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Downstream fish passage on dam spillways: truths, myths, and realities during prototype operation

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ABSTRACT

The movement of fish in natural rivers is affected by in-stream man-made structures, including dams and weirs that may prevent or hinder fish passage and cause fish mortality and injuries. While research on upstream fish passage has been active, the effects of downstream fish passage over dam spillways and weirs has received much less attention. A few exceptions include a recent comprehensive study in large-size physical facilities and some field observations on fish mortality including observations of fish passage over the stepped spillway documented at Paradise Dam (Australia) during two spills in 2010. The downstream fish migration mortality data, captured during these events, are discussed and compared to observations on several spillway structures with smooth and stepped inverts, as well as to natural fish mortality rates, recreational fishing and fish mortality induced by navigation. At the Paradise Dam during the March 2010 event, the number of dead fish downstream of the spillway was one to two orders of magnitude smaller than the natural fish mortality in the reservoir over the same period. The comparative analyses demonstrated that the mortality rates of fish passing on the dam spillway were very low irrespective of the invert type, except at very low unit discharges.

INTRODUCTION

The movements of fishes in natural river systems are affected by in-stream man-made structures, including dams and weirs that may prevent or hinder fish passage and cause fish mortalities and injuries (Dynesius and Nilsson 1994). Nitrogen supersaturation at spillway toe has also been recognised as a major factor affecting fish mortality (Boyer 1971, Ruggles and Murray 1983). The effects of downstream fish passage over dam spillways and weirs have received much less attention than upstream fish passage. Some exceptions encompass the field observations on fish mortality of Schoeneman et al. (1961) and Bell and Delacy (1972) as well as the recent comprehensive investigation in large-size physical facilities of Bestgen et al. (2008,2018).

In 2010, some observations of downstream fish passage mortality were documented at the Paradise Dam (Australia) (Fig. 1) in the fishway and over the spillway (DEEDI 2012). 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 stepped spillway operation. The present document reports some key points and develops a comparison in terms of downstream fish mortality with the relevant literature.

Figure 1. Paradise Dam stepped spillway operation on 5 March 2013 for Q = 2,326 m^3/s and d_c/h = 2.8 (skimming flow regime) (Photograph H.Chanson).

METHODOLOGY

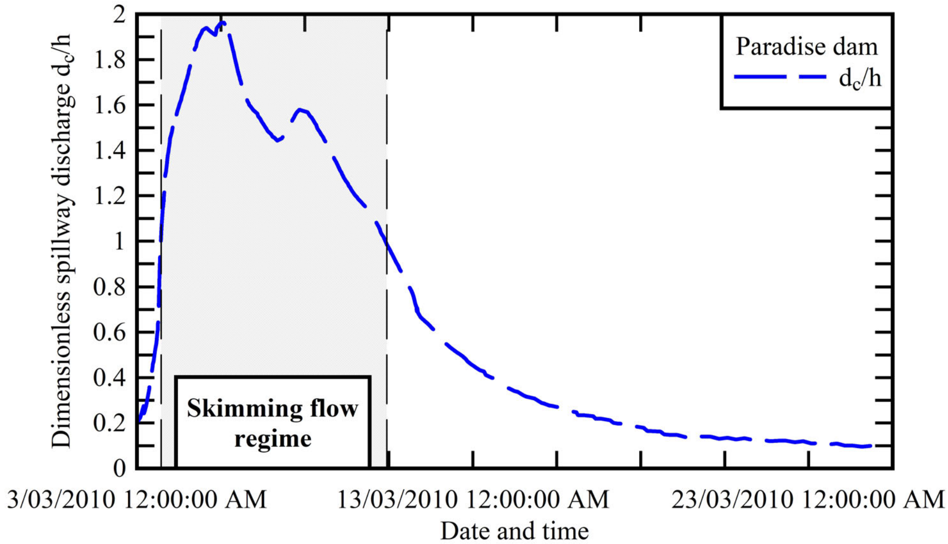
Presentation

The Paradise Dam is a 50 m high roller compacted concrete (RCC) structure. Located on the Burnett River in Central Queensland, the reservoir catchment area is: 33,000 km^2. The dam was originally equipped with a 315 m wide primary spillway, with an un-controlled ogee crest, a stepped spillway and a downstream stilling basin (Fig. 1). The chute slope is 1V:0.64H with 0.62 m high steps. The drop in elevation between the original ogee crest and basin invert was 36.75 m (until 2013). The first author observed the spillway operation in December 2010 and in March 2013 from the right bank (Fig. 1). The figure caption documents the spillway overflow discharge Q and dimensionless discharge d_c/h, where d_c is the critical flow depth ($d_c = (q^2/g)^{1/3}$), q the unit discharge, g the gravity acceleration and h the vertical step height. The Paradise Dam is equipped with two fishways, one to provide upstream fish passage and another for downstream fish passage.

