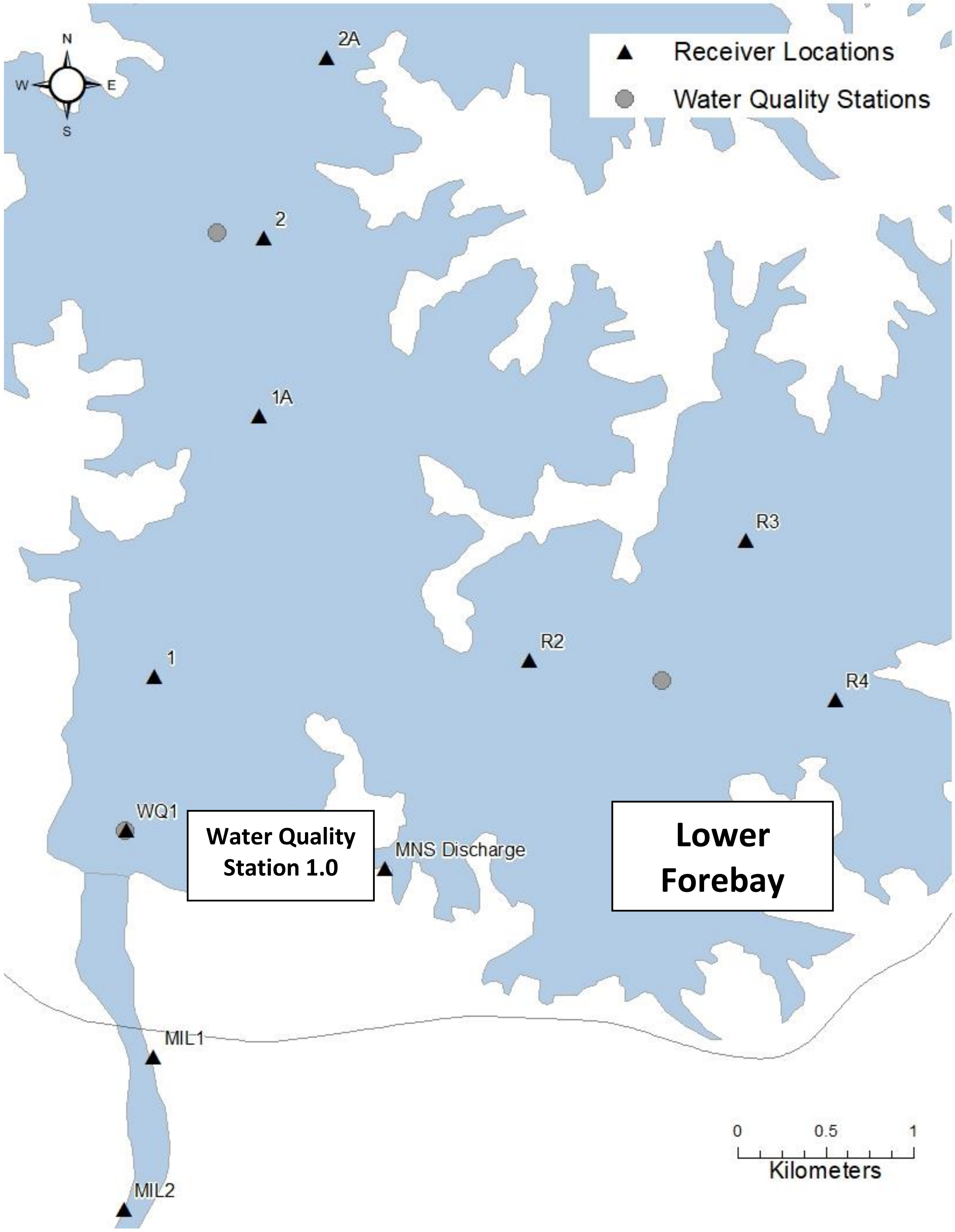
Appendix A.2–Receiver Station ID's by zone.



Appendix A.2–Receiver Station ID's by zone.



Appendix A.2–Receiver Station ID's by zone.



