APPENDIX O

Fish Passage Assessment

Potential impacts of downstream passage of fauna over a labyrinth spillway at Lake Macdonald Six Mile Creek

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Aquatic Biopassage Services

for Seqwater

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1. Executive summary

Seqwater is undertaking a Dam Safety Upgrade for Lake Macdonald to bring the structure into compliance with current industry guidelines and the requirements of the Water Supply (Safety and Reliability) Act 2008. The upgrade will preserve the storage at its current capacity and height but the spillway configuration will be changed to a labyrinth design. The particulars of the proposed upgrade have been determined to trigger assessable development under the Planning Act 2016, and subsequent consequences under the Fisheries Act 1994.

Aquatic Biopassage Services has been retained by Seqwater to provide services associated with the provision of effective and safe passage of fish beyond Six Mile Creek Dam. The current report provides technical input on the spillway design with respect to aquatic fauna downstream passage.

Aquatic fauna such as fish, turtle, crustaceans, platypus and water rats may be affected by passage over the spillway wall at Six Mile Creek Dam. However, the bulk of knowledge on impacts of dams is on fish and to some degree turtles. In regards to spillway passage it is likely that any works to minimise impact on fish and turtles will be of similar benefit to other aquatic fauna.

A labyrinth dam incorporates a spillway that is folded in plan-view to increase the length of the crest, resulting in a higher discharge capacity relative to straight profile dam walls. A literature review failed to identify any labyrinth spillway designs that specifically addressed safe downstream passage for aquatic fauna. The labyrinth design incorporates a vertical drop to the tailwater and substantial research has been performed on vertical drop spillways.

Eight potential sources of fish injury at dam spillways have been identified in North America. Each of the causes were evaluated in an Australian context and potential implications for the design of the upgraded spillway at Six Mile Creek Dam are provided.

The concept designs developed for the Six Mile Creek Dam upgrade have already considered some of the potential issues with safe downstream passage of aquatic fauna. Further development of the design requires close attention to ensure that:

- the spillway crest shape is the most suitable profile;
- the stilling basin depth is increased to provide sufficient plunge pool depth;
- turbulence in the stilling basin is minimised during all flows;
- sources of direct strike impact for fauna are minimised;
- the potential for predation is minimised by reducing fish aggregations;
- only surface quality water is release from the dam outlet;
- the potential for dewatering and stranding of fauna when flows cease is minimised;
- the potential for entrainment of fauna within the intake structure is minimised.

2. Proposed development

Seqwater is undertaking a Dam Safety Upgrade for Six Mile Creek dam, also known as Lake Macdonald, located on Six Mile Creek near Cooroy. The upgrade will address specific dam safety risks to bring the structure into compliance with current industry guidelines and the requirements of the Water Supply (Safety and Reliability) Act 2008.

The spillway upgrade will preserve the storage at its current 8,000 ML capacity and its Full Supply Level (FSL) of 95.32 m AHD. The spillway configuration will change, but spillway height, spill conditions and discharge to Six Mile Creek will remain the same. The particulars of the proposed upgrade have been determined to trigger assessable development under the Planning Act 2016, and subsequent consequences under the Fisheries Act 1994.

Aquatic Biopassage Services has been retained by Seqwater to provide the following:

1. Provide technical input on assessment and selection of a fishway for the Six Mile Creek Dam upgrade
2. Provide technical advice and input into the detailed design process
3. Provide technical input on spillway design with respect to aquatic fauna downstream passage
4. Support engagement with the regulator (DAF), through technical advice on fishway options assessment

The current report addresses Step 3 above.

3. Proposed works

During a Portfolio Risk Assessment (PRA) of its 26 referable dams, Seqwater identified numerous failure modes for Six Mile Creek Dam and the estimated societal risk was assessed to be unacceptable against the ANCOLD risk criteria. Upgrade options all involve increasing the spillway capacity, to meet the 100% acceptable flood capacity (AFC) requirement, which is estimated at approximately 1:10,000,000 Annual Exceedance Probability (AEP) event.

Site conditions and geotechnical constraints require a highly efficient spillway to limit the overall spillway width and the size of flow dissipation infrastructure. A labyrinth weir was selected as the most hydraulically and cost effective spillway option for achieving AFC requirements.

In addition to a new spillway structure, the proposed dam safety upgrade detailed by AECOM (2016) includes:

- Reconstruction of the right embankment
- Buttressing and partial reconstruction of the left embankment
- Construction of a new saddle dam

4. Labyrinth dams

A labyrinth dam incorporates a spillway that is folded in plan-view to increase the length of the crest, resulting in a higher discharge capacity relative to straight profile dam walls. The hydraulic efficiency of labyrinth weirs provide an effective means of increasing spillway capacity under restricted operating conditions. This type of weir is particularly suited to sites where a low head to high discharge relation is required and the topography restricts the spillway width. An infinite number of geometric configurations can be utilised for a labyrinth type spillway; three general classifications based upon cycle shape are triangular, trapezoidal, and rectangular (Figure 1). Triangular and trapezoidal shaped labyrinth cycles are more considered more hydraulically efficient than rectangular labyrinth weir cycles (Crookston, 2010).

