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Injury Risks to a Migratory Freshwater Fish During Downstream Passage Through a Regulated Floodplain Outlet: A Case Study on Golden Perch (*Macquaria ambigua*)

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ABSTRACT

River infrastructures such as weirs, dams, inlet and outlet regulators often impair connectivity, leading to degradation and loss of key habitats for riverine fishes. This also holds true for golden perch (*Macquaria ambigua* Richardson), a migratory species in Australia's Murray–Darling Basin. Regulated outlets between main stem and floodplain habitats can restrict dispersal, and fish may be exposed to harmful hydraulic forces during downstream passage. Associated injury risk for fish mainly relates to rapid decompression (barotrauma), strike and shear stress. In this study, laboratory barometric chamber experiments on juvenile golden perch were conducted to determine decompression thresholds that can cause barotrauma-related injuries. For field validation under realistic operating conditions, autonomous sensors were used to quantify decompression, strike and shear forces golden perch face during passage through a floodplain outlet regulator. The measured decompression was below the threshold that led to serious injuries in the laboratory testing, and also shear forces remained below known injury thresholds. Conversely, mechanical strike was the main risk during passage at the investigated outlet regulator, with severe strike events (> 95 g-force) capable of causing injuries in 73% of runs. The bio-physical thresholds identified can help inform safer river infrastructure design and operation. Targeted modifications to the existing structures could reduce injury and support golden perch persistence across their range.

1 | Introduction

Connectivity is key for the completion of the life cycles of most riverine fish species, which depend on movements between habitats during different life stages and seasons (Hermoso et al. 2021). For instance, access to floodplains which provide nutrient-rich habitats is essential in promoting rapid growth and development (Bayley 1995; Jeffres et al. 2008). For fish species whose life cycles span both river channels and floodplains, physical connection between these habitats is fundamental, both to enable access to floodplain resources and to allow dispersal back to the main channel (Lyon et al. 2010; Stoffels et al. 2022). Short-lived, fast-developing fish species may complete this cycle within a single flood event, whereas medium- to long-lived species often require reconnection across multiple years for populations to benefit (Gorski et al. 2011; Stoffels et al. 2016).

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Although many fish species depend on floodplain access to support growth and development, the connection between main stem and floodplain habitats is often disrupted by structural modifications (Auerswald et al. 2019; Stone et al. 2017). Across the world's large river systems, more than half are affected by fragmentation and flow regulation (Nilsson et al. 2005). River infrastructure such as weirs and regulators has substantially reduced annual streamflow (Grill et al. 2019), with resulting negative consequences on aquatic community composition (e.g., Knott et al. 2024; Mueller et al. 2011). Many floodplains are modified with engineered structures designed to divert, store or re-regulate any incoming water (Knox et al. 2022). Whilst such modifications can offer restoration benefits (e.g., Bond et al. 2014), they also create physical barriers that can limit movement. Fish passage onto and off the floodplain requires movement under, over, or through these structures – a process that carries substantial risk of injury from pressure changes, turbulent forces or uncontrolled collision with hard surfaces (Baumgartner et al. 2006; Boys et al. 2020; Pflugrath et al. 2019). A sound risk assessment requires a quantification of the stressors that occur at river infrastructures and information on the thresholds that can cause harm to the target species in question.

Golden perch (*Macquaria ambigua* Richardson) is a culturally significant and economically valuable native species, widely targeted by recreational fishers across inland waterways of eastern Australia. As a periodic spawner with flexible life-history strategies that often use floodplain habitats to support recruitment, golden perch are cued by rising floodwaters to spawn often following long upstream migrations (Mallen-Cooper and Stuart 2003; Reynolds 1983; Thiem et al. 2025). Their semi-pelagic eggs and drifting larvae disperse passively downstream, sometimes over several hundreds of kilometres (Michie et al. 2025; Stuart and Sharpe 2020). Juveniles settle into nursery habitats such as floodplain lakes, but successful recruitment into adult populations depends on subsequent dispersal back into the river (Stuart and Sharpe 2020).

A clear example of this floodplain–river dynamic is the Menindee Lakes, New South Wales, Australia, a chain of nine natural ephemeral lakes on the Darling-Baaka River floodplain that serves as critical nursery habitat for golden perch (Ebner et al. 2009; Sharpe 2011). Historically, floods regularly filled and reconnected the lakes, enabling downstream dispersal, which is a key population process (Stuart and Sharpe 2020; Zampatti et al. 2021). Since the 1960s, however, a network of weirs and regulators has been used to capture floodwaters and re-regulate upstream inflows, making regulated outlets the primary downstream dispersal pathway. Passage through these outlets could expose juvenile and adult fish to unmeasured risks of injury and mortality.

Understanding the physical and hydraulic risks associated with fish passage through regulated outlets is essential not only for assessing ecological impacts but also for guiding management actions (Baumgartner et al. 2014; Brown et al. 2014). Whilst the susceptibility of golden perch to injury during downstream passage at low-head weirs is recognised (Baumgartner et al. 2006), little is known about the specific pressures and forces these fish experience when passing through outlet regulators, and the thresholds at which these exposures may cause injury or mortality. Understanding the impact of fish passage at outlet regulators is thus an essential component of the conservation management of golden perch.

This study combines laboratory and field experiments to assess the susceptibility of golden perch to barotrauma – a major stressor during river infrastructure passage – under defined laboratory conditions, and to measure the actual physical forces that fish experience at an important outlet regulator of the Menindee Lakes system. We hypothesise that (i) the injury response of golden perch to barotrauma is similar to other native Australian species previously tested, following a specific threshold, and (ii) downstream movement through a floodplain regulator may expose fish to the main hazard of pressure changes that surpass injury thresholds.

2 | Methods

This study combines laboratory and field investigations to examine the sensitivity of golden perch to physical stressors when passing through river infrastructure. Laboratory barometric chamber experiments were used to determine the thresholds for pressure changes that can cause serious injuries and mortality. In a subsequent field study under realistic operating conditions, autonomous sensors were used to quantify the hydraulic and physical stresses juvenile golden perch face during passage of the outlet regulator of Lake Cawndilla – an important habitat in the Menindee Lakes system that supports the dispersal from the Darling-Baaka River sustaining downstream populations in the Murray River (Sharpe 2011; Stuart et al. 2024). It was then examined how these stressors relate to the injury thresholds identified in the laboratory barotrauma experiment.

