

Assessment Methods, Bias Sources, and Improvement Strategies for Fishway Attraction and Passage Efficiency

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Abstract. River-crossing hydraulic structures fragment longitudinal river connectivity and make fishways an important mitigation measure for migratory fish. In post-construction assessment, attraction efficiency (AE) and passage efficiency (PE) are widely used to describe whether fish can find the entrance and then complete passage through the structure. These metrics are useful but not self-evident measures of ecological success. Their values may be distorted by capture stress, sample source, release location, tagging and anesthesia procedures, detector efficiency, monitoring period, and fallback behavior. At the same time, real differences among fish species, body size, swimming ability, habitat preference, fishway type, and hydraulic conditions can produce legitimate variation among studies. Confusing methodological bias with biological or hydraulic heterogeneity may lead to over- or underestimation of fishway performance and then affect engineering modification, flow regulation, and restoration decisions. This review summarizes the meaning of AE and PE, common monitoring methods, major bias sources, interpretation risks, and practical ways to improve reliability. Standardized protocols, detection-probability calibration, method cross-validation, behavioral and physiological indicators, and population-scale monitoring are recommended for more defensible fishway evaluation.

Keywords: fishway, attraction efficiency, passage efficiency, electronic telemetry, assessment bias

1. Introduction

Hydropower stations, diversion dams, and low-head weirs support flood control, power generation, irrigation, and water supply. They also interrupt longitudinal river connectivity and can block routes used by fish for feeding, overwintering, and spawning. For migratory species, the loss of access to critical habitats can reduce reproductive success, alter community composition, and increase the risk of local population decline [1, 2]. Fish passage facilities, including fishways, fish lifts, and trap-and-transport systems, are therefore used to reduce barrier effects, and fishways remain one of the most common engineering options.

The existence of a fishway does not mean that it is ecologically effective. Early evaluations often counted only fish detected at the exit or upstream side. Such counts ignore two separate processes: fish downstream must first locate and enter the entrance, and fish that enter must then negotiate

internal slopes, pools, slots, drops, and turbulent flow. Attraction efficiency and passage efficiency were developed to separate these stages. AE describes the proportion of available or released fish that reach or enter the entrance zone, while PE describes the proportion of entrance-detected fish that reach the exit or upstream water [1, 3].

Electronic telemetry has greatly improved this assessment. Passive integrated transponder (PIT), radio, and acoustic tags allow researchers to monitor individual fish at entrances, internal pools, exits, and adjacent river reaches. These data can separate attraction, entry, delay, successful passage, and fallback events more clearly than mark-recapture or a single video counter [3, 4]. However, telemetry records are still shaped by experimental design and field conditions. A high or low efficiency value should be read as an estimate with assumptions, not as direct proof of ecological benefit.

Uncertainty in fishway assessment has two main sources. Methodological bias affects whether the estimate is accurate; it includes capture stress, tagging effects, artificial release points, detector failure, missed detections, and repeated counts. True heterogeneity reflects actual biological and hydraulic differences among fish species, life stages, fishway types, and flow conditions. The distinction matters because a biased estimate requires methodological correction, whereas real heterogeneity requires stratified interpretation. This review discusses both issues and proposes practical steps to improve the reliability and use of AE and PE.

2. Indicator meaning and measurement methods

2.1. Fishway effectiveness and efficiency indicators

Fishway effectiveness is broader than any single efficiency value. A fishway intended to restore migration should pass the right species at the right season, with limited delay and stress, and should connect fish to suitable upstream habitats where survival and recruitment are possible [4, 5]. AE and PE are therefore important quantitative indicators, but they are only one part of an effectiveness assessment.

In most telemetry studies, AE and PE can be expressed as follows:

$$AE = \frac{N_{\text{entrance}}}{N_{\text{downstream}}} \times 100\% \quad (1)$$

$$PE = \frac{N_{\text{exit}}}{N_{\text{entrance}}} \times 100\% \quad (2)$$

Here, N_{entrance} is the number of tagged fish detected at or inside the entrance, $N_{\text{downstream}}$ is the number of available or released fish downstream, and N_{exit} is the number detected at the exit or upstream. When both metrics are available, overall upstream success can be approximated as $AE \times PE$. This decomposition is useful because failure at the entrance requires different engineering or operational responses from failure inside the fishway.