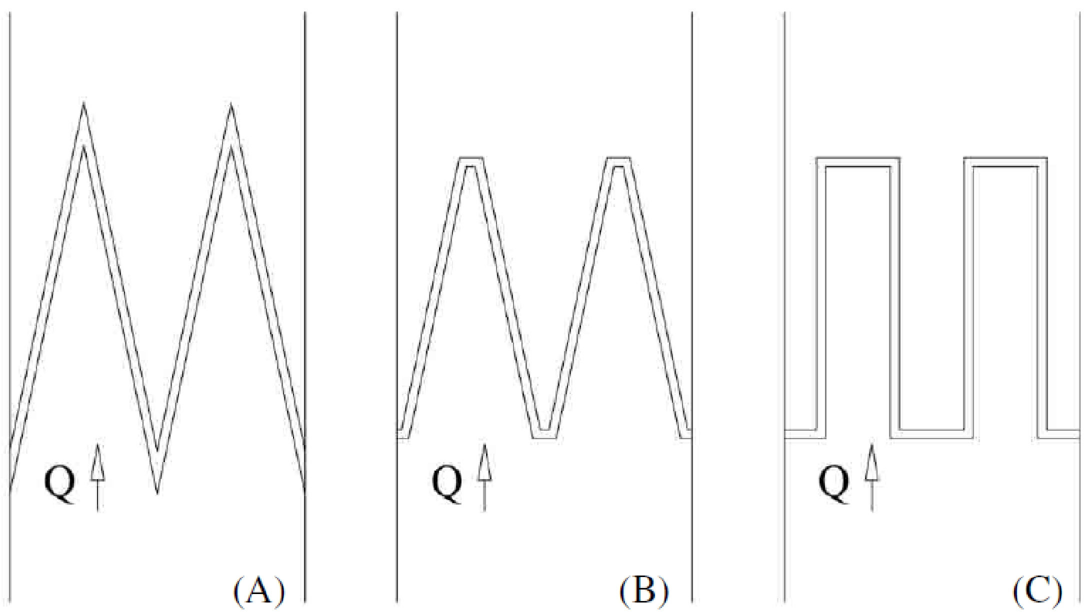

Fig. 2-1. General classifications of labyrinth weirs: Triangular (A), trapezoidal (B), and rectangular (C)

Figure 1. Classifications of labyrinth type spillways, from Crookston, 2010.

A literature review of structures with Labyrinth type spillways identified that they are relatively common overseas and are used extensively at sites where they may be advantageous. Despite potential application at many sites, labyrinth spillways are uncommon in Australia. In 2013, the 13.5 m high Loombah Dam located on Ryan's Creek, approximately 25 km south east of Benalla, Victoria was retrofitted with a rectangular type spillway known as the piano key design (Buchanan *et. al.* 2013). No considerations for fish passage in either direction was implemented into the upgraded structure (Justin O'Connor, Victorian Department of Environment, Land, Water and Planning pers. com.).

Some of the dams and weirs overseas with labyrinth spillways have incorporated fishways for upstream passage, however no mention of downstream fish passage was found for any labyrinth spillway. Many of the retrofitted dams appeared to incorporate a low height labyrinth spillway on top of a previously conventional crest. Very few of the labyrinth spillway designs viewed online incorporate a stilling basin or any type of plunge pool that may protect downstream migrating fauna below the labyrinth spillway, refer Figure 2.

Figure 2. Example of a labyrinth type spillway with no stilling basin or plunge pool, image from Crookston and Tullis (2013).

The spillway crest shape is one of the most important factors that affects the discharge capacity for labyrinth weirs. Figure 3 below illustrates the various crest shapes utilised in labyrinth spillways (Crookston, 2010).

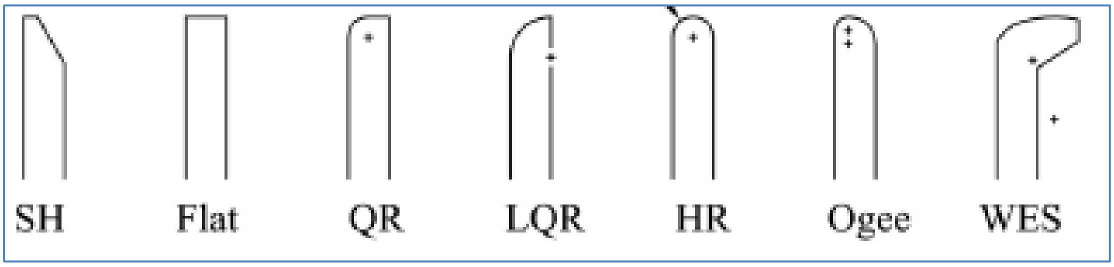

Figure 3. Configurations of crests on labyrinth type spillways, from Crookston, 2010.
SH = sharp, QR = quarter round, LQR = large quarter round, HR = half round, WES = truncated Ogee.

5. Safe passage for fish over spillways

Literature review

Passage over spillways can directly cause fish injury or mortality, or indirectly by increasing susceptibility of disorientated or shocked fish to predation. The manner in which energy is dissipated in the spillway can have a determinant effect on fish injury and mortality rates (Larinier 2000).

The literature review undertaken in the current report failed to identify any locations that utilised labyrinth spillways where the downstream passage of fish was considered. The predominant spill from a labyrinth spillway is a free overfall design with vertical drop to the surface below. Accordingly, most of the aspects that impact on fish survival at any vertical fall spillway apply to the labyrinth spillway design.

A vertical fall from a spillway into a deep plunge pool or tailwater can have negative impacts on fish health. Experiments have shown that significant damage such as injuries to gills, eyes and internal organs occurs when the impact velocity of the fish on the water surface in the downstream pool exceeds 16m/s (Bell & Delacy, 1972). A column of water reaches this critical velocity for fish after a drop of 13 m, beyond this limit injuries may become significant and mortality will increase rapidly in proportion to the drop (Ruggles, 1983).

Passage through a spillway under free-fall conditions (separate from the column of water) is less hazardous for small fish. For larger fish, the hazards are identical whether they pass under free-fall conditions or are contained in the column of water. Passage is generally less hazardous for fish if there is a pool of sufficient volume at the base of the spillway (Larinier 2000). Numerous sources of literature reference the previous statement in Larinier (2000), however no guides were found that assisted in the determination of a sufficient pool volume for a given spillway height.

Australian context

Very little research has been performed on the downstream passage of fish in Australia; however, some of the studies that have been performed have application to Six Mile Creek Dam.

A study of survivorship of fish passing through weirs with overshot (overflow) releases compared to those passing through undershot gates was performed in the Murray River (Baumgartner *et.al.* 2006). The findings were that the majority of larval fish including more than half of the Murray cod (*Maccullochella peelii*) tested died during undershot weir passage. Small-bodied native fish displayed extremely high mortality when passing through undershot weirs and adult life stages of large-bodied species were also affected by undershot weirs but to a much lesser degree.

Results for downstream passage through overshot weirs indicated that few fish died and the main welfare issues arose when water from overshot weirs fell into shallow water, where fish became physically injured when impacting the downstream weir apron. One of the recommendations of the research was that the construction of overshot release weirs with deep plunge pools would provide safer conditions for all fish species and size classes moving downstream (Baumgartner *et.al.* 2006, 2014).