2.1 | Laboratory Barotrauma Experiments

2.1.1 | Fish Handling

A total of 600 juvenile golden perch, ranging from 51 to 71 mm in total length ($M \pm$ SD: 62 ± 3 mm) and weighing between 1.7 and 5.1 g ($M \pm$ SD: 3.3 ± 0.6 g), were sourced from a private hatchery (Native Fish Stockist, Stanley, Victoria). Upon arrival, fish were housed at the Charles Sturt University Fish Laboratory in Thurgoona, NSW, in two 1000 L circular tanks. Water temperature was maintained between 22°C and 23°C, and water quality was supported by an established biological filter system and 10% water exchange every 2 days.

Fish were acclimated for 2 weeks prior to experimentation, during which their health was monitored multiple times daily. No mortality or signs of disease were observed during this period. Fish were fed daily with frozen *Artemia* nauplii. For testing, groups of 10 fish were randomly selected and gently dip-netted using a knotless net and transferred in a 10 L bucket directly into adjacent barotrauma chambers. These chambers operated on the same recirculating water supply as the holding tanks,

TABLE 1 | Simulated decompression treatments used to replicate pressure changes during fish passage through river infrastructure.

Targeted decompression				Achieved decompression			
P_A	P_N	RPC (P_N/P_A)	RPC (P_A/P_N)	P_N	RPC (P_N/P_A)	RPC (P_A/P_N)	Rate of decompression (kPa/s)
101	101	1.00	1.00	101.0–102.0	1.00	1.00	0
101	79	0.78	1.28	78.8–80.3	0.77–0.80	1.26–1.29	7.9–9.3
101	61	0.60	1.66	59.9–61.0	0.59–0.60	1.67–1.69	17.1–17.1
101	48	0.48	2.10	47.1–48.1	0.46–0.47	2.12–2.16	21.6–21.9
101	37	0.37	2.73	36.5–37.5	0.36–0.37	2.69–2.79	25.0–27.3
101	29	0.29	3.48	28.5–30.2	0.28–0.30	3.38–3.54	28.7–29.1
101	23	0.23	4.39	22.9–23.5	0.22–0.23	4.35–4.45	29.1–32.9
101	18	0.18	5.61	17.7–18.6	0.17–0.18	5.50–5.75	30.9–33.7
101	14	0.14	7.21	14.2–15.4	0.14–0.15	6.64–7.20	28.0–35.0
101	11	0.11	9.18	11.4–11.8	0.11–0.12	8.65–8.88	31.1–35.8
122	10	0.08	12.20	9.8–10.2	0.08–0.08	11.93–12.50	44.7–44.9
156	10	0.06	15.60	6.6–10.2	0.05–0.07	15.31–18.60	46.2–58.5
122	6	0.05	20.33	4.4–5.6	0.04–0.05	21.79–27.54	46.6–49.0
200	5	0.03	40.00	3.1–5.6	0.02–0.03	35.78–65.57	327.3–388.8

Note: The pre-programmed (targeted) acclimation (P_A) and nadir (P_N) pressures are shown as well as the ranges of these subsequently achieved in the chambers, alongside the rate of decompression. All pressures are shown in kPa. The calculated ratio of pressure change (RPC) is shown as both P_N/P_A and P_A/P_N. Equating water depth of P_A: 101 kPa = water surface, 122 kPa = 2.2 m, 156 kPa = 5.6 m and 200 kPa = 10.0 m.

ensuring consistent water quality and temperature throughout handling and testing.

2.1.2 | Barotrauma Experiments

Decompression experiments were conducted using two 150 L barometric chambers to test a range of decompression scenarios that can occur during river infrastructure passage and to identify thresholds for barotrauma-related injuries in juvenile golden perch (see Boys et al. (2016) for details of chamber design and operation). To simulate different water depths, 10 fish at a time were first exposed to either atmospheric pressure (101 kPa) or to elevated pressures representing depth acclimation (up to 200 kPa, equivalent to approximately 10 m depth). Depth-acclimated fish were held under these conditions for a minimum of 12 h to allow for swim bladder adjustment, ensuring neutral buoyancy prior to decompression. Acclimation was confirmed by observing a consistent horizontal swimming posture in all fish, as per the methods of Boys et al. (2016).

After acclimation was confirmed, the chamber pressure was rapidly reduced using a computer-controlled actuator that withdrew a piston and altered chamber volume to achieve a pressure drop to a preset target nadir pressure. Fourteen discrete decompression treatments were achieved using a unique combination of acclimation pressure and nadir pressure (Table 1). The resulting ratio of pressure changes (RPCs) ranged from 1.00 (control, no decompression) to 0.02 (the most severe decompression achieved, corresponding to nadir pressures of 3.1 kPa). Each treatment had three replicates, equating to a total of 42 data points for regression analysis.

Immediately after each decompression event, fish were removed from the chamber, euthanised in 100 mg L^{-1} benzocaine (ethyl-p-aminobenzoate), and examined under a dissecting microscope for signs of barotrauma.

2.1.3 | Injury Assessment and Data Analysis

Barotrauma injuries were assessed using the classification and scoring system described in Boys et al. (2016), with both external and internal signs of trauma recorded immediately post-exposure. For each decompression treatment, the proportion of fish (out of 10) exhibiting each injury type was calculated. To determine the maximum injury incidence across all injuries recorded, the maximum value of the injury type with the highest proportion of injured fish was used for each decompression treatment. Relationships between RPC and injury incidence were examined using segmented (breakpoint) regression (Toms and Lesperance 2003), allowing for identification of injury thresholds. Model selection followed the approach in Boys et al. (2016), using adjusted R^2 and p-values to assess goodness of fit and significance. Piecewise regression models with break points were performed in R (version 4.3.3; R Core Team 2024) using the R package segmented (Muggeo 2008), with statistical significance accepted at $p \leq 0.05$.

2.2 | Field Sensor Fish Investigations

2.2.1 | Study Site

The sensor fish investigations were conducted at the outlet of Lake Cawndilla, one of four main lakes in the Menindee Lakes system, located in western New South Wales, Australia (Figure 1). The Menindee Lakes, situated within the Murray–Darling Basin, are naturally occurring ephemeral floodplain lakes that were modified in the early 1960s into a managed storage scheme (total capacity: 1731 GL) to support irrigation, urban water supply and flood regulation in the Darling River (Harriss 2012). A series of inlet and outlet regulators enable controlled filling and release of water to the Darling River and connected channels.

