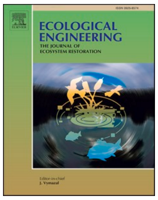
Ecological Engineering 204 (2024) 107267

Contents lists available at ScienceDirect

Ecological Engineering

journal homepage: www.elsevier.com/locate/ecoleng



Downstream fish passage on dam spillway: Low fish mortality rate at Paradise Dam stepped spillway

Hubert Chanson [a,*], Carlos Gonzalez [b]

[a] *The University of Queensland, School of Civil Engineering, Brisbane, Australia*
[b] *SMEC Pty Ltd., Brisbane, QLD 4006, Australia*

ARTICLE INFO

Keywords:
Downstream fish passage
Dam spillways
Fish mortality
Smooth chutes
Stepped chutes
Paradise Dam
2010 floods
Un-gated spillway
Hydraulic jump stilling basin Type I

ABSTRACT

The movements of fishes in natural river systems are affected by in-stream man-made structures, including dams and weirs. The effect of downstream fish passage over dam spillways has received little attention to date. In 2010, some observations of downstream fish passage were conducted at the Paradise Dam spillway, Australia during two markedly different flood events. The spillway was equipped with an un-gated crest, a steep stepped chute and a hydraulic jump energy dissipator without baffle block. The data on downstream fish passage at Paradise Dam are herein re-analysed with a focus on downstream fish passage over the spillway and associated mortality, together with some complementary information on the spillway operation. The mortality rates of fish passing on the Paradise Dam stepped spillway were very low. Under skimming flow conditions, the relative mortality rate was 0.085% of fish passing over the spillway on 3–4 March 2010. A higher mortality rate was seen under nappe flow conditions, although comparable to smooth chute fish mortality data. In average, the fish mortality data downstream of the Paradise Dam spillway was between 7 and 27 times lower than the natural fish mortality in the reservoir. Overall, the present data analyses demonstrated un-equivocally the significance of the spillway flow regime on the downstream fish passage mortality rate. It showed the adverse impact on fish during downstream passage at very-low flows, i.e. $q < 0.01–0.02$ $m^2.s^{-1}$, with both smooth-invert and stepped invert spillways. The finding highlighted a need for efficient downstream fish-friendly passage designs, adapted to the relevant spillway designs, and a number of low-flow fish-friendly channel designs are discussed.

1. Introduction

The movement of fish in natural river systems is affected by in-stream man-made structures, including dams and weirs that may prevent or reduce fish passage and cause fish mortalities and injuries (Dynesius and Nilsson, 1994; Goodwin et al., 2014). Nitrogen supersaturation at spillway toe has been long recognised as a major factor affecting fish mortality, e.g. with steelheads and other salmonids in the Columbia, Osage, and Snake Rivers (USA) (Boyer, 1971, Ruggles and Murray, 1983, Duncan et al., 2018). While research on upstream fish passage has been active (Katopodis and Williams, 2012; Baudoin et al., 2014), the effects of downstream fish passage over dam spillways and weirs have received much less attention, as recognised by several researchers (Larinier and Travade, 2002; Pavlov et al., 2008; Silva et al., 2015). A few exceptions include some field observations on fish mortality (Schoeneman et al., 1961; Bell and Delacy, 1972) and a recent comprehensive study in large-size physical facilities (Bestgen et al., 2008, 2018).

Fish passage at dam spillways may be a direct or indirect cause of fish injury or mortality. The latter may include increased susceptibility of disorientated or shocked fish to predation. The mortality rate greatly varies between different dam sites and geographical locations, from a few percent to 37% at the Lower Elwha dam spillway on the Elwha river (Bell and Delacy, 1972; Ruggles and Murray, 1983). Fish mortalities may be caused by a range of issues, encompassing shearing effects, abrasion on spillway invert, turbulence in the stilling basin at the dam toe, abrupt water velocity and pressure variations when the fish hits the water, physical impact against baffle blocks in energy dissipators and stilling basins (Bell and Delacy, 1972; Deng et al., 2017). Experiments at ski jump dissipators suggested that significant damage with injuries to gills, eyes and internal organs occurs when the impact velocity of the fish on the water surface in the downstream pool exceeds 16 m/s (Bell and Delacy, 1972; Larinier, 2000). With larger nappe impact velocities, the fish mortality increased rapidly in proportion to the drop in vertical

---

* Corresponding author.
E-mail addresses: h.chanson@uq.edu.au (H. Chanson), carlos.gonzalez@smec.com (C. Gonzalez).

https://doi.org/10.1016/j.ecoleng.2024.107267
Received 10 February 2024; Received in revised form 16 April 2024; Accepted 2 May 2024

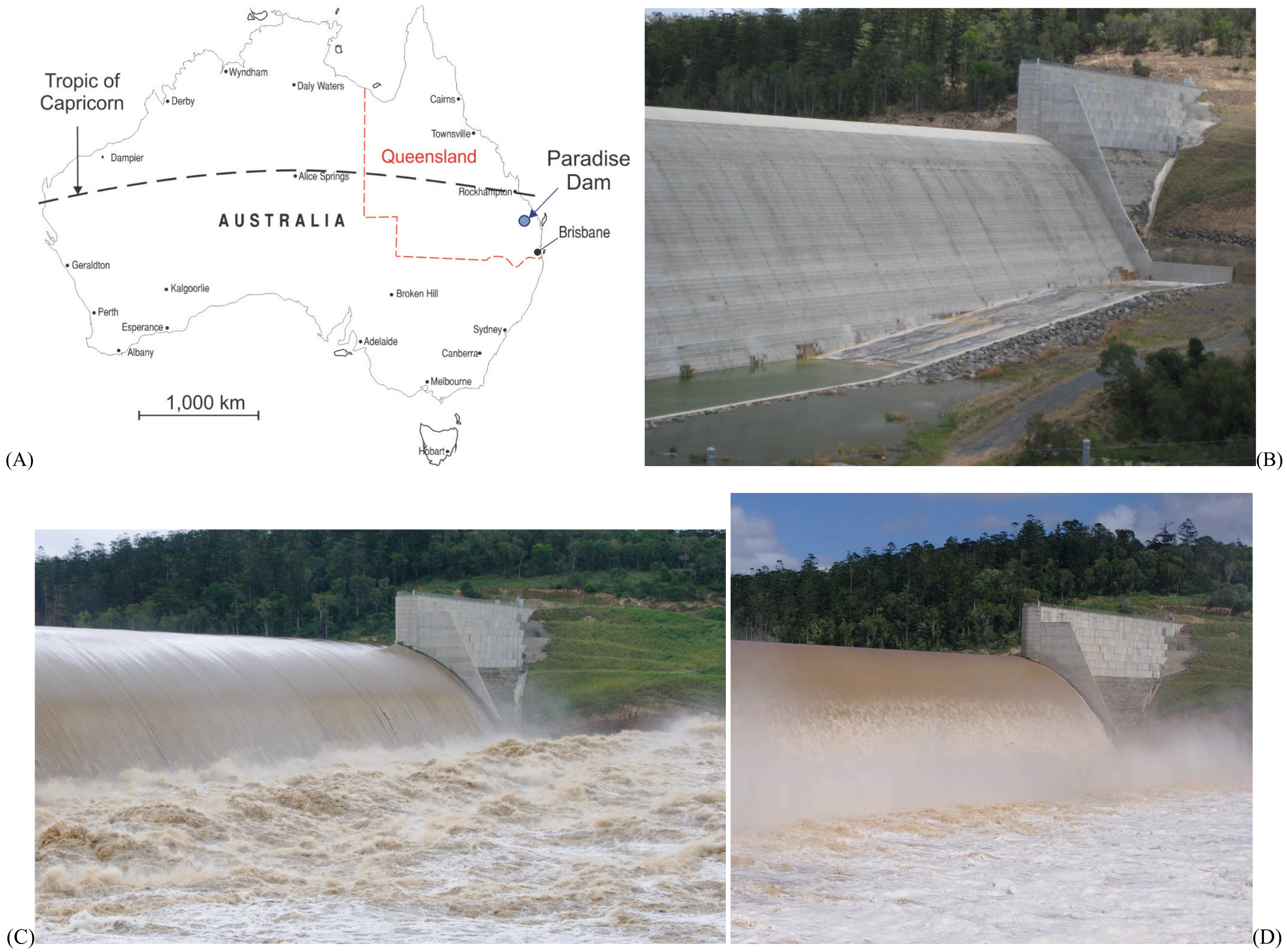


Fig. 1. Paradise Dam spillway - (A) Map of Australia; (B) Dry spillway on 26 December 2008 highlighting the ungated spillway crest and the hydraulic jump stilling basing with baffle blocks at the chute toe; (C) Stepped spillway operation on 5 March 2013 for $Q = 2316$ $m^3.s^{-1}$ and $d_c/h = 2.74$ (skimming flow); (D) Spillway operation on 30 December 2010 for $Q = 5965$ $m^3.s^{-1}$ and $d_c/h = 5.14$ (skimming flow).

height.

In 2010, some observations of downstream fish passage were documented at the Paradise Dam (Australia) at the fishway and over the stepped spillway during two overflow flood events (DEEDI, 2012). The spillway system consisted of an un-gated crest, a steep stepped chute and a hydraulic jump stilling basin without baffle blocks The data on downstream fish passage at Paradise Dam are herein re-analysed with a focus on downstream fish passage over the stepped spillway and associated mortality, together with some information on the spillway operation based on the writers' experience with the dam spillway (Fig. 1), and their respective world-recognised expertise in stepped spillway hydraulics (Chanson, 1995, 2001, Gonzalez, 2005). The present study reports some key outcomes resulting from comparing the downstream fish mortality at Paradise Dam stepped spillway in 2010 with the relevant literature.

2. Stepped spillway hydrodynamics and fish passage

A stepped spillway is a steep chute with a staircase invert (Fig. 1B). During an overflow, the stepped spillway invert acts as uniformly-distributed macro-roughness, that increases the rate of energy dissipation along the spillway chute, in turn reducing the flow velocity and the size, hence the cost, of the downstream energy dissipator (Rajaratnam, 1990; Chanson, 1995, 2001). During major floods, the rate of energy dissipation above the stepped spillway may be enormous and exceed the electrical outputs of large nuclear power plants (Chanson, 2015).