Monitoring of downstream fish passage over the stepped spillway at the 37 m high Paradise Dam on the Burnett River documented fish injury and mortality caused by striking the steps during overtopping flow conditions (SunWater, 2012). Collection of small to medium sized fish that passed over the dam wall during flow events found that 81.9% of fish collected in drift nets were deceased and 94.5% of fish had serious injuries such as abrasion, scaling and head damage.

Large bodied fish species were observed striking the Paradise Dam spillway and were collected deceased during flows up to 1.3 metres over the spillway. The Queensland lungfish was the largest species to pass over the spillway and had the second highest representation of mortality and injuries compared to 15 other medium to large bodied species (SunWater, 2012).

The findings of the study were that fish mortalities were occurring during all flows over the Paradise Dam stepped spillway regardless of the flow condition. The cumulative effect of mortalities of fish passing over the spillway was considered likely to have a major impact on populations of fish in the lower Burnett River over the longer term (SunWater, 2012).

Sources of injury at spillways

Ruggles and Murray (1983) identified eight potential sources of fish injury at dam spillways in North America. Each of the causes are listed below, potential solutions are summarised to suit an Australian context below. Implications for the design of the upgraded spillway at Six Mile Creek Dam are provided in Table 3.

Abrasion against spillway

Caused by direct contact with spillway surfaces, particularly at sites with stepped spillways. Injury can be avoided by minimising the length of concrete chutes, the use of ski-jump spillways where possible, use of streamlined channels to provide a smooth contact surface and by minimising chute velocities.

Impact against base of spillway

Caused by physical impact against stilling basin floor and sills as well as energy dissipators and outlet structures. Injury can be avoided by eliminating any potential sources of direct strike during spillway fall as well as a stilling basin with sufficient depth to minimize impact on the basin floor. The location and design of flow dissipators and stilling basin nib walls should be such that fish that are washed downstream are guided around the structures with minimal risk of a direct strike.

Turbulence and shearing forces in tailwater

Caused by turbulence in the stilling basin at the base of the dam and sudden variations in velocity and pressure as the fish hits the water. Injury can be avoided by increasing the volume and depth of water in the stilling basin and by increasing the length of crest of the spillway.

Impact of fish in free fall entering a stilling basin

Injuries occur when fall velocities over spillways exceed 16m/s, which occurs at heights >13 m. Injuries can be avoided by limiting the free fall of fish to < 13 m, at higher dams use ogee or other type of spillway to eliminate or limit the height of the free-fall portion.

Gas-bubble disease below spillways

Caused by total dissolved gas supersaturation which occurs when water cascades over a dam or waterfall and fish move from one water pressure gradient to another, the impact on fish is analogous to 'the bends' in human divers. Injuries can range from mild to fatal depending on the level of supersaturation, species, life cycle stage, condition of the fish, fish depth and the water temperature. Gas bubble disease has not been reported to occur at Australian dams and may be limited to cold-water sites where the potential for gas supersaturation is increased (author pers. obs.).

Predation above and below spillways

All waterway barriers, natural and anthropogenic, cause delays that create aggregation zones for migrating fish that increase the risk of predation by fish and piscivorous birds. In addition, fish passing over the spillway may be temporarily disoriented and unable to avoid predators. Injuries and death can be minimised by providing effective passage beyond the barrier that reduces delays and if necessary by providing shelter habitat for aggregating fish.

Reduced water quality below spillways

Caused by poor quality water being released from dams either via outlets or over the spillway. Fish injury and mortalities may be reduced by only releasing high quality water via selectable intakes and by avoiding outlet and spillway releases following events such as impoundment rollover.

Dewatering and stranding of fish within and below spillways

Caused by poorly designed multi-level spillways that hold fish during flow and do not permit fish to exit when flow ceases. Dams with large impoundments may cause fish to wash over a non-flowing crest when at full supply during events such as wind seiching. Stilling basins that do not completely drain when flow ceases also have the potential to strand and kill fish when water quality decreases. Injuries and death can be avoided by ensuring that the spillway and stilling basin are designed so that any entrapment of fish is avoided. In situations where entrapment is unavoidable, it may be necessary to provide a flow release from the dam to maintain water quality in the tailwater pool or to implement fish salvage activities according to DAF Guidelines.

6. Aquatic fauna of Six Mile Creek

Fish species

Biological and habitat surveys were completed in Six Mile Creek and in the Lake Macdonald storage by FRC Environmental (2016). A desktop assessment and expert review supported by two onsite surveys determined that 28 native and four alien or noxious species occur in Six Mile Creek.

Table 1. Fish species present in Six Mile Creek from FRC Environmental (2016),
☺ = translocated native species, ☠ = alien/noxious species.
Length size class: small = <100 mm, medium = 100 mm to <300 mm, large = 300 mm to 1000 mm.

Species	**Common Name**	**Size as adults**
Ambassis agassizii	Agassiz's glassfish	small
Ambassis marianus	estuary glassfish	small
Anguilla australis	southern shortfin eel	large
Anguilla reinhardtii	longfin eel	large
Glossamia aprion	mouth almighty	small
Craterocephalus marjoriae	silverstreak hardyhead	small
Craterocephalus stercusmuscarum	flyspecked hardyhead	small
Gobiomorphus australis	striped gudgeon	small
Hypseleotris spp.	common carp gudgeons	small
Hypseleotris compressa	empire gudgeon	small
Mogurnda adspersa	purple spotted gudgeon	small
Philypnodon macrostomus	dwarf flathead gudgeon	small
Philypnodon grandiceps	flathead gudgeon	small
Melanotaenia duboulayi	crimson spotted rainbowfish	small
Maccullochella mariensis	Mary River cod	large
Macquaria novemaculeata	Australian bass	medium
Macquaria ambigua	yellow belly☺	medium
Tandanus tandanus	eel tailed catfish	medium
Neosilurus hyrtlii	Hyrtl's tandan	small
Pseudomugil signifer	Pacific blue eye	small
Retropinna semoni	Australian smelt	small
Nematalosa erebi	bony bream	medium
Neoceratodus forsteri	Queensland lungfish	large
Trachystoma petardi	pinkeye mullet	large
Mugil cephalus	sea mullet	large
Notesthes robusta	bullrout	medium
Leiopotherapon unicolor	spangled perch	medium
Scleropages leichardti	southern saratoga☺	large
Gambusia holbrooki	eastern Gambusia☠	small
Xiphophorus maculatus	platy☠	small
Xiphophorus hellerii	swordtail☠	small
Poecilia reticulata	guppy☠	small

Fish passing downstream over Six Mile Creek Dam will consist of larval life stages up to large fish such as Mary River cod and lungfish greater than 1 m in length.