Lake Cawndilla, the second-largest lake in operation by area (~93 km^2) in the system after Lake Menindee, has a full storage volume of 631 GL. At the time of the sensor fish trials on 21 February 2024, the lake was at 49% capacity (approximately 353 GL; source: https://waterinsights.waternsw.com.au). Lake Cawndilla is supplied by Lake Menindee during high water levels, and water can be released downstream via an outlet regulator into Tandou Creek and subsequently into the ephemeral Great Darling Anabranch, which flows for 480 km, joining the Murray River near Wentworth and connecting golden perch populations between the floodplain nursery habitats and the riverine populations (Stuart and Sharpe 2020). The regulator is capable of discharging up to 2000 ML/day (~23.1 m^3/s), and during the sensor fish experiments, it was operating at a discharge of 388 ML/day (~4.5 m^3/s). The gate opening was 400 mm during the study, resulting in a maximum flow velocity of ~6.0 m/s. Managed water releases from Lake Cawndilla depend on a combination of overall Menindee Lakes storage volumes including for flood management and environmental water allocations.

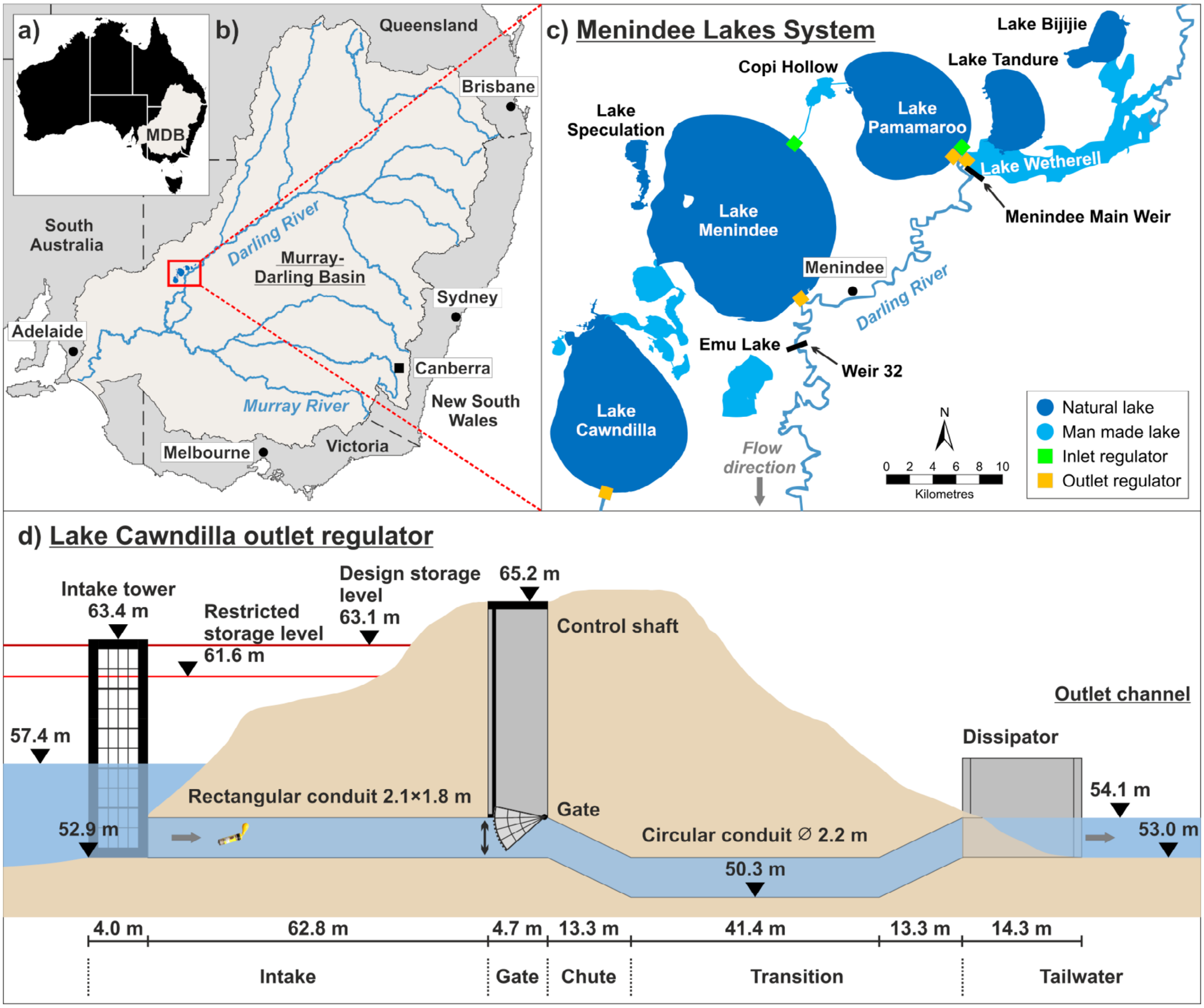

FIGURE 1 | Top left: Location of the Menindee Lakes within the context of (a) Australia and (b) the Murray-Darling Basin (MDB). Top right: (c) Schematic of the Menindee Lakes with positions of the inlet and outlet regulators. Bottom: (d) Schematic longitudinal cross-section of the Cawndilla outlet regulator (not to scale). Water flows in the direction of north to south in (c) and left to right in (d). Heights in (d) refer to Australian Height Datum (AHD), and the four zones between deployment and retrieval correspond to those referred to in the results. [Color figure can be viewed at wileyonlinelibrary.com]

2.2.2 | Data Collection

To investigate the physical and hydraulic forces affecting fish during passage through the Cawndilla outlet regulator, autonomous sensor fish (ARC800; Advanced Telemetry Systems, Isanti, MN, USA) were deployed. These devices measure and record linear acceleration (0–300 g), angular velocity (0°–1400°/s), absolute pressure (0–1400 kPa) and temperature (−40°C to 125°C) at a sampling frequency of 2024 Hz (Deng et al. 2007). The high-resolution data enable the characterisation of exposure to key stressors such as decompression, collisions with hard surfaces (referred to hereafter as a strike) and turbulence during passage through hydraulic structures.

Sensor fish were released at the intake tower of Lake Cawndilla (Figure 1d) and allowed to pass through the outlet regulator. Following passage, devices were recovered in the outlet channel using a combination of radio telemetry and surface balloon tags, as described in Boys et al. (2018). A series of 30 test runs were carried out consecutively. Three sensor fish were not entrained at the intake tower and resurfaced in this area after a delay. All 27 sensor fish that passed through the intake tower also resurfaced in the outlet channel and could be recovered, 26 of which provided usable data.