A stepped spillway flow may be one of several markedly different flow regimes, for a given staircase design, depending upon the discharge per unit width. Considering flat horizontal impervious steps in a rectangular prismatic chute, the spillway overflow is either a jet flow at small unit discharges, a transition flow for a range of intermediate discharges, or a skimming flow at large unit discharges (Ohtsu and Yasuda, 1997; Chanson et al., 2015). The nappe flow regime, also called jet flow, was typically used in ancient stepped spillway designs, i.e. completed during the 18th to early 20th centuries. The nappe flow conditions correspond to a succession of free-falling nappes (Fig. 2A) observed at relatively small discharges per unit width, i.e. $d_c/h < 0.4$ to 0.6 for $\theta > 45^\circ$ with $d_c = (q^2/g)^{1/3}$, q the discharge per unit width, h the vertical step height, g the gravity acceleration and θ the angle between the chute slope and horizontal. The transition flow regime is observed for a range of intermediate discharges, i.e. $0.4–0.6 < d_c/h < 0.8–1$ for $\theta > 45^\circ$. A transition flow is characterised by large hydrodynamic instabilities and strongly chaotic flow conditions, and it is recommended to avoid, unless at relatively small flow rates (Chanson, 2001; Chanson and Toombes, 2004). The skimming flow regime has very distinct flow features (Figs. 1C, D and 2B). The main stream skims as a coherent stream over the pseudo-bottom formed by the step edges. In the step cavities, recirculating vortices develop and the recirculation motion is maintained through the transmission of shear stress from the main flow (Rajaratnam, 1990; Chanson, 1994).

(A) Nappe flow above the Gold Creek Dam spillway on 2008 ($d_c/h << 0.1$ ($\theta = 21°$, h = 1.5 m) (Courtesy of Damien Egan) (Left) and on the Hinze Dam spillway on 2 May 2021 for $d_c/h = 0.08$ ($\theta = 51.3°$, h = 1.5 m) (Right)

(B) Sketch of skimming flow above a stepped spillway

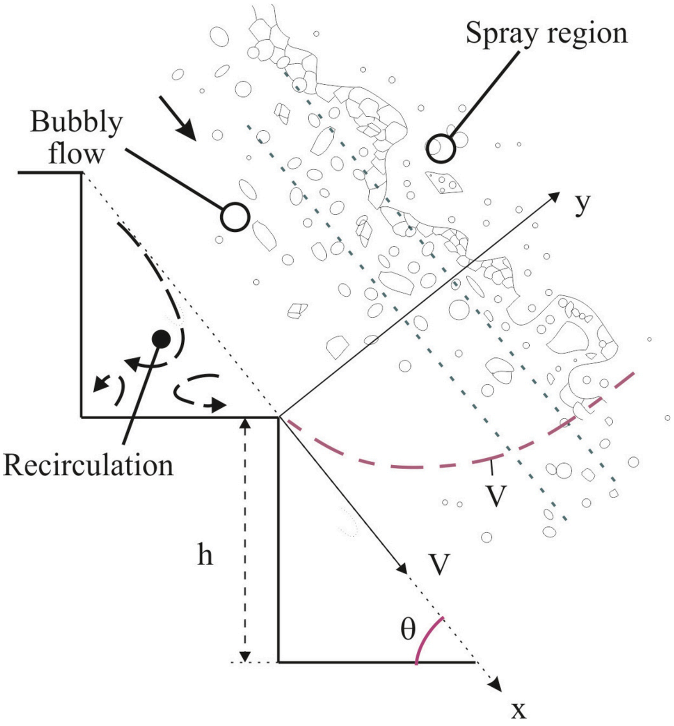


Fig. 2. Hydraulic regimes above a stepped spillway.
(A) Nappe flow above the Gold Creek Dam spillway on 2008 ($d_c/h < < 0.1$ ($\theta = 21°$, h = 1.5 m) (Courtesy of Damien Egan) (Left) and on the Hinze Dam spillway on 2 May 2021 for $d_c/h = 0.08$ ($\theta = 51.3°$, h = 1.5 m) (Right) (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)
(B) Sketch of skimming flow above a stepped spillway.

2.1. *On downstream fish passage over spillways*

The downstream migration of fish over a dam spillway may be affected by the chute invert design: i.e., smooth or stepped invert (Bestgen et al., 2018). Basically, smooth-chute flows are characterised by higher flow velocities, smaller flow depths and greater maximum turbulent shear than stepped chute flows. All these features have negative impact on downstream fish passage, and smooth chutes would be less suitable to downstream migration. In contrast, recirculation zones exist in all types of stepped chute flows in the step cavities, and these may provide resting zones for fish. Further, stepped chutes are renown for a strong re-aeration rate and can improve the water quality of polluted and eutrophic streams (Robison, 1994; Gosse and Gregoire, 1997; Toombes and Chanson, 2005), while the slower chute velocities

Table 1

Comparison of hydraulic characteristics of smooth- and stepped-invert chute overflows in relation to downstream fish passage for identical flow rate per unit width q and chute slope θ (^{1}).

	Smooth		Stepped	chute		Remarks
	invert chute	Very-thin nappe flow ($d_c/h << 0.1$)	Nappe flow	Transition flow	Skimming flow	
Velocity	High	Very small	Small	Small to moderate	Moderate	Depth-averaged flow velocity
Water depth	Small	Thin	Small to medium	Medium to large	Medium to large	
Turbulent shear stress	Uneven with very-large shear region next to invert	Uneven with very-large shear in nappe impact region	Uneven with large shear in nappe impact region	Uneven with very-large shear in cavity region	Reasonably uniformly distributed	Distribution normal to flow direction
Flow aeration	Modest	Very small	Large	Very large	Large	
Impact region	Nil	Very large at nappe impact	Large at nappe impact	Large in cavity region	Nil to small	Related to stagnation pressure
Recirculation zone	Nil	Nil	Small to moderate - Un-connected	Moderate	Important/large in step cavities - Connected	
Re-aeration rate	Poor	Poor	Strong	Strong	Moderate to strong	Incl. re-oxygenation rate

Notes: (^{1}) assuming flat horizontal impervious steps in a rectangular prismatic chute; Blue text: positive effect on downstream fish migration; Red text: major adverse impact on fish migrating downstream.

reduce the risks of nitrogen supersaturation. Fundamental differences between smooth- and stepped-invert chute flows are summarised in Table 1, including the main flow regimes on stepped spillways.

During spillway overflows, the downstream migrating fish may be injured by the chute flow motion and by the downstream flow in the energy dissipator. On a stepped chute operating in skimming flows, the lower flow velocities and lesser shear stress (in comparison to smooth chutes) are likely to cause lesser damage and stress to the fish. At the chute downstream end, the lower chute velocities with a stepped chute yield lesser energy dissipation in the stilling basin, and hence lesser regions with high shear, compared to a smooth-invert chute, implying that the stepped spillway designs are better suited to successful downstream fish passage.

On another hand, very-small discharges over a stepped spillway might create flow conditions unsuitable for downstream fish migration, i.e. with a nappe flow regime with very thin nappes ($d_c/h << 0.1$). This was discussed with early designs of fishways developed for a hydraulic operation in skimming flow regime (Rajaratnam, 1990; Clay, 1995). The nappe flow conditions for small flow rates would yield very small pool depths, with adverse impact on downstream fish migration that are discussed by others (Bestgen et al., 2008, pp. 23–24; Baudoin et al., 2014, p.76) and were observed at the Paradise Dam stepped spillway in 2010 ([1]). Bestgen et al. (2008, 2018) observed higher mortality rates for free-falling nappe when the receiving pool water depth was 0.025 m. For a free-falling jet, the application of the momentum equation at the nappe impact provides a theoretical relationship between the pool depth d_p, the step height h and the unit discharge q (Chanson, 1995, pp. 231–234). For vertical step heights h between 0.3 m and 1.5 m, a pool depth of 0.025 m or less would correspond to unit discharges $q < 0.01$ m^2/s to 0.02 m^2/s, and dimensionless discharges $d_c/h < 0.0025$ to 0.025. Note that, for such discharges, i.e. $q < 0.010$ m^2/s to 0.02 m^2/s, the water thickness down a smooth invert concrete spillway with 45° slope (1 V:1H) would be <5 mm to 8 mm. Such very-shallow water thickness would also allow bruising, grazes, cuts and injuries to most fish species (Bell and Delacy, 1972; Ruggles and Murray, 1983), and be unsuitable for a safe downstream migration of fish.

Altogether, among the five configurations summarised in Table 1, the stepped invert design operating in skimming flow regime may provide the best flow conditions for satisfactory downstream fish migration, including compared to the smooth-invert chute design.

2.2. *Commentary*

The above discussion was developed for stepped spillway designs equipped with flat horizontal impervious steps, of the same identical dimensions, in line with modern stepped spillway designs (Chanson, 2001, Gonzalez, 2005, Matos and Meireles, 2014). There are however other forms of stepped design, including inclined steps, pooled steps and pervious step construction (gabions, timber crib) (Chanson, 1995, 2001).

Many fishway flume designs are basically stepped open channels. Some are simple flat stepped chutes, others are step-pooled channels, while some modified designs include a combination of flat-steps and pooled steps creating three-dimensional (3D) flow patterns to facilitate fish pass (Guenther et al., 2013). Both Rajaratnam (1990) and Chanson (1995) developed some analogy between stepped chute and fishway hydraulics, highlighting strong hydrodynamic similarities. More recently, stepped chute spillways/fishways were successfully developed for fish and invertebrate migrations in Asia and Europe (Yasuda and Ohtsu, 2000; Yasuda et al., 2001, 2002; Bunt et al., 2012; Noonan et al.,

---

[1] "In the [very] early stage of the spillway flow period[,] fish were observed and recorded on video passing over the spillway wall, striking the wall surface and being projected into the air before striking the wall again" (DEEDI, 2012, p. 58).

Table 2
2010 spillway overflow events on the Paradise Dam spillway.

	March	September
	2010	2010
Fish and aquatic life observation period	3–24 March 2010	20–23 September 2010
Cumulative spill volume (m^3) (1) (4)	6.51×10^8	2.70×10^7
Maximum spillway flow rate (m^3.s^{-1}) (4)	1325	254
Nb of days operating in skimming flow	9.5	0
Nb of days operating in nappe/transition flow (2)	12.5	3.5
Nb of dead fish (3)	>661	149
Nb of dead turtles (3)	0	0
Average daily fish mortality rate per unit spillway overflow volume (fish.day^{-1}.m^{-3}) (1)	1.1×10^{-6}	7×10^{-6}

Notes: (1): over the observation period (DEEDI 20212); (2): for $d_c/h < 1$ (i.e. $Q < 512$ m^3/s); (3): observations downstream of the primary spillway; (4) Data source: Bureau of Meteorology (BOM, 2023).

2012; Santos et al., 2012). Both flat step and pooled step fish pass designs were successfully tested in the field. For example, crabs and shrimps were seen ascending a trapezoidal stepped fishpass, while steep (1 V:10H) pooled step fishways were documented with juvenile fish negotiating the pass during sunset periods. However, the step geometry must be optimised for each species (Yasuda et al., 2002; Yasuda, 2011a, 2011b; Baumgartner et al., 2012).