The downstream fish passage during two spillway overflow events at Paradise Dam (March and September 2010) was documented (DEEDI, 2012). A summary of these spillway overflow events are listed in Table 1 alongside some key hydraulic characteristics and biological observations downstream of the primary spillway. Figure 2 presents the dimensionless discharge hydrographs of the primary spillway for both events; note that both plots are drawn with the same horizontal and vertical scales for comparison. The cumulative volume of the March 2010 spillway overflow event was equivalent to 1.3 times the volume of the Sydney Harbour in Australia (which has a volume of 500 Gigalitres) while the cumulative volume of the smaller September 2010 spillway overflow was equivalent to 0.054 times the Sydney Harbour volume. During the September 2010, the spillway operated in 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.

Table 1. Paradise Dam stepped spillway overflows in March and September 2010.

	March 2010	September 2010
Aquatic life observation period	3-24 March 2010	20-23 September 2010
Spill volume	6.5×10^8 m^3 (650 Gigalitres)	2.7×10^7 m^3 (27 Gigalitres)
Maximum spillway discharge	1,325 m^3/s	254 m^3/s
Days operating in skimming flow	9.5	0
Number of dead fish	> 661	149
Number of dead turtles	0	0



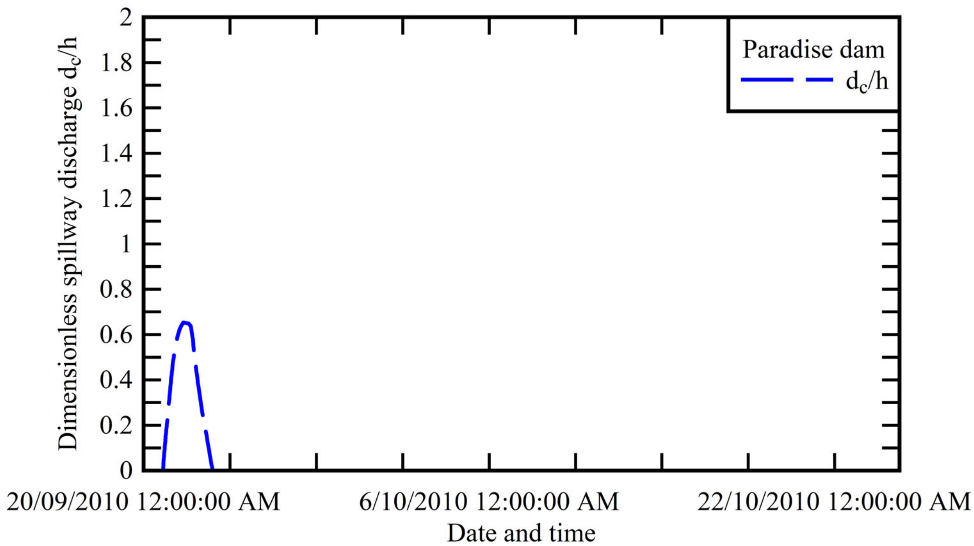


Figure 2. Dimensionless discharge d_c/h over the Paradise Dam stepped spillway in March and September 2010. Data: Bureau of Meteorology (BOM 2023).

Downstream fish passage observations

Detailed observations in terms the fish population passing downstream over the stepped spillway chute between 3 March and 24 March 2010, and between 20 September and 23 September 2010 are reported in DEEDI (2012). The monitoring activities encompassed visual and quantitative observations, 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. It should be noted that there was a greater "*focus on the collection of deceased and injured fish*" than on the number of live fish (DEEDI 2012, p. 52-53).

The data indicated overall a subjective abundance of downstream fish relative to fish abundance during no flow periods. 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 relative abundance out of 22 observed species (DEEDI 2012, Table 11). 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.