2.2. Traditional monitoring methods

Mark-recapture and video observation were among the earliest methods used in fishway studies. Mark-recapture identifies fish with external marks, fin clips, pigments, or similar treatments, and then relies on recapture at the exit or upstream. Video observation uses underwater or bank-based cameras to record fish passing a defined cross-section, and is especially useful in small streams, clear water, or shallow fishway sections [6, 7].

Both methods can provide basic information on fish presence and passage, but their limitations are substantial. Mark-recapture often fails to recapture fish at the entrance, so attraction and passage stages become mixed. Video reduces handling stress and can generate continuous observations, as illustrated in Figure 1, but turbid water, weak light, dense fish schools, and repeated movements can cause species misidentification, missed counts, or duplicate counts. It is also difficult for video alone to determine how many fish downstream actively searched for the entrance.

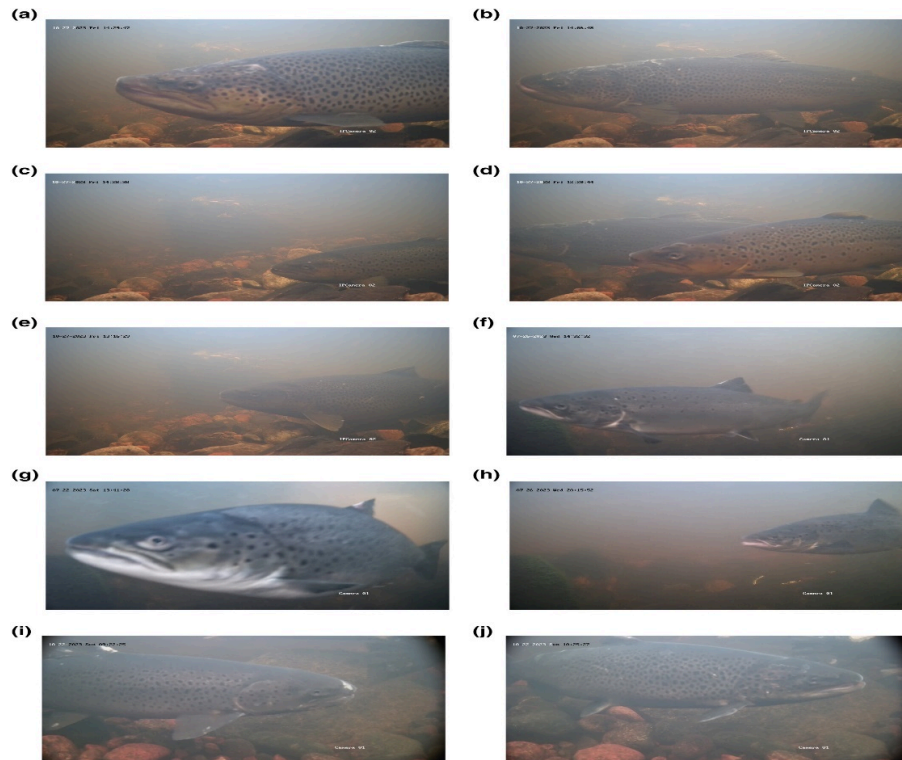


Figure 1. Examples of video observation for salmonids in small rivers. (a-e) sea trout from the Skeboån River; (f) salmon, (g) sea trout, and (h) salmon from the Mörrumsån River; (i,j) salmon, sea trout, or hybrids from the Dalälven River that could not be further separated by the original authors [7]

2.3. Electronic telemetry

Electronic telemetry addresses many weaknesses of traditional methods by giving each tagged fish a unique identity. Common systems include PIT tags, radio transmitters, and acoustic transmitters. Antennas or hydrophones can be placed near the entrance, in selected pools, at the exit, and in upstream or downstream reaches to record the time and direction of movement through different sections [3, 8, 9].