Turtle species

A desktop assessment and expert consultation by FRC Environmental (2016) indicated that six native turtle species were present in Six Mile Creek (Table 2) and that no introduced turtle species are known to occur or likely to occur. Surveys determined that the upstream zone had the highest diversity and abundance of turtles and that the saw shelled turtle was the most abundant species.

Table 2. Turtle species present in Six Mile Creek from FRC Environmental (2016)

Species	**Common Name**
Chelodina expansa	broad shelled river turtle
Chelodina longicollis	eastern long necked
Emydura macquarii krefftii	Krefft's River turtle
Wollumbinia latisternum	saw shelled turtle
Elusor macrurus	Mary River turtle
Elseya albagula	white throated snapping turtle

Impoundment infrastructure has the potential to cause injury and death of turtles that aggregate at the site. Falls from spillways and abutments can cause shell fracture injuries, gated structures may cause crush injuries, and stepped spillways may cause injury during flow events and trap turtles when flow ceases (Latta, 2009). Screens, which prevent trash entering and blocking water, release intakes on the upstream side of impoundment infrastructures can trap large numbers of turtles and cause their death (Limpus, 2008).

Other aquatic fauna such as crustaceans, platypus and water rats may also be affected by passage over the spillway wall at Six Mile Creek Dam. However, little is known in regards to spillway passage of these species. It is likely that any works to minimise impact on fish and turtles will be of similar benefit to other aquatic fauna.

7. Design for the spillway upgrade at Six Mile Creek Dam

Reference to the spillway upgrade in this section refers to Drawing Set 60451967 - 101 to 122 that were developed by AECOM for Seqwater, provides concept designs for the upgrade works. The entire spillway is a trapezoidal shaped labyrinth design with a three cycle arrangement on a low flow section and a five cycle arrangement on a high flow section. The spillway crest is rounded on top with a vertical upstream face and a sloped downstream face set on a 1:12 grade.

The high flow spillway is to be 5.1 m wide on the left bank and 76.8 m wide on the right bank. The level of the spillway is set at RL 97.1 m, which is 0.4 m lower than the modelled 1:100 year AEP flood height. A 44 m wide low flow section that is set at RL 95.4 m with two 5 m wide notches set at RL 95.32 is located between the high flow spillways and across the main channel section of Six Mile Creek. A slab set at RL 89.5 extends along the base of the entire spillway and a secondary floor is set at RL 86.0 m below the low flow spillway section only.

An outlet tower is located on the left abutment of the dam; the intake will incorporate a trash screen and selectable baulks. Releases from the outlet tower will be restricted to low volumes required for environmental purposes under the Mary Basin Resource Operational Plan.

8. Implications for downstream passage at Six Mile Creek Dam

Some of the potential injuries associated with passage over spillways identified in Section 5 have implications for passage over Lake Macdonald Dam. Table 3 below provides a summary of the likelihood of injury.

Table 3. Causes of fish injury and potential to occur at Six Mile Creek Dam.

Cause of injury	Issue at Lake Macdonald spillway?	Comments
Abrasion against spillway	Possible	Spillway crest & vertical walls during shallow flows
Impact with spillway base	Likely	Vertical drop creates high potential for striking
Turbulence in tailwater	Likely	Vertical drop creates high potential for turbulence
Free-fall to stilling basin	Unlikely	Low height of spillway crest reduces potential
Gas bubble disease	Unlikely	Not known as an issue in Australia
Predation	Likely	High potential at all waterway barriers
Reduced water quality	Possible	Avoidable with good design & management
Dewatering and stranding	Possible	Avoidable with good design & management

The causes of injury that are listed in Table 3 as possible or likely to occur at Six Mile Creek Dam are expanded upon below:

Abrasion against spillway

Potential exists for fauna passing over the spillway to strike the spillway crest and vertical surfaces of the wall during low overtopping flows. As shown in Figure 2 there are numerous spillway crest designs available. Investigations into whether the proposed spillway crest shape is the most suitable for minimising the potential for abrasion injury should be considered.

Reducing impact injury

No data could be found that provides guidance for the optimum water depth for a stilling basin relative to spillway height. However, State code 18: Constructing or raising waterway barrier works in fish habitats issued by Department of Infrastructure, Local Government and Planning (DILGP) indicates that a stilling basin depth of 30% of drop may be acceptable. The split-level stilling basin arrangement proposed for the upgraded Lake Macdonald spillway makes a 30% depth an achievable and likely to be suitable for the site.

To achieve a plunge pool depth of 30% from the spillway level of RL 95.32 m to RL 89.5 m the stilling basin nib wall must extend to at least RL 91.3 m. The next stilling pool has a floor set at RL 86.0 m; the nib wall must extend to at least RL 87.6 m. The drawings indicate that the commence to flow tailwater level is approximately RL 85.4 m and the stream bed is approximately RL 84.0 m. In order to achieve a pool depth of 30% the tailwater level at commence to overtop for the dam must be a minimum of RL 85.1 m. Table 4 below provides the level details summarised for consideration in further design development.

The concept designs provided by AECOM indicate that the stilling basin has a flat floor in the centre with sides that slope upwards across the pool width. There is potential for fish that pass over the spillway to strike the shallower sloping surfaces. All areas downstream of the low flow spillway must have a depth in the stilling basin that are equal to or deeper than that specified in Table 4.

Table 4. Levels used to calculate the nib wall heights to achieve a plunge pool 30% of the spillway height.

Spillway level (RL in m)	Still basin floor level (RL in m)	Differential (m)	Height for 30% depth (RL in m)
95.32	89.5	5.82	91.3
91.3	86.0	5.3	87.6
87.6	84.0	3.6	85.1

The stilling basin nib walls have the potential to cause injury to fish that strike them during overtopping flows; particularly at locations where the spillway is close to the nib wall as shown in Figure 4. Modelling of the flow patterns in both of the stilling basins using a technique such as 3D Computational Fluid Dynamics (3D CFD) will provide details to inform an improved wall arrangement.

