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Review

Fish Injury from Movements across Hydraulic Structures: A Review

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Abstract: Fish migration is essential to maintain healthy aquatic ecosystems, but hydraulic structures across rivers have impeded natural fish migration worldwide. While efforts have been made to allow fish to pass some hydraulic structures, there is limited understanding of hydrodynamic effects that cause fish injury in different hydraulic systems, such as spillways and stilling basins as well as hydropower systems. This study reviewed available literature on this topic to identify the current knowledge of fish injury thresholds in laboratory- and field-based studies of hydraulic systems. Often, the hydraulic effects that lead to fish injury have been described with time-averaged simplified parameters including shear stress, pressure changes, acceleration, vortical motions, aeration, collision, and strike, while these hydrodynamic effects often occur simultaneously in the turbulent flows across hydraulic structures, making it difficult to link specific fish injuries to a particular hydrodynamic effect. Strong variations of injury may occur, depending on the type and the intensity of hydrodynamic effects, as well as the fish species and fish sizes. Modelling can provide information of stressors, but real-world tests are needed to accurately assess fish injury and mortality. Fish injury mechanisms at hydropower turbines are well understood, however, clear understanding at other sites is lacking. Future studies should aim to report holistic hydrodynamic thresholds with associated fish injury rates. Multidisciplinary systematic research is required, including laboratory and field studies, using passive tracer sensor packages and state-of-the art instrumentation in conjunction with live fish. This can quantify stressors with meaningful parameters, aiming to improve fish safety with more sustainable design of water infrastructure that reduces fish injury when passing across hydraulic structures.

Keywords: fishways; spillways; pipe flows; energy dissipators; hydraulic systems; hydropower systems; energy dissipator; fish passage; Tube Fishway; multidisciplinary research

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1. Introduction

Natural fish migration occurs in estuaries, rivers and other interconnected freshwater ecosystems that allow fish to migrate upstream or downstream, depending on their life history strategy such as reproduction, habitat shifts for feeding or winter habitats. However, many of the world's freshwater ecosystems have been modified to use water for urban centres, industry, energy production and irrigation [1]. Human intervention usually requires modification of river systems, using hydraulic structures such as weirs, dams or levees and associated flow conveyance infrastructure, such as spillways and energy dissipators, as well as closed-conduit systems for hydropower production. Culverts and bridges are designed to maintain the natural water flows through embankments and causeways but can block fish and other aquatic species [2] or hinder their migration [1,3]. Large water reservoirs store cold, stratified water in the bottom layer, harming ecosystems and fish when released [4–7]. Physiological stress from movement across structures can increase vulnerability to predation [8]. Any type of barrier contributes to declining fish stocks worldwide [2,9–11]. Prevention of downstream fish passage, by bar racks or low flow depths at overflow structures, also poses a threat to fish that need a downstream passage without significant delay [12,13]. Fishways can restore some fish migration, helping improve biodiversity and maintaining fish populations [9,11,14–16], but more sustainable hydraulic structures are needed [17].

Fish move through two major categories of hydraulic structures, i.e., open-channel flow and closed-conduit systems, while they are stopped by barriers (Figure 1). Fish can move upstream or downstream using fishways, spillways or hydropower systems and pumps. There is a need to improve understanding of how flows across hydraulic structures and associated hydrodynamic effects can injure fish to improve overall fish movement and minimise impacts on fish during movement.

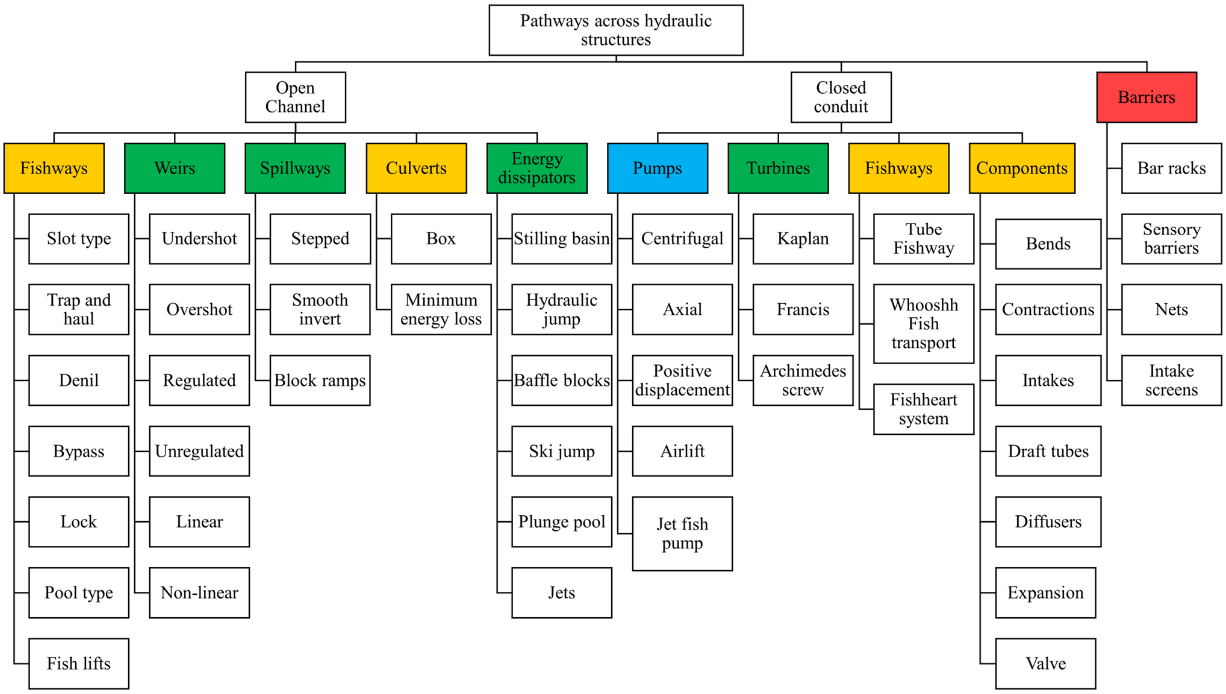

Figure 1. Main pathways for fish across hydraulic structures can be divided into open-channel flows and closed-conduit systems, while barriers prevent fish passage. Fish may move downstream (green), upstream (blue), both ways (orange) or they cannot pass (red).

Although fish can be injured in natural water systems (e.g., during floods) or through poor ecological conditions such as lack of oxygen [18,19] and pollution [20,21], many fish are injured during movement across hydraulic structures. These injuries need to be considered in addition to other existing risks. The relative permanence of hydraulic structures means that the impacts on fish are long lasting and continuous. While fish injury has been documented for turbines [22] and undershot weirs [23,24], there is limited understanding of the interaction of underlying hydrodynamic effects causing fish injuries. Often fish injuries passing through hydraulic structures are assessed by observing fish at both ends of a hydraulic system, which does not provide information on the hydraulic effects causing fish injury. Flows across hydraulic structures are often highly dynamic and complex (Figure 2). Flows across any hydraulic system are always turbulent. Flows are typically three-dimensional with fluctuations of velocities and pressures in space and time. At selected locations along a hydraulic structure, the flows are visibly complex with large vortical motions, air entrainment and strong variations in the free surface found in energy dissipators at the downstream end of hydraulic structures (Figure 2). Considering the complexity of flows in many hydraulic systems, hydraulic effects or structural components causing fish injury are difficult to assess given several hydraulic effects, acting simultaneously or consequently, could be responsible. To improve this, it would be useful to identify how fundamental fluid mechanic processes lead to fish injuries, which could be used to improve the design of structures for fish movement and provide a more sustainable hydraulic infrastructure.

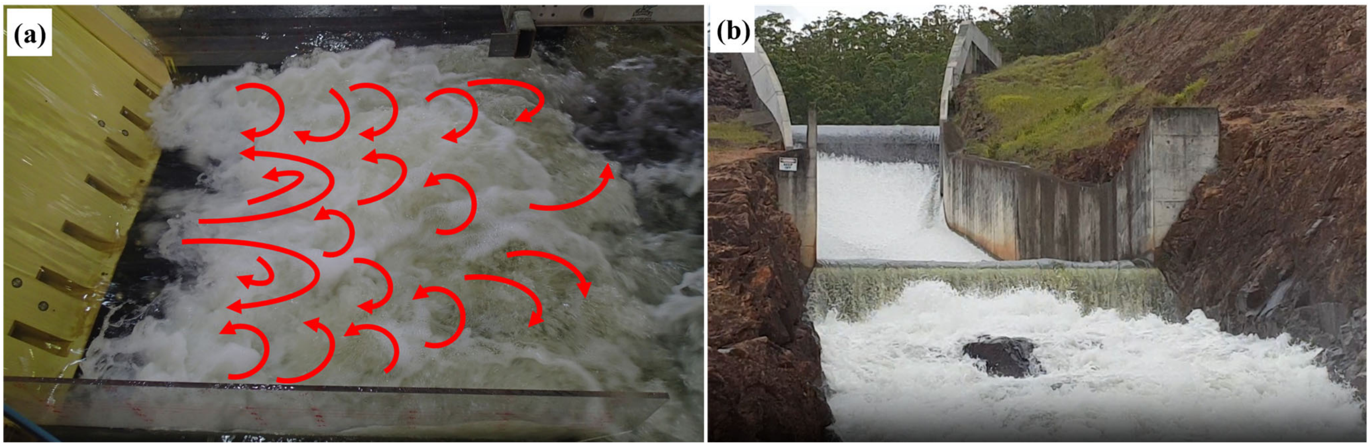

Figure 2. Photos of typical flows across hydraulic structures characterised by high velocities, strong turbulence and flow aeration: (**a**) Physical model of complex 3D flows in a stilling basin with hydraulic jump; arrows indicate large vortical motions that vary in size, space and time; (**b**) Flood release structure of Clarrie Hall Dam, Australia, operating in February 2020; flow becomes aerated in high-velocity flows along spillway and energy is dissipated in hydraulic jump at downstream end (photo courtesy of Mark Callander, Tweed Shire Council).