Appendix A.3–Water Quality (WQ) Station IDs with respective reservoir zones, reservoir areas, and receivers that were within 1,500 m.

Station ID	Lat	Long	Reservoir Zone	Reservoir Area	Receiver ID
82BB	35.4374	–80.9564	Lower Forebay	Dam	WQ, 1
1	35.4376	–80.9571	Lower Forebay	Dam	WQ, 1
5	35.4458	–80.9237	Lower Forebay	Ramsey Creek	R2, R3, R4
7.5	35.4683	–80.9522	Lower Forebay	Lower Lake channel	1A, 2, 2A
82R	35.4869	–80.9415	Upper Forebay	Lower Lake channel	D2, D3, 3, 5
8	35.4880	–80.9465	Upper Forebay	Lower Lake Channel	D8, T3
9.5	35.5098	–80.9085	Upper forebay	Davidson Creek	D2, D3, 3, 5
11	35.5305	–80.9576	Middle	Mid Lake Channel	10, NML
11.5	35.5495	–80.9633	Middle	Mid Lake Channel	12
12.5	35.5657	–80.9909	Middle	Mountain Creek	M3,M5
82M	35.5660	–80.9903	Middle	Mountain Creek	M3, M5
13	35.5784	–80.9562	Middle	Mid Lake Channel	14, 16
82B	35.6056	–80.9438	Middle	Mid Lake Channel	17A, 18
15	35.6058	–80.9432	Middle	Mid Lake Channel	17A, 18
15.9	35.6199	–80.9244	Upper	Upper Lake Channel	18, 18A
62	35.6584	–80.9613	Upper	Upper Lake Channel	23, 20
79A	35.6950	–80.9912	Upper	Mouth or Catawba	Mouth of Catawba

Appendix A.4–Monthly average depth (m) and standard error (SE) of all fish detected on receivers in 2020, 2021, 2022, and all years combined (excludes receivers near discharge water).

	2020		2021		2022		All Years	
	Avg.	SE	Avg.	SE	Avg.	SE	Avg.	SE
January			4.6	0.01	6.1	0.01	5.7	0.01
February			6.6	0.01	6.2	0.01	6.3	0.01
March			4.6	0.03	3.4	0.01	3.6	0.01
April			2.8	0.03	2.1	0.01	2.2	0.01
May	3.6	0.04	4.7	0.02	4.0	0.02	4.3	0.01
June	6.5	0.02	8.3	0.02	8.5	0.03	7.9	0.01
July	8.6	0.03	7.6	0.01	7.8	0.03	7.9	0.01
August	7.1	0.03	6.2	0.01	5.0	0.02	6.2	0.01
September	4.5	0.02	5.3	0.02	4.2	0.02	4.9	0.01
October	3.0	0.02	5.7	0.03	3.0	0.02	4.7	0.02
November	3.0	0.02	5.2	0.02	2.5	0.03	4.4	0.01
December	4.0	0.02	5.6	0.01			5.2	0.01

Appendix A.5–Monthly average temperature (C˚) and standard error (SE) of fish detected on receivers in 2020, 2021, 2022, and all years combined (excludes receivers near discharge water).

	2020		2021		2022		All Years	
	Avg.	SE	Avg.	SE	Avg.	SE	Avg.	SE
January			8.9	0.01	10.9	0.01	10.3	0.01
February			7.9	0.01	9.1	0.00	8.7	0.00
March			10.7	0.02	13.0	0.01	12.5	0.01
April			16.6	0.02	16.6	0.01	16.6	0.01
May	20.8	0.04	21.6	0.01	21.7	0.01	21.6	0.01
June	22.4	0.01	22.5	0.01	22.9	0.02	22.5	0.01
July	24.9	0.03	26.4	0.01	26.7	0.02	26.1	0.01
August	27.0	0.02	28.0	0.00	28.3	0.01	27.8	0.01
September	25.9	0.01	26.7	0.01	26.5	0.01	26.4	0.00
October	21.6	0.01	23.3	0.01	20.1	0.01	22.4	0.01
November	17.9	0.01	16.2	0.01	18.0	0.01	16.8	0.01
December	12.2	0.01	13.1	0.00			12.8	0.00

Appendix A.6–Examples of fish behavior and fates.