2.2.3 | Data Analysis

Sensor fish data were analysed using the semi-automated software Hydropower Biological Evaluation Toolset (HBET; PNNL, Richland, WA, USA; Hou et al. 2018). Based on pressure and acceleration profiles, the passage through the Cawndilla outlet regulator was divided into four distinct zones: intake, gate, chute and transition (Figure 2).

Strikes and shear events were identified using peak duration and magnitude values from linear acceleration and angular velocity data (Deng et al. 2007). All acceleration events exceeding 25 *g* were considered biologically relevant. Acceleration events exceeding 95 *g* were categorised as severe events (cf. Hou et al. 2018) and interpreted as potentially injurious or fatal, based on laboratory studies involving salmonid smolts (Deng et al. 2005).

Pressure-related stress was assessed using two complementary metrics: RPC and the decompression rate. These decompression metrics were compared with injury thresholds for golden perch from the barometric chamber experiments. RPC was calculated as the nadir pressure measured immediately following a rapid decompression event, divided by the acclimation pressure prior to regulator passage. RPC ranged from 0 to 1, with lower values indicating more severe decompression.

Acclimation pressure is critical for determining barotrauma risk (Brown et al. 2014), as it influences both the severity of decompression and the degree of swim bladder inflation at the time of passage – since fish regulate buoyancy to maintain a neutral position in the water column. Because the buoyancy history or migration depth of fish approaching the inlet is unknown, two RPC values were calculated for each sensor fish run: RPC_{max} and RPC_{min}. These represent the upper and lower bounds of the RPC a fish could experience during passage, depending on its acclimation depth.

RPC_{max} assumes the fish was acclimated to the maximum water depth at the intake (~4.5 m at the time of measurement) and therefore had a more inflated swim bladder prior to passage. This scenario reflects the most severe decompression risk, as the fish would experience a larger relative pressure drop. In contrast, RPC_{min} assumes surface acclimation to atmospheric pressure, resulting in a less severe decompression exposure.

Finally, the decompression rate (kPa/s) was calculated as the rate of pressure decline from acclimation pressure to post-decompression nadir pressure. This reflected the speed of pressure change experienced during the decompression.

Comparisons between outlet zones (intake, gate, chute, transition) were conducted using univariate statistics. As data were non-normally distributed, differences were tested using Kruskal–Wallis tests, followed by Bonferroni-corrected

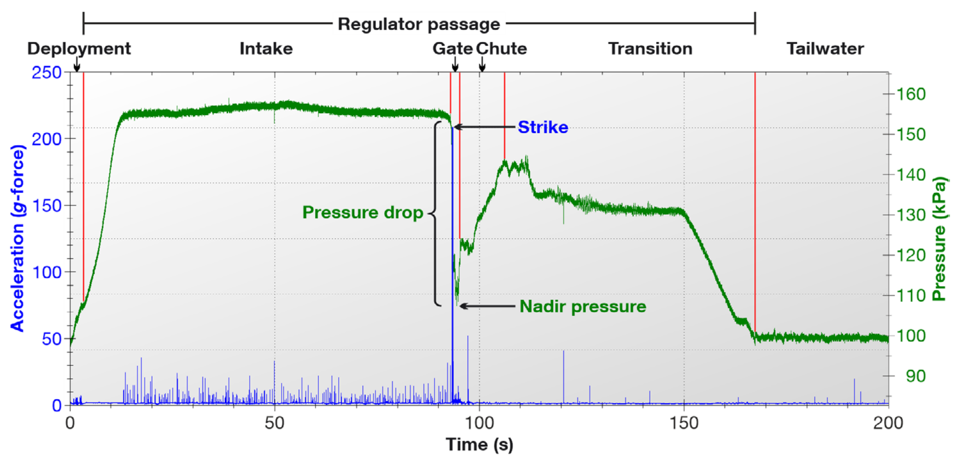

FIGURE 2 | Example of a 'typical' pressure and acceleration profile recorded by sensor fish during the passage of the investigated Cawndilla outlet regulator. The spikes of the blue line (acceleration) indicate strike or shear events, whereas the green line represents fluctuation in pressure. The red lines mark the four zones of the regulator passage between deployment and retrieval of the sensor fish in the tailwater. [Color figure can be viewed at wileyonlinelibrary.com]

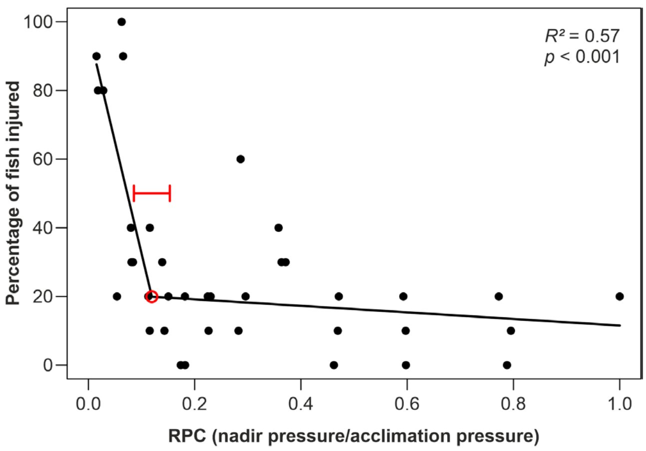

FIGURE 3 | Relationship between pressure change ratio and fish injuries. Display of the percentage of juvenile golden perch (from groups of 10 fish) exhibiting barotrauma injuries following simulated rapid decompression across a range of pressure change ratios (RPC). Points show the maximum injury incidence across all significant injury models. For detailed relationships of individual injuries see Figure A1. The trend line indicates the fitted piecewise linear regression model; the red circle and the bar denote the estimated breakpoint and its 95% confidence interval. [Color figure can be viewed at wileyonlinelibrary.com]

pairwise Mann–Whitney *U* tests for post hoc analysis. All statistical analyses were conducted in R (version 4.3.3; R Core Team 2024). Sensor fish data were visualised using box-and-whisker plots generated with the R package *ggplot2* (Wickham 2016), with statistical significance accepted at $p \leq 0.05$.

3 | Results

3.1 | Injury Thresholds From Barometric Chamber Experiments

The relationship between RPC and injury incidence during controlled decompression confirmed that barotrauma in juvenile golden perch follows a threshold pattern, with a critical RPC value of 0.12 (Figure 3 and Table 2). Above this value, the incidence of injury was absent or declined sharply.