A typical telemetry design combines tag detection, entrance or exit receivers, and auxiliary devices such as collection nets or validation cameras (Figure 2). The method can distinguish fish that never reach the entrance, fish that enter but stall or move back, and fish that complete passage and later fall back. For this reason, telemetry is now the main technical basis for estimating AE, PE, passage time, and migration delay. Its strength, however, depends on careful detector placement and calibration.

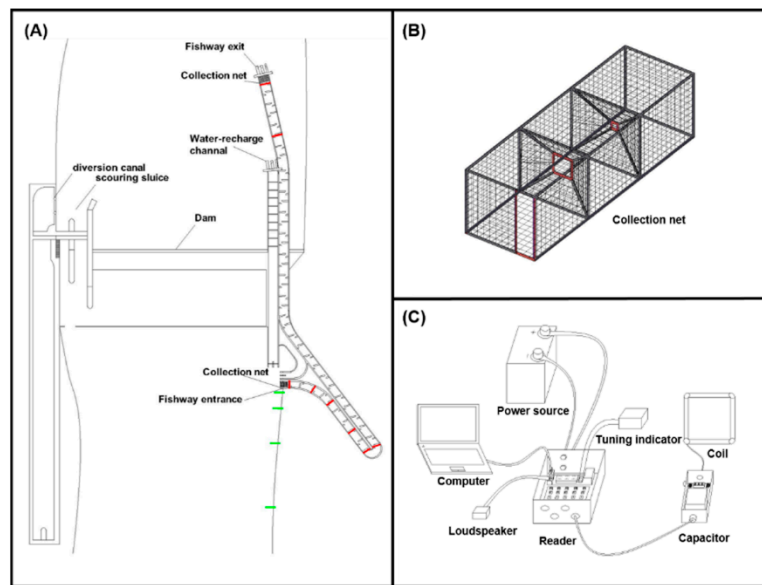


Figure 2. Schematic diagram of a vertical-slot fishway and monitoring equipment. (a) Monitoring layout, with green boxes showing fish release locations and red boxes showing RFID deployment; (b) collection net device with a narrowing mouth and constricted section for upstream migrants; (c) radio frequency identification (RFID) equipment [8]

2.4. Manual tracking and fixed automatic monitoring

Telemetry can be implemented by manual mobile tracking or fixed automatic monitoring. Manual tracking requires researchers to carry receiving equipment along the river or dam area. It is useful for describing search paths, residence areas, and attraction to high-flow zones, but it is limited by field safety, weather, working hours, and the difficulty of tracking many moving fish at the same time.

Fixed automatic monitoring uses antennas or hydrophones at the entrance, exit, and key internal sections. It provides continuous and standardized data for calculating AE and PE. To determine movement direction, paired detectors are often needed at entrances and exits. In practice, the strongest design usually combines fixed monitoring for continuous event detection with manual tracking or video for behavioral interpretation.

3. Methodological bias in efficiency assessment

3.1. Capture method and handling

Most field studies first capture fish and then tag, hold, and release them. Electrofishing, gill nets, trap nets, dip nets, and angling can cause scale loss, fin abrasion, skin injury, acute stress, lactate accumulation, and changes in metabolic state [10, 11]. These effects are especially important during reproductive migration, when fish have high energetic demand and strong sensitivity to disturbance.

Injured or highly stressed fish may remain inactive after release, leave the monitoring reach, move downstream, or swim in abnormal directions. Such responses can reduce apparent AE and PE even when the fishway itself is not the main barrier. Capture method should therefore be treated as part of the experimental design rather than as a neutral preparation step.

3.2. Capture location and sample selection

Capture location strongly affects the biological meaning of a test sample. Fish captured immediately below a dam may include individuals that live in the tailrace but are not actively migrating. Fish captured farther downstream may have less prior experience with the fishway, but some may not yet have entered the migration window. Both choices can affect efficiency estimates [5].

A different bias occurs when fish are taken from within the fishway, from a top trapping pool, or from upstream and then released downstream for a new trial. These individuals may already know the route and pass again more easily, or they may be exhausted after repeated attempts. Sample source and prior fishway experience should therefore be reported and considered before results are generalized to the natural population.