During the start of the March flood overflow event, large numbers of fish moving over the spillway were captured directly downstream of the spillway at: "*an average rate of 60.8 (±30.31) small fish per minute passing over the spillway during the rising hydrograph*" (DEEDI 2012, pp. 9 & 50). Additionally,"*visual observations also identified large fish such as long-finned eel at rates of up to 6 per minute going over the spillway*" (DEEDI 2012, p. 51). Since both sets of numbers are likely to be underestimated because of the breadth of the primary spillway (B = 315 m) and the high water turbidity, it is believed that the counts of passing fish only represented a very modest fraction of the fish population passing downstream over the spillway. Further, fish mortality data recorded downstream of the Paradise Dam spillway during the March and September overflow events were listed (DEEDI 2012, Tables 13 & 14).

Comparison between the March and September 2010 flood events

The March 2010 and September 2010 spillway overflow events were markedly different. The March 2010 flood event was larger and lasted longer (Fig. 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 ($d_c/h < 0.1$). The comparison of number of dead fish between March 2010 and September 2010 suggested several key conclusions. 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. A large number of dead Queensland lungfish (116 individual fish) were also recorded during the September overflow event.

DISCUSSION

Stepped spillway hydraulics and fish passage

The flow pattern on a stepped spillway may be markedly different for different flow rates. Considering flat horizontal steps in rectangular prismatic chute, the overflow can either be a nappe/jet flow for small unit discharges, a transition flow for a range of intermediate discharges, or a skimming flow at large unit discharges (Fig. 3). The nappe flow regime, also called jet flow, corresponds to a succession of free-falling nappes (Fig. 2 Left) observed for $d_c/h < 0.4$ to 0.6 for $\theta > 45°$. The transition flow regime, observed for $0.4\text{-}0.6 < d_c/h < 0.8\text{-}1$ for $\theta > 45°$, is characterised by large hydrodynamic instabilities and strongly chaotic flow conditions. The skimming flow regime has very distinct flow features, i.e. a coherent mainstream skimming over the pseudo-bottom formed by the step edges (Figs. 1 & 3 Right). In the step cavities, recirculating vortices develop and are maintained by the transmission of momentum from the main flow (Rajaratnam 1990, Chanson 1995).

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). 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 a negative impact on downstream fish passage, making smooth chutes potentially less suitable to downstream migration. In contrast, stepped chutes feature a strong re-aeration rate that can improve the water quality of polluted and eutrophic streams (Gosse and Gregoire 1997) and reduce the risks of nitrogen supersaturation, due to slower chute velocities. The fundamental differences between smooth- and stepped-invert chute flows are summarised in Table 2, including the main flow regimes on stepped spillways.

During spillway overflow, the downstream migrating fish may be injured by the chute flow motion and also by the downstream flow in the energy dissipator. On a stepped chute operating in skimming flows, the lower flow velocities and lesser shear stress 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 flow regions with high shear, compared to a smooth-invert chute, this suggests that stepped spillway designs are better suited to successful downstream fish passage.

However, very-small discharges over a stepped spillway might create flow conditions unsuitable for downstream fish migration, i.e. with a nappe flow regime with thin jets. These flow conditions would yield very small pool depths, with adverse impact on downstream fish migration (Bestgen et al. 2008, pp. 23-24; Baudoin et al. 2014, p.76) and were observed at the Paradise Dam stepped spillway: "*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*" (DEDI 2012, p. 58). 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, and vertical step heights h between 0.3 m and 1.5 m, a pool depth of 0.025 m or less would correspond to dimensionless discharges $d_c/h < 0.0025$ to 0.025. Note that, for the corresponding unit 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 (1V:1H) would be less than 5 mm to 8 mm. Such very-shallow water thickness would cause bruising, grazes, cuts and injuries to most fish species, and be unsuitable for the safe downstream migration of fish on a smooth spillway.

