Effects of flow-training on physiological performance and post-stocking movement and survival of hatchery-reared endangered Colorado Pikeminnow in the San Juan River

by

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Abstract

Colorado Pikeminnow (*Ptychocheilus lucius*) in the San Juan River depend heavily on stocking, yet retention and recruitment remain below species recovery goals. We evaluated whether increasing hatchery flow-training velocities would improve physiological performance, post-stocking apparent survival, and retention of stocked fish. Fish were reared in control raceways under low static flow or in treatment raceways exposed to higher static and pulsed flows across three stocking cohorts. We assessed oxygen consumption using intermittent flow respirometry, estimated apparent survival from radio telemetry and PIT tag detections, and modeled downstream detection probability and movement rates. Flow training produced inconsistent physiological responses across stocking cohorts. Radio telemetry indicated no meaningful treatment effect on apparent survival during the first five weeks post-stocking. PIT-tag based models similarly showed little treatment difference in fall stockings, but in a spring stocking flow-trained fish had approximately 7% higher early apparent survival and 88% more expected fish remaining by the end of the 90-day period. Downstream dispersal was strongly correlated with season with spring-stocked fish less likely to be detected downstream than fall-stocked fish. Flow-trained fish stocked during a high flow event in fall 2024 were 15% less likely than controls to be detected at lower arrays. Overall, flow training alone did not produce a consistent survival advantage, and stocking season and environmental conditions explained more variation than treatment. These findings suggest that considering an interaction between stocking season and flow training may provide the greatest management benefit.

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Chapter 1 Effects of flow training on stocked Colorado Pikeminnow in the San Juan River

Introduction

Aquatic systems in the southwestern United States have been radically altered from historical baselines. The Colorado River basin is the main feature of this dynamic landscape, encompassing seven states and supplying water for agriculture, industrial projects, and municipal use for 40 million people (Udall and Overpeck 2017). The basin has been heavily impacted by dams that compromise connectivity, negatively impacting fish assemblages (Propst et al. 2021; Comte et al. 2022; Valentine et al. 2024). The region has suffered from the introduction and spread of invasive species such as smallmouth bass (*Micropterus dolomieu*) and channel catfish (*Ictalurus punctatus*), which might negatively impact native fishes (Olden and Poff 2005; Hedden et al. 2021). With expected flow reductions of up to 35% due to a changing climate and increased water withdrawal demands, the Colorado River basin is becoming an increasingly imperiled ecosystem for native fishes for the foreseeable future (Tidwell et al. 2014; Udall and Overpeck 2017; Comte et al. 2022). Increasing environmental challenges in this region require considerable intervention by managers and stakeholders, including habitat restoration, invasive species control, and propagation and then release of hatchery-reared fishes (Gido et al. 2023).

Although hatchery programs play a critical role in the restoration and maintenance of imperiled species in the American Southwest and elsewhere, the success of these programs can be highly variable. Stocking strategies must be carefully vetted beforehand and evaluated afterwards due to the many factors that can influence success (Cowx 1994). Survival rates of hatchery-reared fish often remain low in the wild, with studies highlighting predator prey mismatch, habitat quality and availability, emigration, and stress-induced mortality as key factors limiting post-stocking success (Franssen et al. 2007; Cochran-Biederman et al. 2015; Archdeacon et al. 2022; Hedden et al. 2023). Some instances of failed stocking due to poor habitat quality have been reported for spikedace (*Meda fulgida*) and loach minnow (*Agosia chrysogaster*) in the Gila River (Hedden 2020). The timing of stocking may also play a role in determining success rates, with studies on salmonids finding recruitment success and even movement patterns depending on time of year and age of fry stocked (Pirhonen et al. 2003; Birnie-Gauvin et al. 2018). Short-term stocking success for brown trout (*Salmo trutta*) was attributed to moving the stocking time from early May to mid-June, before long-term recovery was hampered by other factors (Johnson and Rakoczy 2004). In addition, crucial skills such as predator avoidance and prey acquisition may not be fully developed in a hatchery setting (Olla et al. 1998). To boost survival rates post-stocking, there is increasing interest in using hatchery enrichment techniques to better prepare stocked fish with the skills necessary to survive in the wild.

Hatchery enrichment techniques aim to improve post-stocking survival by mimicking natural conditions and preparing fish for the challenges of the wild. Flow training, which exposes fish to relatively high water velocities during rearing, can enhance swimming performance and post-stocking survival. Research on the razorback sucker (*Xyrauchen texanus*) demonstrated that flow conditioning doubled survival rates during the critical overwintering period post-stocking (Franssen et al. 2021). Studies involving other fish, usually salmonids, have also demonstrated beneficial results such as an increased metabolic scope and endurance, although impact may vary based on a range of factors from each species unique life history and environment (Davison 1997; Ward and Hilwig 2004; Norin and Clark 2016). For example, swimming performance increased for flannelmouth sucker (*Catostomus latipinnis*) by 10%, razorback sucker by 26%, and spikedace by 40% after being exercised in flowing water (Ward and Hilwig 2004). Providing Atlantic salmon fry with exercise and high dissolved oxygen concentration was found to improve growth rates when compared to no exercise or lower dissolved oxygen conditions (Waldrop et al. 2018). Exercise regimes also benefit muscle development in striped bass (*Morone saxatilis*), along with improvements in growth rates and final weights (Young and Cech 1993).

Not all hatchery enrichment attempts have been successful, with some studies finding mixed results or even deleterious impacts of flow training. For example, large yellow croaker (*Larimichthys crocea*) that underwent intense exercise regimes were found to have increased resistance to parasitic infection, but at the cost of induced inflammation from the training (Zeng et al. 2024). Exercise training also did not appear to effect swimming performance of Chinese sucker (*Myxocyprinus asiaticus*), and there was a lower survival rate from predation among exercised individuals (Zhou et al. 2019). Rodgers and Isaza (2024) recommend achieving flows over 2 body length per second for increased growth rates in hatchery fish, also recommending that flow be continuous rather than intermittent. Increasing flow velocities was also the recommendation of Cleveland et al. (in review), who did not observe an effect from flow training Colorado Pikeminnow (*Ptychocheilus lucius*). The goal of this study was to evaluate if increasing the velocities used by Cleveland et al. (in review) to flow train Colorado Pikeminnow would result in a measurable effect on physiology or post-stocking movement and survival.

The Colorado Pikeminnow, henceforth referred to as Pikeminnow, is a piscivorous apex predator and the largest minnow native to the continental United States. Historically, the species was reported to reach total lengths of up to 1.8 m and was a common feature of the Colorado River Basin (Quartarone 1993; Minckley and Deacon 2017). However, like many now imperiled fishes in the region, habitat fragmentation due to impoundments and disruption of environmental flow regimes has led to severe population decline in past decades (Bestgen et al. 2007; Propst et al. 2021; Pennock et al. 2022). This rapid decline led to the species being one of 22 fish originally federally listed under the Endangered Species Act of 1973. Currently, population status varies between the three currently occupied subbasins within the Colorado River Basin, with the San Juan River population believed to be the most diminished compared to the Colorado River and Green River populations (Bestgen et al. 2007).

Even though the Pikeminnow population in the San Juan River is currently dependent on stocking, long-term retention and recruitment rates have remained suboptimal (Clark et al. 2018). Factors such as flow regulation, river fragmentation, predation by invasive species and poor habitat availability may be contributing to poor recruitment (Cochran-Biederman et al. 2015; Hedden et al. 2023). This has led to a growing interest in the use of hatchery enrichment, such as flow training, to help recover this imperiled population by improving post-stocking survival. Thus, the goal of this study is to flow train Pikeminnow and achieve higher current velocities [i.e., 2 body lengths/s recommended by Rodgers and Isaza (2024)] and ascertain if this new regime is sufficient to improve stocking success. First, we asked if oxygen consumption rates would differ between control and flow-trained fish? We anticipated that flow-trained fish would have higher initial oxygen consumption rates but recover sooner than control fish. Second, we asked if flow training would improve initial post stocking survival of hatchery-stocked fish in the San Juan River. We hypothesized that flow-trained fish would have higher survival in the heterogeneous river flows than control fish. Finally, since we anticipated that flow training would better prepare stocked fish for conditions in the wild, we also predicted that flow-trained fish would be less likely to move downstream than control fish.