Significant threshold responses ($p \leq 0.05$) were observed for 13 out of 18 injury types assessed (Table 2 and Figure A1). Breakpoints, indicating the RPC at which the probability of injury began to increase sharply, ranged from 0.09 to 0.18 across most injury types, with a median value of 0.12. Injury

TABLE 2 | Summary of breakpoint regression models (cf. Figure A1) describing the relationship between injury incidence and ratio pressure change (RPC) in juvenile golden perch.

Injury response	p	Adjusted R^2	Estimated breakpoint	Standard error	95% CI
Fin emphysema	< 0.001	0.75	0.12	0.01	0.10 to 0.15
Gill haemorrhage	< 0.001	0.63	0.12	0.01	0.09 to 0.15
Gill emphysema	< 0.001	0.59	0.10	0.01	0.07 to 0.12
Swim bladder rupture	< 0.001	0.58	0.12	0.02	0.09 to 0.16
Kidney haemorrhage	< 0.01	0.54	0.12	0.02	0.08 to 0.16
Pharyngo-clitheral membrane emphysema	< 0.01	0.50	0.14	0.03	0.08 to 0.19
Heart haemorrhage	< 0.001	0.49	0.12	0.02	0.09 to 0.16
Exophthalmia	< 0.01	0.46	0.09	0.02	0.06 to 0.12
Eye haemorrhage	< 0.01	0.43	0.11	0.02	0.06 to 0.15
Liver haemorrhage	< 0.01	0.36	0.09	0.02	0.06 to 0.12
Body cavity wall emphysema	< 0.05	0.32	0.18	0.05	0.08 to 0.27
Heart emphysema	< 0.05	0.32	0.14	0.03	0.07 to 0.21
Fin haemorrhage	< 0.01	0.26	0.15	0.04	0.07 to 0.23
Eye emphysema	> 0.05 ns	0.67	0.05	0.02	0.01 to 0.09
Skin haemorrhage	> 0.05 ns	0.05	0.11	0.08	−0.04 to 0.27
Kidney emphysema	> 0.05 ns	0.01	0.20	0.14	−0.07 to 0.48
Skin emphysema	> 0.05 ns	−0.01	0.30	0.20	−0.12 to 0.71
Cloaca haemorrhage	> 0.05 ns	−0.03	0.77	0.15	0.48 to 1.07

Note: Models are ordered by increasing p-value and, within that, by decreasing adjusted R^2. The estimated breakpoint represents the RPC at which injury incidence begins to increase. Significant models ($p \leq 0.05$) suggest the presence of a distinct injury threshold.
Abbreviation: CI = confidence interval.

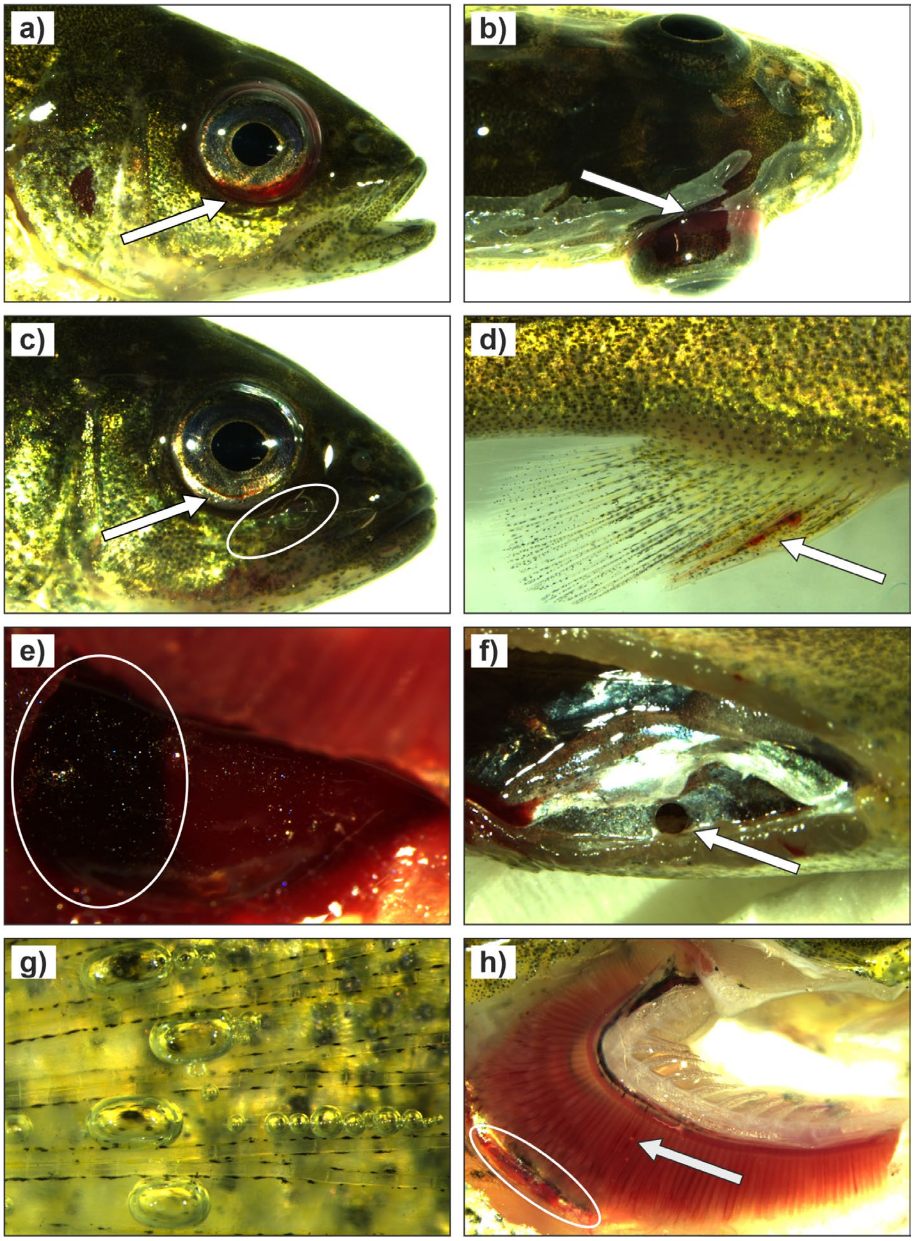

FIGURE 4 | Examples of external and internal injuries observed in golden perch after simulated rapid decompression in barometric chambers: (a) eye haemorrhage, (b) exophthalmia, (c) eye haemorrhage (arrow) and skin emphysema (ellipse), (d) anal fin haemorrhage, (e) heart haemorrhage, (f) swim bladder rupture, (g) fin emphysema, (h) emphysema in gills (arrow) and pharyngo-clitheral membrane (ellipse). [Color figure can be viewed at wileyonlinelibrary.com]

types with the strongest model fits included fin emphysema ($R^2 = 0.75$), gill haemorrhage ($R^2 = 0.63$), gill emphysema ($R^2 = 0.59$), swim bladder rupture ($R^2 = 0.58$) and kidney haemorrhage ($R^2 = 0.54$) (examples shown in Figure 4). These injuries consistently showed breakpoint estimates between RPC 0.10 and 0.14, with narrow 95% confidence intervals. Eye, heart and liver haemorrhages, as well as emphysema in the pharyngo-clitheral membrane, also exhibited significant threshold responses in this range, although with lower adjusted R^2 values.