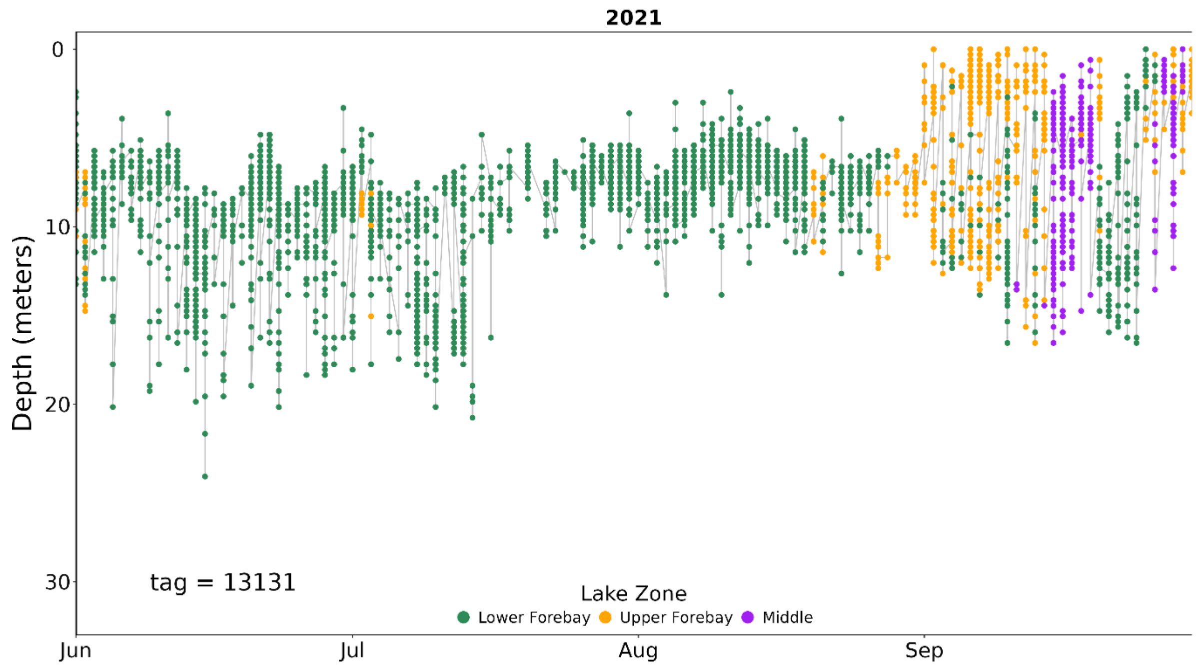


FIGURE A.6.1–Individual 13131 dives into the hypolimnion (i.e., >10 m) until mid-July. They remain in the epilimnion near the oxycline until September when they begin to use multiple zones and depths within the epilimnion and hypolimnion.