Methods

Study Area

The San Juan River is a major tributary of the Colorado River basin and has been greatly altered due to anthropogenic changes to the landscape and flow regimes. The river originates in the mountains of southwest Colorado and terminates in Lake Powell in Utah. After the construction of Navajo Dam in 1962, much of the river structure and flow regime drastically changed (Propst and Gido 2004). Although natural flow regimes in the San Juan river likely benefit native species (Gido and Propst 2012), attempts to mimic natural flow regimes are not often successful because of inadequate appropriation of water resources for environmental considerations (Pennock et al. 2022). The introduction of invasive plants such as Russian olive (*Elaeagnus angustifolia*) has further altered the river habitat by armoring river banks and increasing channelization.

The area of concern for this study extends from a weir at river kilometer (RKM) 269 to the Piute Farms Waterfall at RKM 0, which was the historic intersection with Lake Powell when the reservoir was full (Figure 2). The waterfall prevents upstream fish movement, whereas the weir has a fish passage facility. All fish stocking occurred near the Hogback Diversion at RKM 268.

Hatchery Enrichment

Pikeminnow were reared at the U.S. Fish and Wildlife Service, Southwestern Native Aquatic Resources and Recovery Center (SNARRC) in Dexter, New Mexico. The flow-training experiment took place in two outdoor raceways (Figure 1). The first cohort of fish were spawned in summer 2023 and stocked in the raceways on August 21, 2024, and flow training began on August 27, 2024. A subset of the 2023-year class were also held in ponds over a second winter and stocked in the raceways on February 5, 2025, with flow training beginning on February 10, 2025. A second cohort of fish spawned in summer 2024 were stocked in the raceways on August 19, 2025, with flow training beginning on August 25, 2025. For each of these three experiments, one raceway contained the control group, which experienced a static low flow regime of approximately 0.05 m/s for all three events. The second raceway was used for flow treatment of fish, and experienced static flows measured at 0.17 ± 0.07 m/s in 2024 and 0.18 ± 0.09 m/s in 2025 (Figure 1). Flow-trained fish also underwent three periods of increased mean flow averaging 0.24 ± 0.12 m/s in 2024 and 0.26 ± 0.14 m/s in 2025 each day. The duration of each flow period was increased by 5 minutes for each period every week, with the total time of flow training ranging from 15 minutes on week 1 to 1 hour and 30 minutes by week 6.

Effect of flow training on aerobic scope

Intermittent flow respirometry was used to test the effect of flow training on aerobic scope of pikeminnow. We used a Loligo Systems 5 L swimming respirometry system that has a chamber test section measured 38 x 10 x 10 cm and is recommended for fish sizes of 50 - 150g. Before any fish were placed in the respirometer a blank run was measured to determine the background respiration rate potentially caused by microorganisms (Little et al. 2020). To achieve maximum metabolic rate of pikeminnow, we used an exhaustive chase protocol outlined in previous respirometry studies (Clark et al. 2013; Norin and Clark 2016; Little et al. 2020). Before placing a control fish or flow fish in the chamber, they were placed in a circular tub and continuously chased until exhaustion. The fish was considered exhausted when it failed to swim away from stimuli (Zhang et al. 2020). Once exhausted, the fish was held out of water for 1 min of air exposure then placed in the chamber.

When starting a measurement cycle for blank trials or fish trials, the respirometer cycles through three distinct phases. The flush phase runs for approximately 1.5 min (90 s). Freshwater from the sump system is cycled into the respiration chamber and no oxygen measurements were used from this phase. Following the flush phase was a 1 min (60 s) wait phase, during which freshwater stopped being flushed into the system, no oxygen measurements were used from this phase as well. The final phase was a 10 min (600 s) measurement phase, oxygen measurements that were logged every second were later used for analysis. Only a single period was used for blank trials, occurring both before and after trials involving fish, which consisted of 10 cycles or approximately 2 hours. A static flow of 0.05 m/s was maintained automatically whenever conducting a trial. During trials, a cover was placed over the respirometer to block direct sunlight and potential disturbances to the chamber.

Oxygen consumption rates (mg O_2/hr/g) during the measurement phase were calculated using linear regressions to estimate the rate of decline in dissolved oxygen concentration over time. Background respiration rates were removed using blank control trials conducted before and after fish trials. Bayesian regression models were run for all three respirometry trial groups using 10 periods or roughly 2 hours of time in the chamber for each fish in R studio. The brms package was used with default brms priors (Bürkner 2017a, 2017b), and we tested treatment (flow vs control), period, and their interaction.

Stocking

Fish were stocked at three separate events, occurring in Fall 2024, Spring 2025, and Fall 2025. Stocking events released a varying number of fish which were roughly evenly split by treatment group but varied by mean lengths (Table 1). Spring 2025 stocking was broken up into two separate release dates, with the flow-trained fish stocked on April 6th and the control fish stocked on April 13th. This staggered stocking was an attempt to evaluate if treatment effects on dispersal might be confounded by schooling of fish from different treatment groups.

Effect of flow training on post-stocking survival and dispersal

Radio telemetry

Fifteen flow-trained and control pikeminnow had a transmitter implanted via surgery one week prior to stocking. A unique, non-coded external whiptail radio transmitter (ATS F1545, 1.0 g, ~ 55 day battery life) was inserted after fish were sedated in a container with 50 mg/L concentration of MS222. Fish were treated with salt and antibiotics following surgery to help wound healing. After stocking, daily tracking occurred during the first week and then every two weeks for 60 days post stocking to identify if individuals remained within the study reach and to quantify distance moved from either the stocking location or the previous location. The study reach covered by active tracking encompassed the 36.7 RKM downstream from the stocking site at Hogback for all three stocking events. Active tracking entailed floating by raft or walking by foot on shore in stocked reaches listening for radio frequencies with an Advanced Telemetry Systems (ATS) R4500S receiver and 3-element Yagi antenna.

Using occurrence data from the telemetry surveys, we assessed the effects of treatment (flow training), stocking event (Fall 2024, Spring 2025, Fall 2025), and week (week post stocking) on apparent survival (i.e., fish remaining minus mortality or emigration) using a Cormack-Jolly-Seber (CJS) model in Program MARK (White and Burnham 1999) to account for imperfect detection of radio-tagged fish (Cormack 1964; Jolly 1965; Seber 1965). We only considered an intercept only detection probability model, as detections were not expected to vary across different levels of treatments, stocking events or time. Initially, apparent survival models were ranked using Akaike's information criterion adjusted for small sample sizes (AICc) (Burnham and Anderson 2002; Lee et al. 2014). We selected the highest ranked model assessing our treatment effect since we were evaluating the difference in apparent survival between stocked flow-trained and control fish.

Passive Integrated Transponders (PIT) tag detections

To complement our radio telemetry observations, detections of stocked fish on PIT tag antennas were also used to estimate apparent survival. PIT tag antennas are maintained in the San Juan and adjacent rivers and tributaries to monitor fish movement to key areas. For the purposes of this study, we focused on PIT tag detections in the first 90 days post stocking, and specifically at arrays in the San Juan River at the Hogback stocking site along with the San Juan Restoration Site, Powerline, and McElmo Creek (Figure 2).

We assessed if the initial apparent survival of stocked fish varied between treatment groups for our three stocking events. The staggered stocking of Spring 2025 resulted in each stocking group being part of a different 90-day window beginning at stocking. Similar to above, intercept only detection model was also used while we assessed the effects of treatment (flow training) and stocking event (Fall 2024, Spring 2025, Fall 2025) on apparent survival and their interactions.

