Culvert Flow Analysis

CFD Simulation Report: Baffled and Unbaffled Pipe-Arch Culvert Assessment
Prepared for: S Scott Environmental
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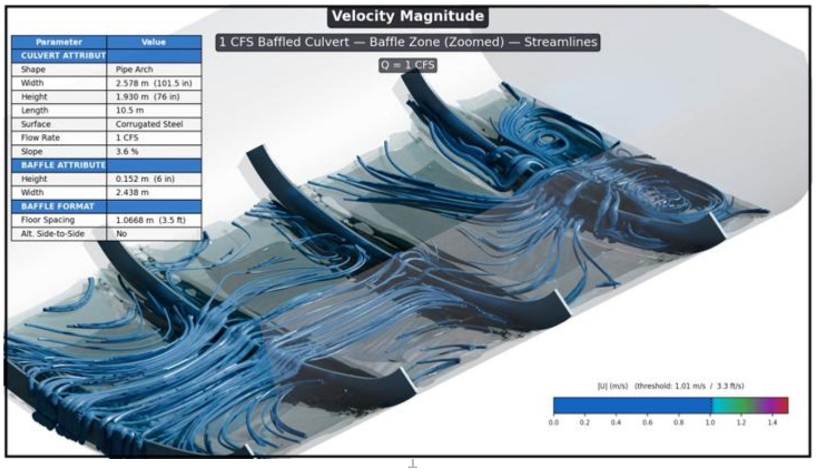
Three-dimensional computational fluid dynamics simulations were performed to characterise hydraulic conditions within a corrugated-steel pipe-arch culvert. Two configurations were analysed — with and without internal baffles — to quantify the effect of energy dissipators on velocity, depth, and flow structure. This report presents simulation results and demonstrates the capability of CFD as a tool for evaluating culvert hydraulics and informing baffle design decisions.

Contents



Parameter	Value
CULVERT ATTRIBUT	
Shape	Pipe Arch
Width	2.578 m (101.5 in)
Height	1.930 m (76 in)
Length	10.5 m
Surface	Corrugated Steel
Flow Rate	1 CFS
Slope	3.6 %
BAFFLE ATTRIBUTE	
Height	0.152 m (6 in)
Width	2.438 m
BAFFLE FORMAT	
Floor Spacing	1.0668 m (3.5 ft)
Alt. Side-to-Side	No

Executive Summary

Objective. Characterise the hydraulic conditions within a pipe-arch culvert, with and without internal baffles, using three-dimensional CFD simulation. Demonstrate that simulation provides the spatial velocity and depth detail needed to evaluate baffle design performance — information not available from one-dimensional hydraulic methods.

Configuration summary:

Culvert Design	Simulation	Baffle Design
Pipe Arch (101.5 × 76 in)	OpenFOAM v2412	4 baffles, 152 mm height
10.5 m length, 3.6% slope	Free-surface VOF	1.067 m spacing
Corrugated steel	k–ω SST turbulence	Conforming to invert

Key Findings

Baffles create distinct low-velocity zones between consecutive baffles, with recirculation pools forming upstream of each baffle.

Without baffles, flow accelerates continuously along the slope, producing higher and more uniform velocities throughout the culvert cross-section.

The velocity glyph and streamline visualisations reveal three-dimensional flow structures that one-dimensional hydraulic methods cannot capture.

CFD simulation provides the spatial velocity and depth detail needed to evaluate and optimise baffle geometry — enabling iterative design before fabrication.

Role of simulation. Traditional culvert hydraulics relies on cross-section-averaged velocity and depth. CFD reveals the spatial distribution of low-velocity zones, recirculation patterns, and depth variations created by baffles — enabling iterative design optimisation before fabrication. This study demonstrates that simulation is an essential tool for baffle configuration, complementing physical modelling and field measurement.

Culvert Design and Baffle Configuration

The culvert is a corrugated-steel pipe-arch defined by three circular arcs (top, corner, and invert) tangentially joined. The pipe is inclined at +2.06° (3.6% downhill grade); the invert elevation follows zinv(x) = −0.036x.

Table1: Culvert cross-section dimensions.

Dimension	Imperial (in)	SI (m)
Span	101.5	2.578
Rise	76	1.930
Top radius Rt	51.3	1.302
Corner radius Rc	26.1	0.664
Invert radius Rb	111.6	2.835
Pipe length	34.4ft	10.5
Baffle length	96	2.438
Slope	3.6%	0.036

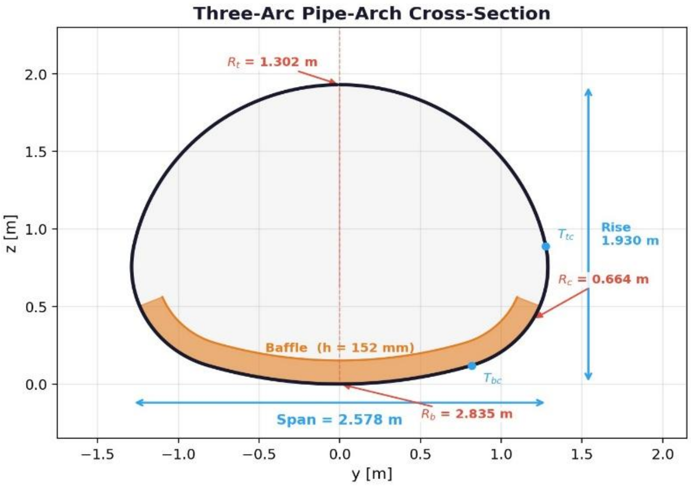


Figure 1: Three-arc pipe-arch cross-section with baffle profile.

2.1 Baffle Configuration

Baffles are flexible elements perpendicular to flow. The bottom edge conforms to the curved invert arc, ensuring no gap between baffle and pipe floor. Baffle front-face positions: x = 0.500, 1.582, 2.664, and 3.745 m (front face).

Parameter	Value	Note
Height	0.152 m	6 in
Thickness	0.015 m	
Spacing (gap)	1.067 m	3.5 ft
First baffle offset	0.500 m	from inlet
Number of baffles	4	
Side clearance	0.050 m	

Table 2: Baffle design parameters

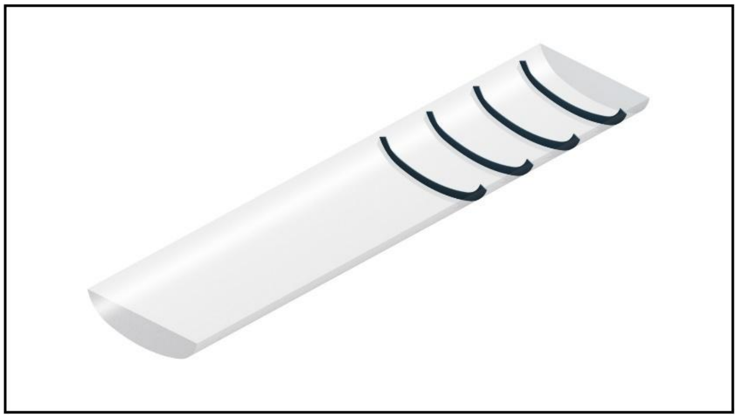


Figure 2: FlexiBaffle configuration
Isometric view showing pipe wall and four conforming baffles.