To identify hydrodynamic effects that potentially cause injuries to fish moving across hydraulic structures, this manuscript critically reviews the published literature on fish injuries in hydraulic systems. It summarises the commonly used definitions of hydraulic effects that are linked to fish injuries and summarises the available thresholds for these hydraulic effects, while critically assessing the limitations of this approach (Section 2). It collates the currently available information on fish injuries for open-channel flow and closed-conduit hydraulic systems showing the complexity to link fish injuries to individual hydraulic effects (Sections 3 and 4). It subsequently discusses potential improvements in understanding relationships between fish injury and hydrodynamic conditions during fish movement across hydraulic structures (Section 5).

2. Fish Injuries in Hydraulic Systems

Fish interact with flows ranging from rheotaxis in fish attraction flows [25] to passively moving with strong flows (e.g., in closed-conduit hydropower systems). This involves diverse hydrodynamic flow characteristics. All flows in hydraulic structures are turbulent, characterised by irregularly fluctuating velocities in both space and time [26]. Typically, fish injuries have, however, been reported in the literature as being caused by specific time-averaged hydraulic effects of shear stress, pressure changes, accelerations, turbulence, aeration and collision/strikes (Section 2.1). This simplified time-averaged approach to fish injury is defined in Section 2.2; differences to more complete fluid mechanic definitions are critically discussed. The limited understanding of threshold conditions causing fish injuries for the reported hydrodynamic effects from the current literature is presented in Section 2.3.

2.1. Fish Injury and Reported Causes

Injuries vary with species and age of fish [27]. Larval and juvenile fish are more likely to be injured beginning at lower hydraulic effects [28,29]. Physostomes (fish with ducts to vent air from swim bladder to gut such as herring (*Clupeidae*), carp (*Cyprinidae*) and salmonids (*Salmonidae*)) are less impacted by pressure changes than physoclistous fish, such as perch (*Percidae*) or bass (*Perciformes*), which have a sealed swim bladder and rely on a gas gland [8,30]. Physostomes can vent swim bladder gas to the gut during decompression, while for physoclistous fish, the consequences of decompression are more severe than compression, as with reduced external hydrostatic pressure, the swim bladder can expand into the throat or rupture [8]. Aeration and subsequent gas supersaturation affect juvenile more than mature fish, considerably varying among species [31]. The effects of turbulence can have a greater influence on smaller fish [32]. The length of fish increases injury potential for strike [33]. Fish injuries are widespread with varied reported causes (Table 1, [8,28,34–42]). Injuries vary substantially, ranging from external injuries such as lacerations damage to eyes or fins, descaling and bruising to internal injuries such as swim bladder damage, internal haemorrhaging, and stress related injury (Table 1). Injuries manifest immediately or over time usually within 96 h [43]. Their effects may allow immediate recovery (minor) or recovery with lasting effects (major) or be fatal (mortality) (Table 1).

Table 1. Types of fish injury caused by different hydraulic effects as reported in the literature [8,28,34–42], with categorisation of injury severity: minor (green), major (yellow) and death (red). Delayed effects are indicated with striped pattern.

Injury	Shear Stress	Pressure Changes	Acceleration	Turbulence	Aeration	Collision	Strike
Amputation							
Bruising							
Change in pigmentation							
Corneal rupture							
Decapitation							
Deformation							
Descaling							
Disorientation							
Egg loss							
Embolism							
Epithelium loss							
Exophthalmia							
Eye loss							
Fin damage							
Gas bubble disease							
Gill damage							
Haemorrhaging							
Increased predation							
Laceration							
Mucus loss							
Operculum damage							
Rotation							
Spinal injury							
Stomach eversion							
Swim bladder rupture							
Torsion							

Table 1 summarises fish injury types for hydraulic effects reported in the literature. Some hydraulic effects have been linked to mortality in fish, with shear stress being most widely reported as causing many types of injuries of varying severity (Table 1). Pressure changes most commonly present as internal injuries, while strike causes the most major injuries and death. The intensity of some reported stressors varies considerably among fish sizes and species, producing a wide range of injury effects (Table 1).

The hydraulic effects represent a broad and simplified categorisation of potential hydrodynamic conditions that may have caused specific fish injuries (Table 1), ignoring that several hydraulic effects often occur simultaneously (e.g., shear stress and acceleration in an underlying turbulent flow) which make it hard to associate specific hydraulic effects with fish injuries. Furthermore, despite descriptions of fish injuries for reported hydraulic effects, there is little quantification that would allow to identify thresholds for fish injuries in relation to fish sizes and species. For example, it is not clear what levels of reported shear stress in relation to fish size result in injuries or at what frequency. Threshold values for injury need to be adequately measured and tested beyond qualitative descriptions.

2.2. Common Categorisation of Hydraulic Effects That Cause Fish Injury

This section presents the hydraulic effects from Table 1 as used in fish-injury literature. Figure 3 presents the hydraulic effects as simplified time-averaged parameters as commonly used to describe the systems encountered by fish. Such a simplified differentiation into specific hydraulic effects does not capture the true complexity of turbulent flows where several hydrodynamic effects occur simultaneously with fluctuations in velocities and pressures.

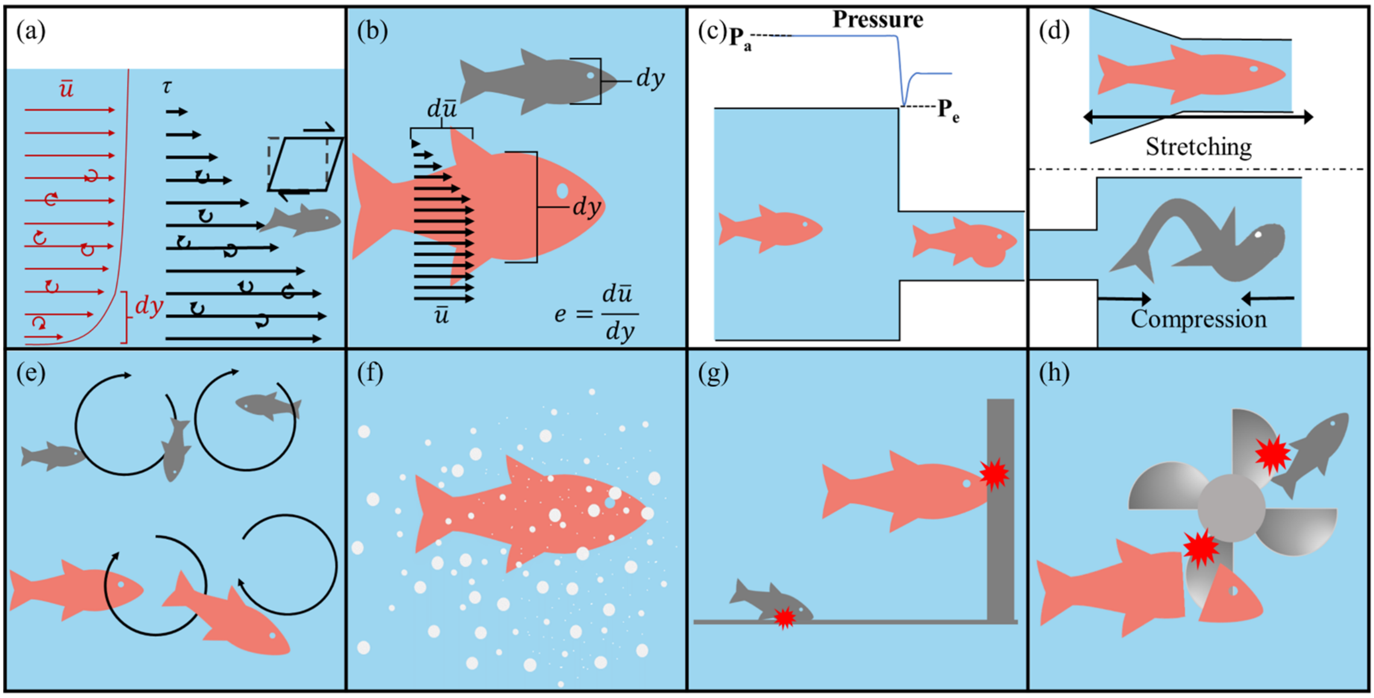

Figure 3. Hydraulic effects that cause fish injury as reported in literature. (**a**) Reynolds shear stress in turbulent open-channel flow; (**b**) an example of time-averaged exposure strain rate for submerged jet with dy presented for two fish; (**c**) pressure changes across a pipe contraction; (**d**) acceleration and deceleration through pipe components; (**e**) large-scale vortical motions entrapping fish; (**f**) aeration; (**g**) collision with wall and bed; (**h**) strike with impeller blades.

Turbulent shear stress $\tau = (\mu + \varepsilon)\frac{d\bar{u}}{dy}$ has been commonly considered in fish-injury literature as the time-averaged shear stress in parallel 2D flows with two layers of moving fluid with mean velocity change $d\bar{u}$, over a distance perpendicular to the flows dy (Figure 3a), where μ is the dynamic viscosity of the fluid and ε is the eddy viscosity which depends on fluid motion and density ρ [44]. In turbulent flows, the eddy viscosity is much larger than μ. Prandtl developed the mixing length theory which expresses turbulent shear stress as a momentum exchange across fluid layers $\tau = \rho l^2 \left(\frac{d\bar{u}^2}{dy}\right)$ with mixing length l.

Turbulent shear stress is often also expressed as Reynolds shear stress $\tau = -\rho\overline{u'v'}$ where u' and v' are the velocity fluctuations in the x and y directions. Several fish studies have used turbulent shear stress as a descriptor for injury thresholds [8,36,45], while another study has also considered the average wall shear stress [46]. In pipe and open-channel flows, the average wall shear stress is often expressed as $\tau_o = \frac{1}{8} f \rho \overline{u}^2$, where f is the Darcy–Weisbach friction factor.

Shear stress differs from 'shearing' against or abrasion on a solid surface, such as a spillway or a pipe wall, which is considered as collision in this study.