We modeled fish movement rate using Bayesian hurdle-lognormal model with the brms package with default brms priors (Bürkner 2017a, 2017b). We chose to use a hurdle model as our data were zero inflated and this approach allowed us to jointly test if there was a treatment difference in the probability of fish leaving the stocking site and if they did, if there was a difference in their movement rates by treatment. Predictor variables in our model were treatment (flow vs control) and stocking event (Fall 2024, Spring 2025, or Fall 2025). The first part of our hurdle model was a logistic model focused on the likelihood of a stocked fish to be detected at a PIT tag antenna downstream of the stocking site. The second part of our hurdle model focused exclusively on the movement rates between control and flow-trained fish. Dispersal rates were generated using known distance from stocking to a given array (San Juan Restoration Site: 38.9 RKM, Powerline: 55.7 RKM, McElmo: 93.7 RKM) and dividing by days to detection post stocking.

Results

Hatchery Enrichment

Total lengths were measured for a subset of stocked fish from both treatment groups prior to release for all three stocking events (Table 1). During the intermittent high flows, these velocities achieved 1.72, 1.76, and 1.22 body lengths/s for Fall 2024, Spring 2025, and Fall 2025 stocking events, respectively.

Effect of flow training on oxygen consumption

In Fall 2024, flow-trained fish consumed 8% more O_2/g/hr than controls in the first period of measurement (Figure 3). Flow-trained fish also reached recovery (i.e., stabilized oxygen concentrations) sooner, consuming 10% less oxygen than control fish. Flow-trained fish in our Fall 2025 trial also consumed 18% more oxygen initially than control fish but maintained higher rates of oxygen consumption throughout the trial. There was no noticeable effect between treatments for Spring 2025 fish throughout the entire respirometry trial. As predicted by allometric scaling, there was a negative relationship between fish mass and per capita oxygen consumption, with lower rates for larger fish in Fall 2025.

Stocking

Environmental conditions varied among stocking events (Figure 4). Mean daily discharge on the day of stocking in Fall 2024 was 93 m^3/s compared to 19 m^3/s in Spring 2025 and 36 m^3/s in Fall 2025. This was due to a large storm prior stocking in Fall 2024. A similar rise in discharge occurred prior to stocking in Fall 2025 but had subsided before stocking. There was an increase in mean daily discharge in Spring 2025 on day 60 post stocking due to spring runoff. Initial water temperatures were about 10ºC, across all stocking events but increased after the spring stocking and declined after both fall stockings (Figure 4). The highest daily mean water temperature for Spring 2025 occurred on day 87 post stocking and was 24.0 (°C). Mean daily water temperature on day 90 post stocking was 0.1 (°C), 23.5 (°C), and 2.5 (°C) for Fall 2024, Spring 2025 and Fall 2025, respectively.

Effect of flow training on post-stocking survival and dispersal

Radio Telemetry

The results from our CJS model from the first five weeks of each stocking event indicate minimal differences in apparent survival between our flow-trained and control fish (Figure 5). Our highest ranked model including a flow-treatment effect (AICc = 327.3, weight = 0.130) with a ΔAICc of 1.23 compared to our highest overall ranked model without a treatment effect (AICc = 326.07, weight = 0.240) (Table 2). Predicted apparent survival differed by week and stocking event, with slightly higher apparent survival of flow-trained fish (Table 3). This model predicted that at week 5 for Fall 2024 that 3 of 15 control fish and 5 of 15 flow-trained fish remained in the study reach downstream of the Hogback stocking site. This was lower than in Spring 2025 in which 10 of 15 control and 12 of 15 flow-trained fish remained in the study reach. Fall 2025 was similar to Fall 2024 with only 4 flow-trained and 6 control fish predicted to be present in the study reach after 5 weeks. Predicted values for flow-treatment and controls were within relatively large 95% confidence intervals.

Passive Integrated Transponders (PIT) tag detections

All stocked fish experienced a steep decline in survival regardless of stocking event, with the vast majority of fish presumed dead or emigrated from the system by the end of the 90-day window (Figure 6). Our top candidate model contained an interactive effect between treatment and stocking event, with no other candidate models within 2 ΔAIC of the top model (Table 4). The results from our CJS model derived from detections on PIT tag antennas for Fall 2024 and Fall 2025 suggest no difference in apparent survival between flow-trained and control fish. However, for Spring 2025 flow-trained fish were predicted to have an approximately 7% higher apparent survival rate than controls (Table 5). Spring 2025 flow-trained fish also ended with a 5% higher apparent survival rate than controls at the end of 12 weeks post stocking. Detections varied by week but notably declined substantially by week 6 for all stocking events (Figure 6). Our results for our CJS model using PIT detections consistently found fewer expected fish remaining at the same time period as the CJS model using radio telemetry detections (Table 6).

The hurdle model suggested similar probabilities of downstream detection between treatment groups (Figure 7, upper panel). Fish stocked in Spring 2025 were less likely to be detected at downstream arrays regardless of treatment groups (44.8% control, 30.0% flow) within the first 90 days post-stocking compared to fall stocking events. Fall 2025 fish were not as likely to be detected downstream as Fall 2024 fish but still 24.2% more likely for control fish and 27.8% for flow-trained fish compared to Spring 2025 fish. The only potential treatment effect was after the Fall of 2024 stocking, where flow-trained fish were 15.0% less likely to be detected at lower arrays rather than being detected at the stocking site compared to controls.

The second part of the hurdle model also predicted an interaction between treatment and stocking event on movement rates (Figure 7, lower panel). In Spring 2025, flow-trained fish moved, on average, 3.4 RKM/day compared to 0.6 RKM/day for controls. This difference was not observed in Fall 2024 or Fall 2025, which had similar movement rates between treatment groups.

Discussion

Although we achieved flow velocities near the body-lengths-per-second threshold recommended to improve hatchery fish performance and higher than other experiments at this facility (Figure 1), the response of Pikeminnow to this training regime was inconsistent across physiological and field metrics. Post-stocking apparent survival was low, and stocking season appeared to explain more variation than flow training alone. Stocked fish often dispersed rapidly downstream, particularly during fall stockings, indicating that retention in the upper river remains an issue. Oxygen consumption responses to flow training differed among stocking cohorts rather than showing a single repeatable treatment effect. Taken together, these results suggest that flow training by itself is not a universally effective enrichment tool for Pikeminnow, but that its value may depend on the environmental context in which fish are stocked.

Our strongest evidence for a positive treatment effect on survival was limited to the Spring 2025 stocking event. In the PIT tag antenna-based CJS analysis, flow-trained fish had approximately 7% higher early apparent survival than controls, which translated to 88% more total fish expected to remain in the study reach by the end of the 90-day modeling period. Even so, absolute numbers of fish remaining were still low, and both PIT tag antenna and radio telemetry detections declined sharply within the first few weeks after stocking. By contrast, neither fall stocking events showed a meaningful difference in apparent survival between treatments. This pattern is important because it suggests that any benefit of flow training was dependent on environmental conditions. This contrasts observations for razorback suckers, where flow conditioning doubled overwinter survival (Franssen et al. 2021). The razorback sucker and the Pikeminnow in both these studies were flow-trained at the same facility but under lower velocities (Figure 1), suggesting interspecific variation in enrichment effects.

Pikeminnow stocked in the fall rapidly dispersed downstream, with spring-stocked fish having higher retention overall regardless of treatment. Apparent survival in this study does not distinguish between true mortality and emigration, so rapid downstream dispersal directly reduces the number of fish available to be detected. Fall-stocked fish dispersed quickly, and in Fall 2024 flow-trained fish were 15% less likely than controls to be detected at downstream arrays, suggesting that flow training may have improved the ability of fish to maintain their position in the river during a high-flow release. The general tendency for hatchery fish to disperse rapidly after release is consistent with previous stocking studies, including work on rainbow trout (*Oncorhynchus mykiss*) and trout cod (*Maccullochella macquariensis*) that documented high post-release movement and reduced persistence of hatchery fish in the wild (Bettinger and Bettoli 2002; Ebner and Thiem 2009). Movement too far downstream in the San Juan River is problematic because fish passing over the Piute Farms Waterfall are effectively lost from the population and exposed to predation risks in Lake Powell. Thus, improvements in retention could increase survival and recruitment if they keep fish within the river network.