3. Material and methods

3.1. Study site

The Paradise Dam is a 50 m high roller compacted concrete (RCC) structure (Herweynen and Griggs, 2006). Located on the Burnett River in Central Queensland, the reservoir catchment area is 33,000 km^2. In 2010, the full water supply volume of the Paradise Dam reservoir was about 300 gigalitres, or 3×10^8 m^3 (Herweynen and Griggs, 2006). During spills, the reservoir volume would be larger. The dam was originally equipped with a 315 m wide primary spillway, with an uncontrolled (un-gated) ogee crest, a steep stepped spillway and a downstream energy dissipator (Fig. 1). The stilling structure was a hydraulic jump stilling basin without baffle block (also called Type I). The final chute slope is 1 V:0.64H ($\theta = 57.38°$) with 0.62 m high steps. The drop in elevation between the original ogee crest and basin invert was 36.75 m. Photographic observations of the spillway operation were taken by the first author in December 2010 and March 2013, from the right bank of the stilling basin (Fig. 1B and C). In Fig. 1, the figure caption documents the spillway overflow discharge Q and dimensionless discharge.

The Paradise dam is equipped with two fishways, one to provide upstream fish passage and another for downstream fish passage. The former was the first high lift fishlock passage facility in Australia (2). The latter was a bypass with its entrance located adjacent to the spillway crest and followed by a downward pipeline with its exit next to the dam spillway toe.

3.2. Data sets

Fish and aquatic life observations were conducted between 5 February 2009 and 31 October 2010 (DEEDI, 2012). During the study period, the downstream fish passage was particularly documented for two spillway overflow events in March 2010 and September 2010 (Table 2 & Fig. 3). Table 2 summarises the two spillway overflow events and some key hydraulic characteristics and biological observations downstream of the primary spillway. Fig. 3 presents the discharge hydrographs of the primary spillway for the two events, both graphs being drawn with the same horizontal and vertical scales for comparison. In March 2010, the cumulative volume of spillway overflow was equivalent to 1.3 times the volume of the Sydney Harbour NSW (Australia) (3). In contrast, the September 2010 event was a much smaller overflow, with a cumulative volume of spill overflow equivalent to 0.054 times the Sydney Harbour volume. During the September 2010, the spillway operated in a nappe flow regime for the entire event. In March 2010, the spillway overflow was a skimming flow regime for about 9.5 days at the start of the event, followed by 12.5 days of transition and nappe flow regime operation (Fig. 3A).

In terms of downstream fish migration, the most abundant species observed in the fishlock were western carp gudgeon (*Hypseleotris klunzingeri*), bony herring (*Nematolosa erebi*), fly specked hardyhead (*Craterocephalus stercusmuscarum*), snub-nosed garfish (*Arrhamphus sclerolepis*), Midgley's carp gudgeon (*Hypseleotris* sp. *A*) and flathead gudgeon (*Philypnodon grandiceps*) (DEEDI, 2012, p. 30).

4. Results

4.1. Flood flow conditions

During the two 2010 spillway overflow events (Table 2), the operation of the downstream migration fishway and the downstream passage of fish above the spillway were documented, however the main focus of the present data re-analysis was on the downstream fish passage over the spillway. The downstream migration fishway was equipped with an intake designed to attract fish during small overflow discharges. Some qualitative and quantitative observations indicated: "*visual observations during overtopping flows in March and September 2010 indicated that fish aggregated at the dam wall and passed over the spillway*" and "*the rate of fish moving over the spillway was considerably higher than fish using the fishway*" (DEEDI, 2012, pp. 50–51). The observations implied that the efficiency of the downstream migration fishway intake was poor in attracting fish during small spillway overflow discharges.

Detailed observations were reported in terms the fish population passing downstream over the primary spillway chute between 3 March and 24 March 2010 (4), and between 20 September and 23 September 2010. The monitoring activities encompassed visual and quantitative observations, including observations from the spillway toe to about 1 km downstream, although with a "*focus on the collection of deceased and injured fish*" (DEEDI, 2012, p. 52–53). The monitoring observations also encompassed a number of live fish, but neither their number nor species were thoroughly documented (5), except for a qualitative comment on barramundi fish (6).

The data indicated overall an abundance of downstream fish passage species compared to no flow periods. The results showed 7 species (32% of observed species) with very high relative abundance compared to no flow periods, 3 species (13.6% of observed species) with high relative abundance and 8 species (38% of observed species) with moderate

---

[2] The fishlock acted also as downstream fish passage for downstream migrating fish when the spillway was not in operation.

[3] The volume of the Sydney Harbour NSW (Australia) is about 500 gigalitres, or 5×10^8 m^3.

[4] Extensive monitoring was conducted with a combination of drift nets downstream of the spillway, dip netting from a boat, electrofishing and visual observations in an area from the base of the spillway to approximately 1 km downstream, especially from 3 to 24 March 2010.

[5] "Live fish not displaying any injuries were captured during electrofishing and drift net sampling downstream of the dam during and after the March 2010 and September 2010 overtopping events. The majority of live fish identified directly below the dam were likely to be fish that have been attracted upstream by the flood flows" (DEEDI, 2012, p. 53),

[6] "Large barramundi were captured downstream of the spillway for the first time during the monitoring program following the overtopping flows in March 2010" (DEEDI, 2012, p. 53).

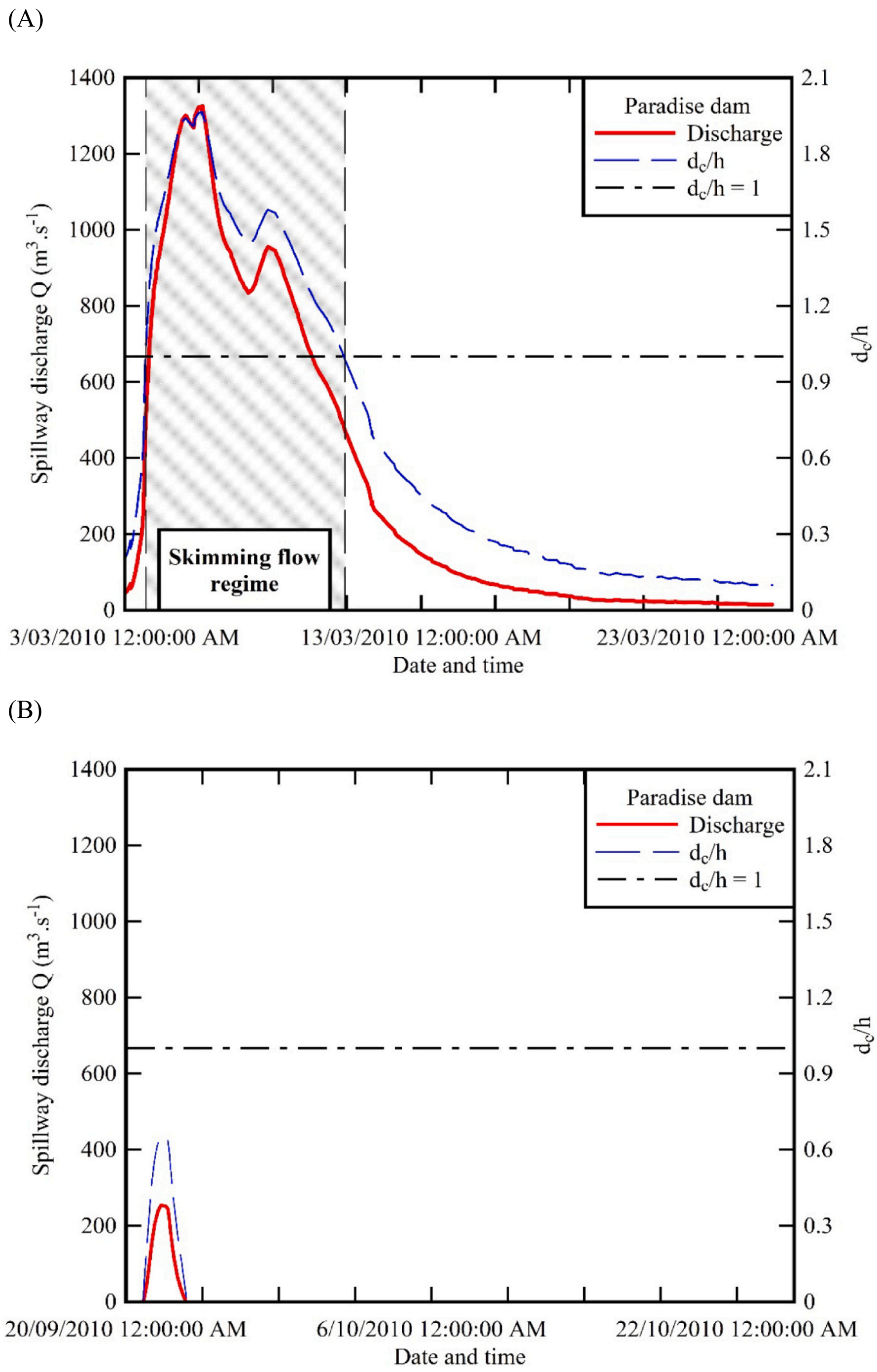


Fig. 3. Spillway overflow discharges Q and dimensionless discharge d_c/h over the Paradise Dam primary spillway in March and September 2010 (Table 2) - Both graphs drawn with the same vertical and horizontal scales - Data: Bureau of Meteorology (BOM, 2023).

relative abundance out of 22 observed species (DEEDI, 2012, Table 11). Altogether, some similar-to-much-higher relative abundance was observed for 82% of observed species, recorded passing over the spillway compared to fish abundance during no spillway flow periods (7).

4.2. *Downstream fish passage over the spillway*

In March 2010, large numbers of downstream fish passage were observed over the dam spillway on 3–4 March 2020 at the start of the flood: "*an average of 60.8 (±30.31) small fish per minute were passing over the spillway during the rising hydrograph*" (DEEDI, 2012, pp. 9 & 50) and "*visual observations identified [additionally] large fish such as long-finned eel at rates of up to 6 per minute going over the spillway*" (DEEDI, 2012, p. 51). The numbers were likely under-estimated because of the breadth of the primary spillway (B = 315 m) and the high turbidity of the flow. That is, it is believed that the counts of passing fish only represented a very small fraction of the fish population passing downstream over the

---

[7] During the no spillway flow periods, any fish passage would only rely upon the fishways.

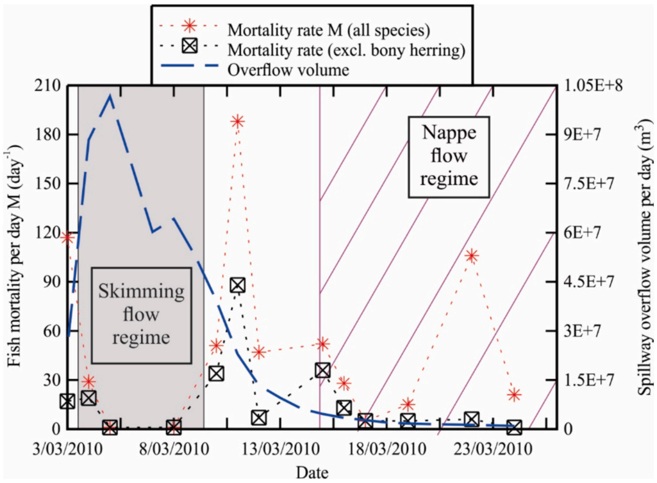


Fig. 4. Daily fish mortality downstream of the Paradise Dam spillway and daily spillway overflow volume during March 2010 flood event - Data: DEEDI (2012) & Bureau of Meteorology (BOM, 2023).

spillway.