A time-averaged exposure strain rate $e = \frac{d\overline{u}}{dy}$, has also been commonly used, where dy has been determined as the width of the fish [47], with mean velocity change $d\overline{u}$ from zero to the maximum flow velocity (Figure 3b). This definition of dy differs from fluid mechanics considerations as the use of the fish width for dy might not necessarily represent the largest fluid strain rate or shear stress a fish could be exposed to in parallel flows. Considering different values of dy can result in different exposure strain rates and shear stresses, which makes quantitative comparison of e and τ between reported results difficult as dy is not the same (Figure 3b). A possible dy considered for fluid strain rate could be the boundary layer thickness (i.e., the distance from the wall to the location of free-stream velocity). The boundary layer thickness is not constant in developing flows and can change depending on flow conditions, which means that the fluid strain rate and shear stress may change for flows across a hydraulic system and a single value cannot be used to describe the entire system. In contrast, the use of the fish width dy means that the exposure strain rate varies based upon the fish sizes and not based upon local hydrodynamic conditions. However, using the fish size as a length scale in the calculation of the exposure strain rate allows some comparison of fish injuries for comparable hydrodynamic conditions. Such considerations are also simplified in terms of time-averaging and parallel flows without considering the fluctuating components that are part of turbulent flows (see below).

Pressure changes occur due to changes in water depths or from abrupt cross-sectional changes in closed-conduit flows (e.g., sudden contraction) (Figure 3c) or in open-channel flows (e.g., flows around baffle blocks in stilling basins). Significant pressure changes harming fish are quick (seconds or less), faster than a fish can accommodate [8]. The ratio of pressure changes (RPC) is commonly used to describe the magnitude of this hydrodynamic effect for fish as RPC = P_a/P_e [48]. P_a is the acclimation pressure (i.e., the pressure that a fish would naturally experience at a certain water depth (e.g., $P_a \approx 111$ kPa at 1 m depth)), and P_e is the exposure pressure (i.e., the minimum/maximum pressures experienced along a system for decompression/compression, respectively). Conceptually, there can be sudden pressure loss through a pipe entrance with associated P_a and P_e (Figure 3c). All these parameters represent time-averaged pressures, while pressures fluctuate in turbulent flows. Irrespective of this, the consideration of time-averaged pressures allows simple estimates of pressure drops across hydraulic systems.

Acceleration or deceleration occur with velocity change in closed-conduit or open-channel flow systems (Figure 3d). In an accelerating flow (e.g., a pipe contraction), the tip of a fish may experience a higher velocity compared with its tail and the fish may be stretched [38]; in a decelerating flow (e.g., a sudden pipe expansion), fish may compress (Figure 3d). Accelerations and decelerations are closely linked with variations in hydrodynamic properties including shear stress, strain rate, pressures (as mentioned above), as well as flow turbulence.

Turbulent flows are characterised by eddies of various sizes, associated with strong temporal and spatial variations of velocity and pressures, as well as chaotical mixing (Figure 3a,e). Turbulent flow characteristics are present in all hydraulic effects shown in Figure 3. In the context of reported fish-injury literature, turbulence has been typically considered as large-scale vortical motions, which can entrap fish causing direct injury (Figure 3e) or cause collisions with walls or other solid parts of the passage system (e.g., hydraulic jump roller in a stilling basin). The effect of vortical motions on fish depends on the fish size and fish species [49] with turbulent length scales used to estimate such effects [50,51]. Fluctuating velocity components dominate the overall shear stress in turbulent flows (see above).

Aeration is common in high-velocity flows on spillways and in violent flows in energy dissipators (Figures 1 and 3f); it is strongly linked with flow turbulence. If air is entrained for extended periods, this can lead to supersaturation of dissolved gases especially in plunge pools or energy dissipators with strong aeration [52]. Supersaturation of gases in the water is transferred to fish body tissues, causing gas bubble trauma (GBT) in fish when the fish returns to normal conditions.

Collision or strike is considered as the direct impact of fish hitting a solid boundary or object. Collision can be caused by flows causing fish to slide along the invert of a spillway in low flows or colliding with a baffle block in a stilling basin (Figure 3g). Fish can also be struck by a turbine blade in a hydropower system (Figure 3h).

While these listed hydrodynamic effects are present in flows across hydraulic structures, they often occur simultaneously, varying in intensity (Figure 2). For example, rougher surfaces and faster flows generate more friction and turbulence, while the strength of the large scale vortical motions in hydraulic jumps and the associated aeration are related to the inflow conditions of the supercritical inflows [53].

Shear stress and exposure strain as described in this section can only hold for parallel flow. The velocity tensor can be used to describe the motion of flow [54]. Stress and strain are tensor quantities which are time- and spatially varying. Acceleration and deceleration along a streamline can also be described by the strain tensor. Rotational components of the velocity gradient tensor can also account for the above descriptions of rotational movements or swirling motions of fish. Turbulence is the chaotic fluctuation of velocity and pressure, and injuries attributed to this are only a result of these underlying fluctuations surpassing a critical threshold. A question arises regarding whether time-averaged quantities accurately represent the actual flow dynamics encountered by a fish which may cause injury.

2.3. Reported Injury Thresholds

This section presents injury thresholds for the hydraulic effects explained in previous sections. As noted above, these hydraulic effects are a simplified characterisation of the flows that cause fish injuries and some injuries may occur from complementary hydraulic effects that are difficult to separate. Some experimentally derived injury thresholds have been reported for specific hydrodynamic effects on fish for shear stress (Table 2), exposure strain rate (Table 3), pressure changes (Table 4) and acceleration (Table 5). For the other hydrodynamic effects, there is limited research. Exposure strain rate, similar to shear stress in effect, is presented separately, given threshold values have been separately reported.

Table 2. Reported fish injury and mortality threshold values for shear stress τ.

Fish Species	τ (Pa)	Injury/Mortality	System for Tests	Reference
White perch larvae (*Morone americana*)	35 (τ_o) *	Mortality 38%—1 min exposure, 52%—2 min exposure, 75%—4 min exposure.	Concentric rotating cylinders	[46]
Striped bass larvae (*Morone saxatilis*)		Mortality 9%—1 min exposure, 30%—2 min exposure, 68%—4 min exposure.		

Table 2. *Cont.*

Fish Species	τ (Pa)	Injury/Mortality	System for Tests	Reference
Atlantic herring (*Clupea harengus*)	206	Complete mortality at 7 days. Loss of mucus coating	Jet shear flume (fish inserted into submerged jet)	[45]
Salmonoids (*Salmonidae*)	774	Minor scale loss, no other injuries or mortality, 7 days		
Atlantic salmon (*Salmo salar*)	3410	12% mortality, 32% eye injury; 5% scale loss per fish.		
Brown trout (*Salmo trutta*)		10% mortality, 10% eye injury, 10% gill damage, 5% scale loss per fish.		
European eel (*Anguilla anguilla*)		No injury or mortality		
Twaite shad (*Alosa fallax*)		Complete mortality; 90% scale loss per fish		
Juvenile salmon (*Salmonidae*)	1920	10% injury and mortality	Jet shear flume (fish inserted into submerged jet)	[8]
Atlantic salmon (*Salmo salar*) (~174 mm), hybrid bass (*Morone saxatilis*×*M. chrysops*) (~172 mm), rainbow trout (*Onchorhynchus mykiss*) (~191 mm)	50 (Reynolds shear stress)	Minor injury and disorientation at 10 min exposure; no mortality 48 h after tests	Turbulence tank	[36]

Note: * Wall shear stress τ_o defined at moving boundary of concentric rotating cylinders (see Equation (1) in [46]).

Table 3. Reported fish injury threshold values for exposure strain rate *e* using the fish width as *dy*.

Fish Species	*e* (1/s)	*dy* (mm)	Comment on Injury	System for Tests	Reference
Salmon (*Salmonidae*)	600 *	18	Minor scale loss, no other injuries or mortality	Jet shear flume (fish inserted into submerged jet)	[45]
American shad (*Alosa sapidissima*) (85–115 mm)	517	18	Onset for death and injuries	Jet shear flume (fish inserted into submerged jet headfirst)	[35]
Chinook salmon (*Oncorhynchus tshawytscha*) (135–154 mm), steelhead (*Oncorhynchus mykiss*) (175–232 mm)	517	18	Onset of minor injury		
Rainbow trout (*Onchorhynchus mykiss*) (147–173 mm)	688	18	Onset of minor injury		
Chinook salmon (*Oncorhynchus tshawytscha*) (135–154 mm)	852	18	Onset of minor injury	Jet shear flume (fish inserted into submerged jet tail first)	
Chinook salmon (*Oncorhynchus tshawytscha*) (135–154 mm), rainbow trout (*Onchorhynchus mykiss*) (147–173 mm), steelhead (*Oncorhynchus mykiss*) (175–232 mm)	1008	18	No significant major injury or deaths		
Salmonids (*Oncorhynchus*)	495	18	Threshold for estimated 10% minor injury in juvenile salmonids.	Jet shear flume (fish inserted into submerged jet headfirst)	[47]