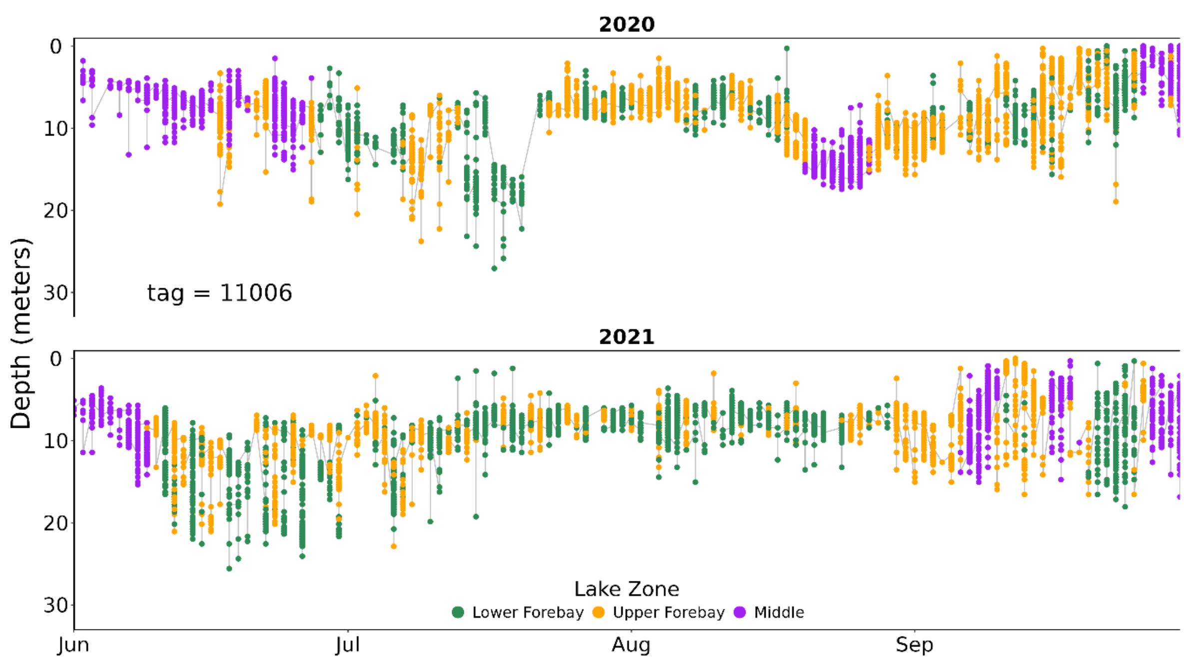


FIGURE A.6.2–Individual 11006 dives into the hypolimnion (i.e., >10 m) until mid-July. They remain in the epilimnion near the oxycline until September when they begin to use multiple zones and depths within the epilimnion and hypolimnion.