Seasonal and environmental context likely contributed substantially to these movement and survival patterns. Fall 2024 fish were released with substantially higher mean daily discharge measured at 93 m^3/s compared to 19 m^3/s for Spring 2025 and 36 m^3/s for Fall 2025. Those conditions likely promoted immediate downstream displacement and may help explain observed treatment differences in Fall 2024. Spring 2025 presented the opposite pattern: downstream detections were rare for both treatments, overall apparent survival was higher, and water temperatures increased steadily after stocking rather than declining toward winter. This seasonal contrast is also consistent with prior observations that juvenile Colorado Pikeminnow tend to move upstream in spring and summer and downstream in fall (Durst and Franssen 2014). Spring stocking may therefore provide advantages independent of flow training. First, fish appear less prone to downstream dispersal under lower initial discharge and warming conditions. Second, fish stocked in spring enter the river ahead of the period when larval fishes become available as prey in early summer, potentially improving opportunities for feeding and acclimation before winter. Although these hypotheses are derived from a single spring stocking event, combining seasonal stocking and flow-training might yield high enough recruitment to offset costs of maintaining fish overwinter in the hatchery.

Support for our hypothesis that flow training with alter fish physiology was much weaker and less consistent than expected. Flow-trained fish initially consumed more oxygen than controls in both fall cohorts, but recovery trajectories differed. In Spring 2025, however, there was little separation between treatments. Physiological responses to flow training may be strongly masked by hatchery conditions such as fish size and raceway density. Pikeminnow in Fall 2025 were more than 2X the mass of fish in fall stocking cohorts and had lower mass-specific oxygen consumption. It is possible, this allometric scaling minimized treatment differences. More notably, the Spring 2025 raceways held far more fish than either fall cohort. That density difference may have increased schooling behavior, which can reduce individual energetic costs through hydrodynamic benefits, reduced tail-beat frequency, and lower oxygen consumption (Weihs 1973; Herskin and Steffensen 1998). Similar to metabolic scaling, if schooling reduced energetic expenditure in the raceway, it may have dampened or obscured any treatment-driven physiological response.

Additional aspects of the physiological work also caution against overinterpreting respirometry results as a direct predictor of field success. We assumed that higher initial oxygen consumption after exhaustive chase would indicate improved recovery capacity, but the observed differences among treatments were modest and did not translate into a consistent survival benefit across stocking events. More broadly, maximum metabolic measurements do not always translate cleanly to ecological performance, and their relevance can depend strongly on assay design and interpretation (Norin and Clark 2016). Previous work has shown that performance in swim tunnels can reflect behavior in confinement as much as pure swimming capacity (Haro et al. 2004; Peake and Farrell 2006; Kern et al. 2018). We would observe sporadic spikes in oxygen consumption during some trials, which were not linked to any known external stressors which reinforce that point. Together, these results suggest that aerobic measurements can be used for comparing cohorts, but that they should be interpreted alongside hatchery context and field outcomes rather than as a standalone measure of stocking readiness.

Several study limitations also shape how these results should be interpreted. PIT tag antennas sampled a much larger downstream extent than radio telemetry surveys, but detections depended on fish passing a limited number of antenna locations and antenna performance varied across time. Radio telemetry had a relatively high estimated detection probability, yet it covered a shorter reach and could still miss fish that entered side channels or were removed from the river corridor by predators, a possibility also raised by Cleveland et al. (in review). In addition, the Spring 2025 staggered release created a one-week difference between treatments, meaning that some of the apparent treatment advantage could reflect short-term environmental differences rather than flow training alone. Handling and transport stress may also have contributed to early losses but were not measured directly (Johnson and Metcalf 1982). Even with those limitations, both detection methods converged on the same general conclusion, post-stocking losses were rapid, fall fish dispersed more than spring fish, and any benefit of flow training was small relative to the broader effects of season and river conditions.

Management Recommendations

From a management perspective, the evidence here does not support adopting flow training alone as a standard practice for fall stocking of Pikeminnow. Flow training produced no clear survival advantage in either fall event, and the physiological response was inconsistent across cohorts. This agrees with Cleveland et al. (in review), which only considered fall stocking. By contrast, the spring stocking consistently produced the most favorable combination of retention and apparent survival, making season of release something managers should consider. Should spring flow training be attempted again, researchers should consider standardizing fish size and raceway density across treatments. There are other methods of hatchery enrichment that show some promise for Pikeminnow on the San Juan River, particularly prey acquisition and predator avoidance, which are often poorly developed in hatchery environments and can sometimes be improved with training (Olla and Davis 1989; Olla et al. 1998). These methods could improve initial survival of Pikeminnow, with predation and adjusting to wild forage remaining potential bottlenecks to stocking success.

Figures

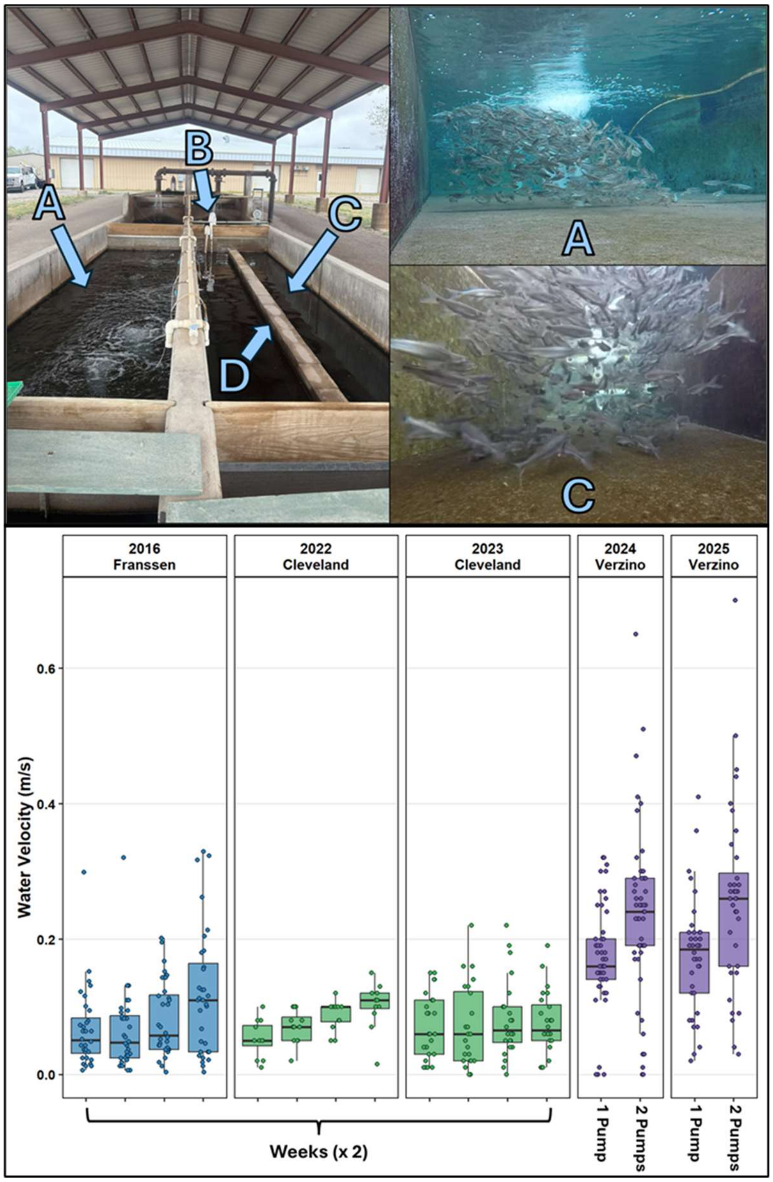

Figure 1: Outdoor raceways located at the Southwestern Native Aquatic Resources and Recovery Center (SNARRC) in Dexter, New Mexico. Fish in the control raceway (A) experienced static flow of 0.05 m/s for six weeks prior to stocking. Fish in the flow raceway (C) experienced static flows measured at 0.17 ± 0.07 m/s in 2024 and 0.18 ± 0.09 m/s in 2025 when one pump was running for six weeks prior to stocking. Two pumps (B) ran three times a day for a duration of 5 min with mean flows measured at 0.24 ± 0.12 m/s in 2024 and 0.26 ± 0.14 m/s in 2025. These cycles increased in duration by 5 min per-cycle each week. The flow raceway also contained a cinderblock divider (D) down the middle of the raceway. Box plots quantify flow velocities from previous studies (Franssen et al. 2021; Cleveland et al., in review) and this study (purple). The horizontal line is the median, boxes represent the 25th and 75th percentiles, whiskers the 10th and 90th percentiles, and circles outliers.