Why simulation matters for baffle design? Baffle height, spacing, and offset collectively determine the velocity field within the culvert. Small changes in configuration can shift recirculation zones, alter pool depths, and change the velocity distribution across the cross-section. CFD allows rapid evaluation of design variants without physical prototyping.

3 Flow Conditions

Table 3: Design flow conditions simulated.

Condition	Q (CFS)	Q (m3/s)	hn (m)	Ubulk (m/s)	Exceedance
High flow	49	1.388	0.372	2.98	5%
Low flow	1	0.028	0.076	0.37	95%

Normal depth computed via Manning’s equation: n =0.024, S =0.036, three-arc invert profile.
Two flow conditions are simulated for both the baffled and unbaffled configurations, giving four cases in total. The 49 CFS condition represents the 5% annual-exceedance high-flow design event. The 1 CFS low-flow condition represents a near-base-flow scenario.

4 Simulation Approach

4.1 What is CFD?

Computational Fluid Dynamics (CFD) is a branch of engineering analysis that uses computers to simulate the behaviour of fluids — in this case, water flowing through a culvert. Rather than relying on simplified formulas that describe the flow as a single average number at each cross-section, CFD divides the entire volume of interest into millions of small cells and solves the fundamental laws of physics (conservation of mass, momentum, and energy) in every cell simultaneously.

The result is a complete, three-dimensional picture of the flow: not just one average velocity for the whole pipe, but a velocity value at every point in space — along the walls, between the baffles, near the water surface, and everywhere in between. This spatial detail is what makes CFD uniquely valuable for culvert hydraulic design, where the question is not “what is the average velocity?” but “what is the velocity distribution across the entire cross-section?”

4.2 What the Simulation Solves

At each of the millions of cells, the solver computes several physical quantities at every moment in time:

Water velocity — speed and direction of flow in three dimensions. Velocity magnitude and its spatial distribution are the primary quantities for evaluating baffle performance.

Pressure — the force exerted by the water column. Pressure gradients drive the flow and determine the water surface elevation along the culvert.

Turbulence — the chaotic, swirling component of flow. Turbulence is not directly visible in the averaged results, but it affects how energy is transferred from fast-moving flow to slower regions. The simulation tracks turbulence intensity and its dissipation rate throughout the domain to accurately predict velocity profiles near walls and baffles.

Water–air interaction — culvert flow is an open-channel problem: water flows along the bottom while air occupies the space above. The simulation tracks the interface between water and air as it rises, falls, and deforms around obstacles. This captures water depth variation along the culvert and the influence of baffles on the free surface.

4.3 How the Culvert is Modelled

The physical culvert and its surroundings are represented as a computational mesh — a three-dimensional grid of cells that fills the entire flow region. The mesh is finer (smaller cells) near the baffle surfaces and the pipe wall where flow changes rapidly, and coarser (larger cells) in open regions where the flow is more uniform.

Table 4: Computational mesh summary.

	Baffled	No baffles
Total computational cells	2,304,599	420,452
Smallest cell size	∼5 mm	∼20 mm
Largest cell size	∼83 mm	∼83 mm

The baffled case requires nearly five times more cells than the unbaffled case because the thin baffles and their surrounding wake regions demand very fine resolution to capture the flow accurately.

4.4 Computational Cost and Value

CFD simulation is computationally intensive. The baffled case in this study required approximately 48 hours of continuous computation on a cloud server using 40 processor cores running in parallel. This represents a significant investment in computing resources.

However, the cost of simulation is small compared to the alternatives:

Physical modelling — building and instrumenting a scaled laboratory model of the culvert costs tens of thousands of dollars and weeks of facility time. Each design change requires physical modification of the model.

Field testing — installing baffles in an actual culvert and measuring the results requires construction, permitting, equipment, and site access. If the design does not perform as expected, the cost of modification is substantial.

Trial and error — without simulation or physical testing, baffle design relies on rules of thumb and engineering judgement. The risk of an underperforming installation is high.

The value proposition. A single CFD simulation produces more spatial detail than dozens of point measurements in a physical model. Once the computational model is built, design variants — different baffle heights, spacings, or configurations — can be evaluated in days rather than weeks. The cost of a simulation run is a fraction of a single physical test, and the turnaround is faster. CFD does not replace physical testing or field measurement, but it dramatically reduces the number of physical iterations needed to arrive at an effective design.

4.5 Software

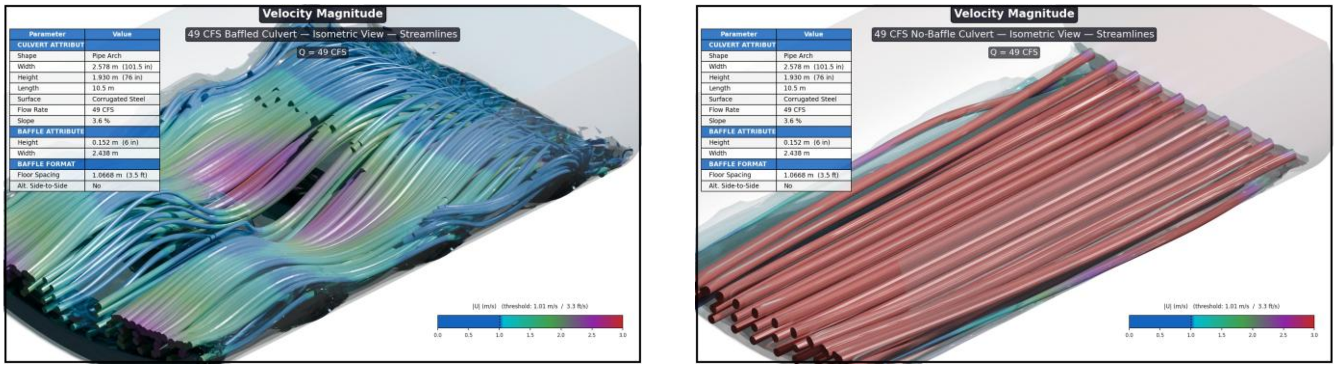
The simulations were performed using OpenFOAM v2412[4], an open-source CFD platform widely used in academic research and industrial practice. OpenFOAM has been validated for baffled culvert hydraulics by Zhang & Chanson[2] and Leng & Chanson[3], among others. The turbulence model used (k–ω SST[1]) is an industry-standard approach for wall-bounded flows with separation — exactly the conditions found around baffles in a culvert.

The complete technical specification of boundary conditions, discretisation schemes, and fluid properties is provided in Appendices A–C.

5 Results — Baffled vs. Unbaffled

Results are presented as side-by-side comparisons of the baffled and unbaffled configurations for both the 49 CFS high-flow and 1 CFS low-flow conditions. Each view uses a consistent camera framing, colour scale, and parameter table to allow direct comparison across all four cases.

