Fish Passage Revisited

(Discussion document 2026)

TOC

Executive summary.

Shifting the Paradigm in Fish Passage Design: From Simplistic Metrics to Structured Complexity

Traditionally, regulations for fish passage have relied on strict, long-standing criteria based on decades-old research. While ecologists recognized the inherent complexity of aquatic systems, translating this knowledge into quantifiable, compliance-based habitat standards has proved challenging. This necessity led to an oversimplification of dynamic environments, resulting in a set of design criteria that were easy to enforce but fundamentally simplistic and misleading. Design focus narrowed primarily to three conventional cornerstones:

- **Maximum average velocity**
- **Maximum gradient**
- **Avoid turbulence**

However, these three metrics are insufficient in isolation:

- **Maximum average velocity** is largely irrelevant for fish and is only accurately measurable in laminar type flows. Successful passage is determined by the maximum velocity encountered over a specific distance coupled with complexity. In heterogeneous (complex) flow fields, average velocity becomes ecologically inert because individual fish navigate radically different, often slower, flow paths around roughness elements.
- **Maximum gradient** is misleading without considering crucial co-factors such as flow-rate, channel roughness, and overall hydraulic complexity. It is a proxy that obscures the operative variable: the spatial distribution of velocity across the cross-section and along the flow path.
- **Avoiding turbulence** is an oversimplification. Turbulence encompasses various facets, and a thorough assessment is needed to determine if it truly constitutes a barrier to fish movement. This conventional approach, which produced homogeneous, symmetrical designs not found in nature, ignores that fish actively exploit *organized*, periodic vortex structures (Kármán gaiting) to reduce metabolic cost. High Turbulent Kinetic Energy (TKE) measurements alone fail to resolve this necessary temporal structure.

Latest research, including Computational Fluid Dynamics (CFD) simulation, indicates that fish primarily use two distinct mechanisms in complex flows:

1. **Flow Refuging:** Exploiting low-velocity zones (spatial heterogeneity) behind boulders, baffles, or within boundary layers as connected rest positions, allowing for incremental upstream progress without sustained swimming against the mean velocity.
2. **Vortex Capture (Kármán Gaiting):** Synchronizing body movements with organized, periodic vortex structures (temporal structure) to extract energy from the flow field and reduce muscular effort.

Reframing assessment around flow complexity means the design target is no longer hydraulic uniformity; it is **structured heterogeneity**. The goal is to create a flow field that simultaneously contains fast and slow water, organized and dissipated vortex zones, and deep and shallow areas, allowing fish of different species and life stages to select a viable path. Roughness elements and baffles are considered architectural components that introduce essential spatial and temporal variation.

Depth is also critical, specifically the usable, low-velocity near-bed boundary layer, which is the navigable zone for small-bodied benthic species and scales with substrate roughness. Furthermore, **heterogeneous flow paths** force individual water particles to travel different routes, hydraulically "lengthening" the structure and reducing the effective gradient for slower paths.

For post-construction or post-remediation monitoring, a complexity-based assessment shifts the question from "did fish pass?" to "does this structure provide the hydraulic conditions within which fish passage is reasonable to expect?". This moves away from expensive, limited fish count surveys toward a structured visual assessment of flow complexity, depth, and connectivity, scored against the natural channel immediately upstream as a reference. This reference comparison is the key innovation, establishing hydraulic conditions for passage if the structure scores comparably to the natural reach.

To modernize, standardize, and strengthen fish passage guidance, a new descriptive and definitional approach is emerging. This contemporary framework centers on two key documents:

1. *Fish Passage Principles & Outcomes (2025) (appendix 1)*
2. *The Flow Type Classification Metric (2026) (FTCM) (appendix 2)*

These tools provide a comprehensive overview of the necessary environmental conditions for successful fish migration, offering meaningful design criteria with a high probability of success for diverse species and life stages. The overall challenge is to embrace this new understanding of aquatic mechanisms in both practical and regulatory frameworks to ensure consistency across designs, permits, and compliance monitoring.

Reframing Fish Passage: From Single Metrics to Structured Complexity

The problem with conventional assessment

Fish passage design and monitoring have historically been organised around three measurable variables: average velocity, turbulence intensity, and channel gradient. The appeal is obvious as all three are relatively straightforward to quantify, and all three can be expressed as thresholds against which a structure either passes or fails. If mean velocity through a culvert is below the sustained swimming speed of the target species, passage is assumed. If turbulence intensity (expressed as turbulent kinetic energy, TKE) exceeds a threshold, passage is assumed to be impaired. If the gradient is too steep, the structure is flagged for remediation.