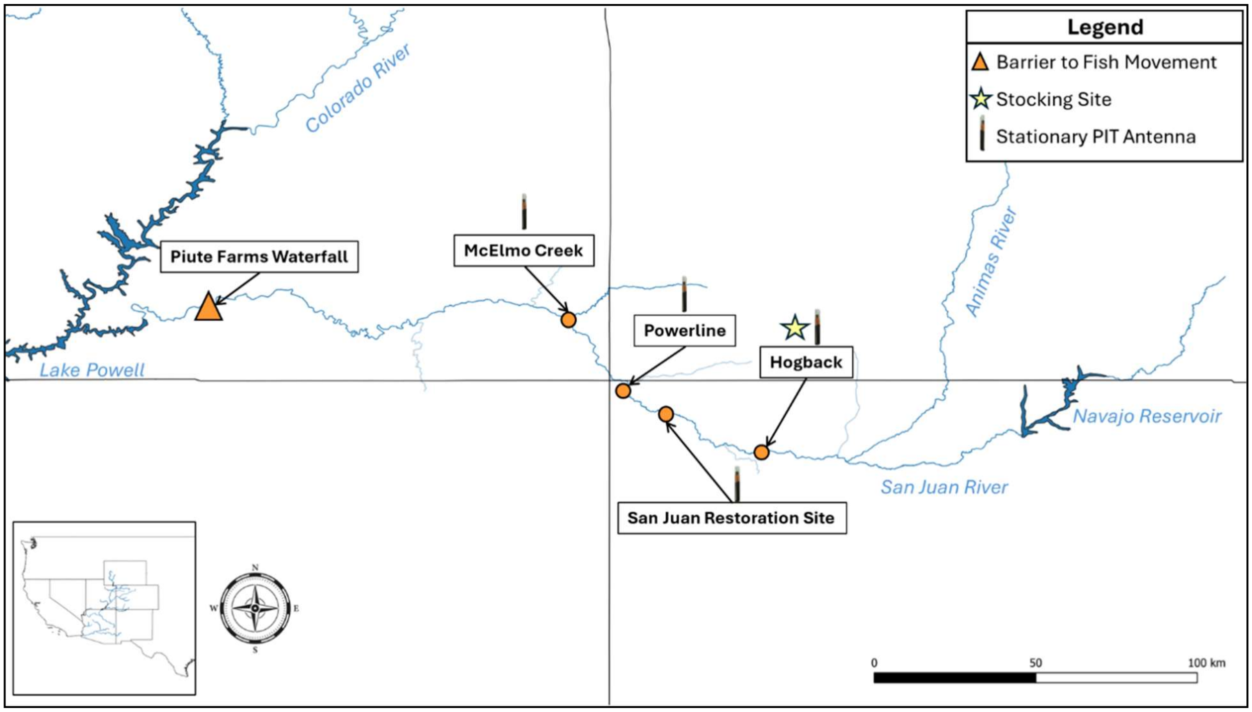

Figure 2: Study area of the San Juan River located in the southwestern United States. For all three stocking events, fish were released at Hogback (star,) which is also the location of stationary PIT antennas just upstream of the stocking site. Downstream stationary PIT antennas foccused on in this study are also denoted by name and location. The San Juan terminates into Lake Powell after the Piute Farms Waterfall (RKM 0), which is a barrier to upstream fish movement and where fish are considered out of the system once crossed.

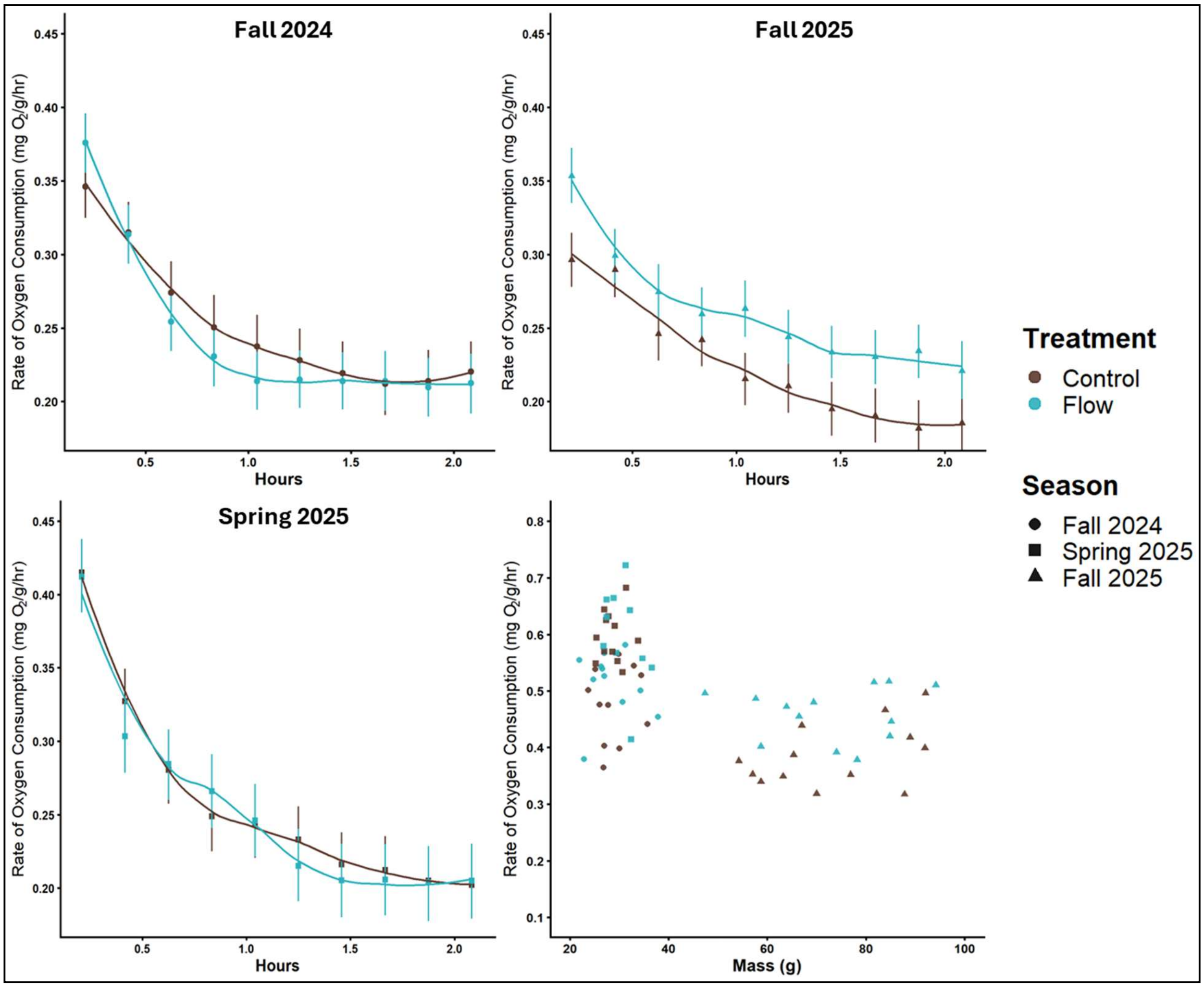

Figure 3: Results from all three respirometry trials with Fall 2024 (top left), Spring 2025 (bottom left), and Fall 2025 (top right). Raw respiration rates per fish and season are also plotted by weight of individual fish (bottom right). Brown represents control fish and blue represents flow fish, with circles indicating Fall 2024 trials, boxes Spring 2025, and triangles Fall 2025.