5.1 49 CFS — High-Flow Condition (Q =49 CFS =1.388 m3/s)



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Shape	Pipe Arch
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Height	1.930 m (76 in)
Length	10.5 m
Surface	Corrugated Steel
Flow Rate	49 CFS
Slope	3.6 %
BAFFLE ATTRIBUTE	
Height	0.152 m (6 in)
Width	2.438 m
BAFFLE FORMAT	
Floor Spacing	1.0668 m (3.5 ft)
Alt. Side-to-Side	No

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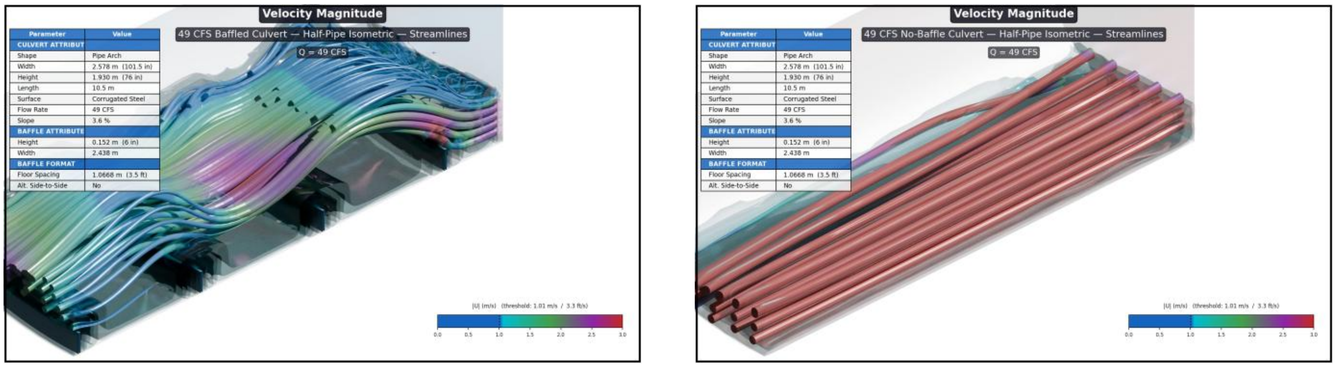
Alt. Side-to-Side	No

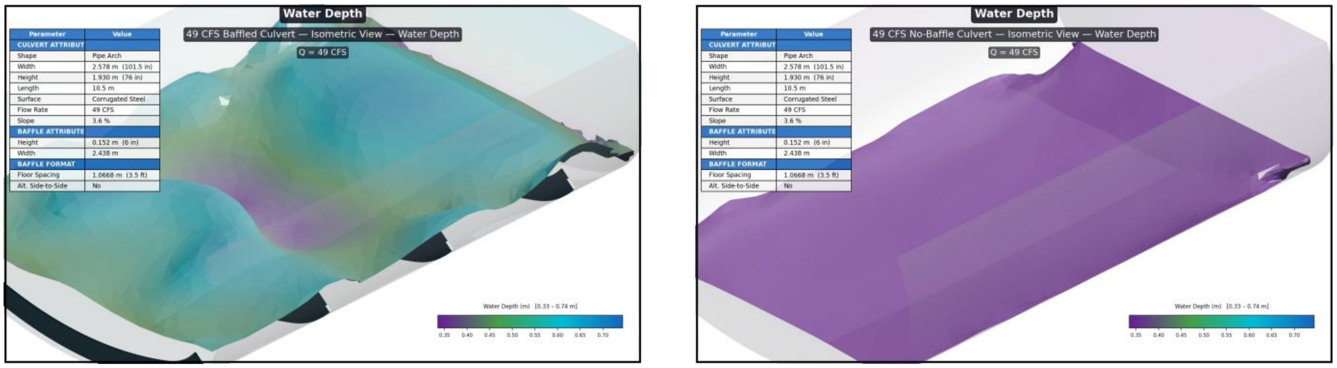
(a) Baffled (b) No baffles

Figure 3: 49 CFS — isometric view of 3D streamlines coloured by velocity magnitude (0–3 m/s; fish-passage colormap, threshold 1.2 m/s); pipe wall shown as semi-transparent shell. (a) baffled, (b) no baffles.



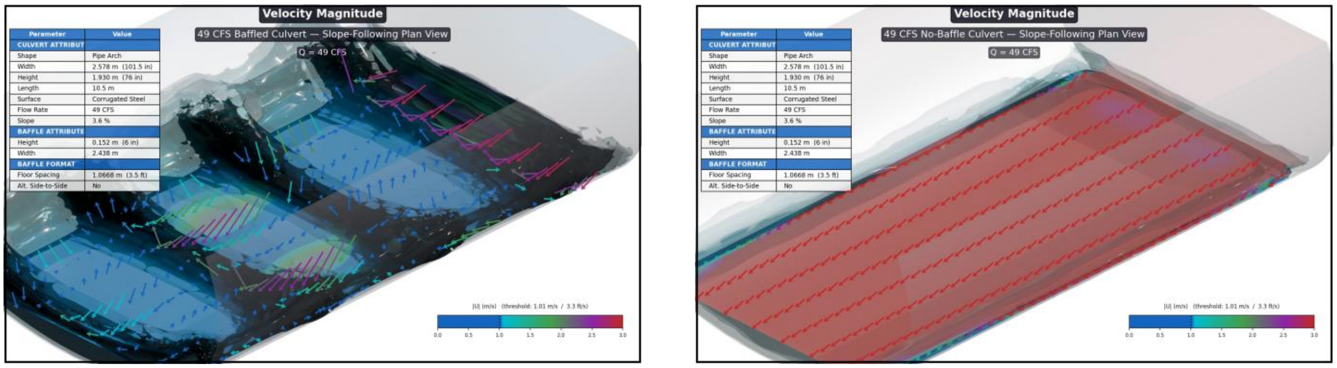
(a) Baffled (b) No baffles

Figure 4: 49 CFS — half-pipe cutaway (symmetry half removed) with 3D streamlines coloured by velocity magnitude (0–3 m/s; fish-passage colormap). (a) baffled, (b) no baffles.



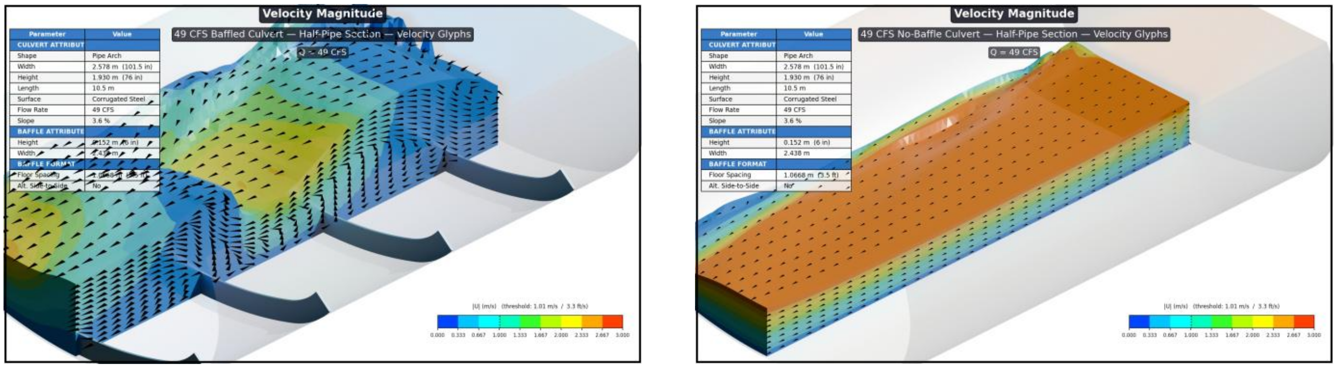
(a) Baffled (b) No baffles

Figure 5: 49 CFS — isometric view of the free water surface coloured by local depth (scale: 0.33–0.74 m; cyan = shallow, purple = deep). (a) baffled, (b) no baffles.