Table 3. *Cont.*

Fish Species	*e* (1/s)	*dy* (mm)	Comment on Injury	System for Tests	Reference
Chinook salmon (*Oncorhynchus tshawytscha*) (93–128 mm)	677	18	Onset of minor injuries	Jet shear flume (fish inserted into submerged jet headfirst)	[37]
	761	18	Onset of major injuries		
	933	18	Onset of fatal injuries		
Silver shark (*Balantiocheilos melanopterus*) (~65 mm)	880	18	Onset of mortality	Jet shear flume (fish inserted into submerged jet)	[55]
Silver perch juveniles (*Bidyanus bidyanus*) (~20 mm)	2002 **	5	10% mortality	Jet shear flume (fish inserted into submerged jet tail first)	[28]
Golden perch juveniles (*Macquaria ambigua*) (~20 mm) Murray cod juveniles (*Maccullochella peelii*) (~20 mm)	2002 **	5	No mortality		
Blue gourami (*Trichopodus trichopterus*) (~58 mm)	852	18	27% immediate mortality	Jet shear flume (fish inserted into submerged jet)	[56]
Iridescent shark (*Pangasianodon hypophthalmus*) (~60 mm)	1185	18	40% immediate mortality		
Silver perch (*Bidyanus bidyanus*) (~21 mm) (27 days post hatching)	2002	5	10% mortality.	Jet shear flume (fish inserted into submerged jet tail first)	[29]
Golden perch (*Macquaria ambigua*) (~20 mm) (26 days post hatching)	2023	5	10% mortality.		
Murray cod (*Maccullochella peelii*) (~11 mm) (29 days post hatching)	890	5	10% mortality.		
Gambusia (*Gambusia holbrooki*) (~24 mm)	1853	10	Estimated 80% survival	Jet shear flume (fish inserted into submerged jet)	[57]
Black carp (*Mylopharyngodon piceus*), grass carp (*Ctenopharyngodon idella*), silver carp (*Hypophthalmichthys molitrix*), bighead carp (*Hypophthalmichthys nobilis*) (~70 mm)	2179	8	Behaviour changes and onset of minor injuries returning to normal within 10 min. No mortality	Unsteady pipe surge (headfirst)	[58]
Bighead carp (*Hypophthalmichthys nobilis*) (~70 mm)	1780	8	Behaviour changes and onset of minor injuries returning to normal within 10 min. No mortality	Unsteady pipe surge (tail first)	
Redfin juveniles (*Perca fluviatilis*) (~116 mm)	1687	10	No mortality	Jet shear flume (fish inserted into submerged jet headfirst)	[59]
	1853	10	70% survival		

Notes: * As calculated by [35], compare [45], τ = 774 Pa in Table 2. ** Corrected value for strain rate (see [29]).

2.3.1. Shear Stress Thresholds

Shear stress (τ) refers to the interactions between moving layers of fluid, and therefore, it has less impact on larger fish (Table 2). Some species can tolerate considerable shear stress, such as European eel (*Anguilla anguilla*), while other species such as herring or larval fish can die (Table 2). Further, increasing the exposure time to shear stress increases the likelihood of injury or death [8,36,46].

2.3.2. Strain Thresholds

There is considerable variability in thresholds to exposure strain rate (e) across species for onset of injuries and death (Table 3). This is also affected by direction of flow relative to the fish, where flow from tail to head causes injuries at low values of e. Neitzel et al. [35] recommended e = 850 1/s as a limit for juvenile fish of multiple species. Although e differs significantly in some cases due to variation of fish sizes, comparison of jet velocities showed injuries typically occurring at ~10 m/s across some species [28,35]. These jets of same flow conditions (including velocity) have different exposure strain rates e due to variation in tested fish sizes (see Section 2.2).

2.3.3. Pressure Change Thresholds

Fish injury thresholds vary with pressure change (Table 4), reflected in ratio of pressure change RPC (Section 2.2). Sometimes, rate of pressure change is a useful additional descriptor [60] but it has a far smaller effect on fish wellbeing than RPC [48,61]. Further, much of the pressure change in hydraulic systems occurs in <1 s, far faster than a fish can adjust without ill effects [8]. Physoclistous fish may exhibit greater mortality than physostomes for similar RPC [8]. Variation also occurs among different species in the same river environment (cf. Murray cod (*Maccullochella peelii*) and silver perch (*Bidyanus bidyanus*) [28]). Larval fish are also typically more resistant to pressure changes than juveniles [28]. Decompression ($P_a > P_e$) is worse for fish than compression ($P_a < P_e$) as significant increases in P_e did not manifest mortalities [8]. Injuries and mortality increase with RPC within the same fish group. Even recommended levels for hydropower passage (RPC = 3.3, [62]) may still harm some fish (Table 4), requiring lower RPC threshold recommendations (RPC = 1.6, [8]).

Table 4. Reported fish injury threshold values for ratio of pressure change RPC.

Fish Species	RPC	Comment on Injury	System for Tests	Reference
Sockeye salmon smolts (*Oncorhynchus nerka*)	3.06	21% mortality	Pressure chamber	[63] *
Fallfish (*Semotilus corporalis*), lake trout (*Salvelinus namaycush*), and Atlantic salmon (*Salmo salar*)	0.05	No mortality	Pressure chamber (Instantaneous compression with 10 min return to atmospheric conditions)	[64] *
Perch (*Percidae*)	3.00	70% mortality	Pressure chamber	[65] *
Largemouth bass (*Micropterus salmoides*)	1.89	25% mortality (over 5 days)	Pressure chamber	[66] *
	2.77	42% mortality		
	3.65	46% mortality (over 1 h)		

Table 4. *Cont.*

Fish Species	RPC	Comment on Injury	System for Tests	Reference
Chinook salmon (*Oncorhynchus tshawytscha*) (71–205 mm)	2.12	Infrequent injury; low mortality (<10%)	Pressure chamber	[48]
	4.5	Considerable injury; ~55% mortality		
Silver perch (*Bidyanus bidyanus*) (22 days post hatching)	2.63	Onset of injury	Pressure chamber	[28]
Golden perch (*Macquaria ambigua*) (12 days post hatching)	2.12	Onset of injury		
Murray cod (*Maccullochella peelii*) (25 days post hatching)	2.38	Onset of deflated swim bladder		
Murray cod juvenile (*Maccullochella peelii*) (~66 mm)	1.59 **	Onset of injury (viscera haemorrhage only)		
	2.50	Onset of other pressure related injuries		
Silver perch juvenile (*Bidyanus bidyanus*) (~80 mm)	1.47 **	Onset of injury (kidney haemorrhage only)		
	2.04	Onset of other pressure related injuries		

Notes: * As presented in [8]. ** Large uncertainty in presented value.

2.3.4. Acceleration and Deceleration Thresholds

Salmon can endure considerable acceleration of 18 G (Table 5). When using acceleration data of electronic sensors, "shear events" were defined as when 70% of the maximum acceleration magnitude of a peak occurred for a duration of longer than 0.0075 s [67]. Based on shear flume experiments, a maximum peak acceleration of ≥95 G [37] was required to qualify as a "shear event". This "shear event" is not the same as fluid shear stress (measured in Pa) and does not represent the same shear as understood in fluid mechanics theory. Such acceleration trends may also show similar extended peaks (albeit with lower maximum acceleration) when the fluid velocity changes, and no collision or shear event occurs such as during a prolonged acceleration through a pipe bend. The choice of a 95 G event threshold underestimates injuries at sites, given that thresholds for 10% major injury of chinook salmon are far lower at 34.7 G (Table 5) and minor threshold injuries have 100% probability at this acceleration [37].

Table 5. Reported fish injury threshold values for acceleration.

Fish Species	Acceleration (G)	Comment on Injury	System for Tests	Reference
Chinook salmon (*Oncorhynchus tshawytscha*) (93–128 mm)	18.3	10% probability of minor injuries	Jet shear flume (fish inserted into submerged jet headfirst)	[37]
	34.7	10% probability of major injuries		
Chinook salmon (*Oncorhynchus tshawytscha*) (~114 mm)	45.1	10% probability of minor injuries	Jet shear flume (fish entrained in submerged jet entering still water)	[68]
	68.6	10% probability of major injuries		

When fish are initially entrained inside the submerged jet and released into still water, the 'fast fish to slow water' configuration [68], minor injury thresholds were more than double of fish inserted into the jet (Table 5). This suggests that either deceleration is less harmful to the fish size tested, or other stressors contribute when fish were inserted into the flow. When a fish is inserted into the jet, injury may arise from the jet forcing gills to open and damaging scales. There is a need for more understanding of how acceleration and deceleration thresholds vary with size, age and species.

2.3.5. Thresholds for Other Hydraulic Effects

Other hydraulic effects, as reported in the literature (turbulence, aeration, collision and strike)—anthropogenic and natural, also injure fish, but thresholds are not as well established.

Turbulence effects have been likely captured with the other hydraulic conditions presented in Tables 2–5 as the experiments were conducted in turbulent flows. More broadly, there are large changes in the hydraulic conditions in the natural living environment of fish (e.g., larger turbulence during a flood event), which harm fish if exposed for extended distances or periods of time. Fish expend more energy swimming in high-intensity turbulence [50], losing stability when the length scale of turbulence is about 45–50% of the length of the fish and when the dominant rotation is in the vertical plane relative to the fish [51]. Some fish such as salmonids use turbulent vortices at certain scales to reduce energy expenditure [49].

Total dissolved gas (TDG) levels, length of exposure, as well as fish species and age affect severity and occurrence of gas bubble trauma (GBT) [52,69]. TDG = 110% is a conservative threshold to avoid GBT for salmonoids in shallow waters, whereas they may be able to tolerate TDG up to 125% in deeper waters of several metres [31]. Depth compensation allows fish to be exposed to higher TDG levels without developing GBT [70]. Excess oxygen saturation may assist in preventing GBT [31]. This is consistent with aquaculture applications which transport fish with high dissolved oxygen levels of 100–150% [71]. In any hydraulic system, aeration is strongly linked to flow turbulence and fish injuries could be caused by compounding effects rather than aeration only.

Collisions occurring head-on cause bruising and spinal injury, while side collisions can cause descaling or abrasions. However, there is no systematic study of collisions. The angle of strike can reduce severity with glancing blows less harmful than direct hits and tail strike less harmful than head or body strikes [72]. Longer fish and eels are at greater risk of being by strike [33]. In some systems with complex flows, the fish physiology may have been already compromised by other factors (Figure 3) before incurring the physical evidence of collision or strike.

2.3.6. Summary

Thresholds for fish injuries due to various hydraulic effects are dependent on fish species, age and size and therefore may vary considerably. It is difficult to isolate each hydrodynamic effect from others. For example, shear stress and turbulence occur simultaneously and are accompanied by accelerations in jet shear flume experiments used for the establishment of thresholds [37,47,68]. There is a general difficultly in thoroughly investigating fish response in turbulent flow. The overlap of hydrodynamic effects may increase the likelihood of injury and the dominant effect may not be identified. Future research should assess these stressors in more detail to establish injury thresholds as they would occur in the real world.