The data for daily fish mortality, M, downstream of the Paradise Dam spillway were recorded during the March 2010 flood overflow event (Fig. 4), which presents the daily fish mortality M data downstream of the Paradise Dam spillway during the March 2010 flood event. The data include the total fish mortality rate, as well as the mortality rate of all species excluding bony herring (*Nematolosa erebi*). The daily spillway overflow volume is included in Fig. 4 for comparison, with the daily overflow volume being calculated as:

$$\int_{24h} Q \times dt \qquad \text{Units : m}^3\text{.day}^{-1} \tag{1}$$

and Q the spillway overflow discharge (Fig. 3A). In Fig. 4, the data are absolute values and do not consider the relevant water volume. Simply, a mortality rate M of 20 fish per day is not the same when it occurs within a 25 m long swimming pool (e.g. 1000 m^3 or 1 megalitres) or at the Sydney Harbour (Australia) (i.e. 5 × 10^8 m^3 or 500 gigalitres). As such, mortality estimates must be normalised and unbiased to be physically meaningful (Southwick and Loftus, 2003).

In the current study, the daily fish mortality data were normalised as:

$$\frac{M}{\int_{24h} Q \times dt} \qquad \text{Units : fish.day}^{-1}\text{.m}^{-3} \tag{2}$$

with M being the daily fish mortality downstream of the Paradise Dam spillway (Fig. 4) and the daily spillway overflow volume, which was calculated from the observed spillway discharge data (Eq. (1) & Fig. 3A). The normalised daily fish mortality data downstream of the Paradise Dam spillway indicated a low fish mortality during the skimming flow operation of the spillway in March 2010, with the largest fish mortality reported at the tail of the flood when the spillway operated in a nappe flow regime. During the September 2010 flood event, only very small overflow discharges occurred (Fig. 3B), but an average daily fish mortality per unit volume (7×10^{-6} fish.day^{-1}.m^{-3}) >6 times larger than that recorded during the March 2010 flood event (1.1×10^{-6} fish.day^{-1}.m^{-3}) was observed. Refer to Fig. 5B where the normalised daily fish mortality data for both March and September events are compared.

4.3. Comparison between March 2010 and September 2010 overflow events

The March 2010 and September 2010 spillway overflow events were markedly different. The March 2010 flood event was larger and lasted longer (Fig. 3 & Table 2). In September 2010, the water flowed down the stepped spillway as a nappe flow regime for the entire event, including two days in a very-thin nappe flow motion ($d_c/h < 0.1$) while in the March event nappe flow only occurred at the beginning and end of the event. A detailed comparison of number of dead fish between March 2010 and September 2010 (DEEDI, 2012, Tables 13 & 14) suggested the conclusions below. A comparatively large number of dead fish (about 150 individuals) were observed in September 2010, with an average daily fish mortality rate per unit spillway overflow volume nearly six times larger than that in March 2010. Besides direct fish mortality over the spillway operating in a nappe flow regime, some fish might experience indirect mortality after spillway passage, as they could become disorientated, and more prone to predators and might also be in a critical physiological state. A large number of dead Queensland lungfish (116 individual fish) were also recorded during the September overflow event. However, a few contradictory observations between the March and September 2010 overflow events were also reported (Chanson, 2023).

5. Discussion

5.1. Comparison with other spillway structures, natural fish mortality rates, recreational fishing and fish mortality induced by navigation

Any discussion and comparison of downstream fish migration mortality data must be un-biased and conducted based upon data relative to the relevant time and water volume scales. The data are typically presented in daily mortality rate, i.e. with a unit time equal to one day, to account for changes in hydrodynamic and environmental conditions between different days. In this section, the downstream fish migration mortality data are compared to observations on other spillway structures, natural fish mortality rates, recreational fishing, and fish mortality induced by navigation etc.

During the rising hydrograph of the March flood overflow event, "*an average of 60.8 small fish per minute*" were recorded migrating downstream over the spillway. For the same period, on 3 and 4 March 2010, the data showed a combined mortality of about 150 fish over the two days. Compared to the observed migration rate of 60.8 fish per minute, or 175,104 fish over two days, the relative mortality rate represented 0.085% of small fish passing over the spillway ([8]). This number is very small, and it may be compared to fish mortality observations during downstream passage over dam spillways (Table 3 & Fig. 6A). Table 3 presents well-documented observations of mortality rate during downstream fish passage over dam spillways. For smooth-invert ogee profile spillways, the mortality rate ranged from 1.6% to 7.75%, with some observations on rough and weathering concrete invert of fish mortality rate up to 16.9%. Simply, the comparison showed conclusively that the mortality rate recorded on the Paradise Dam stepped spillway during the 2010 events was two to three orders of magnitude smaller than that on smooth-invert spillway chutes. In addition, results demonstrate that fish mortality rate on the Paradise Dam stepped spillway was more than one order of magnitude lower when operating in skimming flow in comparison to periods when operating in nappe and transition flow, i.e. 0.085% versus 2.9% (Table 3). This comparison was consistent with the different mortality rates observed in March and September 2010 at Paradise Dam: i.e., the daily fish mortality per unit spillway overflow volume during nappe flow conditions in September 2010 was about six times larger than on 3–4 March 2010, when the spillway operated in skimming flow conditions (Fig. 6B).

The fish mortality numbers were compared to the natural fish mortality rates in lakes and reservoirs. In March 2010, the fish mortality

---

[8] It is acknowledged that the fish migration patterns varied throughout the day, and it is a simplification to assume that the rate of movements was constant, i.e. 60.8 fish/min, throughout the two days.

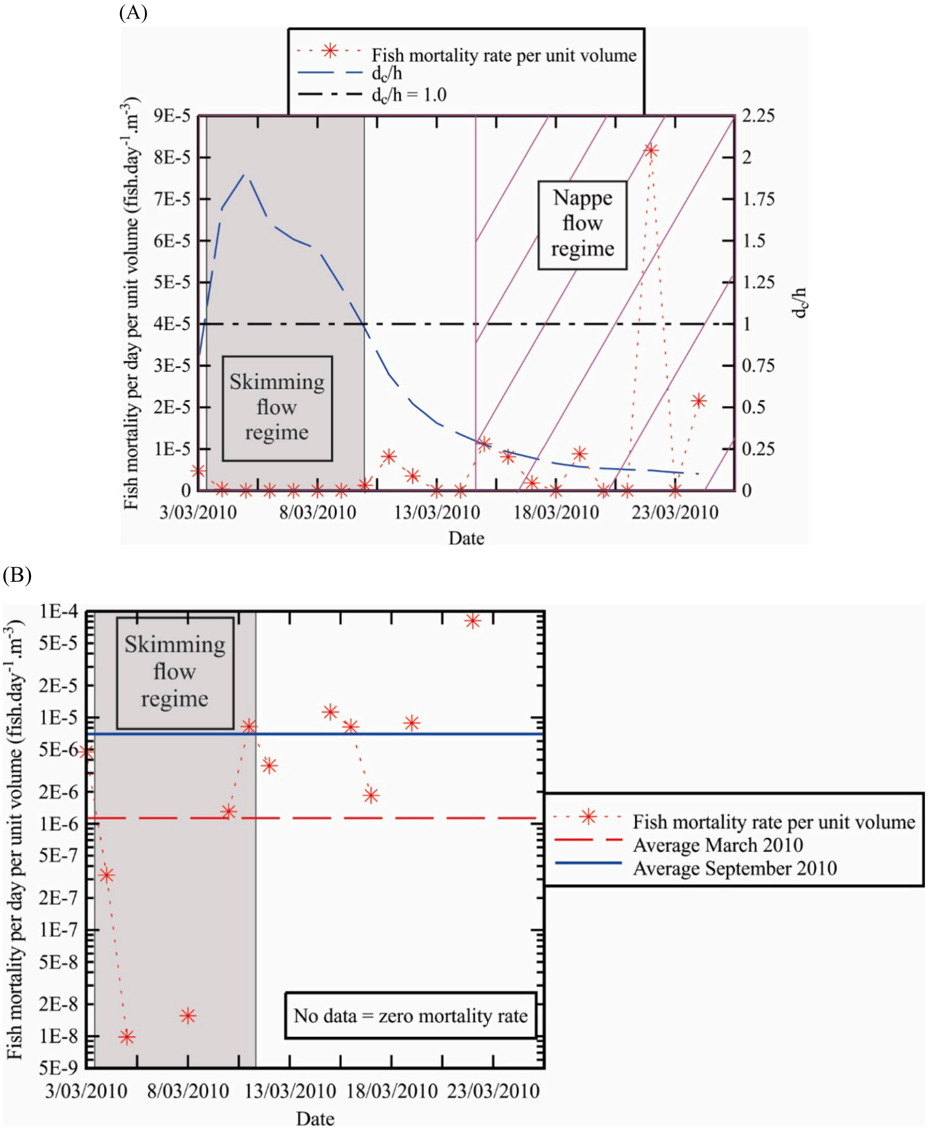


Fig. 5. Daily fish mortality per unit spillway overflow volume downstream of the Paradise Dam spillway during March 2010 and September 2010 flood events (Units: fish.day^{-1}.m^{-3}) - Data: DEEDI (2012) & Bureau of Meteorology (BOM, 2023).

(A) Daily fish mortality per unit spillway overflow volume (Eq. (2) - Units: fish.day^{-1}.m^{-3}) and dimensionless discharge during the March 2010 spillway overflow event - Data: DEEDI (2012, Table 13).

(B) Daily fish mortality per unit spillway overflow volume (Eq. (2) - Units: fish.day^{-1}.m^{-3}) presented with a logarithmic scale - Missing symbols correspond to zero fish mortality downstream of the Paradise Dam spillway - Data: DEEDI (2012, Tables 13 & 14).

observations reported over 661 dead fish ([9]) in 22 days (i.e. approximately 30 fish.day^{-1}). In September 2010, 149 dead fish were observed in 4 days (i.e. approximately 37 fish.day^{-1}). Assuming a fish density in the reservoir of 50 fish.ha^{-1} and 200 fish.ha^{-1} in March and September events respectively (Schneider, 1998, 1999; Ebener et al., 2010) and assuming a natural mortality rate of 50% per year (Schneider, 1998, 1999; Halliday and Young, 1996; Lowry and Suthers, 2004; Creque and Rutherford, 2005; Mazumder et al., 2005), the natural fish mortality in the Paradise Dam reservoir would range from 205 fish per day to 822 fish per day, assuming a full supply level (FSL) for which the Paradise dam reservoir occupies 30 km^2 or 3 × 103 ha (Herweynen and Griggs, 2006). That is, the downstream fish passage mortality data recorded during 3 March 2010 and 24 March 2010, i.e. 30 fish.day^{-1} in average, represented between 3.6% and 15% of the natural fish mortality estimate in the Paradise Dam reservoir (Fig. 7). In other words, the mean fish mortality downstream of the Paradise Dam spillway in March 2010 was drastically smaller than the natural fish mortality in the Paradise Dam reservoir over the same period. The finding was consistent with observations at Los Padres Dam: "*the greatest losses occurred in the reservoir*" (Ohms et al., 2022, p. 2210).