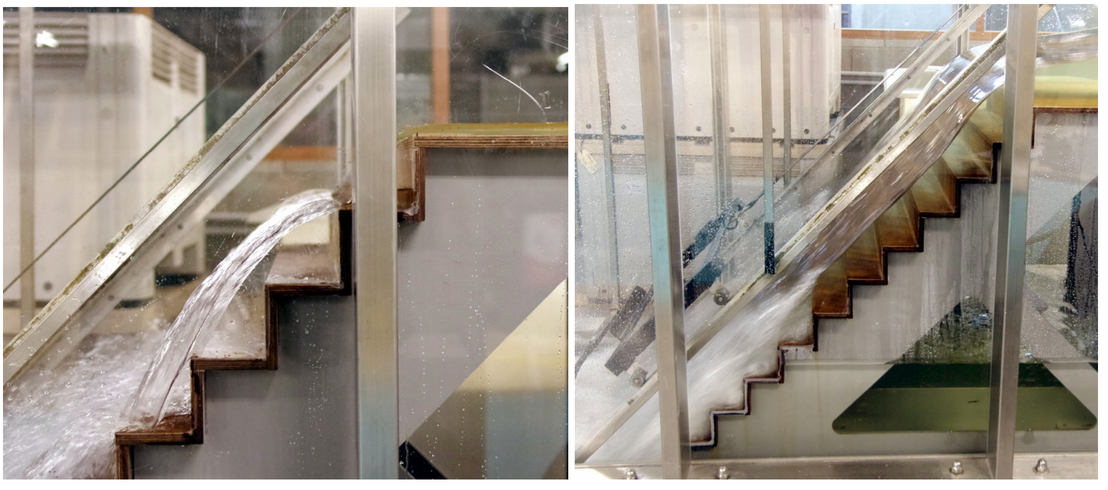


Figure 3. Nappe and skimming flows on 1V:1H stepped chute (left and right respectively).

Table 2. Comparison of hydraulic characteristics of smooth- and stepped-invert spillway flows in terms of downstream fish passage for identical flow rate per unit width q and chute slope.

	Smooth spillway	Stepped spillway		
		Nappe flow	Transition flow	Skimming flow
Velocity	High	Small	Small to moderate	Moderate
Water depth	Small	Small to medium	Medium to large	Medium to large
Turbulent shear stress	Uneven with very high-shear region next to invert	Uneven with large shear stress at impact	Uneven with very-large shear in cavity region	Reasonably uniformly distributed
Impact region	Nil	Very large at nappe impact	Large in cavity region	Nil to small
Recirculation zones	Nil	Small	Moderate	Important in step cavity / connected
Re-aeration rate	Poor	Strong	Very strong	Moderate to strong

Downstream fish passage mortality at spillways

A discussion on downstream fish migration mortality must be un-biased and conducted based upon data relative to the relevant time and water volume scales, and this current approach is consistent with world-class guidelines (Southwick and Loftus 2003, p. 46). In the following discussion, the downstream fish migration mortality data at Paradise Dam stepped spilway are compared to observations on other spillway structures and natural fish mortality rates.

In March 2010, during the rising hydrograph, "*an average of 60.8 small fish per minute*" were recorded migrating downstream over the Paradise Dam stepped spillway (DEEDI 2012, p. 9). For the same period, on 3 and 4 March 2010, the data showed a combined mortality rate of about 150 fish over the two days. Compared to the observed migration rate of 175,104 fish over two days, the relative mortality rate represented less than 0.085% of fish passing over the spillway. This number is very small in compared to fish mortality observations during downstream passage over other dam spillways. At the McNary Dam smooth invert spillway (USA) and Big Cliff Dam smooth chute (USA), the mortality rate of fingerling and yearling chinook salmon was 2% during three series of field observations (Schoeneman et al. 1961). At the Detroit Dam smooth-invert chute (USA), the mortality rate of juvenile rainbow trout, with 125 mm total length in average, ranged between 9.5% and 16.9% in 2009 depending upon the unit discharge (Duncan and Carlson 2011). A recent comprehensive study in large-size physical facilities yielded mortality rates of about 2% in smooth and stepped-invert spillways: "*we did not observe increased mortality in the stepped spillway even at lower flows*" and "*the hypothesis that small-bodied fish survival would be reduced in a stepped ogee-shaped spillway design compared to a smooth one, under the conditions we tested, was not supported*" (Bestgen et al. 2018, p. 148).