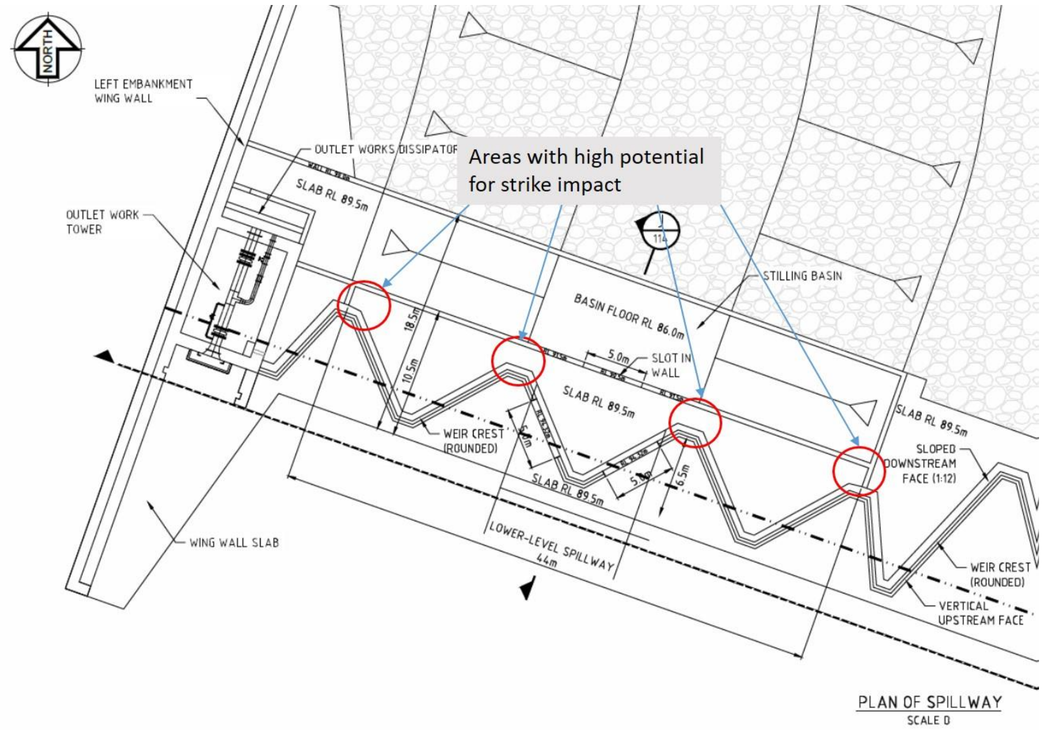

Figure 4. Low flow section of labyrinth spillway showing areas with high potential for strike (from AECOM Drawing 60451967 - 113).

Turbulence and shearing forces in tailwater

No data could be found that provides guidance for the maximum level of turbulence in a stilling basin that would prevent injury to fish. The pool volume in the first stilling basin is reduced by the cycles of the trapezoid. The turbulence levels in the stilling basin may be excessive particularly during high overtopping flows. Modelling of the turbulence levels in both of the stilling basins using 3D CFD may provide details on the level of turbulence that will occur and inform an improved design volume or arrangement for the stilling basins. Options to reduce turbulence will also reduce likelihood of injury due to shear forces.

Predation above and below spillways

The most effective way to minimise predation at waterway barriers is to maximise fish passage efficiency under all conditions both in an upstream and downstream direction. The labyrinth design will release high volumes of flow with low depth over the spillway; ongoing design should seek to facilitate downstream passage via a dedicated sluice or fishway.

Reduced water quality below spillways

The concept designs for the dam upgrade provided by AECOM indicates that the intake for downstream environmental releases from the dam will incorporate selectable baulks. Active management of the baulks in order to always ensure that surface quality water is being released downstream is paramount in maintaining suitable water quality.

Dewatering and stranding of fish within and below spillways

The arrangement of the stilling basins shown in the concept designs for the dam upgrade provided by AECOM may have the potential to trap fish that have passed over the spillway after flows have ceased. However, at this early stage it is difficult to identify potential issues with dewatering and stranding of fish. Further design of the stilling basin should consider means to ensure that the stilling pools are free draining and that fish and turtles are able to safely exit as the water levels fall.

Other potential impacts

The outlet structure to be used to provide environmental water has the potential to cause fish and turtle injury or death. The primary focus of the proposed trash screen should be as a primary screen prevent damage caused by large floating debris. A secondary screen sufficient to prevent intake of fish as small as 20 mm in length is necessary. Entrainment of fish and turtles can be prevented by providing a screen with sufficiently large surface area to ensure velocities at the screen are sufficiently low.

The level of the high flow spillway is set so that overtopping only occurs at flow approaching the 1:100 year AEP event. Under this flow condition, the tailwater level is predicted to be at approximately RL 91.1 m. The potential for fish or turtles to strike objects downstream that may cause injury should be assessed during further development of the design for the upgraded dam.

9. Conclusion

The concept designs developed for the Six Mile Creek Dam upgrade have already considered some of the potential issues with safe downstream passage of aquatic fauna. Further development of the design requires close attention to ensure that:

- the spillway crest shape is the most suitable profile;
- the stilling basin depth is increased to provide sufficient plunge pool depth;
- turbulence in the stilling basin is minimised during all flows;
- sources of direct strike impact for fauna are minimised;
- the potential for predation is minimised by reducing fish aggregations;
- only surface quality water is release from the dam outlet;
- the potential for dewatering and stranding of fauna when flows cease is minimised;
- the potential for entrainment of fauna within the intake structure is minimised.

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Addendum to Potential impacts of downstream passage of fauna over a labyrinth spillway at Lake Macdonald Six Mile Creek

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for Seqwater

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Background

Seqwater is undertaking a Dam Safety Upgrade for Lake Macdonald to bring the structure into compliance with current industry guidelines and the requirements of the Water Supply (Safety and Reliability) Act 2008. The upgrade will preserve the storage at its current capacity and height but the spillway configuration will be changed to a labyrinth design. Aquatic Biopassage Services has been retained by Seqwater to provide technical input on the spillway design with respect to downstream passage of aquatic fauna.

A literature review by Berghuis (2017) failed to identify any labyrinth type spillway designs that specifically addressed safe downstream passage for aquatic fauna. The original labyrinth design for Six Mile Creek Dam incorporated a vertical drop to a mid-level stilling basin that then dropped into another pool and into the tailwater.