A third comparison was made against recreational volume. During the March 2010 overflow event, the cumulative volume of spilled water was 6.51 × 10^8 m^3, corresponding to 1.3 times the volume of the Sydney Harbour, and a total of 661 dead fish were observed downstream of Paradise Dam spillway. Considering that the daily recreational fishing in Sydney Harbour is 1986 fish (Ghosn et al., 2010), the total number of dead fish between 3 March 2010 and 24 March 2010 barely represented 1.5% of the average recreational fishing in the Sydney Harbour for the same period, or 1.2% of average recreational fishing in the Sydney Harbour for a similar 22 days period in 2007–2008 and the same water volume (Fig. 7). In terms of normalised data, the average recreational fishing catch in Sydney Harbour is 4.0 × 10^{-6} fish.day^{-1}.m^{-3}, compared to the average daily fish mortality per unit spillway overflow volume of

---

[9] or 233 dead fish excluding bony herring.

Table 3
Observed fish mortality rate p during downstream passage over dam spillways.

Study	Spillway	Δz_o (m)	Flow conditions	Fish & species	Mortality rate p (%)
DEEDI (2012)	Paradise Dam, stepped spillway, $\theta = 57.4°$, $B = 315$ m, $h = 0.62$ m, un-controlled ogee crest	36.75	3–4 March 2010 $\bar{q} = 4.4$ m.s^{-2}, skimming flow	western carp gudgeon, bony herring, fly specked hardyhead, snub-nosed garfish, Midgley's carp gudgeon, flathead gudgeon, barramundi, lungfish, …etc	0.085% (1) (3)
Schoeneman and Junge (1954)	Glines Dam, Free-fall jet	54.86	April–June 1953	Silver yearlings	7.75% (1)
				Chinook fingerlings	5.87% (1)
Schoeneman et al. (1961)	McNary Dam smooth-invert chute, gate-controlled ogee crest	~25–27	1955–1956	fingerling and yearling chinook salmon	2% (1)
	Big Cliff Dam smooth-invert chute, gate-controlled ogee crest	~27	1957		
Duncan and Carlson (2011)	Detroit Dam, smooth-invert (4) chute, gate-controlled ogee crest, $\theta = 53°$	27.7	July 2009 $q = 3.45$ m.s^{-2}	juvenile rainbow trout: $\overline{TL} = 125$ mm	9.5% (2)
			$q = 6.66$ m.s^{-2}		16.9% (2)
Colotelo et al. (2014)	Lower Granite Dam, smooth chute, gated spillway, $B = 156.1$ m, plunge pool	–	18 Apr-6 July 2012 8.78 m.s^{-2} $< q <$ 33.8 m.s^{-2}	steelhead kelts	9%
Colotelo et al. (2014)	Lower Granite Dam, smooth chute, gated spillway, $B = 156.1$ m, plunge pool	–	11 Apr-27 June 2013 7.33 m.s^{-2} $< q <$ 24.9 m.s^{-2}	steelhead kelts	5.5%
Bestgen et al. (2008,2016)	Free-fall jet & plunge pool	5.7	$q = 0.008$ m.s^{-2}, Pool depth: 0.15 m & 0.30 m	fathead minnow: $\overline{TL}$=22.8 & 44.7 mm, trout: $\overline{TL}$= 27.4 & 51.8 mm, razorback sucker: $\overline{TL}$= 25.0 mm	2% (2)
	Smooth-invert chute, un-controlled ogee crest ($\theta = 56°$, $B = 0.35$ m)	5.4	$q = 0.012$–0.24 m.s^{-2}, $V_{end} = 0.30$–0.92 m.s^{-1}		1.8% (2)
	Stepped-invert chute, un-controlled ogee crest ($q = 56°$, $h = 0.31$ m, $B = 0.35$ m)	5.4	$q = 0.012$–0.24 m.s^{-2}, $V_{end} = 0.18$–0.50 m.s^{-1} $d_c/h = 0.08$–0.58, nappe & transition flow		2.9% (2)
Castro-Santos et al. (2021)	Free-fall jet & plunge pool	2.63 to 5.79	$q = 0.23$ & 1.42 m.s^{-2}, Pool depth: 0.60 m, 1.2 m & 1.8 m	juvenile blueback herring (*Alosa aestivalis*)	< 20%
Ohms et al. (2022)	Los Padres Dam smooth chute, $\theta = 9°$, $B = 196$ m, un-controlled ogee crest, free-fall & plunge pool	28.3	$q > 0.02$ to 0.08 m.s^{-2}, Pool depth: 3 m	steelhead juveniles (parr, smolts) & kelts	< 12%

Notes: B: chute width; dc: critical flow depth $d_c = (q^2/g)^{1/3}$; h: vertical step height; q: unit discharge; TL: fish total length; V_{end}: downstream chute velocity; Δz_o: drop in chute invert elevation; θ: chute slope; (1) measured (absolute) mortality rate data un-corrected for natural mortality and background factors; (2): corrected mortality rate; (3): percentage of small fish (only) passing over the spillway; (4): rough and weathering concrete surface; (—-): data not available.

1.1×10^{-6} fish.day^{-1}.m^{-3} in March 2010 and 7.0×10^{-6} fish.day^{-1}.m^{-3} in September 2010 downstream of Paradise Dam spillway.

A further comparison with fish mortality and propeller strike in navigational channels was made. Field observations of fish mortality rate were documented in the Mississippi and Illinois Rivers with trawl hauls behind towboats moving upstream and downstream (Gutreuter et al., 2003; Killgore et al., 2011). Between 1996 and 2001, the data yielded 2.66 kills.km^{-1} for the two main species, i.e. gizzard shad (*Dorosoma cepedianum*) and skipjack herring (*Alosa chrysochloris*), and 3.72 kills.km^{-1} for four species including for shovelnose sturgeon and smallmouth buffalo (Gutreuter et al., 2003). With trawl hauls at speeds averaging 1.5 m.s^{-1}, these data corresponded to 344.7 mortality.day^{-1} (0.00399 mortality.s^{-1}) and 482 mortality.day^{-1} (0.00558 mortality.s^{-1}) respectively. In a follow-up study, from May to November 2006 and 2007 (Killgore et al., 2011), the observations showed that 2.4% of entrained fish exhibited injuries that were consistent with direct propeller strike. That is, the rates of fish injury/mortality by propeller strike on the Upper Mississippi and Illinois Rivers were nearly two orders of magnitude larger than the fish mortality downstream of Paradise Dam during the stepped spillway operation in March and September 2010 (Fig. 6A).

Finally, it must be acknowledged that the dead fish count data are underestimates (Southwick and Loftus, 2003, p. 18) and that many dead and injured fish are washed away and removed by scavengers before they can be counted (La and Cooke, 2011). Similarly, the observations in terms of numbers of fish using the Paradise Dam spillway chute were very likely under-estimated because of the broad width (B = 315 m) of the primary spillway combined with high turbidity of flow, and the counts of passing fish represented a very limited fraction of the fish population passing over the dam spillway.

As a final comment, the quasi-passive fate of fish eggs and larval fish were not investigated during the original study, although is an important component of natural habitats for species that spawn in main channel. Graser et al. (1979) observed successful downstream passage of larval fish on the John Sevier Dam stepped spillway, albeit the mortality and injury rates were higher than reported data for juvenile and adult fish species.

5.2. Regulatory recommendations

In Queensland, the State Development Assessment Provision Guideline, State Code 18: Constructing or raising waterway barrier works in fish habitats (DAF, 2022) sets the guidelines to maintain fish movement and connectivity throughout waterways and within and between fish habitats. The purpose of this guideline is to assist infrastructure projects that include constructing or raising waterway barrier works (such as dams and weirs) to undertake due diligence, identify issues regarding fish passage through waterway barrier works and ultimately develop a solution that is approved to be built by the Queensland Department of Agriculture and Fisheries (DAF). Code 18 states:

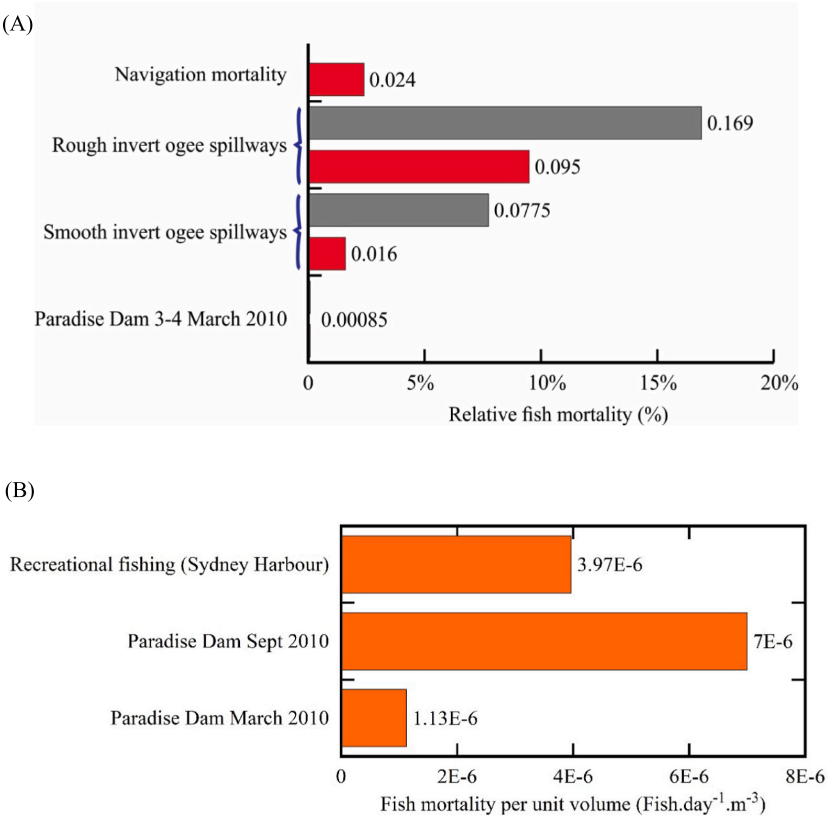


Fig. 6. Comparison of fish mortality rates and relative fish mortality downstream of Paradise Dam during spillway overflows in 2010, fish mortality caused by navigation ad propeller strike, fish mortality during downstream passage over smooth- and rough-invert ogee spillways, and recreational fishing in Sydney Harbour.
(A) Relative fish mortality downstream of Paradise Dam during spillway overflows on 3–4 March 2010, natural fish mortality in Paradise Dam reservoir, fish mortality caused by navigation and propeller strike, fish mortality during downstream passage over smooth- and rough-invert ogee spillways and recreational fishing in Sydney Harbour.
(B) Fish mortality rate per unit volume (fish.day^{-1}.m^{-3}) downstream of Paradise Dam during spillway overflows in March and September 2010, and recreational fishing in Sydney Harbour.

