Navigating Together: Using Boids-Based ABM to Improve Fish Passage for Schooling Species

Despite significant advancements in fish passage design, many structures still fail to account for the complex schooling behaviors that certain species rely on for successful migration. Traditional agent-based models (ABMs) in fish passage research emphasize individual responses to environmental conditions, often overlooking the critical inter-agent interactions that shape group dynamics. To address this gap, this study incorporates a Boids-based algorithm to simulate schooling, offering a more comprehensive approach to understanding fish passage dynamics and improving design outcomes for schooling species. ABMs are comprised of goal-oriented, autonomous software agents that interact within a simulated environment. These agents perceive their surroundings, assess internal conditions (e.g., fatigue), navigate obstacles, and make decisions to maximize well-being, all while pursuing a shared objective of successful passage. Through ABMs, we can assess how individual interactions, such as those found in schooling, influence overall fish passage performance.

In 2006, Goodwin developed the Eulerian-Lagrangian-Agent Method (ELAM) to assess downstream fish passage performance, integrating Eulerian descriptions, Lagrangian formulations, and agent-based frameworks into a single simulation environment (Weber, 2006). Goodwin’s work demonstrated the potential of ABMs to simulate fish behavior in artificial or modified waterways, providing insight into the effectiveness of passage structures like ladders and bypasses (Goodwin, 2006). Building on this foundation, studies have refined ABMs, incorporating habitat preferences and environmental conditions by 2010 to improve accuracy and predictability in fish passage assessments (Friedman et al., 2010). By 2015, researchers developed multi-species models, enabling interactions between fish species and different passage structures (Biro et al., 2015). Recent advancements highlight the adaptability of ABMs in exploring climate impacts and habitat changes on fish migration (Miller et al., 2018). Models now combine swimming performance with fluid dynamics to simulate upstream movements under turbulent conditions, which is crucial for managing fish movement in challenging ecological scenarios (Zelinski, 2018). Modifications to ABMs allow agents to occupy dynamic positions within the computational domain, creating smoother trajectories and improving passage estimates compared to earlier CFD-ABM combinations (Gilmanov, 2019).

While previous ABMs in fish passage modeling have primarily focused on individual responses to environmental conditions, this study extends these models by incorporating Reynolds' (1987) Boids algorithm to simulate schooling behavior. The Boids algorithm operates through three simple rules—cohesion, separation, and alignment—that, when applied to individual agents, generate emergent group dynamics similar to natural schooling, flocking, or herding behaviors. These rules enable agents to maintain proximity to neighbors, avoid crowding, and align their direction of movement, creating realistic group formations without centralized control (Reynolds, 1987). Boids has been influential in fish behavior research, especially in simulating schooling, which is critical for energy conservation, coordinated movement, and predator evasion. For example, Couzin et al. (2005) applied Boids principles to analyze collective decision-making in fish, showing how individual interactions produce effective group responses to environmental cues. Similarly, Weihs (1973) demonstrated that schooling enhances hydrodynamic efficiency, a behavior that Boids-style models can replicate through cohesion and alignment rules. More recent studies, such as Herbert-Read et al. (2011), have used Boids-based algorithms to simulate collective vigilance and fast, accurate group decision-making in fish shoals. By integrating Boids into an ABM for fish passage, this study aims to address congestion-related delays and improve the understanding of how collective behavior impacts passage success in schooling species.