Early concept designs developed for the spillway upgrade had already considered some of the potential issues with safe downstream passage of aquatic fauna. Aspects identified for further development of the most suitable spillway profile shape for downstream passage in Berghuis (2017) are:

- the spillway crest shape is the most suitable profile;
- the stilling basin depth is increased to provide sufficient plunge pool depth;
- turbulence in the stilling basin is minimised during all flows;
- sources of abrasion and direct strike impact for fauna are minimised;
- the potential for dewatering and stranding of fauna when flows cease is minimised.

Spillway Development

Seqwater has been working with AECOM and Aquatic Biopassage Services to develop solutions to minimise fauna injury in the spillway and stilling basin design. The initial concept design for the labyrinth spillway is shown in Figure 1.

Crest Shape

The crest shape selected for the proposed labyrinth spillway was a quarter round shape, which results in a rounded upstream crest and aeration behind the spilling flows to allow a free fall plunge. For fish passage, this arrangement leads to a smooth, rounded approach surface to the spillway crest as well as minimisation or avoidance of an abrasion source downstream of the crest on the vertical drop as is shown in Figure 2. However it should be noted that in low spillway overtopping flows, aeration may be ineffective in separating the spilling flow from the downstream vertical face of the spillway.

The design for downstream plunge pool walls is for rounded upstream crests to minimise sharp upstream edges, this is not shown in the early concept designs in Figure 1 and 2.

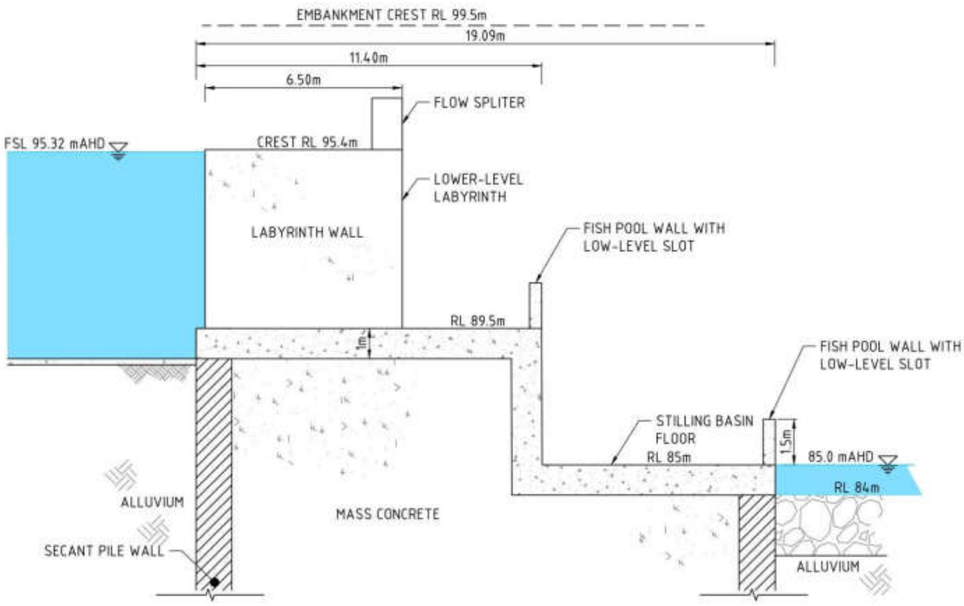

Figure 1. Six Mile Creek Dam –Concept design of the original layout of the labyrinth spillway. (Provided by AECOM)

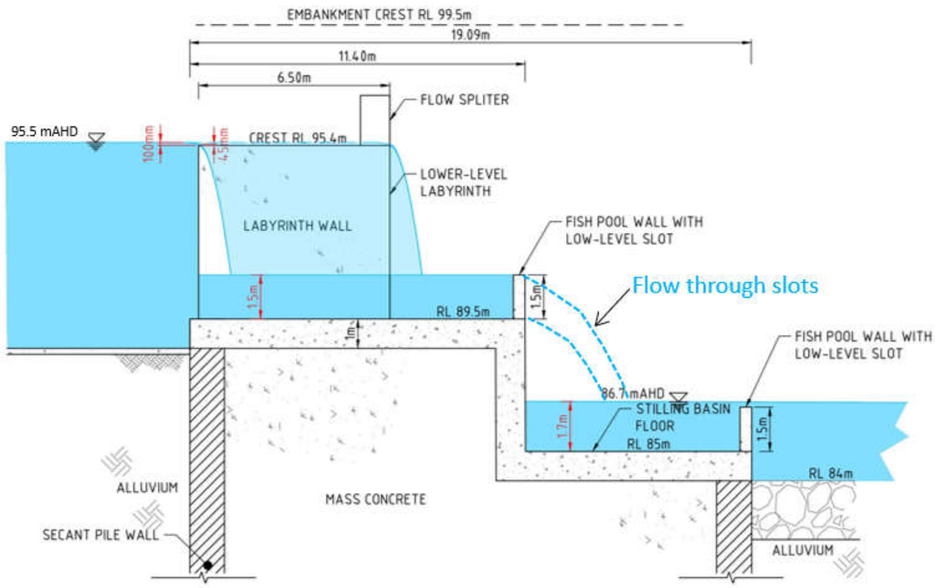

Figure 2. Conceptual water profiles for the original layout of the labyrinth spillway crest and plunge pools. (Provided by AECOM)

Spillway Modelling

Computational Fluid Dynamic (CFD) modelling of spillway flow conditions at various rates of overtopping has been performed by AECOM in association with design development. CFD modelling was used to simulate flows through the labyrinth spillway and gave visual outputs to assess the efficacy of the spillway plunge pools, turbulence and likelihood of direct strikes.

For reference, Figure 3 shows a 3D sketch of the concept design labyrinth spillway used as a starting point for spillway modelling.