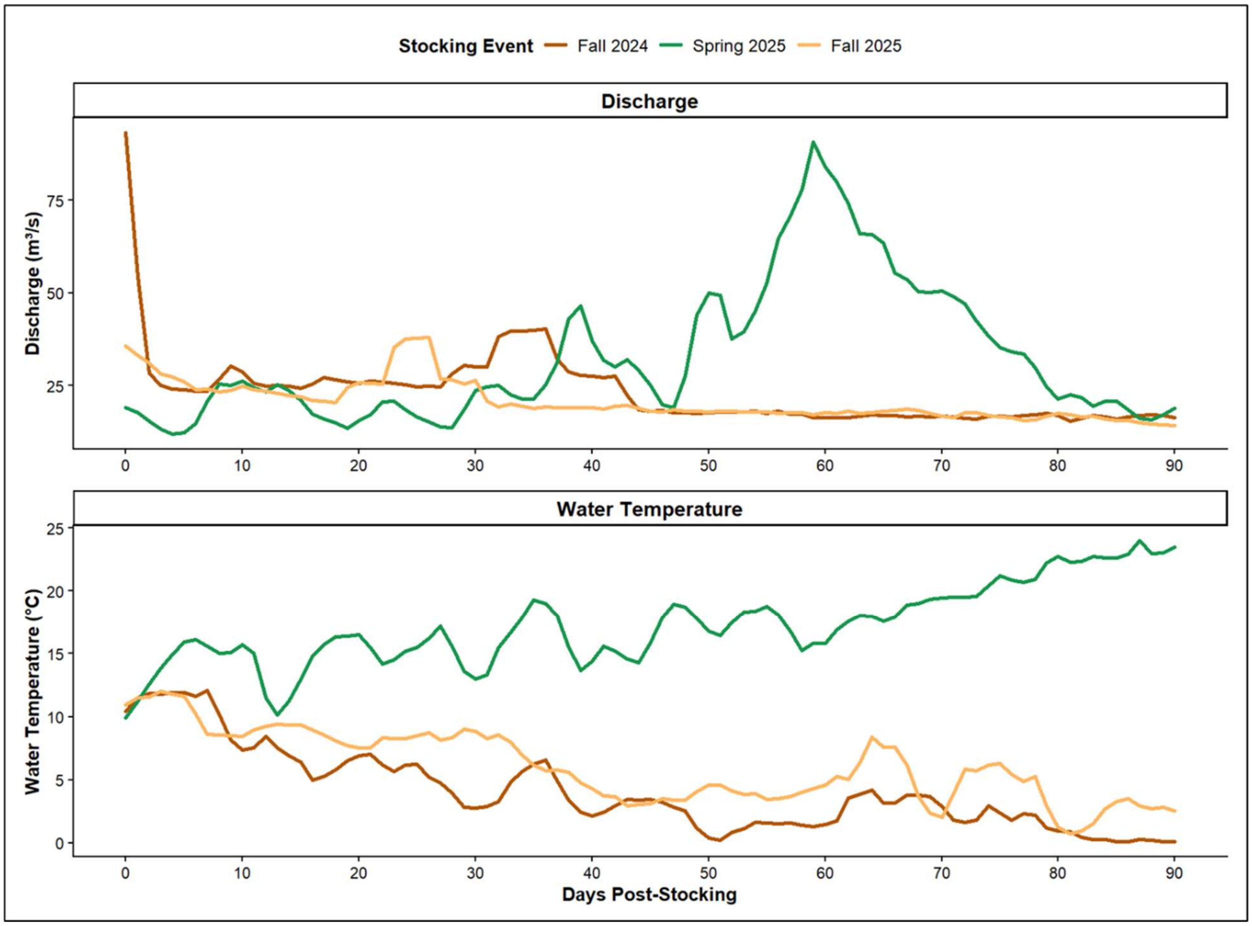

Figure 4: Environmental conditions (Discharge – Top, Water Temperature – Bottom) over 90 days post stocking. Discharge and water temperature data was gathered from USGS Shiprock Gauge and mean daily discharge and mean daily water temperatures were calculated for 90 days after each stocking event. Fall 2024 is denoted in orange, Spring 2025 is denoted in green, and Fall 2025 is denoted in gold.

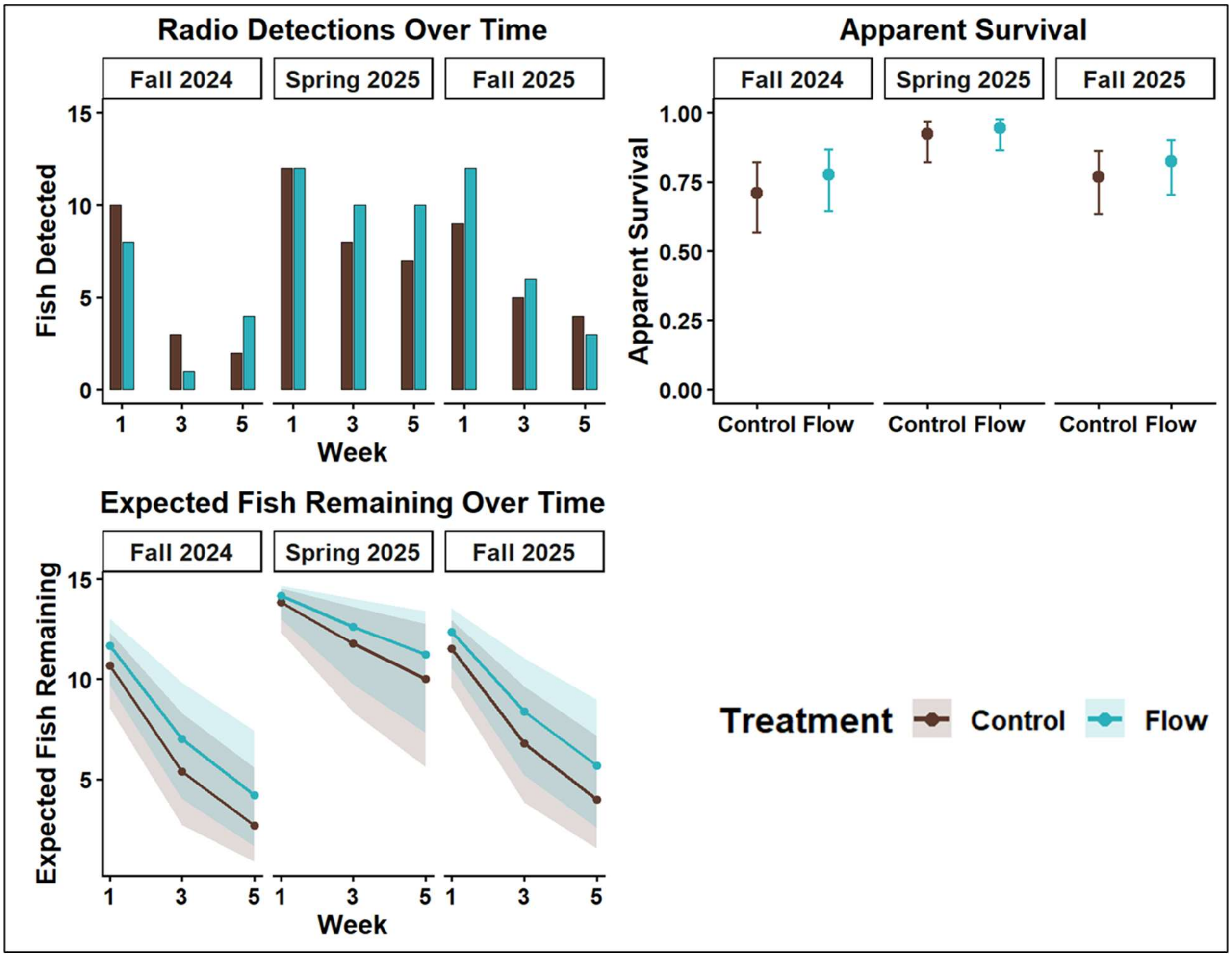

Figure 5: Number of radio tagged fish detected by week (top left), estimated apparent survival (top right) and predicted radio tagged fish remaining (bottom left) from Cormack-Jolly-Seber model over first 5 weeks post-stocking for all three stocking events. Detection probability was estimated at 0.74 (95% CI = 0.64 – 0.83). Estimated apparent survival for is applied to stocked radio tagged fish for each treatment group, control fish (brown) and flow-trained fish (blue). Expected fish remaining decreases quickly after stocking for Fall 2024 and 2025, but is less steep for Spring 2025. There is no meaningful difference between treatment groups by the end of the tracking period for all stocking events.