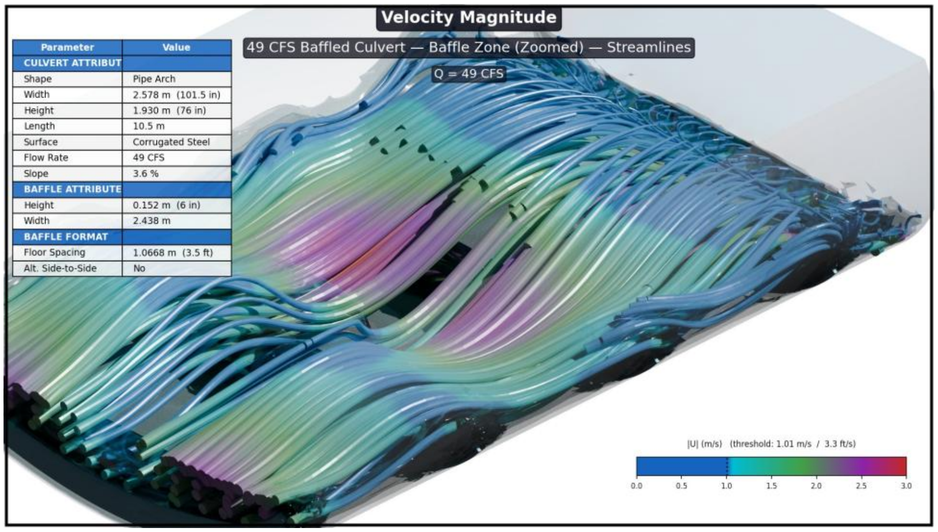
(a) Baffled (b) No baffles

Figure 6: 49 CFS — slope-following plan view with velocity glyphs on a plane at fixed height above the invert, coloured by horizontal velocity magnitude (0–3 m/s; fish-passage colormap, threshold 1.2 m/s). (a) baffled, (b) no baffles.



(a) Baffled (b) No baffles

Figure 7: 49 CFS — half-pipe cutaway: free-surface and y=0 centre-plane section coloured by velocity magnitude (fish-passage colormap, 0–3 m/s); in-plane velocity vectors on both surfaces; back-half pipe and baffles intact for 3D context. (a) baffled, (b) no baffles.



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Floor Spacing	1.0668 m (3.5 ft)
Alt. Side-to-Side	No

Figure 8: 49 CFS, baffled — zoomed isometric view of the baffle zone. Streamlines coloured by velocity magnitude (0–3 m/s; fish-passage colormap).

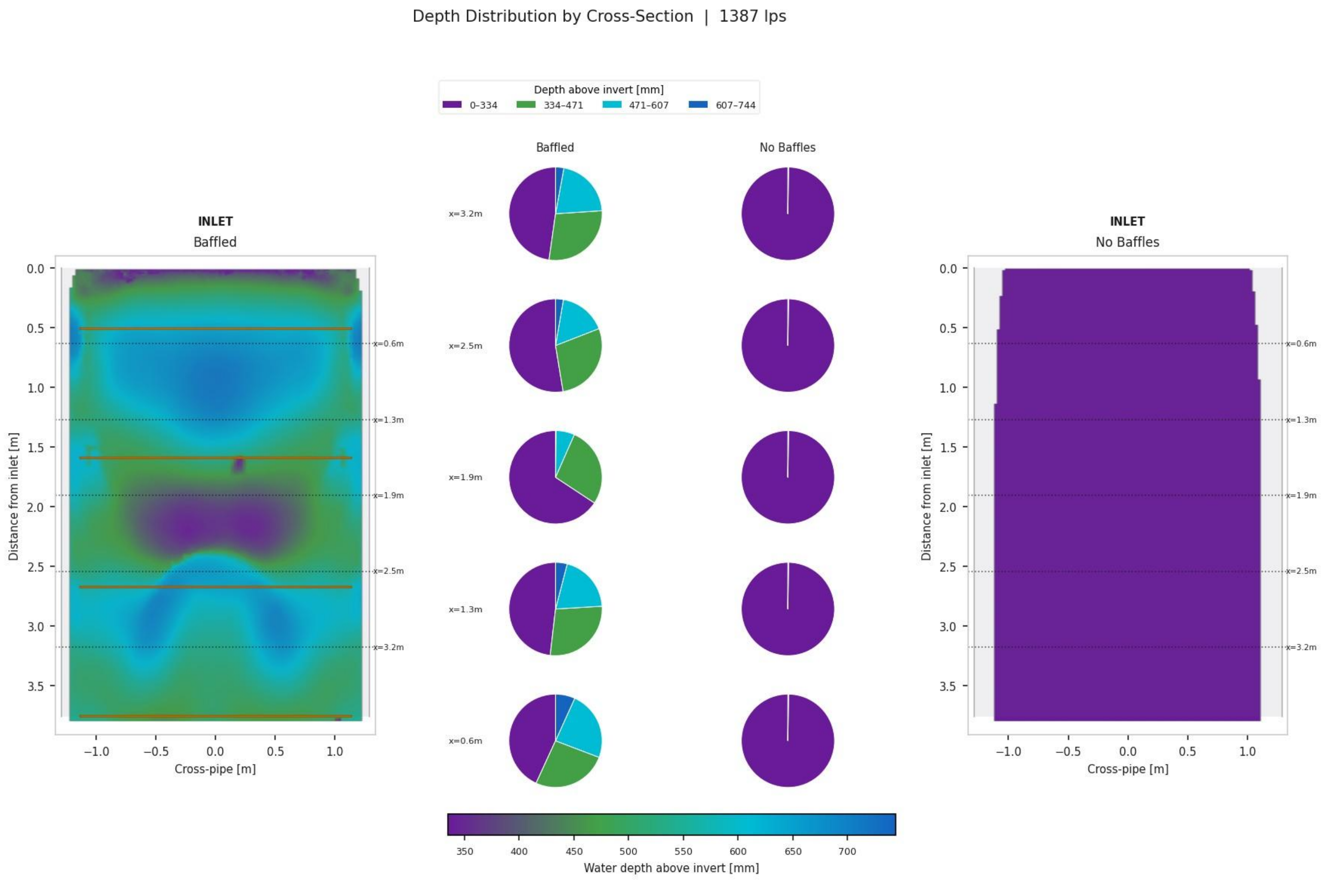


Figure 9: 49 CFS — depth distribution infographic. Left and right panels: plan-view water depth maps for the baffled and unbaffled configurations across the 3.81 m baffle zone (x = 0–3.81 m); same colormap as Figure 5. Centre: pie charts showing the fraction of wetted cross-sectional area in each of four depth bins at five equally spaced cross-sections. Depth scale: 0–744 mm (0–2.0hn, where hn = 0.372 m is the Manning normal depth at 49 CFS); bins and colours shown in the legend.