The problem is not that these variables are wrong. It is that they are incomplete descriptors of what fish actually experience, and optimising for them in isolation has produced a generation of structures, and a monitoring culture, that measures the wrong things resulting in ultra-conservative design criteria. (Appendix 1)

Average velocity is only a meaningful predictor of passage conditions in hydraulically simple, uniform flows: the smooth-walled culvert, the straight flume, the unobstructed pipe. In these cases, mean velocity closely approximates the maximum velocity any fish will encounter, and the metric has genuine predictive value. The moment the flow field becomes spatially heterogeneous (complex), and the moment substrate, baffles, or vegetation introduce variation in flow paths, average velocity becomes ecologically inert. Individual water particles, and the fish navigating among them, take radically different routes through the structure. Some travel fast paths; many travel slower, longer paths around and between roughness elements. The mean velocity of these paths tells a fish nothing, and it tells an assessor very little either.

Turbulence, as conventionally applied, suffers a deeper problem: the term itself is doing contradictory work. In hydraulic engineering, turbulence refers to a specific physical condition — stochastic velocity fluctuations characterised by Turbulent Kinetic Energy (TKE) and Reynolds shear stress. The design instinct to minimise turbulence is founded on the reasonable observation that high TKE destabilises swimming fish. But this framing collapses a rich, multi-dimensional flow environment into a single scalar, and in doing so discards the very structural properties of turbulence that fish depend on. Experimental work has demonstrated that fish can actively exploit organised, periodic vortex structures to reduce metabolic cost using behaviour known as “Kármán gaiting”, even when those flows carry higher TKE than simpler alternatives. A flow with greater turbulence intensity, if its vortex structure is organised and periodic, can be easier for a fish to negotiate than a lower TKE flow with chaotic, unpredictable fluctuations. The drive to eliminate turbulence has therefore produced structures that are hydraulically clean but biologically impoverished: devoid of the organised vortex streets, boundary layer refugia, and velocity heterogeneity that fish in natural streams actively seek out and exploit. Passage through these types of structures relies solely on low velocities only achievable by low gradients.

Gradient, similarly, is a proxy that obscures more than it reveals. A steep gradient in a smooth-walled structure produces uniformly high velocities which is a genuine barrier. The same gradient in a structure with large roughness elements, varied depth, and abundant low-velocity refugia may be entirely navigable for a broad range of species and size classes. The gradient itself is not the operative variable; what matters is what the gradient produces in terms of the spatial distribution of velocity across the cross-section and along the flow path.

What fish actually use

The research literature, including Computational Fluid Dynamics (CFD) simulation, has converged on a clearer picture of how fish navigate complex flows, and it points firmly away from bulk hydraulic descriptors toward the fine-scale structure of the natural flow environment. (Appendix 2)

Fish use two distinct mechanisms in complex flows, utilising their lateral line sensory organs to detect boundary layers where differing currents meet. The first is flow refuging, being the exploitation of low-velocity zones embedded within faster ambient flow. Behind boulders, within boundary layers near rough substrates, in the lee of baffle faces, water moves significantly slower than the bulk flow. For small-bodied or weak-swimming species, these zones function as stepping stones: a series of connected rest positions that allow a fish to make incremental upstream progress without ever needing to sustain swimming against the mean velocity. This mechanism requires spatial heterogeneity i.e., the co-occurrence of fast and slow water across the cross-section, and it is entirely invisible to a mean velocity measurement.

The second mechanism is vortex capture, or Kármán gaiting. When roughness elements generate organised, periodic vortex structures with predictable rotation, fish can synchronise their body kinematics to extract energy from the vortex field, reducing the muscular effort required to maintain position or advance upstream. This mechanism requires temporal structure i.e., not the absence of turbulence, but turbulence with a degree of predictability and organisation. It also has a scale dependency: when vortex diameter approaches or exceeds roughly two-thirds of a fish's body length, the rotating structure introduces destabilising torque rather than usable energy. The same flow field that benefits a large adult may be harmful to a juvenile, and vice versa. A dimension that TKE measurement cannot resolve at all.

Both mechanisms are simultaneously available in a natural mixed-grade stream channel: spatial heterogeneity from substrate variation provides refugia, while the wakes of emergent and submerged elements generate the organised vortex structures that fish exploit for energy recovery. The natural channel is not a design problem to be engineered away from. It is the ecological benchmark that remediated structures should be attempting to approximate.

The shift to flow complexity, depth, and heterogeneous flow paths

Regardless of scale, a waterway (natural or manmade) may have sections with one or more flow characteristics over a relatively short distance. Reframing assessment around flow complexity means moving from the question "is the velocity acceptable?" to the question "does this structure provide the range of hydraulic conditions that allows fish to select their own path?"