No significant breakpoint was detected for the five injury types cloaca haemorrhage, skin haemorrhage or for skin, kidney and eye emphysema ($p > 0.05$), indicating no clear injury threshold to decompression for these traits under the tested conditions.

3.2 | Physical and Hydraulic Forces at the Lake Cawndilla Outlet Regulator

Peak accelerations across all runs ranged from 1.8 to 276.6 g, with a mean of 69.8 ± 66.3 g. Physical strikes (> 25 g) occurred in all 26 replicate runs, and severe strikes (> 95 g) were recorded in 73% of runs (Table 3).

The highest accelerations were observed at the gate, with a mean of 141.1 ± 84.8 g (Table 3). This was significantly greater than values recorded in the intake, chute, and transition zones (pairwise Mann–Whitney U tests, $p < 0.001$) (Figure 5a). Severe collisions were most frequent at the gate (62% of runs), followed by the chute (27%) and the transition area (4%) (Figure 5b and Table 3). The intake zone recorded frequent

TABLE 3 | Summary of sensor fish data recorded during passage through the Cawndilla outlet regulator.

	Nadir [kPa]	RPC_{min}	RPC_{max}	Rate of decompression [kPa/s]	Acceleration [g-force]	Strike > 25 g	Strike > 95 g	Shear > 25 g	Shear > 95 g
	M **± SD (range)**	***M*** **± SD (range)**	***M*** **± SD (range)**	***M*** **± SD (range)**	***M*** **± SD (range)**	***n*** **(%)**	***n*** **(%)**	***n*** **(%)**	***n*** **(%)**
Intake	N/A	N/A	N/A	N/A	39.9 ± 16.1 (4.1–86.1)	24 (92)	0	0	0
Gate	114.4 ± 6.0 (91.7–120.5)	1.13 ± 0.06 (0.91–1.19)	0.79 ± 0.04 (0.63–0.83)	111.6 ± 38.9 (49.6–259.4)	141.1 ± 84.8 (18.4–276.6)	25 (96)	16 (62)	4 (15)	0
Chute	N/A	N/A	N/A	N/A	62.6 ± 50.0 (3.6–176.0)	17 (65)	7 (27)	2 (8)	0
Transition	N/A	N/A	N/A	N/A	35.9 ± 26.7 (1.8–134.0)	19 (73)	1 (4)	0	0
Entire passage	N/A	N/A	N/A	N/A	69.8 ± 66.3 (1.8–276.6)	26 (100)	19 (73)	6 (23)	0

Note: Nadir refers to the lowest pressure value recorded following rapid decompression. RPC (ratio of pressure change) is presented relative to surface-acclimated fish (RPC_{min}) and depth-acclimated fish (RPC_{max}). For decompression and acceleration, both the range and arithmetic mean ± standard deviation are provided. The number of runs (*n*) in which any (> 25 *g*) and severe (> 95 *g*) shear or strike events occurred is shown, along with the corresponding percentage of total runs.

but generally less intense collision events, with no instances of severe acceleration.

Shear forces exceeding 25 *g* were recorded in six runs (23%), occurring in four instances at the gate and twice in the chute. No shear forces exceeded 95 *g* in any zone, and no shear events were observed in the intake or transition zones (Table 3).

Sensor fish recorded pressure fluctuations throughout passage, with distinct decompression observed at the gate (Figure 2). Pressures in the intake zone reached up to 160 kPa, followed by a rapid decrease at the gate to an average post-decompression nadir pressure of 114.4 ± 6.0 kPa (Table 3). Pressure then recovered to approximately 151 kPa in the chute before gradually returning to atmospheric pressure in the outlet channel. The maximum decompression rate at the gate was 259.4 kPa/s, with a mean of 112 ± 39 kPa/s.

The nadir pressures following decompression at the gate remained above atmospheric pressure in all but one trial, where a single sensor fish recorded a nadir of 92 kPa. The RPC_{min} calculated (based on surface-acclimated fish) averaged 1.13 ± 0.06, whilst the RPC_{max} (based on depth-acclimated fish) averaged 0.72 ± 0.04 (Table 3). If the lowest possible nadir measured (92 kPa) is considered, the most extreme RPC that could be possible would not be lower than 0.57 (i.e., more severe) under the tested conditions.

4 | Discussion

By combining laboratory and field experiments, critical pressure thresholds for golden perch were established, the severity of the occurring physical forces was quantified and the zones of highest injury risk at a typical outlet regulator of the Menindee Lakes System, where this species occurs in the wild, were identified. Contrary to the hypothesis that decompression is the main hazard during outlet regulator passage, it was found that there is a high injury risk due to mechanical strike, which is particularly relevant for fishes such as golden perch that depend on connectivity between the main stem and floodplain to complete their life cycle. This study also provides a sound basis for assessing barotrauma-related impacts of such river infrastructure on other species than golden perch for which such data is not yet available. Once species-specific critical thresholds have been identified, future studies are able to assess the risk of barotrauma injuries at various river infrastructures without the use of test fish, thereby avoiding and replacing animal testing in line with the objectives of the 3R principles (Replacement, Reduction and Refinement) (Russell and Burch 1959).