3.3. Release location after tagging

Release location determines the starting point of the entrance search and the hydraulic environment encountered by fish. Releasing fish directly at the entrance, in the attraction flow, or inside the fishway can be useful for diagnosing local hydraulic problems. It cannot, however, represent complete attraction efficiency because the natural downstream search process has been bypassed.

For whole-fishway performance, tagged fish should be released in a downstream reach that represents natural upstream movement. For diagnosis of a pool, slot, or drop, internal release can be used, but the result should be described as a passage-stage or local hydraulic test rather than as an estimate of overall fishway effectiveness.

3.4. Timing and recovery

Fish migration is regulated by reproductive condition, water temperature, discharge, season, and diel rhythm [5, 10]. If capture, tagging, holding, and release do not match the natural migration window, efficiency values may be biased. Disturbance during a migration peak can cause fish to retreat, while release during a non-peak period may underestimate motivation and passage ability.

Recovery after tagging is equally important. Anesthesia and surgery can temporarily reduce swimming or sensory ability. If fish are released before recovery, PE may be underestimated; if fish are held too long, their natural migration rhythm and energy state may change. Studies should therefore report holding time, release criteria, water temperature, flow, and date of release.

3.5. Tagging and anesthesia protocol

Electronic tags can be implanted internally, attached externally, or placed in the stomach. Tag mass and size increase drag and energy expenditure, especially for small fish. Anesthesia reduces handling injury but can temporarily affect neural response, olfactory orientation, and swimming performance [11, 12]. Tag type, burden ratio, surgery time, anesthetic concentration, and recovery condition should therefore be reported in detail.

Internal implantation is often preferred for long-term studies, but it can still cause incision injury, inflammation, scarring, or variable healing. External attachment is faster and may suit short-term monitoring, but detachment, external drag, and attachment-site injury can also change behavior. Figure 3 illustrates that wounds, scars, tag migration, and tissue encapsulation have been observed across different fish species after electronic tagging.



Figure 3. Healing and injury conditions of electronically tagged fish observed in the field. (a) *Raja undulata* acoustic-tag incision healed after 1085 d; (b) *Anguilla anguilla* scarring about 1 year after tagging; (c) *Carassius auratus* with remaining suture about 15 months after tagging; (d) *Esox lucius* suspected fin injury from suture irritation; (e) *Carcharodon carcharias* dorsal fin wound after temporary camera-accelerometer attachment; (f) *Galeocerdo cuvier* satellite transmitter with biofouling and migration; (g) *Squalius cephalus* transmitter encapsulated by tissue; (h) *Heterodontus portusjacksoni* incision healing 42 d after surgery, unsutured at left and sutured at right; (i) *Lethrinus miniatus* incision healing 132 d after surgery; (j) *Thunnus thynnus* acoustic transmitter site and pop-up satellite tag detachment site [12]

3.6. Detection probability and equipment stability

Telemetry reliability depends on tag operation, antenna or hydrophone placement, power supply, data storage, and decoding performance. Turbulent water, floating debris, noise, changing submergence depth, and temporary power failure can all reduce detection. PIT antennas may miss tags when several fish pass at once, and radio or acoustic systems can suffer from signal masking, collision, false detections, or positioning error [9].

Uncalibrated equipment can shift both numerator and denominator of AE and PE. A missed entrance detection can make a fish appear never attracted, while a missed exit detection can make a successful passage appear as failure. Paired detectors, test tags, routine calibration, and reporting of detector downtime are essential for credible estimates.

3.7. Fallback and repeated detection

Fallback occurs when fish pass upstream and later descend through the fishway, spillway, turbines, or other routes. It may reflect foraging, habitat search, migration path correction, or attraction to strong upstream currents and spillway flow [13]. If monitoring cannot distinguish first passage, repeated passage, and reascension after fallback, PE and total escapement can be misinterpreted.

Video counting is particularly vulnerable because the same fish may be counted several times. Telemetry can identify individuals, but only if detectors are arranged to infer direction and the analysis removes repeated records. Otherwise, passage may be overestimated. Conversely, if mortality or delay after fallback is incorrectly attributed to the fishway itself, passage capacity may be underestimated.