While thresholds for individual hydraulic effects as described in this section are valuable in assessing potential harm to fish, during movement of fish across hydraulic structures (Figure 1), several hydraulic effects interact throughout the movement of fish. The simplification of such hydraulic effects cannot provide conclusive injury estimates to be used across hydraulic structures. The following sections will therefore present the available knowledge on injuries of fish travelling along open-channel flow systems (Section 3) and closed-conduit systems (Section 4).

3. Fish Injuries during Open-Channel Flow Movement across Hydraulic Structures

The hydraulics of open-channel flows are well understood [73,74]. They are omnipresent in natural water systems. When a hydraulic structure is built within a natural system, the flow conditions often remain as open-channel flow. Weirs and other structures can rapidly change flows from slow subcritical flows to supercritical flows characterised by shallow depth with high velocities. Along spillways, high-velocity flows can cause self-aeration, while the energy of supercritical flows downstream of spillways and undershot weirs is often dissipated by violent flows in hydraulic jumps.

Figure 4 conceptualises typical open-channel flows across hydraulic structures including the dominant hydrodynamic characteristics. The flow processes are well described in the literature [75–77]. In the following sections, the hydrodynamic characteristics and their potential impact on fish injuries are critically discussed in the context of available knowledge on fish injuries in hydraulic structures.

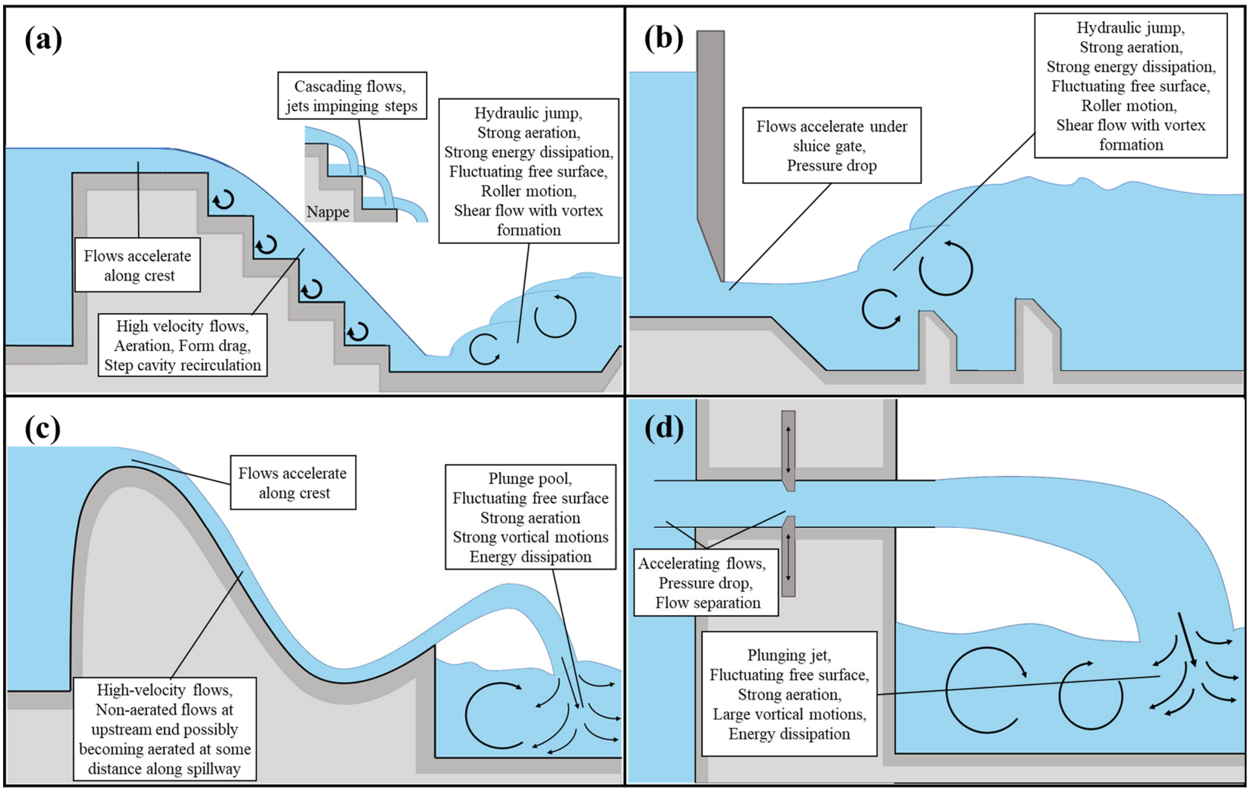

Figure 4. Typical turbulent open-channel flows fish are exposed to when moving across different hydraulic structures: (**a**) a broad-crested weir, with an embankment sloped stepped spillway with skimming flows (inset figure: nappe flows) and downstream energy dissipator with hydraulic jump; (**b**) a weir with an undershot sluice gate and a downstream baffle block stilling basin with hydraulic jump; (**c**) ogee crest weir with smooth spillway with flip bucket and downstream plunge pool dissipator; (**d**) a dam with regulated gate resulting in a jet that is dissipated in a plunge pool.

3.1. Fish Movement across Weirs

Weirs are common instream structures with similar functions to dams. They can have various shapes and sizes ranging from low-head weirs to major structures. They can be uncontrolled with fixed crest height (e.g., sharp, broad or ogee crest shapes or with a non-linear crest) or controlled with undershot or overshot gates that allow a variation in weir height and upstream water levels (Figure 4). They do not allow upstream fish migration unless submerged under flood conditions or a fishway enables movement. In contrast, downstream migration of fish is always theoretically possible when (a section of) a weir is overflowing, when an undershot sluice gate is open or when a fishway enables downstream passage.

At fixed and overshot gated weirs, water flows over the top of the structure (Figure 4a). Sites for potential fish injury include the crest, travel along the spillway (see Section 3.2) or energy dissipation at the base of the weir (see Section 3.3). Reported injuries at low head weirs are limited. There were no reported external injuries and no deaths over a period of 12 months at the 2 m high Kennedy's Weir in Victoria, Australia [78]. Pressure changes in overshot weirs are usually minimal [24]. Higher discharge may result in lower mortality at the same weir [79]. For overshot weirs with free-falling nappe, appropriate downstream water depths (40% of the difference between upstream and downstream water levels) minimises the likelihood of collision injuries during jet overfalls downstream [24], and the velocity of the impacting nappe onto the downstream water surface should be limited to 15 m/s [61]. The information on safe fish movement across weirs is insufficient, including a lack of quantitative information for different fish species, weir heights and weir designs. For example, nonlinear weirs such as piano key weirs and labyrinth weirs are becoming increasingly popular with limited information on their impact on safe fish movement. The flows associated with non-linear weirs are highly three-dimensional, and fish may be more disoriented than in linear weirs, increasing collision probability.

Undershot weirs (Figure 4b) have been reported to result in greater fish injury and mortality compared with overshot weirs [23,24,80]. At undershot weirs, flow is directed under a sluice gate varying in its opening. Rapid pressure changes occur as the water depth changes either side of the gate, as the flows accelerate. Larger sluice gate openings reduce pressure changes and accelerations, reducing collision risk while releasing a greater volume of water. Accurately determining cause of injury or death at undershot weirs is difficult [23], with shear stress blamed for the mortality of some Australian larval-stage fish in low head structures [24]. Sudden pressure changes through undershot weirs also kill more mature fish with developed swim bladders [81]. Radio-tagged fish have survived passage under medium head (6.5 m) undershot weirs [78]. Using acceleration and pressure sensors, Boys et al. [82] showed the likelihood of injury through an undershot weir of 5 m was negligible using an acceleration threshold of 25 G for shear or collision events, as defined in Deng et al. [67]. Applying this same acceleration threshold to the work of Pflugrath et al. [24], 90% of trials resulted in low risk of fish injury at tested weir sites.

Introduction of fish immediately downstream of an undershot weir gate ('no weir') had 4–18% greater mean mortality compared with overshot weirs for laboratory tested weir and 'no-weir' experimental conditions [23]. Further, overshot weirs had reduced turbulence downstream compared with undershot configurations for low head structures [23], suggesting overshot weirs would be better for fish wellbeing, although in these experiments, the flow rate was low, with calculated velocities of 0.19 m/s from provided data. Baumgartner et al. [23] did not define and quantify turbulence in their study and hence the exact cause for fish injury remains unclear. Both over- and undershot weirs require downstream energy dissipators with large risk to fish (see Section 3.3).

In summary, reported fish mortality at low head structures is low but this is where much of the research has focussed. To better understand fish injury during weir passage, hydraulic effects, mimicking the flow past the weir crest for overshot weirs or through the gate of undershot weirs, should be replicated to better understand the cause of fish injury at weirs. The compounding effects of energy dissipators downstream should be removed to ensure that the results reflect safe movement across weirs alone.

3.2. Fish Conveyance along Spillways

Spillways move water from a high to low elevation, often across a dam or weir. The length of a spillway depends on the height of the barrier or dam wall and the slope of the spillway. The hydrodynamic conditions, such as flow depth and flow velocity, also depend on the inflow rate, the width of the spillway and the roughness of the spillway materials. Most common spillway designs have a "smooth" invert made of concrete (Figure 4c), while a stepped invert design (Figure 4a) has become increasingly popular due to the extra energy dissipation along the spillway from enhanced form drag of the steps. Depending on the spillway design (e.g., smooth, stepped, etc.) and the flow conditions, spillway flows may become aerated at some distance downstream of the crest (Figure 2b), which can be enhanced by flow aerators to reduce risk of cavitation damage to the structure. When a spillway is operating (Figure 4c), fish may pass over the crest and down the spillway without being able to stop until they reach the stilling basin at the toe of the spillway (see Section 3.3).