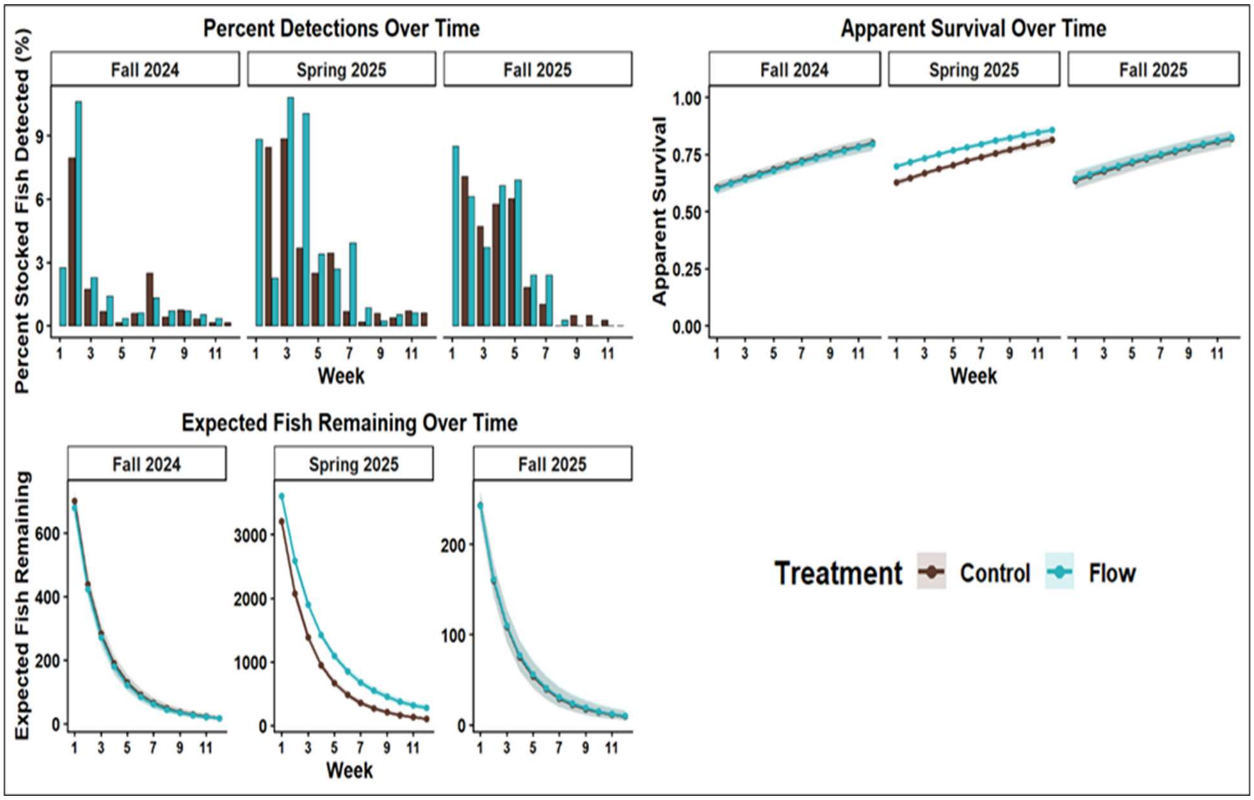

Figure 6: Percent of stocked fish detected over time (top left), estimated apparent survival by treatment (top right) and predicted PIT tagged fish remaining (bottom left) from Cormack-Jolly-Seber model over first 12 weeks post-stocking for all three stocking events. Detection probability was estimated at 0.17 (95% CI = 0.16 – 0.18). Expected fish remaining decreases quickly after stocking for all stocking events. There is an observed treatment effect for fish stocked in Spring 2025 with flow-trained fish having a higher apparent survival, most notably over the first four weeks post stocking.

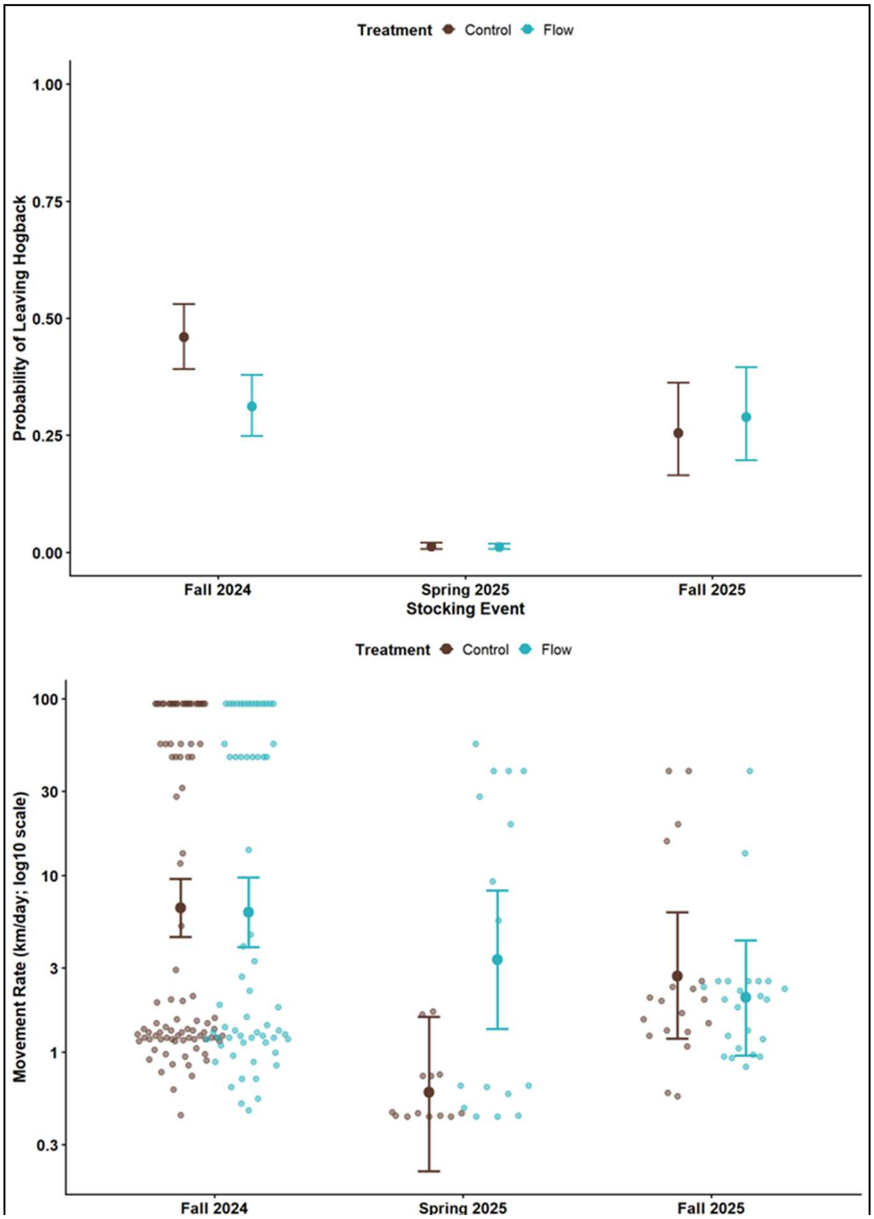

Figure 7: Probability a fish was detected downstream from stocking by treatment group and stocking event (top) and predicted movement rates in km/day on the log scale by treatment group and stocking event (bottom). Flow-trained fish (blue) were 15% less likely to be detected downstream from stocking than their control counterparts in Fall 2024. Spring 2025 fish in general were far less likely (<5%) to bet detected at downstream arrays for both treatment groups. Raw movement rates for fish detected downstream were calculated using distance to array/days since stocking and are denoted by circles for individual fish on a log10 scale. For Fall 2024 n=153, Spring 2025 n=30, and Fall 2025 n=42. Model predicted movement rates (circle) with credible intervals (bars) are overlayed for Fall 2024, Spring 2025 and Fall 2025 stocking events by treatment group, also on the log scale.