4. True heterogeneity affecting interpretation

4.1. Fish species and behavior

Species differences are not simply measurement error. Fish differ in endurance, burst speed, body size, water-column preference, rheotaxis, and migration motivation. Many early fishways were designed for strong-swimming salmonids, so applying the same thresholds to non-salmonids, benthic species, or small-bodied fish can be misleading [1, 2].

Meta-analyses show that salmonids generally pass more successfully than many non-salmonid groups, but non-salmonids are not a single functional group (Figure 4). Some cyprinids can perform well under suitable hydraulic conditions, while benthic species may depend on bottom low-velocity routes [2, 10, 11]. Efficiency data should therefore be reported by target species, body size, and ecological type.

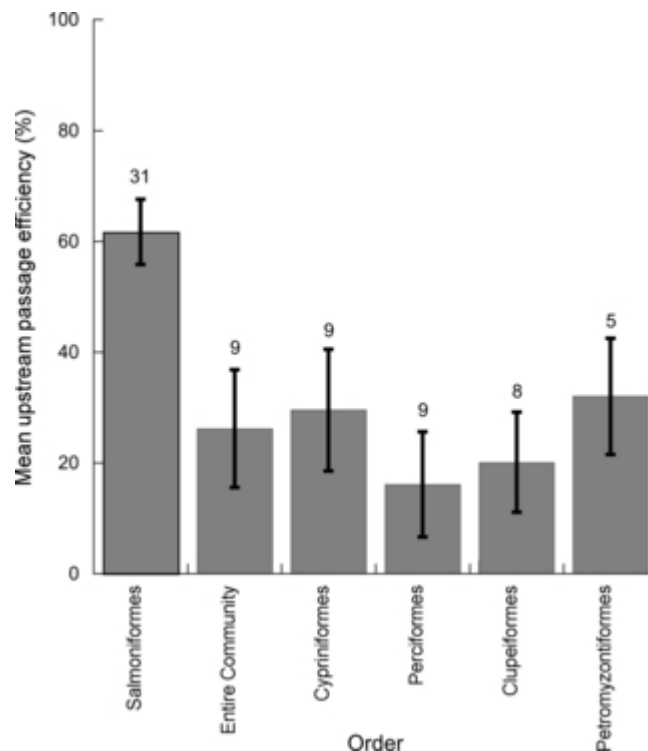


Figure 4. Mean upstream passage efficiency among fish groups. The original figure reports order-level mean $\pm$ SE for groups with sample size $N \geq 5$; "entire community" denotes the non-salmonid community without separation into orders, and numbers above bars indicate sample sizes [1]

4.2. Fishway type and hydraulic structure

Fishway type creates real variation through entrance velocity, slope, pool structure, energy dissipation, and turbulence. Pool-and-weir fishways can produce a clear attraction flow but may

contain drops and high-velocity zones that restrict weak swimmers. Nature-like fishways often provide gentle slopes and more natural microhabitats after entry, but weak entrance velocity may reduce long-distance attraction. Vertical-slot fishways tolerate changing water levels, but slope, pool length, and slot velocity still affect passage [2, 6].

For this reason, fishway assessment should not seek a universal ranking of designs. Figure 5 shows that suitability can differ between salmonids and non-salmonids. A type with moderate overall performance may still be appropriate for a particular species or flow condition. Treating structural and hydraulic variation as measurement bias would hide the real design question.