At the Paradise Dam spillway during the whole March 2010 overflow event, the fish mortality observations reported over 661 dead fish in 22 days, while 149 dead fish were observed in 4 days in September 2010. The numbers must be compared to the natural fish mortality rates in Paradise Dam reservoir. At full supply level (FSL), the Paradise dam reservoir occupies about 3000 ha. The natural fish mortality would range from 205 to 822 fish per day, assuming a fish density in the reservoir of 50 to 200 fish per ha respectively and assuming a natural mortality rate of 50% per year (Ebener et al. 2011, Creque and Rutherford 2005). That is, between 3 March 2010 and 24 March 2010, the downstream fish passage mortality data, i.e. 30 fish per day in average, represented between 3.6% and 15% of the natural fish mortality estimate in the Paradise Dam reservoir. Simply, this highlights that the observations of fish mortality downstream of the Paradise Dam spillway during the March 2010 event was significantly smaller than the natural fish mortality in the Paradise Dam reservoir over the same period.

Implications on design

In Queensland, the State Development Assessment Provison 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 Angriculture and Fisheries (DAF).

Code 18 states: *"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 20202, p.27 and 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 the state.

It is believed that this position was reached after the analysis of the field observations of fish passage over the stepped spillway documented at Paradise Dam (Australia) during the two spills in 2010 (DEEDI, 2012). This position is arguable in the 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 for downstream fish passage.

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. For both mass concrete and Roller Compacted Concrete (RCC) dams, a stepped spillway design is technically and economicaly preferred as the stepped profile contributes to the optimisation of energy dissipation structures (Matos and Meireles 2014). Further, overtopping studies in stepped-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 (USBR, 2017). New techniques such as Immersion Vibrated Roller Compacted Concrete (IVRCC) can expedite the rate of RCC placement allowing a smooth face. While this technique has been used in cofferdams for Nam Theun I Hydroelectriuc in Laos (Potts et al., 2019), as of 2022 no spillway has been built using IVRCC as a stepped configuration is still preferred for energy dissipation purposes (Bass and Randall, 2022).

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, the ban on stepped chutes in Queensland results in siginificant costs that might not be justified given the low moratility of fish during downtream fish passage.

CONCLUSION

This review of downstream passage of fish above spillway chutes presents a re-analysis of the fish mortality data collected downstream of Paradise Dam during the March and September 2010 overflow events. This 2010 data set on downstream fish passage mortality at Paradise Dam (DEEDI 2012) constitutes an unique data set, obtained at a medium-head large dam with a maximum spillway discharge in excess of 1,300 m^3/s in March 2010. Two spillway discharge events were documented, with 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 (Fig. 5-1B), while the September 2010 flood event lasted four days corresponding to low unit discharges and primarily nappe flow conditions.

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, and the data must be presented in a normalised form, e.g. as individual fish mortality per unit volume and per unit time. 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 mortality rate on the Paradise Dam stepped spillway was two to three orders of magnitude smaller than the literature on fish mortality rates observed in smooth-invert dam spillways, and much lower than the natural fish mortality in the resevoir for the same periods.

Stepped-faced dams and stepped spillways can be rapidly constructed, be safely overtopped and provide much-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, the ban on stepped chutes in Queensland results in siginificant costs that might not be justified given the low moratility of fish during downtream fish passage.

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BIOGRAPHY

Hubert Chanson is Professor of Civil Engineering at the University of Queensland, where he has been since 1990, having previously enjoyed an industrial career for six years. His main field of expertise is environmental fluid mechanics and hydraulic engineering, both in terms of theoretical fundamentals, physical and numerical modelling. He leads a group of 5-8 researchers, largely targeting flows around hydraulic structures, two-phase (gas-liquid and solid-liquid) free-surface flows, turbulence in steady and unsteady open channel flows, using computation, lab-scale experiments, field work and analysis. He has published over 1,350 peer reviewed publications including two dozen of books. He serves on the editorial boards of International Journal of Multiphase Flow, Flow Measurement and Instrumentation, and Environmental Fluid Mechanics, the latter of which he is currently a senior Editor. His Youtube channel is: {https://www.youtube.com/@Hubert_Chanson}.

Carlos Gonzalez is a Technical Principal at SMEC with 20+ years international experience in the field of hydraulics and hydrology. He has played key roles in several projects both domestic and internationally, conducting hydrologic studies and designing hydraulic structures. His experience includes hydrodynamic modelling (1D/2D/CFD), flood forecasting, catchment hydrology, hydraulic and hydrologic modelling for dams and spillways, fish passage through hydraulic structures and scour analysis and erosion protection design. Carlos is familiar with local and State policies for Queensland and New South Wales.