At the Lake Cawndilla outlet regulator, juvenile golden perch face their greatest risk of injury during passage through the outlet gate, where strike events were frequent and intense. More than half of all sensor fish deployments recorded strikes exceeding 95 *g*, a threshold previously associated with high injury risk (Hou et al. 2018). In contrast, shear forces remained low relative to published injury benchmarks derived largely from salmonid studies (Richmond et al. 2009). Whilst species- and stage-specific shear thresholds are not yet available for juvenile golden perch, early life-stage trials show that golden perch

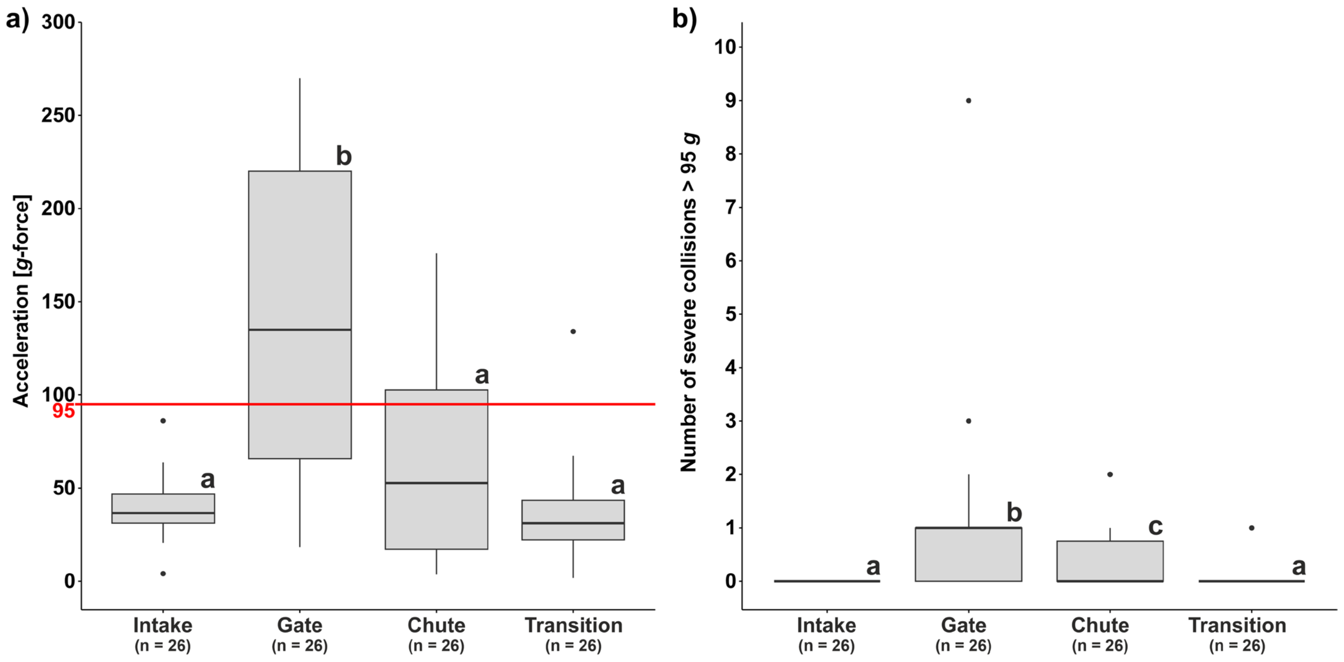

FIGURE 5 | (a) Comparison of maximum acceleration (*g*-force) measured between the zones of passage through the Cawndilla regulator outlet (cf. Figures 1 and 2), with the 95*g* threshold highlighted (red line), above which the forces were judged to be severe collisions. (b) Comparison of the number of severe collisions > 95*g* measured between different zones. Box represents the interquartile range (25th to 75th percentile), with the horizontal line indicating the median. Whiskers extend to 1.5 times the interquartile range, and dots represent values beyond this range (potential outliers). Different lower-case letters indicate significant differences ($p \leq 0.05$; pairwise Mann–Whitney *U* tests). n = number of replicate sensor fish 'runs'. [Color figure can be viewed at wileyonlinelibrary.com]

tolerance to shear increases rapidly with age and that susceptibility becomes negligible by ~25 days post-hatch (Navarro et al. 2019). Barometric chamber trials indicated that the levels of decompression detected by sensor fish were insufficient to cause barotrauma-related injury. Together, these findings identify mechanical strike at the outlet gate, rather than pressure or shear stress, as the primary hazard under the operating conditions tested.

Barometric chamber trials enabled us to define a critical decompression threshold for juvenile golden perch, with injuries observed when RPC fell below 0.12. This sharp breakpoint in the injury response corresponds with the lower end of thresholds previously reported for Murray cod (*Maccullochella peelii* Mitchell) and silver perch (*Bidyanus bidyanus* Mitchell), which exhibited barotrauma injuries across broader RPC ranges of 0.10–0.70 and 0.30–0.70 respectively, depending on injury type (Boys et al. 2016). Whilst golden perch exhibited a more consistent threshold across injury types than those of other species, it is evident that RPC values low enough to injure golden perch would also pose risks to other fish species native to Australia. This consistency reinforces the value of defined RPC thresholds as a tool for interpreting sensor fish data and evaluating biological risk. It also underscores the importance of identifying and, if required, managing pressure changes at infrastructure sites to protect the broader suite of species likely to co-occur in these systems.

With decompression not appearing to pose a significant hazard at the Lake Cawndilla outlet regulator, focus turns to the dominant risk identified in this study: mechanical strike. The concentration of strike risk at the gate corroborates prior findings at undershot structures, where rapid acceleration and turbulence near the gate opening increase the likelihood of impact (Boys et al. 2020; Cox et al. 2022; Pflugrath et al. 2019). However, the risks observed in this study may underestimate injuries. All sensor fish trials were conducted at moderate hydraulic head (Lake Cawndilla at 49% of effective full supply level). Previous research has shown that higher upstream storage levels can intensify flow contraction and turbulence at undershot gates, increasing strike risk (Cox et al. 2022; Pflugrath et al. 2019). This suggests that the severity of impacts at Lake Cawndilla could be greater under higher discharges or lake levels when fish are more likely to be present. Additional testing across a wider range of operational scenarios, and across different structures in the Menindee Lakes system, is needed to define the full extent of risk and guide adaptive operational strategies. Since fish size likely also influences how acceleration at river infrastructures translates into shear- and strike-related injury risk (cf. Deng et al. 2007), subadult or adult individuals may experience different injury intensities for the same acceleration compared to juvenile fish. Therefore, incorporating fish size and weight would probably provide a more comprehensive understanding of injury thresholds and individual susceptibility. However, in the context of our study both the sensors and laboratory subjects were scaled to be representative of the predominant size of fish passing at this study site.