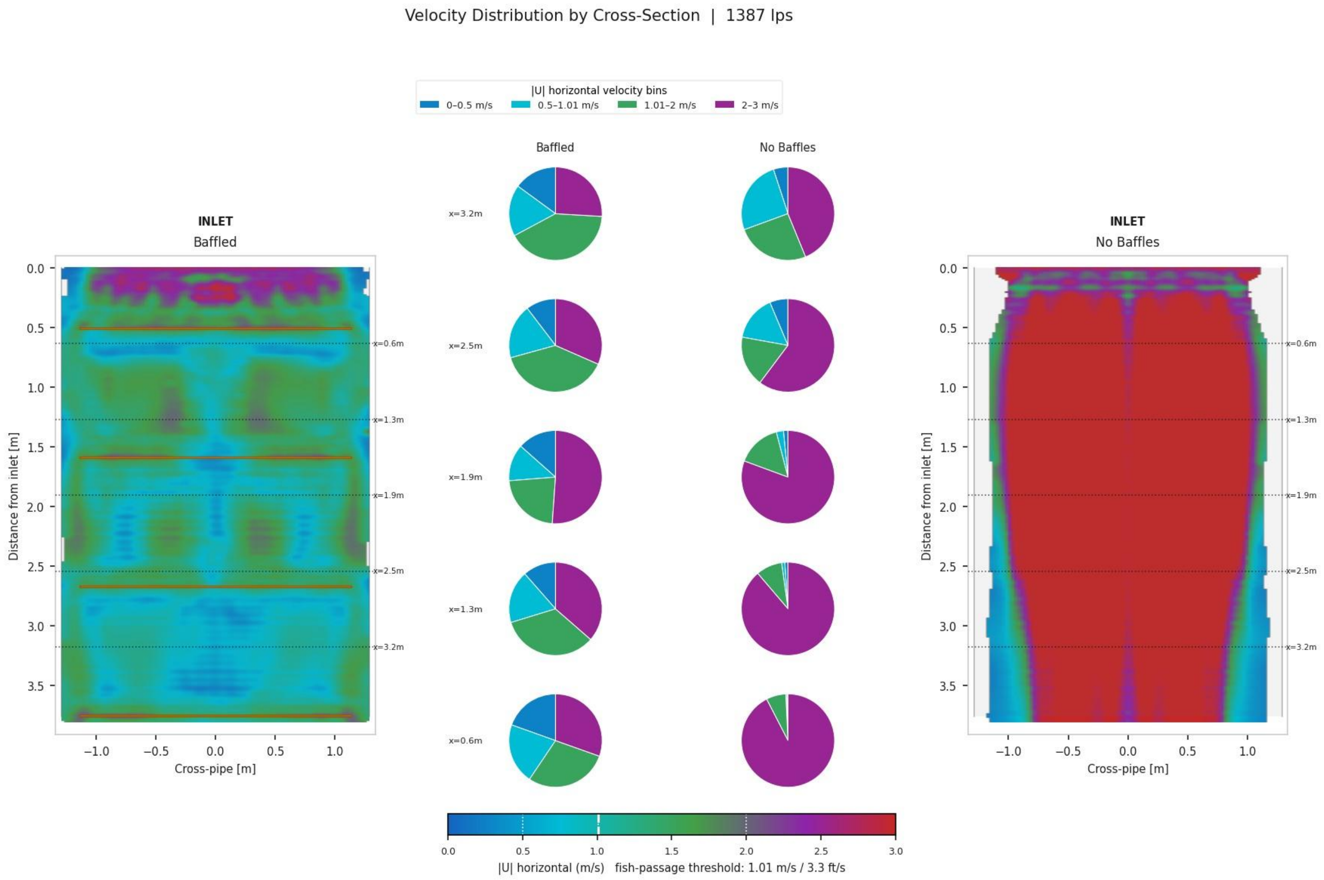
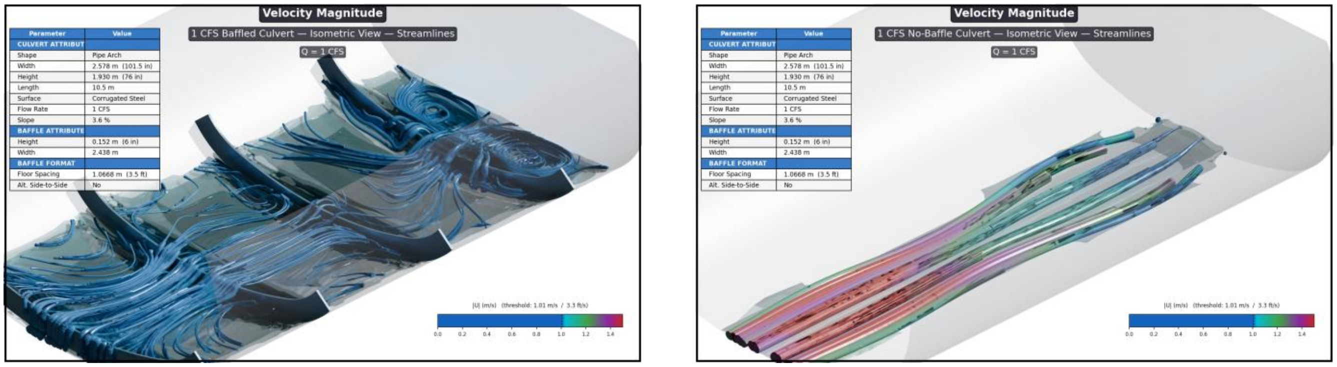


Figure 10: 49 CFS — velocity distribution infographic. Left and right panels: stacked partition-of-unity profiles for the baffled and unbaffled configurations across the 3.81 m baffle zone (x = 0–3.81 m), showing the volume weighted fraction of wet cells in each of four horizontal-velocity bins at 50 evenly spaced cross-sections; inlet at top. Centre: pie charts of the same bin fractions at five cross-sections. Velocity bins (m/s): 0–0.5, 0.5–1.01 (below fish-passage threshold of 1.006 m/s / 3.3 ft/s), 1.01–2, 2–3; colours shown in the legend.