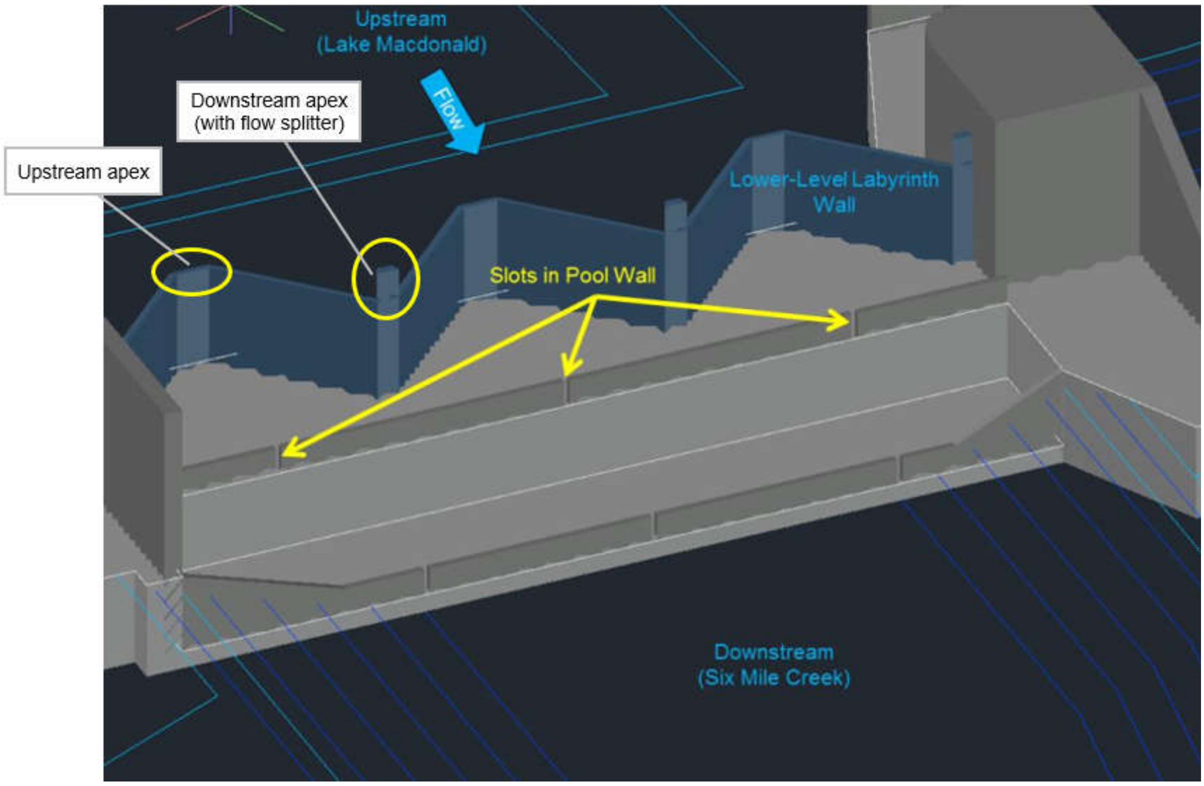

Figure 3. 3D sketch of concept design labyrinth spillway an plunge pools (Configuration 1)
(Provided by AECOM)

Modelling tests were run as an iterative process and led to a number of configurations being run, which were numbered as 1, 2, 4, 5 & 6. For each configuration, various reservoir heads (spillway overtopping flows) were modelled to understand performance changes with flow. Configuration 1 was the starting point concept design (Figure 1 and Figure 3). For intermediate configurations, a reference reservoir head of 600 mm was used to speed up the development of modelling results.

The following comments are provided regarding the modelling tests for each configuration:

Configuration 1: Original layout (upper pool depth = 1.5m; lower pool depth = 1.5m):

- The 100 mm spillway overtopping flow had the potential for vertical flow from the spillway to cause abrasion for fish passing along the spillway wall.
- At overtopping flows of 300 mm and 600 mm, flows at the upstream apex of each labyrinth trapezoid cycle fall vertically against the spillway wall, with potential for abrasion.
- At overtopping flows of 300 mm and 600 mm high velocity areas where the flow jet hits the stilling basin floor and dissipator wall may have caused strike injury.
- At the 600 mm overtopping depth, flow patterns within the stilling basin indicated a highly turbulent condition that may have injured and disoriented fish.

Configuration 2: Increased upper pool wall height (to 2m), lowered second floor (RL 84m), sloped pool walls (upper pool depth = 2.0m; lower pool depth = 1.5m).

The modelling results for 600 mm overtopping flow indicated:

- Modification to the stilling basin wall reduced the potential impact of the plunging flow where the spillway is at an acute angle to the flow.
- In areas where the water column descended vertically, there was high velocity and most likely highly turbulent flow in the stilling basin at the base of the spillway.

Configuration 4: Further increased upper pool depth (to 2.5m), lowered top floor (by 1m), extended bottom floor downstream (by 3m) (upper pool depth = 2.5m; lower pool depth = 1.5m)

Tested at 600 mm overtopping flow only:

- A deeper upper pool reduced turbulence but continued to represent issues with striking on spillway pool walls.

Configuration 5: Sensitivity configuration to check outcomes of no intermediate pool – i.e. single drop from labyrinth spillway into a deep pool, with a tall downstream end sill and free draining to creek (single pool depth = 4.5m).

The modelling results for 600 mm overtopping flow indicated:

- A higher fall between spillway crest to plunge pool surface, but with a deeper plunge pool and fewer hard surface locations for fish strike.
- Velocities in tailwater pool are generally lower apart from in localised areas along the basin floor at higher overtopping flows.
- Clear reduction in flow velocities as water enters the dissipator pool.
- Flow jet continues to have high velocities in upstream apex of the spillway cycle.
- Eliminates the risk for fish stranding by providing a floor level similar to the creek bed level and maintains connectivity with the creek in no flow.

Configuration 6: Sensitivity configuration to check outcomes of more pools with lower fall heights – multiple small drops into pools (five pools, all with pool depth = 1.5 m).

The modelling results for 600 mm overtopping flow indicated:

- Configuration was ruled out due to minimal benefit on the jet impinging on floors.
- Multiple drops increased potential for strike on end sill walls and added complexity with drainage and fish stranding risk.

Final Configuration for development

Configuration 5, with a single pool arrangement, has been selected as the final plunge pool design to move forward to detailed design. A cross section of this configuration is provided in Figure 4. The CFD modelling produced by AECOM for the latest iteration of the Configuration 5 plunge pool design indicates favourable conditions for flow over the acute angle sections of the spillway. Issues with high velocity and potential for abrasion are eliminated for the lower range of flows and reduced to acceptable levels for higher flows up to 1.5m (1:30 AEP) spillway overtopping events. The outputs for flow scenarios with overtopping rates from 0.3m to 1.5m are provided in Appendix A (Figures 1-4).