Downstream of the gate, the Cawndilla structure presents a complex geometry (Figure 1d), yet surprisingly, no elevated risk of strike or shear was detected in this zone. One possible explanation for this is that the stepped dissipator and long circular conduit may dissipate energy and stabilise flow. The 41.4 m conduit attenuates velocity (as evident from the acceleration data) before water reaches the dissipator, whilst the stepped apron may also help to slow the flow. These features may explain why fish were less likely to encounter injurious forces once past the gate. This reinforces a key insight from Pflugrath et al. (2019): it is not complexity per se that drives injury risk, but the hydraulic conditions a structure creates under real-world operations. Whilst sensor fish provide insight into the physical forces that fish experience, it is also valuable to consider whether these forces translate into real-world injury.

The Lake Cawndilla outlet gate, like many undershot regulators, features a flat, narrow opening that produces abrupt flow contraction and acceleration – conditions that elevate strike risk. However, safer alternatives are not only conceptually viable but practically achievable. Cox et al. (2022) showed that a bell-mouth pipe entry dramatically reduced flow acceleration, pressure drops, and strike. Similar hydraulic principles could be applied to undershot gates: by maximising gate opening, fish would gain greater clearance from hard surfaces and encounter gentler acceleration.

5 | Conclusion

Growing evidence (this study and Baumgartner et al. 2006; Boys et al. 2020; Pflugrath et al. 2019) demonstrates that infrastructure designed for efficient water delivery can impose unintended risks on fish. As demonstrated in this study, combining information on susceptibility of target species with an assessment of the physical and hydraulic forces these fish experience can help identify critical zones that hamper safe passage between the floodplain and main river channel that are crucial for recruitment in species like golden perch. These findings, combined with previous findings on the susceptibility of fish to stressors when passing river infrastructure, offer great potential for standardised assessment and improvement of fish passage not only for fish species native to Australia but worldwide. The challenge now is for engineers and managers to co-develop reliable, cost-effective solutions that can be integrated into new infrastructure and retrofitted to existing systems, thus ensuring that water delivery structures serve both people and aquatic life.

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Ethics Statement

All animal-based procedures were conducted with approval and oversight from the NSW DPIRD Fisheries Animal Ethics Committee (Animal Research Authority No. 616) and the Charles Sturt University Animal Ethics Committee (Animal Research Authority No. A2041).

Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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Appendix A

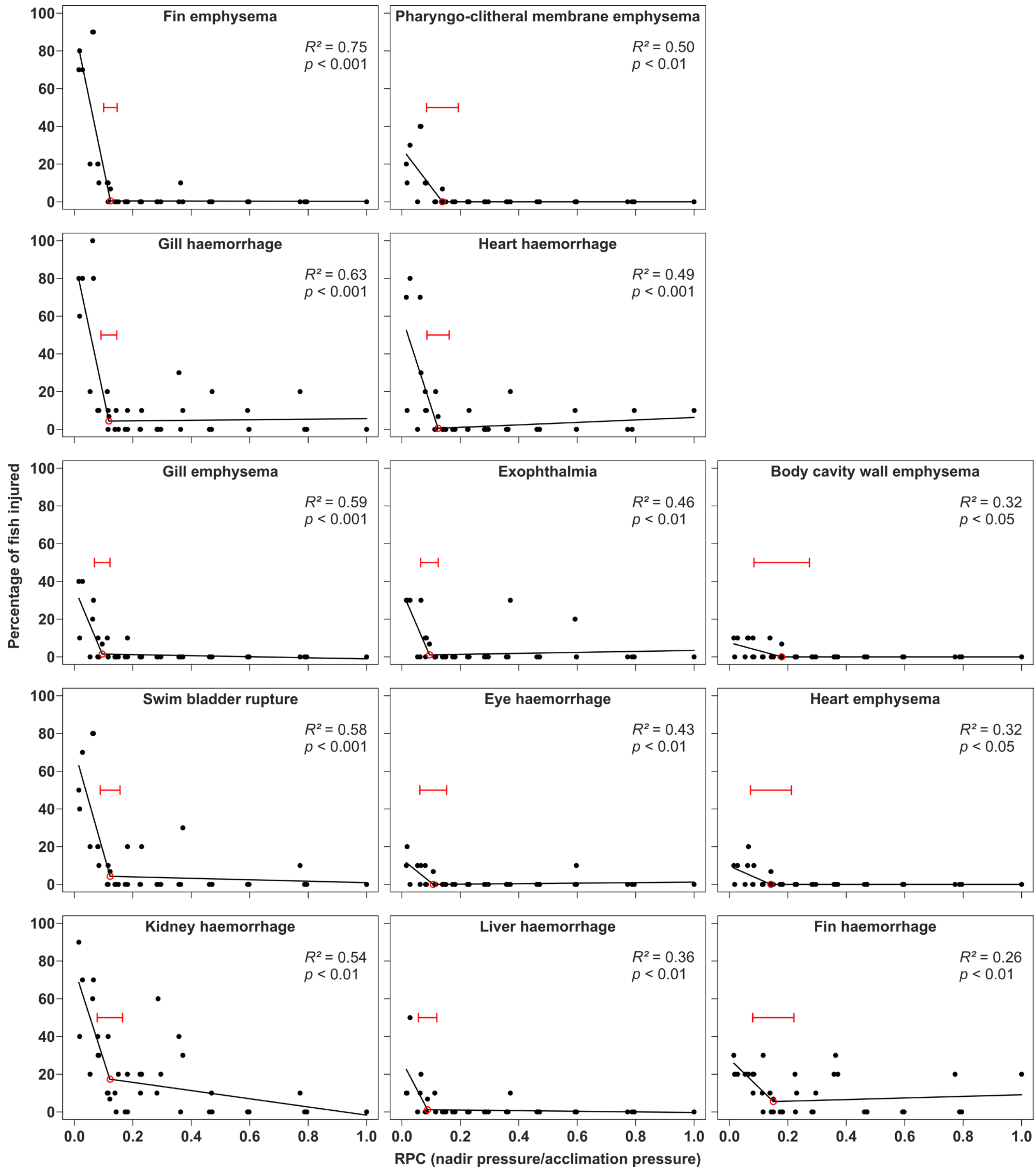

FIGURE A1 | Percentage of juvenile golden perch (from groups of 10 fish) exhibiting barotrauma injuries following simulated rapid decompression across a range of pressure change ratios (RPC). Each panel represents a specific injury type. Points show observed injury incidence; trend lines indicate fitted piecewise linear regression models; red circles and bars denote the estimated breakpoint and its 95% confidence interval. Only significant models ($p \leq 0.05$) are shown. Adjusted R^2 values are provided for each regression. Plots are ordered by descending R^2 value (top to bottom, left to right). [Color figure can be viewed at wileyonlinelibrary.com]