5.2 1 CFS — Low-Flow Condition (Q =1 CFS =0.028 m3/s)



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Height	1.930 m (76 in)
Length	10.5 m
Surface	Corrugated Steel
Flow Rate	1 CFS
Slope	3.6 %
BAFFLE ATTRIBUTE	
Height	0.152 m (6 in)
Width	2.438 m
BAFFLE FORMAT	
Floor Spacing	1.0668 m (3.5 ft)
Alt. Side-to-Side	No

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Alt. Side-to-Side	No

(a) Baffled (b) No baffles

Figure 11: 1 CFS — isometric view of 3D streamlines coloured by velocity magnitude (0–3 m/s; fish-passage colormap, threshold 1.2 m/s); pipe wall shown as semi-transparent shell. (a) baffled, (b) no baffles.

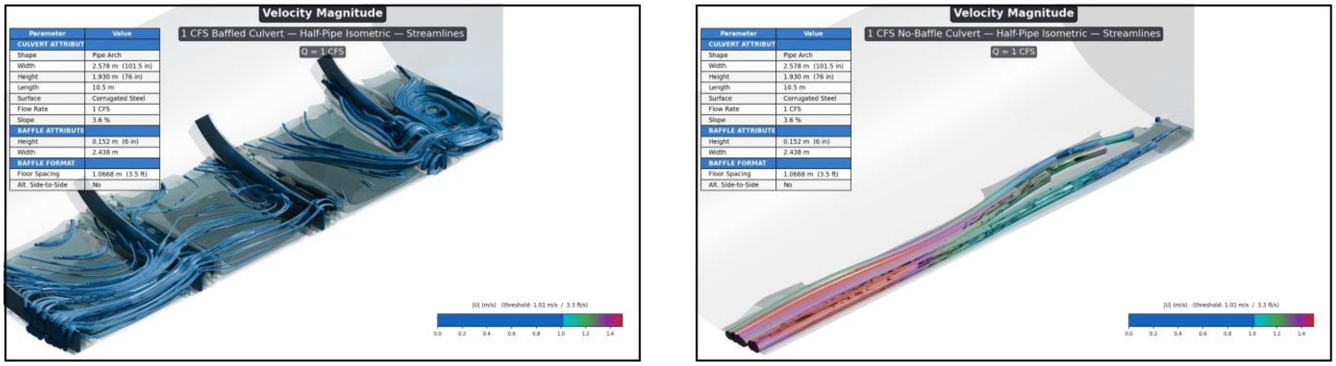

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Figure 12: 1 CFS — half-pipe cutaway (symmetry half removed) with 3D streamlines coloured by velocity magnitude (0–3 m/s; fish-passage colormap). (a) baffled, (b) no baffles.

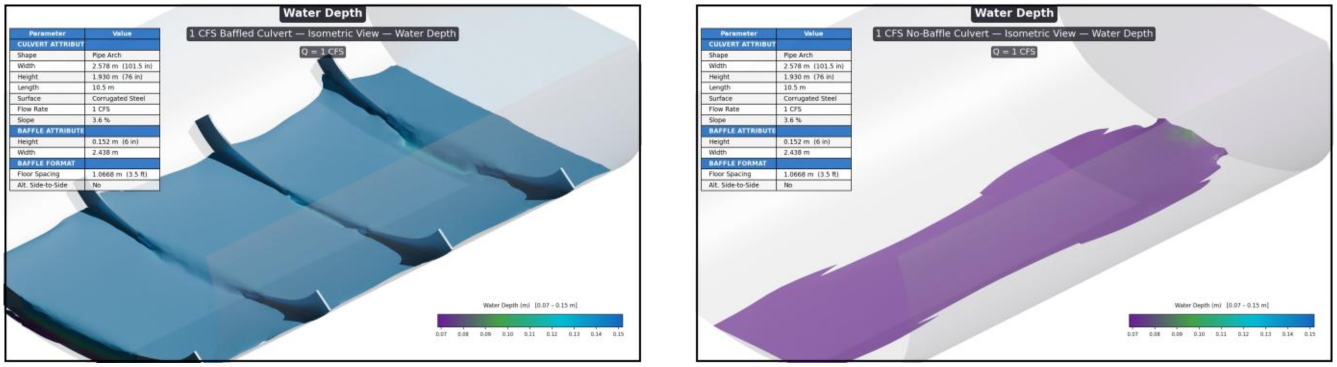

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Figure 13: 1 CFS — isometric view of the free water surface coloured by local depth (scale: 0.07–0.25 m; cyan = shallow, purple = deep). (a) baffled, (b) no baffles.

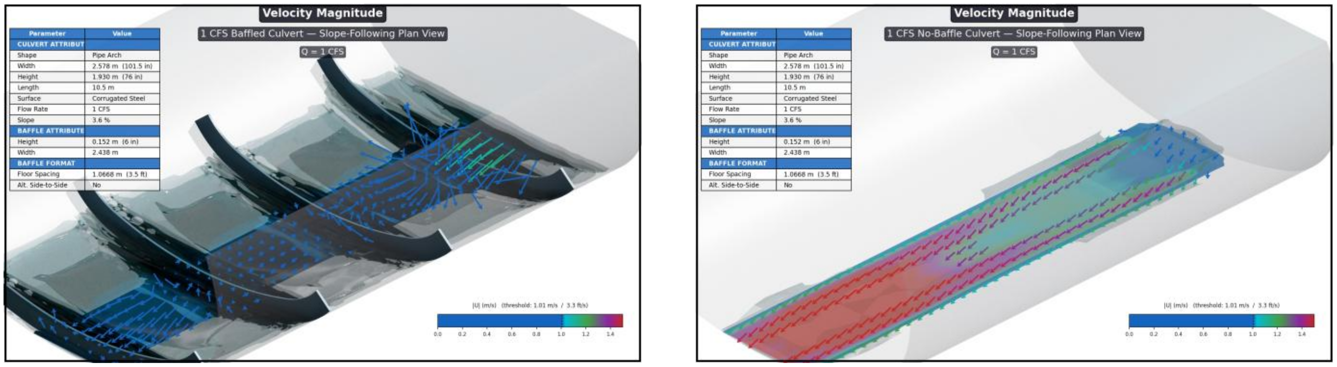

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Figure 14: 1 CFS — slope-following plan view with velocity glyphs on a plane at fixed height above the invert, coloured by horizontal velocity magnitude (0–3 m/s; fish-passage colormap, threshold 1.2 m/s). (a) baffled, (b) no baffles.