Spillways are assumed to be relatively safe for fish movement when the surface material is considered smooth [9]; however, 'smooth' spillways made of concrete can be rough, causing fish injury through abrasions [14,61,83]. Moreover, pressure and velocity fluctuations in turbulent flows that can injure fish are more likely to occur for large flows [9,14,84]. Ogee-crest spillways (Figure 4c) are among the safest designs, with good survival rates in North America [27,61,85]. Fish movements are reportedly safer over smooth spillways than the bypass or turbine of North American sites, with survival rates of >98% for Chinook salmon (*Oncorhynchus tshawytscha*) and steelhead (*Oncorhynchus mykiss*) [84]. Low flow can increase collisions along the spillway [86], as shallower depths limit fish's ability to avoid abrasive injuries from the surfaces. An epoxy-coated spillway at Tallowa Dam, Australia, creates a smooth surface atypical of concrete spillways. No immediate mortalities were recorded for Australian bass (*Macquaria novemaculeata*) (250–270 mm long) passing over the Tallowa Dam spillway at low (50 ML/day) and high (500 mL/day) flow rates with subsequent mortalities after 72 h; there was only 19% mortality for both low and high flow rates compared with 31% mortality in a control group introduced directly into the stilling basin [14]. Handling problems may have caused increased mortality in the control group.

Stepped spillways are also common, characterised by different flow regimes (Figure 4a). For the lowest flows in the nappe flow regime, the flows are characterised by jet impingement on subsequent steps [87], which could lead to fish repeatedly colliding with concrete surfaces with high likelihood of injury. For high flows in the skimming flow regime, the flow surface is parallel to the step edges, probably with reduced collision of fish with the step edges. Inevitably, a nappe flow regime always occurs at the onset of spillway operation with design flows in the skimming flow regime, but there is little research on the effects of either of these flow regimes on fish injuries.

Three fish species were moved over smooth and stepped spillways in a laboratory study with 5.4 m crest height and step heights of 0.31 m, and there were no significant differences in mortality, averaging 2% [83]. However, nappe flows on the stepped spillways had slightly higher rates of injuries, with bruising significantly increasing for razorback suckers (*Xyrauchen texanus*) from 2% on smooth to 22% on the stepped chute [83]. The relatively low mortality in the laboratory contrasts observations of high mortality at large structures in the field [88]. Generally, laboratory experiments produce lower mortality of fish than in real-world structures [22]. For example, there was 82% fish mortality, with 94.5% of fish incurring injuries, over the stepped spillway of Paradise Dam, Australia, with bony herring (*Nematalosa erebi*), Queensland lungfish (*Neoceratodus forsteri*), long-finned eel (*Anguilla reinhardtii*), freshwater catfish (*Tandanus tandanus*) and golden perch (*Macquaria ambigua*) being the most affected [88]. Collision with the steps of the spillway were the likely cause [2]. A total of 733 dead fish were collected downstream of the spillway over a 22-day period. More than 100 dead fish per day were collected in three days under both nappe and skimming flow regimes. During the two days of the largest flows, only two dead fish were collected. On such occasions, additional dead fish could have washed too far downstream to be collected, or the flows were sufficient to entirely submerge the structure avoiding injury or fish did not move across the structure during these flows [88]. Possibly, low flows (including nappe flows) are more likely to injure fish.

Some spillways have ski jumps, aerators, or deflectors. Ski jumps may assist safe fish movement with less harmful landings into stilling basins [27,61]. Aerators can significantly increase aeration occurring along a spillway increasing total dissolved gases, however, energy dissipators downstream of spillways are more damaging with even greater aeration [33,89] (Section 3.3). Deflectors slightly decreased survival (3–5%) of chinook salmon and steelhead across spillways at two sites [84]. Baffle blocks on the spillway of Boundary Dam, USA, increased collision of passive sensors by 45% [60]. Fish movement across spillways was improved with changes to the spillway of Ice Harbor Dam, USA, by decreasing the slope from 55 degrees to 42 degrees and increasing the turning radius of the deflector at the base from 4.57 m to 9.14 m. In this study, the injury rate decreased from 14.3% to 1.8% and the 48 h mortality from 3.5% to 2.1% of yearling Chinook salmon, and collisions of sensors were reduced from 47% to 27% [86].

3.3. Fish in Energy Dissipators

Energy dissipators come in the form of stilling basins (Figure 4a,b) and plunge pools (Figure 4c,d). Stilling basins are designed to dissipate energy via hydraulic jumps to prevent downstream scouring. The greater the Froude number (inertia-to-gravity force ratio, [90]), the more violent the hydraulic jump, with high energy dissipation and potential to injure fish [27]. Hydraulic jump roller motions can trap fish and may push them onto the stilling basin floor or other hard objects [61]. The stilling basin of Tallowa Dam, Australia, which was used as the control case for spillway tests (see Section 3.2), may have caused 27.5% death of migrating fish observed over 72 h [14], suggesting the hydraulic jumps with its strong turbulence and aeration as the cause for injury and death. Reduction in energy dissipated at hydraulic jumps, reflected by a lower Froude number, may reduce fish injury, but has yet to be investigated. Increasing the tailwater depth of stilling basins may decrease fish mortality [27], but further evidence is needed. Aeration has been attributed to fish mortalities downstream of stepped spillways due to gas supersaturation [83,91]. However, when total dissolved gas levels were <126% in the energy dissipator downstream of spillways, gas bubble trauma was found in very few juvenile and adult salmonids (0.1–2%) [89,92]. Despite the common occurrence of hydraulic jumps to dissipate energy downstream of hydraulic structures and the potential risk they pose to fish, the current understanding of fish injuries is insufficient.

Plunge pools also dissipate the energy of fast-moving water jets when landing in a large volume of water. If they are adequately deep, they can provide safe landing for fish [27,60,61,83]. By mimicking free overfall spillway conditions in the laboratory with a 5.7 m jet overfall height into a pool depth of 2.5 cm, the survival rates of Flathead minnow of lengths 25 mm and 50 mm were 88% and 78%, respectively, trout (25 mm)—94% and razorback (25 mm) —80% and for pool depth of 15 cm, they were 98% across all species (82). This shows that both fish size and species as well as pool depth can influence the likelihood of injury. Fish can survive falls into deep still water through air or a jet of water [61]. Most fish of length 75–175 mm (97–100%, $n = 100$) survived terminal velocities of ~16 m/s, falling through air [61]. For fish falling within a water jet, survival was lower when velocities were greater than 13.7 m/s [61]. Fall height, jet velocity and water depth are all related to fish mortality [27]. Where plunge pools are shallow, survival is limited [61]. Plunge pools also supersaturate large volumes of water increasing risk of GBT [31]. This risk can be reduced with baffle blocks on spillways with lower total dissolved gas levels inside the plunge pool [60]; this is due to the jet becoming fragmented and not entraining as deeply into the plunge pool. However, further research on the quantitative effects of aeration is needed.

3.4. Fishways and Other Diversion Structures

Traditional open-channel fishways include pool-type, denil, lock, trap and transport, rock ramp, bypass, and elver pass [10,93]. Their design is based on swimming capabilities of fish using head difference, turbulence intensity, and flow velocities as metrics, with requirements for resting pools at set distances. Other bypass fishways or nature-like fishways have low gradient channels, resting pools and meanderings that mimic natural streams. All these fishways are assumed to be safe for fish, but injuries can occur during floods from collisions with parts of fishways or debris [94]. Higher velocities may also increase injury and mortality in vertical slot fishways, with 5% of juvenile Australian bass dying at velocities of 2.2 m/s and up to 20% mortality at 2.6 m/s [95]. The cause of these deaths was uncertain, however, as fish did not successfully navigate the fishway at these velocities.

The National Oceanic and Atmospheric Administration (NOAA) bypass transfers juvenile fish downstream past dams [96]. Fish are attracted or diverted away from hydropower intakes, using diversion structures, into a smooth pipe with a minimum 254 mm diameter. This creates a free-surface flow of more than 40% of the pipe diameter and velocities of 1.8–3.7 m/s. Its bends have gentle rounding in 11.25-degree segments and operate in supercritical flows without the formation of a hydraulic jumps [96]. Adhering to these guidelines should achieve minimal fish injury, but no further information on direct fish studies has been reported [96].

Guidance structures, debris screens and sensory barriers can also assist fish in navigating fishways or bypasses [97,98]. Screens should have appropriate opening sizes to exclude fish while maintaining a velocity that does not exceed sustained swimming speed of fish to prevent collision [32,99]. Mechanical barriers guide fish, triggering avoidance with flow changes [100,101]. There are also sensory barriers, with electric fields, water jets, lights, chemicals or air, which direct fish away from exclusion areas [97,102]. Electrical barriers may cause injury in fish due to pulse patterns, voltage gradients or design of the barrier [103]. During floods or low flows, fish can collide with such guidance structures [22,32].

4. Fish Injuries during Closed-Conduit Transport

Closed-conduit flows transport water to and from water supply systems and hydropower plants. Their fluid mechanics are well understood [90]. Typically, fish encounter a range of closed-conduit flow structures, including mechanical pumps in water supply and irrigation settings (Figure 5a), specifically designed transport pumps in aquaculture (Figure 5b), hydropower plants (Figure 5c) and closed-conduit fishways such as the Tube Fishway (Figure 5d). Pressure changes are common in these systems and can harm fish, with strike often occurring in pumping and hydropower structures from operating blades (Figure 5a,c). Sudden opening and closing of valves can also cause injuries to fish.