Tables

Table 1: Count of radio tagged and PIT tagged experiment pikeminnow stocked by stocking event and date released. Spring 2025 stocking event was split into two batches, with release dates of 4/6 and 4/13. Mean lengths (mm) for each treatment group for all three stocking events are reported with standard deviations for each group.

Date Released	Stocking Event	Treatment	# PIT Tagged	# Radio Tagged	Mean Length (mm)
10/22/2024	Fall 2024	Control	1141	15	144.29 ± 11.01
10/22/2024	Fall 2024	Flow	1114	15	139.56 ± 11.54
4/6/2025	Spring 2025	Control	0	0	0
4/6/2025	Spring 2025	Flow	5236	15	147.98 ±19.53
4/13/2025	Spring 2025	Control	5003	15	153.68 ± 20.42
4/13/2025	Spring 2025	Flow	0	0	0
10/22/2025	Fall 2025	Control	368	15	216.16 ± 21.22
10/22/2025	Fall 2025	Flow	362	15	213.91 ± 19.78

Table 2. Candidate Cormack–Jolly–Seber model comparison for radio telemetry detections of Pikeminnow post-stocking. Models evaluated apparent survival, ϕ, as a function of treatment, stocking event, and week, while detection probability, p, was held constant across all candidate models. Week was modeled as a continuous covariate using telemetry sampling occasions at weeks 1, 3, and 5. Parameters is the number of estimated parameters, AICc is Akaike's Information Criterion corrected for small sample size, ΔAICc is the difference from the lowest-AICc model, and AIC Weight is the AICc model weight.

Model	Parameters	AICc	ΔAICc	AIC Weight
ϕ(Stocking event), p(.)	4	324.55	0.00	0.488
ϕ(Treatment + Stocking event), p(.)	5	325.84	1.28	0.257
ϕ(Stocking event + Week), p(.)	5	326.71	2.15	0.166
ϕ(Treatment × Stocking event), p(.)	7	329.00	4.44	0.053
ϕ(Treatment × Stocking event + Week), p(.)	8	331.31	6.76	0.017
ϕ(Treatment + Stocking event × Week), p(.)	8	332.56	8.01	0.009
ϕ(.), p(.)	2	333.67	9.11	0.005
ϕ(Treatment), p(.)	3	334.64	10.08	0.003
ϕ(Week), p(.)	3	335.80	11.24	0.002
ϕ(Treatment × Stocking event × Week), p(.)	13	341.51	16.96	<0.001

Table 3: Predicted Apparent Survival by week and expected fish remaining at week 5 post stocking from Cormack-Jolly-Seber model for radio telemetry by stocking event and treatment group.

Stocking Event	Treatment	Week 1 Apparent Survival	95% CI	Week 3 Apparent Survival	95% CI	Week 5 Apparent Survival	95% CI	Final Expected Fish Remaining	95% CI
Fall 2024	Control	0.80	0.53 – 0.93	0.38	0.20 – 0.61	0.62	0.28 – 0.88	3	0 – 7
Fall 2024	Flow	0.86	0.63 – 0.96	0.49	0.28 – 0.70	0.72	0.37 – 0.92	5	1 – 9
Spring 2025	Control	0.96	0.82 – 0.99	0.79	0.56 – 0.92	0.91	0.65 – 0.99	10	5 – 13
Spring 2025	Flow	0.97	0.87 – 0.99	0.85	0.67 – 0.94	0.94	0.73 – 0.99	12	6 – 14
Fall 2025	Control	0.85	0.60 – 0.96	0.48	0.27 – 0.68	0.71	0.35 – 0.92	4	1 – 9
Fall 2025	Flow	0.90	0.69 – 0.97	0.58	0.37 – 0.77	0.79	0.44 – 0.95	6	2 – 11

Table 4. Candidate Cormack–Jolly–Seber model comparison for apparent survival of Pikeminnow during the first 90 days post-stocking. Models evaluated apparent survival, ϕ, as a function of treatment, stocking event, and week, while detection probability, p, was held constant across all candidate models. Week was modeled as a continuous covariate. Parameters is the number of estimated parameters, ΔAIC is the difference from the lowest-AIC model, and AIC Weight is the Akaike model weight.

Model	Parameters	AIC	ΔAIC	AIC Weight
ϕ(Treatment × Stocking event + Week), p(.)	8	37,278.95	0.00	1.000
ϕ(Treatment + Stocking event + Week), p(.)	6	37,297.09	18.14	<0.001
ϕ(Treatment + Week), p(.)	4	37,339.45	60.50	<0.001
ϕ(Treatment × Stocking event), p(.)	7	37,383.91	104.96	<0.001
ϕ(Treatment + Stocking event), p(.)	5	37,393.50	114.55	<0.001
ϕ(Week), p(.)	3	37,424.55	145.60	<0.001
ϕ(Stocking event), p(.)	4	37,439.06	160.11	<0.001
ϕ(Treatment), p(.)	3	37,458.99	180.04	<0.001
ϕ(.), p(.)	2	37,508.85	229.90	<0.001

Table 5: Predicted Apparent Survival initially and on the final week of monitoring and expected fish remaining at 90 days post stocking from Cormack-Jolly-Seber model for PIT detections by stocking event and treatment group.

Stocking Event	Treatment	Initial Apparent Survival	95% CI	End Apparent Survival	95% CI	Final Expected Fish Remaining	95% CI
Fall 2024	Control	0.61	0.58 – 0.63	0.80	0.77 – 0.83	18	11 – 26
Fall 2024	Flow	0.60	0.57 – 0.63	0.80	0.76– 0.82	16	10 – 24
Spring 2025	Control	0.63	0.61 – 0.64	0.81	0.79 – 0.83	107	83 – 136
Spring 2025	Flow	0.70	0.69 – 0.71	0.86	0.84 – 0.88	276	225 – 258
Fall 2025	Control	0.64	0.60 – 0.68	0.82	0.78 – 0.85	9	5 – 16
Fall 2025	Flow	0.64	0.61 – 0.68	0.83	0.79 – 0.86	10	5 – 17

Table 6: Percent of stocked fish expected remaining at week 5 post stocking from CJS models for both radio telemetry and PIT detections by stocking event and treatment. Percent difference denotes the percent difference of expected fish between both sampling methods.

Stocking Event	Treatment	Radio Week 5 Expected Fish Remaining	95% CI	PIT Week 5 Expected Fish Remaining	95% CI	Percent Difference
Fall 2024	Control	3 (20%)	0 – 7	129 (11%)	107 – 154	9%
Fall 2024	Flow	5 (33%)	1 – 9	122 (11%)	100 – 146	22%
Spring 2025	Control	10 (67%)	5 – 13	670 (13%)	609 – 733	54%
Spring 2025	Flow	12 (80%)	6 – 14	1095 (21%)	1022 – 1170	59%
Fall 2025	Control	4 (27%)	1 – 9	54 (14%)	40 – 69	13%
Fall 2025	Flow	6 (40%)	2 – 11	56 (15%)	42 – 71	25%

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