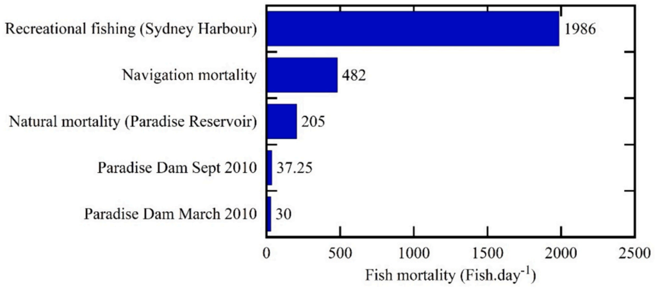


Fig. 7. - Daily fish mortality data (fish.day^{-1}) downstream of Paradise Dam during spillway overflows in March and September 2010, daily natural fish mortality in Paradise Dam reservoir, daily fish mortality caused by navigation ad propeller strike, and daily recreational fishing in Sydney Harbour.

"*The use of stepped spillways cannot comply with this code*" (DAF, 2022, p.1), "*Waterway barriers with stepped spillways have been shown to cause physical injury to adults passing over the crest of the structure. Any proposal that includes stepped spillways will not comply with this state code*" and "*Stepped spillways are not acceptable*" (DAF, 2022, pp. 27–28), this effectively prohibits the use and implementation of a stepped configuration in any new spillway, weir (or any other structure classified as a waterway barrier work) across Queensland.

It is believed that this position was reached after the analysis of the field observations of fish passage over the Paradise Dam stepped spillway (Australia) during the two spills in 2010 (DEEDI, 2012). This position is arguable in light of the above data re-analyses and low fish mortality rates at Paradise Dam stepped spillway, while it needs to be compared to regulations in other Australian states and overseas (Chanson, 2023). Based on the literature review conducted as part of this study, while fish mortality has been linked to downstream passage in spillways, specifically for low flows, no other state in Australia or country in the world has banned the use of stepped chutes due to downstream fish passage associated fish mortality. The consequences of this ban are most significant economically for asset owners, as all new dam spillway chutes in Queensland must now be rendered to create a smooth-invert surface, regardless of the proposed construction technique and costs.

Concrete dams and spillways can be built using several types of downstream facing, such as unformed Roller Compacted Concrete (RCC, compacted or un-compacted) or formed RCC, Conventionally Vibrated concrete (CVC), Grout Enriched RCC (GERCC) and Immersion Vibrated RCC (IVRCC) (Bass, 2022). For both CVC and RCC dams, a stepped spillway design is technically and economically preferred as the stepped profile contributes to the optimisation of energy dissipation structures (Matos and Meireles, 2014). While rendering the downstream face of a RCC dam/spillway as a smooth surface might not represent a significant cost, specifically when using recent techniques such as IVRCC (that require less forming and can expedite the rate of RCC placement), a stepped configuration is still preferred for energy dissipation purposes. As of 2022, this IVRCC face smoothening technique has only been used in cofferdams where large energy dissipation was not required due to high tailwater levels (Potts et al., 2019), however it has not been used to build any spillway (Bass, 2022). Further, overtopping studies in stepped-

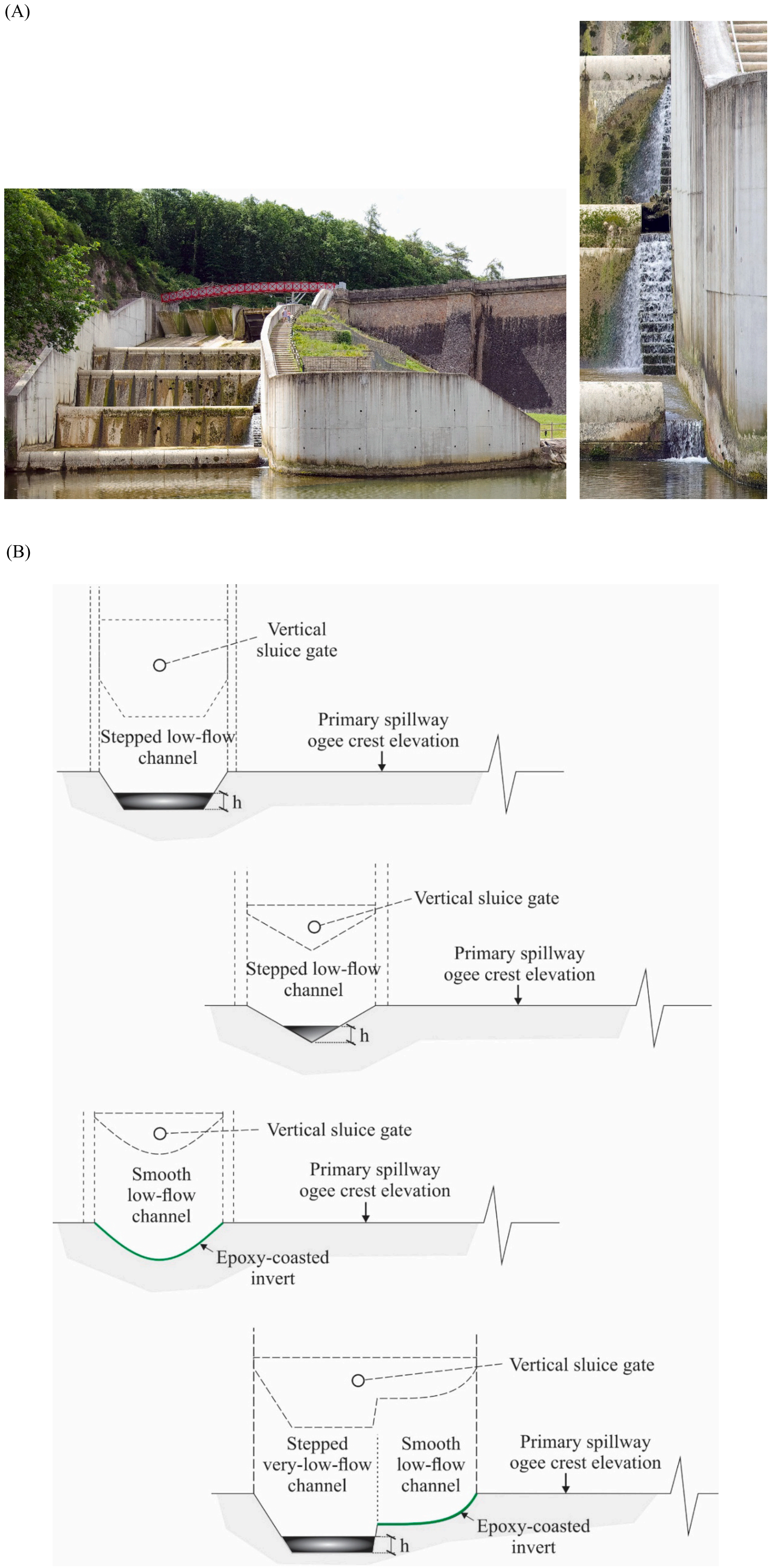


Fig. 8. - Low-flow fish-friendly channel for downstream passage embedded in spillway designs.
(A) Small stepped channel at Le Pont Dam (France), or also called Pont et Massène Dam, on 6 June 2022 - The dam is 23.1 m high, and the spillway chute is 35 m at the crest and 16 m at the downstream end - Inset: details of the low-flow stepped channel along the left training wall of the primary stepped spillway (Low-flow channel width ~ 0.6 m);
(B) Sketches of low-flow fish-friendly channel for downstream passage, looking upstream of the spillway crest and low-flow fish-friendly channel.

faced RCC dams have shown that a significant portion of the energy dissipation at a dam spillway (50% or more) can be provided by the stepped downstream face of the dam itself, thus further reducing the design requirements for a downstream stilling basin or energy dissipation structure (Chanson, 2001; Frizell and Svoboda, 2012; Hu and Chanson, 2023).

In summary, stepped-faced dams and stepped spillways can be rapidly constructed, be safely overtopped and provide improved energy dissipation requirements, which contributes to decrease its construction time and overall risks, as well as to increase drastically its cost effectiveness. As such, any ban on stepped chutes, e.g. as in Queensland, would result in significant costs that might not be justified given the low mortality of fish during downstream fish passage.

5.3. Downstream fish passage under low spillway overflow conditions

The observations of dead fish downstream of Paradise Dam during the spillway overflows showed that the largest fish mortality rates were observed under very-low flow conditions, i.e. at the tail of the flood in March 2010 and during the small overflow event in September 2010 (Figs. 3 and 4). The high fish mortalities were observed in the nappe flow regime with $d_c/h < 0.4$ and $q < 0.35$ $m^2.s^{-1}$, for which the reservoir elevation above spillway crest was <0.35 m. For smooth chutes, similarly, fish injury and mortality may occur when the water depth down the steep chute is too shallow, i.e. <10–15 mm. Such a range of water thickness down a smooth invert concrete spillway with 45° slope (1 V:1H) would correspond to unit discharges about $q < 0.05$ $m^2.s^{-1}$.

The development of low-flow fish friendly passage may be required to provide alternatives to existing fishways, often inefficient as observed at Paradise Dam. One possible alternative may be a low flow stepped channel with small step heights (e.g. $h = 0.03$ m to 0.05 m) to generate skimming flow conditions conducive to successful downstream fish migration. An alternative design may be a smooth-invert open channel lined with smooth coating (e.g. epoxy coating) to reduce bruises and injuries to fish during downstream passage at low discharges. Fig. 8 illustrates some examples, with a small-stepped channel in Fig. 8A and some conceptual design sketches in Fig. 8B. For all low-flow channel designs, a small gate system would be included to prevent any reduction in reservoir capacity with ungated spillways, as illustrated in Fig. 8B. The downstream low flow section may have a range of shapes, with a few designs illustrated in Fig. 8B. In the authors' opinion, a small trapezoidal stepped channel design (Fig. 8B top and bottom) might be some preferred option as the sideslope may assist the passage of other aquatic life (Yasuda et al., 2001).