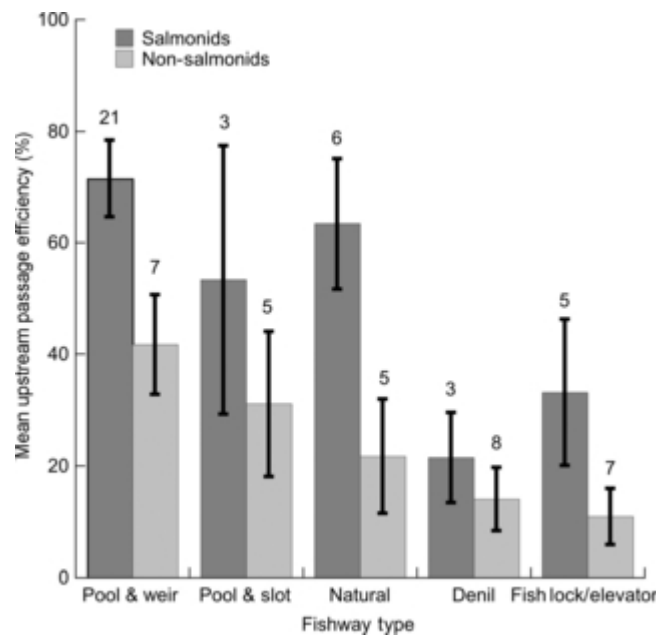


Figure 5. Upstream passage efficiency of salmonids and non-salmonids across fishway types. The original figure reports mean $\pm$ SE values and sample sizes for five fish passage types [1]

5. Decision risks from biased estimates

5.1. Overestimation

Overestimated efficiency can make a flawed fishway appear successful. Managers may postpone entrance modification, flow adjustment, or supplementary monitoring, and a problematic design may be copied to other projects. Ecologically, overestimation can hide migration delay, post-passage mortality, unsuitable upstream habitat, or passage by non-target species. A high AE or PE therefore does not prove restoration success unless the right fish pass at the right time and contribute to recruitment.

5.2. Underestimation

Underestimation can also mislead management. A fishway that works for the target species may be judged inefficient because of capture injury, tag burden, missed detections, or poor release timing. This can trigger unnecessary engineering modification or inappropriate flow changes. It can also distort the evidence base for future design by making useful fishway types appear ineffective.

5.3. Over-generalization

A further risk is over-generalization. Efficiency values should not be reduced to simple claims that a fishway type is good or bad. Results are conditional on species, life stage, monitoring method, tag burden, release point, detector performance, discharge, and structure. These conditions should be stated clearly so that conclusions are applied only where they are justified.

6. Improvement strategies

6.1. Transparent protocols

Reliable assessment begins with transparent methods. Studies should report capture gear, capture location, fish size, tag model, tag burden, anesthesia, surgery time, recovery criteria, release location, detector layout, operating flow, water temperature, and equipment downtime. Without these details, later readers cannot know whether differences among studies reflect fishway performance or experimental design.

Where possible, control or barrier-free reaches should be used to estimate natural migration failure and background detection performance [4]. Applying multiple methods to the same fish or same period, such as PIT plus video or acoustic telemetry plus manual tracking, can identify systematic bias and improve confidence in AE and PE.

6.2. Equipment calibration

Before formal monitoring, antennas, hydrophones, receivers, and tags should be field-tested under relevant water levels and flows. Key sections should use paired detectors to determine movement direction. Detection probability and outage periods should be reported and, when possible, included in correction models. For PIT systems, multiple-tag conflicts should be tested; for acoustic and radio systems, signal collision, noise, and positioning error should be evaluated [9].

6.3. Reduced disturbance and biological interpretation

Fish handling should preserve natural behavior as far as possible. Low-injury capture gears, short air exposure, appropriate tag burden, and release only after recovery are basic requirements. Release locations should match the research goal: downstream releases for whole-fishway performance, and internal releases only for local hydraulic diagnosis.

Efficiency estimates also become more informative when paired with behavior and physiology. Attempt number, entrance residence time, passage time, fallback frequency, search path, gonadal stage, condition index, or blood indicators can help distinguish an unsuitable fishway from a fish that simply lacks migration motivation [14]. For non-salmonids and small fish, such species-specific information is especially important.

6.4. Population-scale assessment

Fishway evaluation should not stop at individual passage. Upstream survival, spawning success, juvenile recruitment, genetic exchange, and long-term population trends determine whether passage contributes to conservation. Combining telemetry, video, environmental DNA, molecular markers, and population models can link AE and PE to broader restoration outcomes [5].

7. Conclusion

AE and PE are useful because they separate entrance attraction from internal passage and help locate where a fishway fails. They are not, however, automatically reliable. Capture, tagging, release, detection probability, timing, and fallback can bias estimates, while species traits and fishway hydraulics create real variation among studies. Future assessments should standardize and disclose field protocols, calibrate equipment, cross-check methods, incorporate behavioral and physiological information, and extend evaluation to population outcomes. Only then can fishway efficiency data support sound engineering design and river-restoration decisions.

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