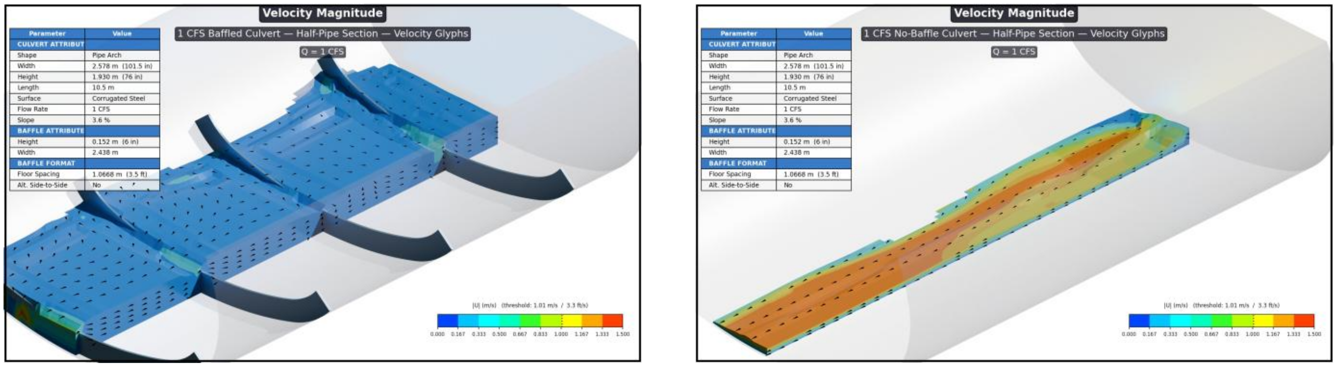

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Figure 15: 1 CFS — half-pipe cutaway: free-surface and y=0 centre-plane section coloured by velocity magnitude (fish-passage colormap, 0–1.5 m/s); in-plane velocity vectors on both surfaces; back-half pipe and baffles intact for 3D context. (a) baffled, (b) no baffles.

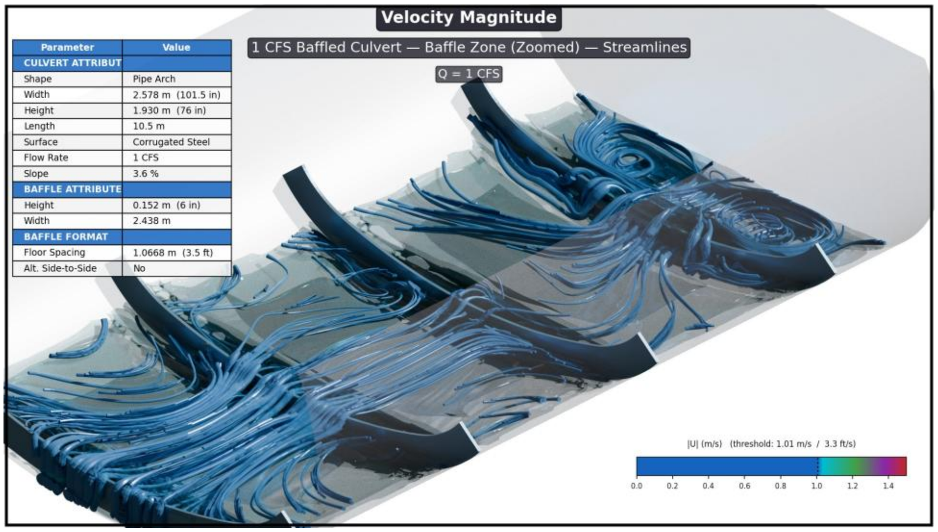

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Figure 16: 1 CFS, baffled — zoomed isometric view of the baffle zone. Streamlines coloured by velocity magnitude (0–3 m/s; fish-passage colormap).

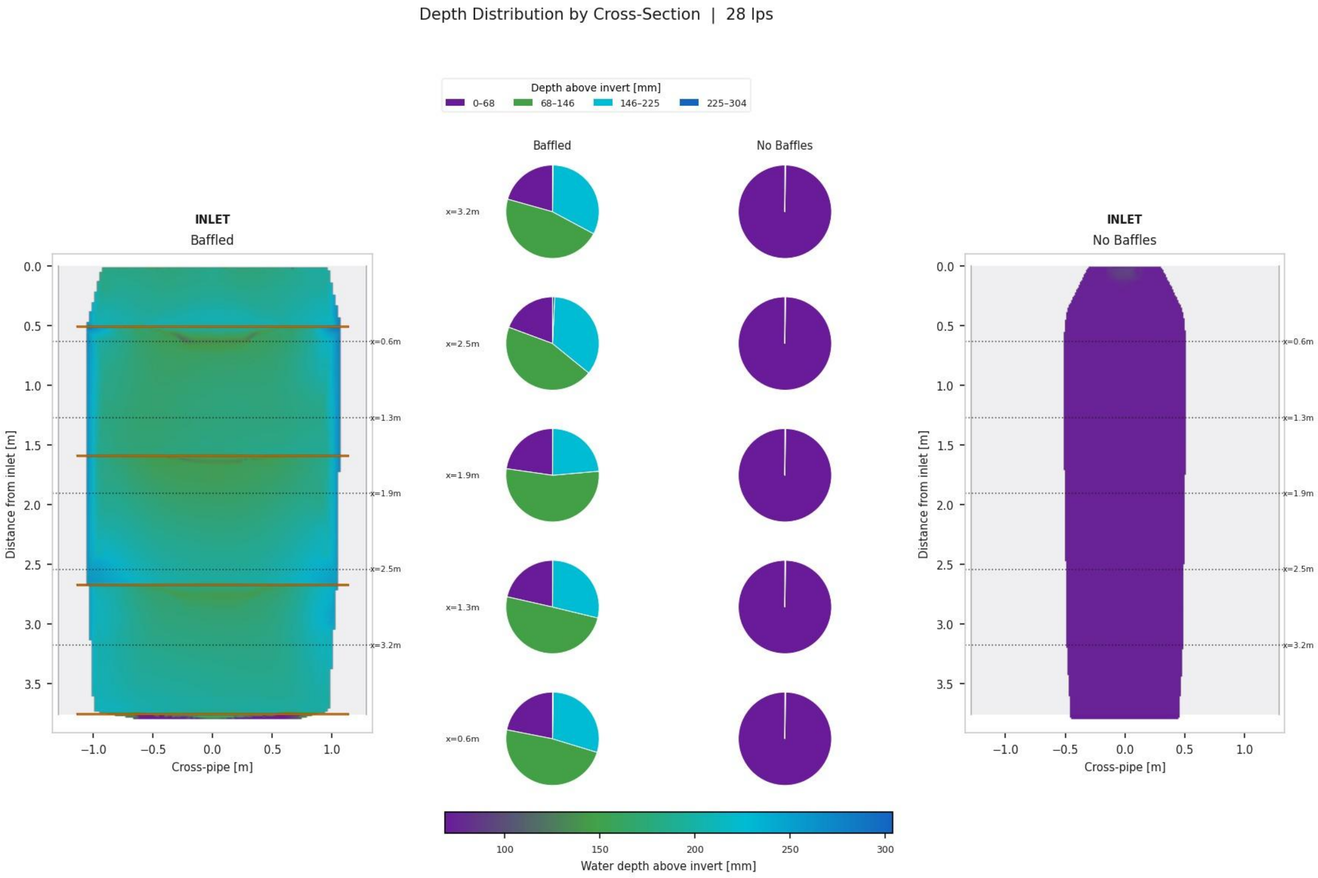

Figure 17: 1 CFS — depth distribution infographic. Left and right panels: plan-view water depth maps for the baffled and unbaffled configurations across the 3.81 m baffle zone (x = 0–3.81 m); same colormap as Figure 13. Centre: pie charts showing the fraction of wetted cross-sectional area in each of four depth bins at five equally spaced cross-sections. Depth scale: 0–304 mm (0–4.0hn, where hn = 0.076 m is the Manning normal depth at 1 CFS); bins and colours shown in the legend.