During a flood event, the intake of the low-flow fish-friendly channels would be opened with the early flood inflow, i.e. rising hydrograph, before the reservoir elevation reaches the spillway crest elevation. Thus, the only overflow would take place in the low-flow fish-friendly channel which would be the only option for fish to migrate downstream. The intake of the low-flow fish-friendly channel would thus need to be appropriately located. During a major flood overflow, the low-flow fish-friendly channel could continue to operate without affecting the flood capacity of the dam spillway. At the end of the overflow, the low-flow fish-friendly channel would be shut to maintain the reservoir at full supply level (FSL).

6. Conclusion

The observations on downstream fish passage mortality at Paradise Dam stepped spillway constitute a unique data set, obtained at a medium-head large dam during large floods with a maximum spillway discharge in excess of 1300 $m^3.s^{-1}$ (i.e. 114.5 $GL.day^{-1}$) in March 2010. Two overflow events were documented at the spillway structure, equipped with an un-gated crest, a steep steppe chute and a hydraulic jump stilling basin without baffle block. The flood events presented markedly distinctive differences between the March 2010 and September 2010 floods. The March 2010 overflow event was documented for 22 days, including 9.5 days of operation in skimming flow regime, while the September 2010 flood event lasted four days corresponding to low unit discharges and primarily nappe flow conditions. The present re-analyses emphasised that the fish mortality rates should be normalised and reported relative to the relevant water volume and time span scales to eliminate some bias. The approach is consistent with world-class guidelines. Namely, the data for downstream fish passage mortality must be presented in a normalised form, e.g. as individual fish mortality per unit volume and per unit time.

A few key conclusions derived from the present work:

- The number of dead fish downstream of Paradise Dam during the 2010 spillway operation showed a higher mortality rate under nappe flow conditions, and a very low mortality under skimming flow conditions.
- The present data analysis demonstrated very clearly the significance of the spillway flow regime on the downstream fish passage mortality rate. On the Paradise Dam stepped spillway, very low fish mortality was observed during the spillway's skimming flow operation. Higher numbers of dead fish were reported during the stepped spillway operations in transition and nappe flows (i.e. $d_c/h < 1$), although the mortality rates then were comparable to or smaller than observations of fish mortality downstream of smooth-invert dam spillways.
- The fish mortality data downstream of Paradise Dam during the 2010 spillway operation was compared to a number of relevant observations at other spillway structures, natural fish mortality rates, recreational fishing and fish mortality induced by navigation …. Most comparisons were presented in a normalised form, including discussions in terms of daily mortality rate per unit volume (Units: $fish.day^{-1}.m^{-3}$). The comparative analyses indicated that the mortality rates of fish passing on the Paradise Dam stepped spillway were very low.
- Based upon fish mortality data in shallow plunge pools (Bestgen et al., 2018), high fish mortalities are predicted in very-thin nappe flow regime on stepped spillway and for very-low flows on smooth-invert spillways because of the shallow water depths, i.e. <10 mm, which would correspond to unit discharges $q < 0.01$ $m^2.s^{-1}$ to 0.02 $m^2.s^{-1}$ for both smooth- and stepped-invert chutes.
- For very-low unit discharges, an efficient downstream migration fish passage system is a basic requirement. A number of low-flow fish-friendly channel designs were proposed (Fig. 8B).

Overall, the current detailed re-analyses of the Paradise Dam fish mortality data demonstrate un-equivocally that the downstream fish passage mortality rates over the Paradise Dam stepped spillway were very small, to negligible especially compared to the benefits of the downstream fish migration in terms of migrating fish numbers, fish species numbers and bio-diversity. Plainly, the fish mortality over a stepped spillway is not substantially different than that for a smooth spillway design, and much lower in skimming flows. The present work highlights further the adverse impact on fish during downstream spillway passage at very-low flows, i.e. $q < 0.01–0.02$ $m^2.s^{-1}$, with both smooth-invert and stepped-invert spillways. Implicitly, the finding highlights the need for efficient downstream fish-friendly passage designs, adapted to the relevant spillway designs. Finally, it is acknowledged that the present analyses, review and discussion focused on the spillway chute, with little consideration for the stilling basin design. At the Paradise Dam, the stilling basin was a classical hydraulic jump (CHJ) stilling basin design (Type I) without baffles. This type of design is often considered the best in terms downstream fish passage survival rate (Bell and Delacy, 1972; Ruggles and Murray, 1983).

CRediT authorship contribution statement

Hubert Chanson: Writing – review & editing, Writing – original draft, Visualization, Resources, Project administration, Methodology, Formal analysis, Data curation, Conceptualization. **Carlos Gonzalez:** Writing – review & editing, Methodology, Formal analysis.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors. The academic research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Data availability

Data will be made available upon reasonable request

Acknowledgements

The authors thank Dr. José Maria Santos (University of Lisbon, Portugal) for his detailed comments. Hubert Chanson thanks Professor Richard Brown (Q.U.T.), Michael Hughes (Sunwater), and Dr. David Roberts (Seqwater) (in alphabetical order) for helpful advice and assistance. Some input from Prof. Daniel Bung (F.H. Aachen University of Applied Science), Dr. Brian Crookston (Utah State University), Dr. Sébastien Erpicum (University of Liège), Prof. Rob Ettema (Colorado State University), Dr. Chris Katopodis (KatopodisEcohydraulics), Prof. Jorge Matos (IST Lisbon), Dr. Pierre Sagne (INP Toulouse), and Dr. José Maria Santos (University of Lisbon, Portugal) (in alphabetical order) is acknowledged.

References

Bass, R.P., 2022. Design Manual for RCC Spillways and Overtopping Protection - EB218, 2nd edition. Portland Cement Association, Washington D.C., USA. 120 pages.

Baudoin, J.M., Burgun, V., Chanseau, M., Larinier, M., Ovidio, M., Sremski, W., Steinbach, P., Voegtle, B., 2014. Evaluer le franchissement des obstacles par les poissons. Principes et méthodes. Onema, France, 200 pages (in French).

Baumgartner, L.J., Marsden, T., Singhanouvong, D., Phonekhampheng, O., Stuart, I.G., Thorncraft, G., 2012. Using an experimental *in situ* fishway to provide key design criteria for lateral fish passage in tropical rivers: a case study from the Mekong River, Central Lao PDR. River Res. Appl. 28, 1217–1229.

Bell, M.G., Delacy, A.C., 1972. A compendium of the survival of fish passing through spillways and conduits. U.S. Army Corps of Engineers, North Pacific Division, Portland OR, USA, pp. 1–50.

Bestgen, K.R., Mefford, B., Compton, R.I., 2008. Survival and injury rates of early life stages of fishes passed over three diversion spillway models. In: Final Report to the U.S. Bureau of Reclamation, Denver CO, USA, 47 pages.

Bestgen, K.R., Mefford, B., Compton, R.I., 2018. Mortality and injury rates for small fish passing over three diversion dam spillway models. Ecol. Eng. 123, 141–150.

BOM, 2023. Burnett R at Paradise Dam HW (Wall) - Station number 136024A. Water Data Online, Bureau of Meteorology, Australia. http://www.bom.gov.au/waterdata/}. accessed on 31 March 2023.

Boyer, P.B., 1971. Gas Supersaturation Problem in the Columbia River. In: Proc. International Symposium on Man-Made Lakes. American Geophysical Union, Knoxville TN, USA, pp. 701–705.

Bunt, C.M., Castro-Santos, T., Haro, A., 2012. Performance of fish passage structures at upstream barriers to migration. River Res. Appl. 28, 457–478. https://doi.org/10.1002/rra.1565.

Castro-Santos, T., Mulligan, K.B., Kieffer, M., Haro, A.J., 2021. Effects of plunge pool configuration on downstream passage survival of juvenile blueback herring. Aquacult. Fish. 6, 135–143.

Chanson, H., 1994. Hydraulics of skimming flows over stepped channels and spillways. J. Hydraul. Res. IAHR 32 (3), 445–460. https://doi.org/10.1080/00221689409498745.

Chanson, H., 1995. Hydraulic Design of Stepped Cascades, Channels, Weirs and Spillways. Pergamon, Oxford, UK. Jan., 292 pages (ISBN 0-08-041918-6).

Chanson, H., 2001. The Hydraulics of Stepped Chutes and Spillways. *Balkema*, Lisse, The Netherlands, 418 pages (ISBN 90 5809 352 2).

Chanson, H., 2015. Energy dissipation in hydraulic structures. In: IAHR Monograph. CRC Press, Taylor & Francis Group, Leiden, The Netherlands, 168 pages (ISBN 978-1-138-02755-8).

Chanson, H., 2023. Paradise Dam Downstream Fishway and Spillway Monitoring Program 2010 - A Commentary on Downstream Fish Passage on Dam Spillway and Low Fish Mortality Rate. Research Report No. CE163. School of Civil Engineering, The University of Queensland, Brisbane, Australia. https://doi.org/10.14264/fceda3a, 67 pages. (ISBN 978-1-74272-408-9).

Chanson, H., Toombes, L., 2004. Hydraulics of stepped chutes: the transition flow. J. Hydraul. Res. IAHR 42 (1), 43–54. https://doi.org/10.1080/00221686.2004.9641182.

Chanson, H., Bung, D., Matos, J., 2015. Stepped spillways and cascades. In: Chanson, H. (Ed.), "Energy Dissipation in Hydraulic Structures." IAHR Monograph. CRC Press, Taylor & Francis Group, Leiden, The Netherlands, pp. 45–64.

Clay, C.H., 1995. Design of Fishways and Other Fish Facilities, 2nd edition. Lewis Publishers, Boca Raton FLa, USA. 249 pages.

Colotelo, A., Harnish, R., Jones, B., Hanson, A., Trott, D., Greiner, M., McMichael, G., Ham, K., Deng, Z., Brown, R., Weiland, M., Li, X., Fu, T., 2014. Passage distribution and Federal Columbia River Power system survival for Steelhead Kelts Tagged above and at lower Granite Dam, year 2. In: Pacific Northwest National Laboratory Report no. PNNL-23051. Pacific Northwest National Laboratory, Washington, USA, 129 pages.

Creque, S.M., Rutherford, E.S., 2005. Use of GIS-Derived Landscape-Scale Habitat Features to Explain Spatial Patterns of Fish Density in Michigan Rivers, vol. 25. North American Journal of Fisheries Management, pp. 1411–1425.

DAF, 2022. State Development Assessment Provisions guideline. State code 18: Constructing or raising waterway barrier works in fish habitats. Department of Agriculture and Fisheries, Queensland State Government, Brisbane, Australia. V. 1.0, 60 pages.

DEEDI, 2012. Paradise Dam Downstream Fishway Monitoring Program. DEEDI Fisheries Queensland, Queensland Department of Employment, Economic Development and Innovation. Final V1.1 Report, 93 pages. https://www.sunwater.com.au/wp-content/uploads/Home/About/Publications/Paradise_Dam_Downstream_Fishway_Monitoring_Program.pdf. Retrieved on 1 April 2023.

Deng, Z., Duncan, J.L., Arnold, J., Fu, T., Martinez, J., Lu, J., Titzler, P., Zhou, D., Mueller, R., 2017. Evaluation of boundary dam spillway using an autonomous sensor fish device. J. Hydro Environ. Res. 14, 85–92.