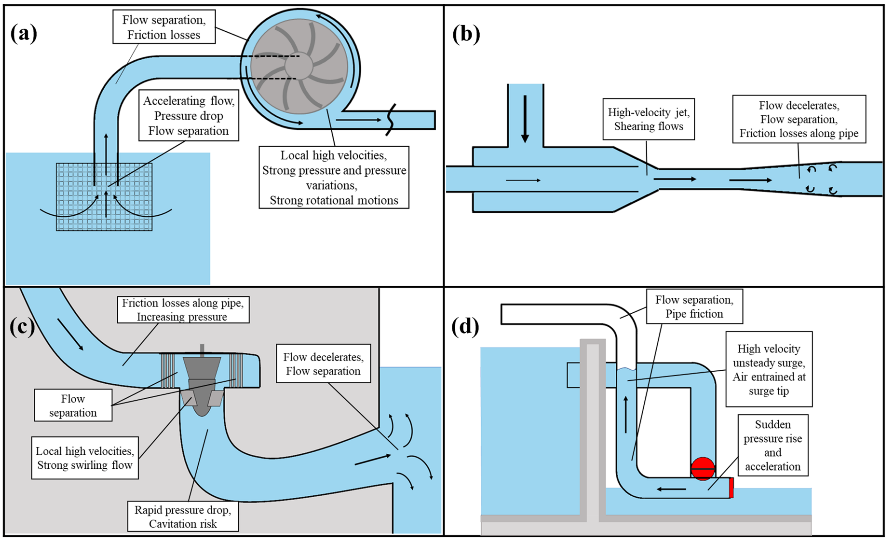

Figure 5. Typical turbulent closed-conduit flows fish are exposed to when moving across different hydraulic structures: (**a**) mechanical pump delivering water from river with fish screen; (**b**) movement through jet fish pump; (**c**) pipe intake and turbine at a hydropower plant; (**d**) upstream fish passage with a Tube Fishway.

4.1. Fish in Pump Systems

Many different pump types exist (Figure 1). Mechanical pumps (Figure 5a) operate as reversed hydropower turbines moving water for drainage, water supply and flood protection. A pump intake may exclude fish via bars or fish screens [104,105], but often fish are injured in a pump system by strike and collision with pump impellers. About 7.5% of fish of varying sizes were injured or killed by impeller irrigation pumps, with small fish (<50 mm) being the most susceptible to flow effects, whereas large fish (>200 mm) collided or were struck by blades [106]. Even exclusion screens at irrigation pumps cause injury when velocities exceed fish swim speed, producing recommendations to 10 min pumping bursts to allow trapped fish to escape [107]. Propeller pumps are more dangerous than Archimedes screw pumps. For example, 97% of eels (400–810 mm) were killed in propellor pumps compared with 19% of eels (392–831 mm) in Archimedes screw pumps at a pumping station in Europe [108]. Higher operating speeds of pumps also increase strikes and fish injuries [41].

Pumps can safely transport fish between hatcheries and storage tanks. Tasmanian fish farms transport salmon (mass = 1 kg) with open impeller centrifugal pumps, through 900–1500 m long and 0.28 m diameter pipes, at velocities of 1.5 m/s [109]. Salmon survived, providing evidence that fish can be safely moved through long pipes, when velocities and shear stresses are low and oxygen in the water is adequate. Salmon were damaged if the head in the pipes exceeded ~5 m during pumping [109]. Pumps with few blades or blunted blades can reduce injury and mortality [110], although they cannot eliminate fish injury [41].

The jet fish pump (JFP) also transports large numbers of fish in aquaculture (Figure 5b), with minimal mortality or injury reported in Chinese goldfish (*Carassius auratus*), Wuchang bream (*Megalobrama amblycephala*) and grass carp (*Ctenopharyngodon Idella*) of 100–130 mm length [38,111,112], although the latter were the most vulnerable to injury. Less than 10% of these fish were injured at maximum velocities of 9.8 m/s [112], while descaling occurred in 32% of tested fish, increasing when velocity was 14.27 m/s but without mortality [111]. Hormonal stress levels in fish increased following transport, returning to normal after 24 h [111,112]. Cavitation caused most severe injuries and mortality with eyes, operculum and internal organs being more susceptible [38,42]. RPC < 1.68 did not injure swim bladders, but they were ruptured when RPC > 2.53 [42]. Maximum strain rates reported in the JFP (7270 1/s) [111] far exceeded threshold guidelines (e = 495 1/s) [47], however, the selected dy in the calculation of the strain rate was the nozzle tip thickness (2 mm) and not the fish size as used for the effective strain rate (see Section 2). Recalculation using the provided width of tested fish (24.9 mm) results in exposure strain rate of e = 584 1/s which is much closer to other reported thresholds (Table 3). This highlights the difficulty of quantifying and comparing provided shear stress and strain rate across different studies and fish species.

These observations of safe travel through pipes are supported by work on unsteady surges with four species of juvenile Chinese carp (Black carp (*Mylopharyngodon piceus*), grass carp (*Ctenopharyngodon idella*), silver carp (*Hypophthalmichthys molitrix*), bighead carp (*Hypophthalmichthys nobilis*)) of average length 70 mm and width 6 mm [58]. Fish safely travelled through a smooth acrylic pipe with 16 mm diameter at a velocity of 14.24 m/s (e = 2373 1/s), with some behavioural responses subsiding within 10 min but increasing injury frequency and severity at 17.43 to 22.51 m/s [58]. The small pipe size probably restricted fish to turn around, limiting injury. This suggests that if pipes are smooth, straight sections are the least likely to cause fish injury.

Furthermore, airlift pumps move fish between tanks for sorting in aquaculture, experiencing low mortality (<1%) [113]. They have also successfully moved eels downstream with no mortality [114]. Airlift pumps should use the correct amount of air to prevent supersaturation and subsequent GBT in fish [71].

4.2. Fish Movement through Turbines

Fish often incur severe injuries moving through hydroelectric turbines, with mortality averaging 22.3% around the world [115]. Turbines are usually large, extract energy from water, generating considerable pressure changes just after the turbine, where fish are highly vulnerable to strike by blades, collision and shear (Figure 5c). These cause significant fish injury and death in turbines [8,28–30,34,59,82,116–119]. Blades in the turbines are the most dangerous regions [9,85] and most common cause of injury [119,120]. Injuries and death increase with faster rotations and more blades per turbine [32,33,119,121–124]; and increased fish length [8,32,33,57,98,115,120]. Mid-body strikes cause more death than tail strikes [72].

Turbine types also vary, with average mortality varying from 28% for Francis turbines, 26% for OssbergerCrossflow, 11% for Hydrokinetic and 9% for Kaplan turbines across all taxa in turbines in the USA [39]. Kaplan turbines, described as "fish-friendly", are consistently safer for fish, with –12% mortality for salmon [39,119]. Sea trout (*Salmo trutta*) in Sweden were safer when moving through Kaplan (13 cm gap) than Francis turbines (10 cm gap) with respective mortalities of 25% and 69% [125]. Further, smolts survived better (11% mortality) moving through a 4-blade Kaplan turbine (8.7 m head) compared to a 16-blade Francis turbine (5.5 m head) (35% mortality) on a river in Sweden [122]. There was also higher nadir pressure and lower acceleration events (strike/collision) through Kaplan than Francis turbines [126]. Kaplan turbines are not universally safe for fish [127], however, causing mortality rates of 31.2% for cyprinids and percids (3.74 m head) [128,129] and 33% for Atlantic salmon smolts (12 m head) [124]. The severity of injury increases in Kaplan turbines with increasing head [130].

Controlled experiments in pressure chambers and shear flumes showed large gambusia (47 mm) were injured with low probability (6%) at any stage during movement [57]. Juvenile and adult redfin survived exposure strain rate of up to e = 1853 1/s, with limited blade strike due to small fish size [59]. These experiments probably poorly reflect actual shear experienced by fish moving through a real pump or turbine.

Computational fluid mechanics (CFD) has modelled effects of shear, pressure drops and collision in hydropower turbines [62,117,120,131,132], indicating that collision causes most injuries to fish in turbines, followed by pressure changes. Assumed injury thresholds for shear are generally based on data from shear flume experiments (Tables 2 and 3) [28,29,37,47,68]. However, the combination of shear flume data and CFD does not adequately capture the shear stress fish may experience in turbines [8,117], as fish may not enter the regions of highest shear stress. Thresholds from pressure chambers can accurately replicate real-world timings [82] and provide good injury risk estimates when combined with CFD modelling.

Avoiding fish movements through turbines is difficult to achieve with narrow openings of screens and diversions, given the considerable size of turbines and operational implications [98]. Fitted bypass systems and guidance screens may successfully divert some fish species [133], but many fish still travel through hydropower systems despite these installations [34,122,124,134], particularly smaller fish with maximum length <200 mm [135].

Attempts to improve the fish friendliness of turbines have been made, however, fish mortalities still occur. A key difficulty in turbine studies is identifying a definite cause of injury or death [23,43]. Fish may have been injured or died before reaching the turbine [115] with blade strike disguising the initial injuries or cause for mortality. There is a need to systematically investigate other potentially injurious components such as intakes, connections and draft tubes in hydropower systems beyond the actual turbine.

4.3. Closed-Conduit-Type Fishways

Early observations identified that salmonids safely moved through pipes at low flows [136]. In such systems, injuries can be related to fish size relative to pipe size [41]. Recently, three closed-conduit fishways have been used to transport fish: Whooshh Fish Transport System (WFTS) [137], the UNSW Tube Fishway [16,138] and the hydraulic fishway of Fishheart [139]. Whooshh transports mostly large fish (e.g., salmon), through an air-filled tube, using a vacuum. Velocities range from 3.75 to 7.5 m/s [140], with instantaneous acceleration peaks at 17.9 G and pressure at near atmospheric with RPC = 1.02 at the entrance [141]. Various species have been successfully transported, including rainbow trout (*Oncorhynchus mykiss*) (445 mm, [142]) and Chinook salmon (845 mm, [137]; and 750 mm, [140]). There was no obvious injury or mortality [142], but cortisol and lactate increased after transport, quickly returning to normal after 1 h [142]. There were also few injuries (2%) and one death out of 225 fish transported [140]. Spawning and old fish have high mortality in tubes of 12 m length (31% mortality) and 77 m length (23% mortality) although not different to a control group (33%) [137]. Comparison between a Whooshh system of 335 m tube length and 30.5 m elevation difference and hand and haul of Chinook salmon showed comparative mortality of 18% (for 58 fish) and 15% (for 65), respectively, with near-equivalent egg viability of 97% and 95% for both transport modes [143].