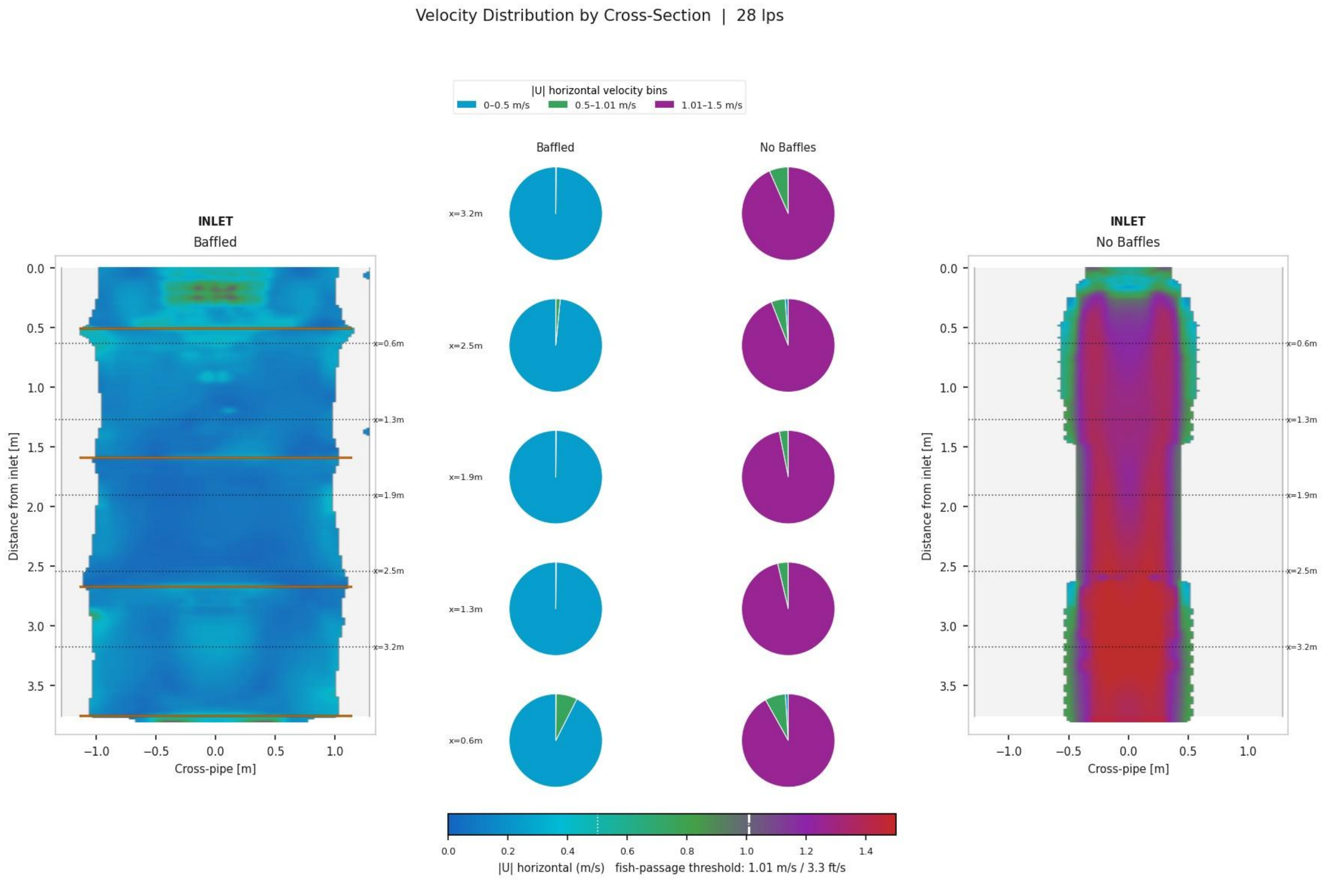

Figure 18: 1 CFS — velocity distribution infographic. Left and right panels: stacked partition-of-unity profiles for the baffled and unbaffled configurations across the 3.81 m baffle zone (x = 0–3.81 m), showing the volume weighted fraction of wet cells in each of four horizontal-velocity bins at 50 evenly spaced cross-sections; inlet at top. Centre: pie charts of the same bin fractions at five cross-sections. Velocity bins (m/s): 0–0.5, 0.5–1.01 (below fish-passage threshold of 1.006 m/s / 3.3 ft/s), 1.01–2, 2–3; colours shown in the legend.

Conclusions

Three-dimensional CFD simulations of a 10.5 m pipe-arch culvert were completed for 49 CFS and 1 CFS flow conditions, with and without four internal baffles, giving four cases in total.

Baffles create distinct low-velocity zones between consecutive baffles, with recirculation pools forming upstream of each baffle.

The unbaffled culvert produces higher, more uniform velocities throughout the cross-section at both flow conditions.

The velocity glyph, streamline, and depth visualisations demonstrate the three-dimensional flow detail that CFD provides — spatial information not available from one-dimensional methods.

CFD simulation is a practical, effective tool for baffle design, providing the spatial velocity and depth detail needed to evaluate and optimise configuration before fabrication.

Simulation value. The ability to evaluate multiple configurations computationally reduces design risk, shortens iteration cycles, and enables performance assessment before physical construction. A single CFD model produces more spatial detail than traditional cross-section-averaged analysis, supporting evidence-based design decisions.

A. Boundary Condition Specification

Table 5: Boundary conditions for primary field variables.

Patch	Velocity (U)	Pressure (prgh)	Phase (αwater)
Inlet	flowrate∗	fixedFluxPressure	exprFixedValue
Outlet	pressureInletOutletVelocity	fixedValue (0)	inletOutlet
Culvert wall	noSlip	fixedFluxPressure	zeroGradient
Baffles	noSlip	fixedFluxPressure	zeroGradient
Atmosphere	pressureInletOutletVelocity	totalPressure	inletOutlet

∗variableHeightFlowRateInletVelocity — prescribes volumetric flow rate Q and distributes velocity across the wetted inlet area based on the local water fraction.

Turbulence fields (k, ω) use wall functions at solid boundaries (kqRWallFunction, omegaWallFunction) and low-turbulence fixed values at the inlet. Turbulent viscosity (νt) uses nutkWallFunction at walls and calculated elsewhere.

B. Numerical Settings

Table 6: Discretisation schemes and solver controls.

Parameter	Setting
Time scheme	Euler (first-order implicit)
Momentum convection	Gauss linearUpwind
VOF convection	Gauss vanLeer
Turbulence convection	Gauss upwind
Laplacian / snGrad	uncorrected
PIMPLE outer correctors	1
Pressure correctors	3
Non-orthogonal correctors	5
Momentum predictor	off
Max Courant number	0.5
Max interface Courant	0.5

C. Fluid Properties

Table 7: Fluid properties used in all simulations.

Property	Water	Air	Unit
Kinematic viscosity ν	1×10−6	1.5×10−5	m2/s
Density ρ	1000	1	kg/m3
Surface tension σ		0.07	N/m

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