Duncan, J.P., Carlson, T.J., 2011. Characterization of Fish Passage Conditions through a Francis Turbine, Spillway, and Regulating Outlet at Detroit Dam, Oregon, Using Sensor Fish, 2009. Pacific Northwest National Laboratory Report PNNL-20365, Richland WA, USA, 290 pages.

Duncan, J., Deng, Z., Arnold, J., Fu, T., Trumbo, B., Carlson, T., Zhou, D., 2018. Physical and ecological evaluation of a fish-friendly surface spillway. Ecol. Eng. 110, 107–116.

Dynesius, M., Nilsson, C., 1994. Fragmentation and flow regulation of river systems in the Northern Third of the World. Science 266, 753–762.

Ebener, M.P., Brenden, T.O., Jones, M.L., 2010. Estimates of fishing and natural mortality rates for four Lake Whitefish stocks in Northern Lakes Huron and Michigan. J. Great Lakes Res. 36, 110–120.

Frizell, K.W., Svoboda, C.D., 2012. Performance of Type III Stilling Basins - Stepped Spillway Studies do Stepped Spillways Affect Traditional Design Parameters? Hydraulic Laboratory Report HL-2012-02, US Department of the Interior, Bureau of Reclamation, Denver CO, USA, 27 pages.

Ghosn, D.L., Steffe, A.S., Murphy, J.J., 2010. An assessment of the effort and catch of shore-based and boat-based recreational fishers in the Sydney Harbour estuary over the 2007/08 summer period. In: Fisheries Final Report Series No. 122. Industry & Investment NSW, Australia, 62 pages.

Gonzalez, C.A. (2005). An Experimental Study of Free-Surface Aeration on Embankment Stepped Chutes. Ph.D. thesis, Department of Civil Engineering, The University of Queensland, Brisbane, Australia.

Goodwin, R.A., Politano, M., Garvin, J.W., Nesyler, J.M., Hay, D., Andersob, J.J., Weber, L.J., Dimperio, E., Smith, D.L., Timko, M., 2014. Fish navigation of large dams emerges from their modulation of flow field experience. Proc. Natl. Acad. Sci. (PNAS) 111 (14), 5277–5282.

Gosse, P., Gregoire, A., 1997. “Dispositif de Réoxygénation Artificielle du Sinnamary à l'Aval du Barrage de Petit-Saut (Guyane).” ('Artificial Re-Oxygenation of the Sinnamary, Downstream of Petit-Saut Dam (French Guyana).'). Hydroécologie Appliquée 9 (1–2), 23–56 (in French).

Graser, L.F., Hackney, P.A., Starnes, L.B., Hogue, J.J., 1979. Investigations of Dynamics and Fate of Larval Fish in the Vicinity of the John Sevier Steam-Electric Plant. Office of Natural Resources, Tennessee Valley Authority, Norris TN, USA, 48 pages.

Guenther, P., Felder, S., Chanson, H., 2013. Flow aeration, cavity processes and energy dissipation on flat and pooled stepped spillways for embankments. Environ. Fluid Mech. 13 (5), 503–525. https://doi.org/10.1007/s10652-013-9277-4.

Gutreuter, S., Dettmers, J.M., Wahl, D.H., 2003. Estimating mortality rates of adult fish from entrainment through the propellers of river towboats. Trans. Am. Fish. Soc. 132, 646–661.

Halliday, I.A., Young, W.R., 1996. Density, biomass and species composition of fish in a subtropical *Rhizophora stylosa* Mangrove Forest. Mar. Freshw. Res. 47, 609–615.

Herweynen, R., Griggs, T., 2006. Burnett RCC Dam. An innovative approach to floods. In: Proc. 22nd ICOLD Congress, Question 84, Response 18, Vol. I, pp. 279–297.

Hu, J., Chanson, H., 2023. Hydraulics and energy dissipation on a steep stepped spillway: Physical modelling in a large-size facility. In: Proceedings of 31st Hydrology and Water Resources Symposium HWRS2023, Sydney, Australia, 12-15 November-, Published by Engineers Australia, Paper ID# 5, 10 pages (ISBN 978-1-925627-81-7).

Katopodis, C., Williams, J.G., 2012. The development of fish passage research in a historical context. Ecol. Eng. 48, 8–18.

Killgore, K.J., Miranda, L.E., Murphy, C.E., Wolff, D.M., Hoover, J.J., Keevin, T.M., Maynord, S.T., Cornish, M.A., 2011. Fish entrainment rates through towboat propellers in the Upper Mississippi and Illinois Rivers. Trans. Am. Fish. Soc. 140, 570–581.

La, V.T., Cooke, S.J., 2011. Advancing the science and practice of fish kill investigations. Rev. Fish. Sci. 19 (1), 21–33.

Larinier, M., 2000. Dams and fish migration. In: Technical Paper 26, World Commission on Dams. FAO Fisheries, 30 pages.

Larinier, M., Travade, F., 2002. Downstream migration: problems and facilities. Bulletin Français de Pêche et Pisciculture 364 (Supplement), 181–207.

Lowry, M., Suthers, I., 2004. Population structure of aggregations, and response to spear fishing, of a large temperate reef fish *Cheilodactylus fuscus*. Mar. Ecol. Prog. Ser. 273, 199–201.

Matos, J., Meireles, I., 2014. Hydraulics of stepped weirs and dam spillways: Engineering challenges, labyrinths of research. In: Chanson, H., Editors, L. Toombes (Eds.), "Hydraulic Structures and Society – Engineering Challenges and Extremes", The University of Queensland, Brisbane, Australia, Proceedings of the 5th IAHR International Symposium on Hydraulic Structures (ISHS2014), 25-27 June 2014, Brisbane, Australia. https://doi.org/10.14264/uql.2014.11, 30 pages.

Mazumder, D., Saintlilan, N., Williams, R.J., 2005. Temporal variations in fish catch using pop nets in mangrove and saltmarsh flats at Towra Point, NSW, Australia. Wetl. Ecol. Manag. 13, 457–467.

Noonan, M.J., Grant, J.W.A., Jackson, C.D., 2012. A quantitative assessment of fish passage efficiency. Fish Fish. 13, 450–464. https://doi.org/10.1111/j.1467-2979.2011.00445.x.

Ohms, H.A., Charguailaf, D.N., Brooks, G., Hamilton, C., Palkovacs, E.P., Boughton, D.A., 2022. Poor downstream passage at a dam creates an ecological trap for migratory fish. Can. J. Fish. Aquat. Sci. 79, 2204–2215. https://doi.org/10.1139/cjfas-2022-0095.

Ohtsu, I., Yasuda, Y., 1997. Characteristics of flow conditions on stepped channels. In: Proc. 27th IAHR Biennial Congress, San Francisco, USA, Theme D, pp. 583–588.

Pavlov, D.S., Mikheev, V.N., Lupandin, A.I., Skorobogatov, M.A., 2008. Ecological and behavioural influences on juvenile fish migrations in regulated rivers: a review of experimental and field studies. Hydrobiologia 609, 125–138.

Potts, J., Forbes, B.A., Escobar, G., Goltz, M., Ross, K., 2019. Construction Innovations for RCC cofferdams to speed up construction and reduce costs. Accessed online on 7 August 2023. https://afry.com/sites/default/files/2022-04/2019_africa_08.03._goltz_m.pdf}.

Rajaratnam, N., 1990. Skimming flow in stepped spillways. J. Hydraul. Eng. ASCE 116 (4), 587–591.

Robison, R., 1994. Chicago's waterfalls. Civ. Eng. ASCE 64 (7), 36–39.

Ruggles, C.P., Murray, D.G., 1983. A Review of Fish Response to Spillways. Canadian Technical Report of Fisheries and Aquatic Sciences No. 172, Department of Fisheries and Oceans, Halifax NS, Canada, 31 pages.

Santos, J.M., Silva, A., Katopodis, C., Pinheiro, P., Pinheiro, A., Bochechas, J., Ferreira, M.T., 2012. Ecohydraulics of pool-type fishways: getting past the barriers. Ecol. Eng. 48, 38–50.

Schneider, J.C., 1998. Fate of dead fish in a small lake. Am. Midl. Nat. 140, 192–196.

Schneider, J.C., 1999. Dynamics of quality bluegill populations in two Michigan Lakes with dense vegetation. N. Am. J. Fish Manag. 19, 97–109.

Schoeneman, D.E., Junge Jr., C.O., 1954. Investigations of mortalities to downstream migrant salmon at two dams on the Elwha River. In: Research Bulletin No. 3. Washington Department of Fisheries, April, USA.

Schoeneman, D.E., Pressey, R.T., Junge Jr., C.O., 1961. Mortalities of downstream migrant salmon at McNary Dam. Trans. Am. Fish. Soc. 90 (1), 58–72.

Silva, A.T., Katopodis, C., Tachie, M.F., Santos, J.M., Ferreira, M.T., 2015. Downstream swimming behaviour of catadromous and potamodromous fish over spillways. River Res. Appl. 32 (5), 935–945.

Southwick, R.I., Loftus, A.J., 2003. Investigation and Monetary Values of Fish and Freshwater Mussel Kills. American Fisheries Society, Specific Publication 30, Bethesda, Maryland, USA, 177 pages.

Toombes, L., Chanson, H., 2005. Air-water mass transfer on a stepped waterway. J. Environ. Eng. ASCE 131 (10), 1377–1386. https://doi.org/10.1061/(ASCE)0733-9372(2005)131:10(1377.

Yasuda, Y., 2011a. Guideline of Fishway for Engineers. Corona Publishing, NPO Society for Fishway in Hokkaido, Japan, 148 pages (ISBN: 978-4-339-05233-6). (in Japanese).

Yasuda, Y., 2011b. Guideline for Fish Passages for Engineers - based on Flow Conditions and Structure of Fish Passages. Corona Publishing, NPO Society for Fishway in Hokkaido, Tokyo, Japan, 144 pages (ISBN: 978-4-339-05233-6).

Yasuda, Y., Ohtsu, I., 2000. Characteristics of plunging flows in stepped channel chutes. In: Minor, H.E., Hager, W.H. (Eds.), International Workshop on Hydraulics of Stepped Spillways, Zürich, Switzerland. Balkema Publ, pp. 147–152.

Yasuda, Y., Ohtsu, I., Hamano, T., Miya, Y., 2001. A proposed fishway to facilitate the upstream and downstream migration of freshwater shrimps and crabs. In: Proc. 29th IAHR Congress, Beijing, China, Theme B. Tsinghua University Press, Beijing, pp. 312–317.

Yasuda, Y., Ohtsu, I., Koizumi, N., Junaidi, A., 2002. Installation test of ladder-type fishway at diversion weirs in Japan and Indonesia. In: Proc. 13th IAHR-APD Congress, Singapore, pp. 947–950.