The UNSW Tube Fishway (Figure 5d) uses an unsteady water surge to transport fish through pipes at velocities of up to 3.6 m/s [16,138,144]. Laboratory trials observed injury-free transport of Australian bass (*Macquaria novemaculeata*) and silver perch (*Bidyanus bidyanus*) (<137 mm) across 4 m and 8 m elevations with wall shear stress of 40 Pa and instantaneous acceleration of 25 G. Minor bruising of one large silver perch (length ~137 mm) was observed [144], likely from collision with pipe bends or the base of the shallow outlet reservoir. As fish travel close to the front of the unsteady flow surge, they experience near-atmospheric pressure throughout the passage, with pressure sensor data remaining near-atmospheric for the whole journey ($0.87 \leq$ RPC ≤ 1.04) [144]. Potential issues that require further research are large fish-to-pipe ratios, large fish travelling around bends, burst swimming speed of large fish preventing fish to travel with the surge front, and scale effects when the system is scaled to large systems in the field (both pipe lengths and diameters). There is a potential strike risk of the automated valve at the fishway entry that must also be considered. Despite reporting no health impact to transported salmonids through Fishheart, no data are provided of any hydraulic conditions, such as flow rate, velocity, upstream head, or pipe diameters as well as tested fish species or size [139]. Therefore, its applicability or effectiveness cannot be verified for different species.

Recent innovative research is considering the use of sediment bypass systems for fish movement when not needed for sediment flushing [145]. These systems may operate sometimes pressurised and sometimes as free-surface flows depending on the inlet and outlet locations, grade and upstream flow conditions, and potential fish injuries would need to be closely assessed.

5. Discussion

Many fish moving across hydraulic structures die or are injured. The range of hydraulic structures causing injury or death include weirs, spillways, energy dissipators, pumps, turbines and other closed-conduit systems. Understanding of the extent of injury and mortality, relative to the effective hydrodynamic mechanisms, remains relatively poorly understood. Injury at hydropower turbines has been studied in greater detail with more knowledge on injury and mechanisms [40,127], although this can be improved using a greater variety of fish species and life stages [146]. Much of the information relates to numbers of fish affected but seldom relates to the hydraulic cause of the injury or mortality. In this manuscript, the current knowledge on hydraulic effects that can cause fish injury is summarised and the knowledge on fish injuries moving across hydraulic structures is critically reflected.

Strike and collision are assumed the most common cause of significant injury or mortality [2,41,60,61,119]. Designs to minimise or completely avoid this should be the leading consideration in structures where fish may travel. To lessen the severity of collision-related injuries, materials smoother than concrete need to be used, potentially with dedicated separate fish transport structures. Flows may need to be designed to allow fish travel away from objects, obstructions, or shallow areas where impact may occur. Reducing collisions from vortical motions is also relevant to design.

In some studies, mortality may be the only metric recorded, without information of non-lethal injuries which may lead to subsequent mortality [140,147]. Some fish may also be more vulnerable to predation after sublethal injury, which may account for up to 70% of total mortality [147]. Moreover, some studies euthanise all fish to identify internal injuries, but some fish could possibly have recovered if they were not euthanised. Increased stress levels in fish are also a possible cause of death [23] but difficult to quantify without hormone analysis from blood samples (e.g., cortisol levels). Fish may also die from exhaustion following movement across the structure after extreme exertion [148].

Most studies of fish injuries are 'black box' studies, providing little understanding of hydraulic causes. Many studies use few selected species which cannot provide a broad image of the overall effects to the full fish community at that site [146]. Fish ecological studies often show deficits with respect to insufficiently described experimental conditions and the choice of simplified hydraulic parameters. For example, the use of acceleration measurements to assess 'shear events' limits the ability to identify and describe the hydraulic effects causing injury in fish. It is important to identify which hydraulic effects cause injuries [23], allowing for targeted improvements. When fish move across a hydraulic structure, different structural components may separately injure fish, causing mortality. For example, abrasion over a gated weir may be followed by abrasion on the floor of the plunge pool. The influence of these synergistic effects is not known in relation to different thresholds (Tables 2–5). The cumulative injury and mortality of fish passing across several hydraulic structures on the same waterway is well recognised as detrimental to fish populations [83,84,94,98,149,150] however, it is rarely investigated in detail and requires further assessment [146].

Larger structures have more intense hydraulic effects and as a result are more likely to injure fish. Fishways which provide alternate routes around these structures are always safer for fish, however, harm is not negligible in all cases. Mortality and injury at low head structures is low, with undershot weirs presenting greater risk from pressure changes and collision than overshot weirs with adequate downstream water depth [23,24,80]. As such, overshot weirs are recommended rather than undershot weirs. Spillways when designed appropriately provide a safe movement option [9]. However, fish are injured or die from collisions on spillways, particularly stepped ones and ones with additional components such as baffles [60,83,86,88]. Spillways can be modified for improved fish passage by reducing slope, increased turning radii and using smoother materials than concrete [14,86]. Research in these areas remains limited. Energy dissipators are generally present downstream of almost all hydraulic structures. These are the most hydrodynamically variable and intense type of open-channel flows and present a significant risk to fish from violent flow motions, intense aeration and high collision risk. Current understanding of the impact of energy dissipators on fish is poor. Innovative solutions are needed to separate fish transport from the high-energy flows that must be safely dissipated to ensure the integrity of the hydraulic structure for all flow conditions. Fish entrained in such high-energy flows can be injured due to multiple hydraulic effects. Separating fish from such flows appears to be the most promising solution. There is a need for improved joint research of engineers, fish biologist, ecologists and asset owners to assess these hydraulic structures in greater detail.

Despite efforts to create safer versions of pumps and turbines, studies have shown that "fish-friendly" does not universally apply to all species [127]. In both cases, strike is assumed as one of the most severe causes of injury and death for fish travelling through these systems, identifying the cause for death is difficult however, as fish may have been injured or died before reaching the blades [23,43,115]. These sites should aim to provide effective bypasses that avoid all turbomachinery. Newer innovations such as the jet fish pump or closed-conduit fishways can safely transport fish at high velocities through pipes, without obstructions [112,144]. This points to smooth pipes as key to wellbeing during fish movement in closed conduits. Changes in hydraulic conditions at bends, contractions or expansions could lead to injury but there is a lack of current systematic research. These additional components should be investigated piecewise to determine their safety for fish movement through closed-conduit systems.

Despite the growing understanding of the extent of fish mortality and injury, the relative hydraulic causes are generally poorly understood. There is considerable understanding of the fluid dynamics of weirs, spillways and hydraulic jumps but this has not been linked with fish transport or injury. It is therefore recommended to establish a database which records quantitative thresholds of hydraulic effects causing injuries or death, other than strike and collision, assisting engineers to improve structures for fish populations. This would be a valuable addition to existing databases of fish species and their tolerances to water quality and other ecosystems indicators.

Much can be learnt from laboratory studies where hydraulic effects can be controlled and influence on injuries measured. However, laboratory tests may fail to accurately represent real hydraulic effects on fish. For example, jet shear flumes (Section 2.3) inaccurately represent the hydraulic effects of fish moving through pipes or turbines, given that fish may not swim perpendicular to a shear zone. The restrictive introduction through a narrow tube may cause half the fish to be exposed to the jet while the other remains inside the delivery tube. These bending motions can crease the fish and injure internal organs [8]. Laboratory experiments designed to address shear in turbines have been repeated to measure acceleration thresholds (Table 5). These thresholds have then incorrectly been used for weirs [24,28] and spillways [86] with considerably different hydraulic characteristics. Further, applying threshold values developed for a particular fish species to other species and sizes is problematic. For example, Murray cod (*Maccullochella peelii*) can better tolerate pressure changes causing eye injury compared with silver perch (*Bidyanus bidyanus*), possibly due to their head shape [30]. Injury patterns can also vary considerably for another species at the same site [40]. Recommendations for fish movements across hydraulic structures need to be specific for the species and region or river [11]. Overall, improvements in safety of fish movements across hydraulic structures should be founded on real-world field trials [94], given that models have limited ability to accurately represent real-world outcomes with variation in mortality of up to 50% [119]. Trials of live fish showed variations in wait times to assess delayed mortality ranging from 1 to 14 days. Two days is recommended as the minimum wait period from the analysis of this review for studies of live fish.

There is a need for multidisciplinary approaches to this problem involving laboratory and field studies as well as CFD modelling combining all available techniques to tackle this complex problem. There should also be large-scale studies which can eliminate scale effects and identify combined hydraulic effects of structures on fish health. This must involve experts from all affected areas including researchers, practitioners and other stakeholders. State-of-the-art technology can characterise hydrodynamic flow conditions for fish travelling through a hydraulic system. Small sensor packages provide important hydrodynamic data on pressures and accelerations, useful to quantify potential injuries. They also reduce the need to use live fish, reflecting guiding principles for ethical animal usage in scientific research. In all cases, hydraulic structures which no longer serve their intended purpose should be removed to improve fish movements and eliminate unnecessary injury.

6. Conclusions

This manuscript reviewed current understanding of hydraulic effects present in flows across hydraulic structures on fish health. There are reported thresholds for selected fish species and sizes for several average hydraulic parameters (shear stresses, pressure changes and accelerations), which may not accurately represent the complexities of the flows that lead to fish injuries. Impact (strike or collision) caused most reported injuries and death. There remain fundamental gaps in understanding relationships between fish movements across hydraulic structures and fish injuries and mortality, complicated by cumulative or compounding interaction of different effects, differentially delaying and indirectly affecting mortality. There are also limitations in applications of laboratory to real-world problems. Multidisciplinary research is essential to adequately understand fish biology and engineering impacts, informed by laboratory and field research, with sensors and live fish. Quantification of hydraulic effects is essential to provide direction in the development of more fish-friendly design, applicable across different species, sizes and ages. These must be addressed in their full complexity and uncoupled form. The scale of this problem is significant and largely unreported, requiring more accountability and focused research collaboration with stakeholders, government agencies and asset owners.

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