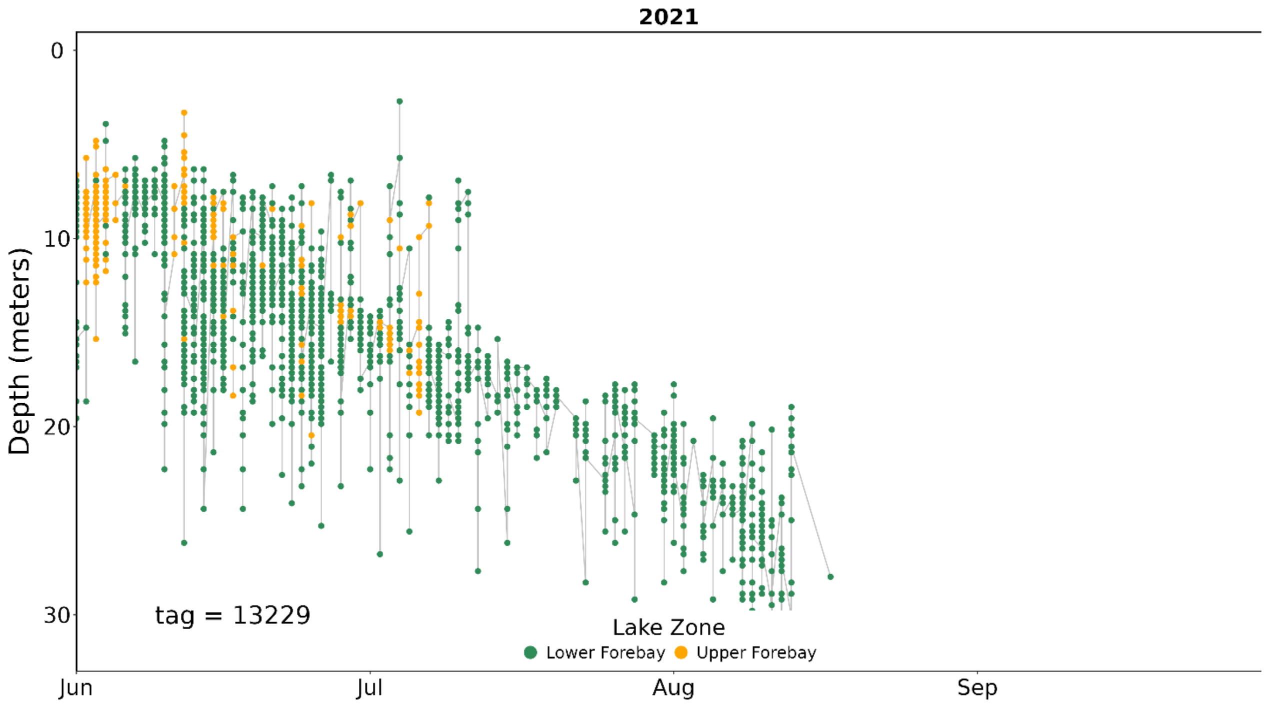


FIGURE A.6.3–Individual 13229 dives within the hypolimnion and progressively utilizes deeper water until they suffered a mortality event mid-July and were censored.

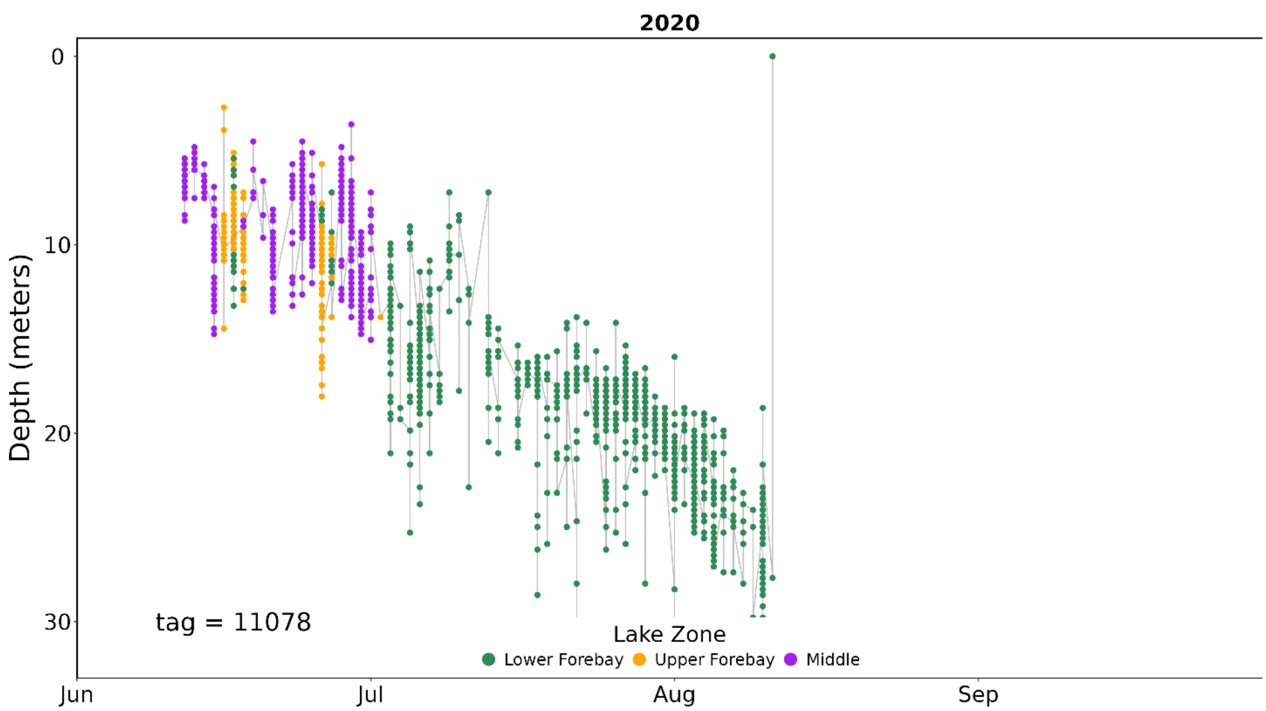


FIGURE A.6.4–Individual 11078 dives within the hypolimnion and progressively utilizes deeper water until they are caught by an angler where they were detected at the surface and then never detected again.