This is a meaningful conceptual shift, and it has practical consequences for both design and monitoring.

For design, the target is no longer hydraulic uniformity. The goal is to create structured heterogeneity: being a flow field that simultaneously contains fast and slow water, organised and dissipated vortex zones, deep and shallow areas, so that fish of different species, sizes, and locomotive strategies can find a viable path. Roughness elements, baffles, and substrate material are not turbulence generators to be used cautiously; they are the architectural components of a complex flow environment. Their value lies precisely in the spatial and temporal variation they introduce. Closely-spaced, large baffles with bed material between them produce a fundamentally different environment from widely-spaced small baffles on a smooth floor, even if the mean velocity through both structures is identical.

Depth is equally critical and is often underweighted relative to velocity in conventional assessment. For small-bodied benthic species, the near-bed boundary layer is the navigable zone. Boundary layer thickness scales with substrate roughness. A smooth bed compresses it to millimetres, while large rough elements expand it to centimetres. A structure that provides adequate mean depth but smooth walls and a clean bed may offer no practical navigable depth to a juvenile galaxiid. The relevant depth question is not just "is the water deep enough to cover the fish?" but "is the usable, low-velocity zone, the boundary layer, the rest pool, the eddy, deep enough to allow the fish to hold position and move through?"

Heterogeneous flow paths deserve particular attention because they are the mechanism by which complexity translates into passage. When physical elements within the flow column e.g., rocks, baffles, vegetation etc., force individual water particles to travel different distances and routes, the effective gradient for the slower paths is reduced. The structure is, in hydraulic terms, lengthened. A fish navigating a well-baffled culvert is not swimming against the gradient and velocity implied by the inlet-outlet head difference; it is working through a series of locally gentler flow conditions, connected by brief high-velocity sections it can burst-swim through. The availability of these alternative paths is what the Flow Type Classification Metric (appendix 3) is designed to capture: not a single velocity number, but a structured assessment of how many viable hydraulic choices the flow field actually offers.

Implications for post construction or post-remediation monitoring

The monitoring implications follow directly. Fish count surveys above and below structures (the traditional compliance tool) carry significant limitations: they are expensive, seasonally variable, difficult to replicate, and often cost more than the remediation itself. They also measure outcomes without explaining mechanisms, making it difficult to distinguish a passage failure due to hydraulic conditions from one due to seasonal migration timing, survey method artefacts, barriers further downstream, or population factors unrelated to the structure.

The Fish Passage Principles & Outcomes document (appendix 4) is a high-level set of criteria that can be used throughout the design, build and monitoring process to give guidance and to gauge likelihood of successful fish passage at any given structure.

A complexity-based assessment framework changes the monitoring question from "did fish pass?" to "does this structure provide the hydraulic conditions within which fish passage is reasonable to expect?" This is not a retreat from ecological rigour; it is a recognition that the structural conditions that enable passage are more consistently measurable, more repeatable across time, and more directly actionable for engineers and regulators than fish count data. A structured visual assessment of flow complexity, depth, and connectivity, scored against the natural channel immediately upstream as a reference, and produces a repeatable, communicable record that is available at the time of inspection, without seasonal variation, and at a cost commensurate with the remediation itself. This approach can also serve as a measure of change pre and post remediation.

The upstream and/or downstream reference comparison is the key innovation in this framing. Rather than measuring a structure against an abstract velocity threshold, the assessor measures it against the natural channel system the fish already use successfully. If the structure scores comparably to the upstream reach on flow complexity, provides adequate depth, and is connected (not perched), the hydraulic conditions for passage are established. The burden of proof moves from expensive ecological surveys after the fact to a structured hydraulic assessment at the point of design or remediation.

Conclusion

Many fish passage guidance documents and subsequent statues are now seemingly inflexible. They have not best served the engineering nor ecology sectors.While fish clearly have a better chance of navigating low velocities and gentle slopes, these conditions do not always represent the natural environment and often put a considerable burden on those wishing to design or remediate structures. Designs and permit conditions do not always guarantee successful outcomes.The challenge is to embrace this new way of viewing aquatic mechanisms in both the practical and regulatory frameworks to provide fish passage with a greater degree of confidence by taking into account the range of locomotions across various species and life-stages. To ensure consistency across designs, permit conditions, and compliance monitoring, ecologists, engineers, regulators and practitioners should utilise aligned methodologies and a shared narrative as outlined above.

"One of our biggest challenges over the next 5–10 years is figuring out how we fix all those structures so more rivers are accessible," says Dr Paul Franklin (Earth Sciences New Zealand - NIWA).

Links to Appendices

1. Guidelines review
2. Example of CFD report
3. Hydraulic Complexity Index
4. Fish Passage Principles & Outcomes