Flows over the upstream apex section continue to present potential issues with spillway abrasion at the 300 mm overtopping flow and potential for injury during flows of 1.0m overtopping and above. The issue does not appear to be related to the plunge pool design but rather to an effect known as nappe interference, which is described in Falvey (2003) as an effect caused by the flow over the acute angle crest influencing the flow from the upstream apex section of the crest. Further development of the plunge pool arrangement is unlikely to improve the impact of nappe interference downstream of the crest, within the range of flows where it may be an issue for fish.

Further development of the Configuration 5 design has retained the single drop with the floor set at RL 84.0 m AHD (approximate creek bed level) and a lower sloped nib wall at the downstream end. The single drop configuration will lead to a higher vertical fall compared to the double plunge pool configurations. The maximum fall is estimated to be 10.32 m into a 1.0 m deep pool at commence to flow.

The tailwater level in Six Mile Creek rises rapidly during flow and by the time a 100 mm overtopping flow occurs the fall scenario is lessened to a 7.92 m fall into a 3.4 m deep tailwater pool. Table 1 below provides the range of flows up to the 1:100 AEP with the predicted overtopping levels, plunge pool depth, fall height from headwater surface to tailwater surface and pool depth as a percentage of fall height. In all flow cases over 100 mm overtopping, the maximum fall height is greater than the 30% spillway drop to plunge pool ratio recommended as a starting point by Berghuis (2017). Furthermore, none of the fall heights exceed the predicted fish injury threshold of 13 m, as outlined in Ruggles and Murray (1983).

Total Outflow	Reservoir Head	Pool Depth	Fall Height (FSL to tailwater surface)	Pool Depth as a Percentage of Fall Height
m^3/s	mAHD	m	m	%
0	0.00	1.00	10.32	9.69
7	0.10	3.40	7.92	42.93
14	0.20	3.95	7.37	53.60
21	0.30	4.28	7.04	60.80
28	0.40	4.50	6.82	65.98
41	0.50	4.85	6.47	74.96
55	0.60	5.12	6.20	82.58
70	0.70	5.33	5.99	88.98
84	0.80	5.50	5.82	94.50
102	0.90	5.67	5.65	100.35
122*	1.00	5.83	5.49	106.19
141	1.10	5.96	5.36	111.19
161*	1.20	6.10	5.22	116.86
183	1.30	6.28	5.04	124.60
206*	1.40	6.47	4.85	133.40
230	1.50	6.62	4.70	140.85
254*	1.60	6.77	4.55	148.79
278	1.70	6.89	4.43	155.53
306*	1.80	7.03	4.29	163.87

Table 1. Range of flows up to 1:100 AEP with overtopping levels, plunge pool depth and fall height.
***** represents ~1:5 AEP, ~1:10 AEP, ~1:20 AEP, ~1:50 AEP and ~1:100 AEP events respectively (AECOM data).

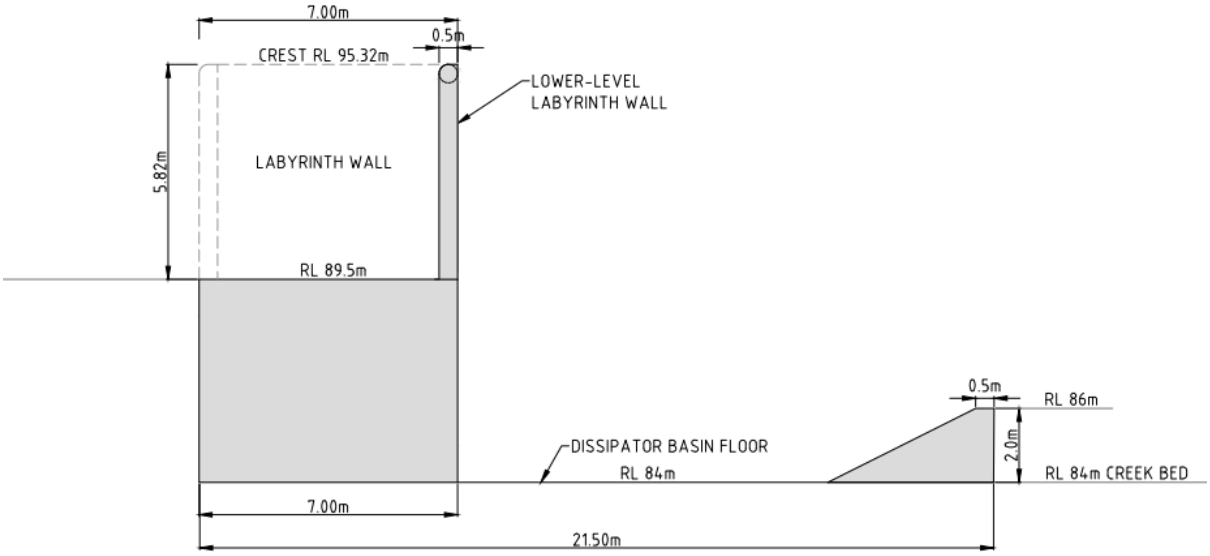

Figure 4. Cross-section of single pool labyrinth arrangement (Configuration 5)

Conclusion

The design process leading to the development of Configuration 5 has addressed the majority of the issues with the original spillway design that were identified in Berghuis (2017) and is supported as the most suitable to take forward to detailed design. The only matter that may continue to represent issues with fish injury or survival of fish occurs at the upstream apex sections of the spillway. The majority of each spillway cycle is set at an acute angle and upstream apex sections only represent a small proportion of the overall spillway. As demonstrated by the CFD model result in Appendix A Figure 5 the impact in the stilling basin is localised. Despite this fact there is potential for fish to be injured as they pass over the upstream apex sections of the spillway cycle and in a creek system that includes large Mary River cod and Queensland lungfish it is imperative that injury be minimised.

A physical model of the spillway incorporating the Configuration 5 plunge pool design is currently being developed at the University of NSW hydraulics laboratory and tests will be performed in early February 2019. It is recommended that the physical model be utilised to develop final solutions to the nappe interference issue at the upstream apex and to continue to develop the design to minimise spillway injuries to the greatest extent possible.

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Appendix A CFD Model Runs for Configuration 5

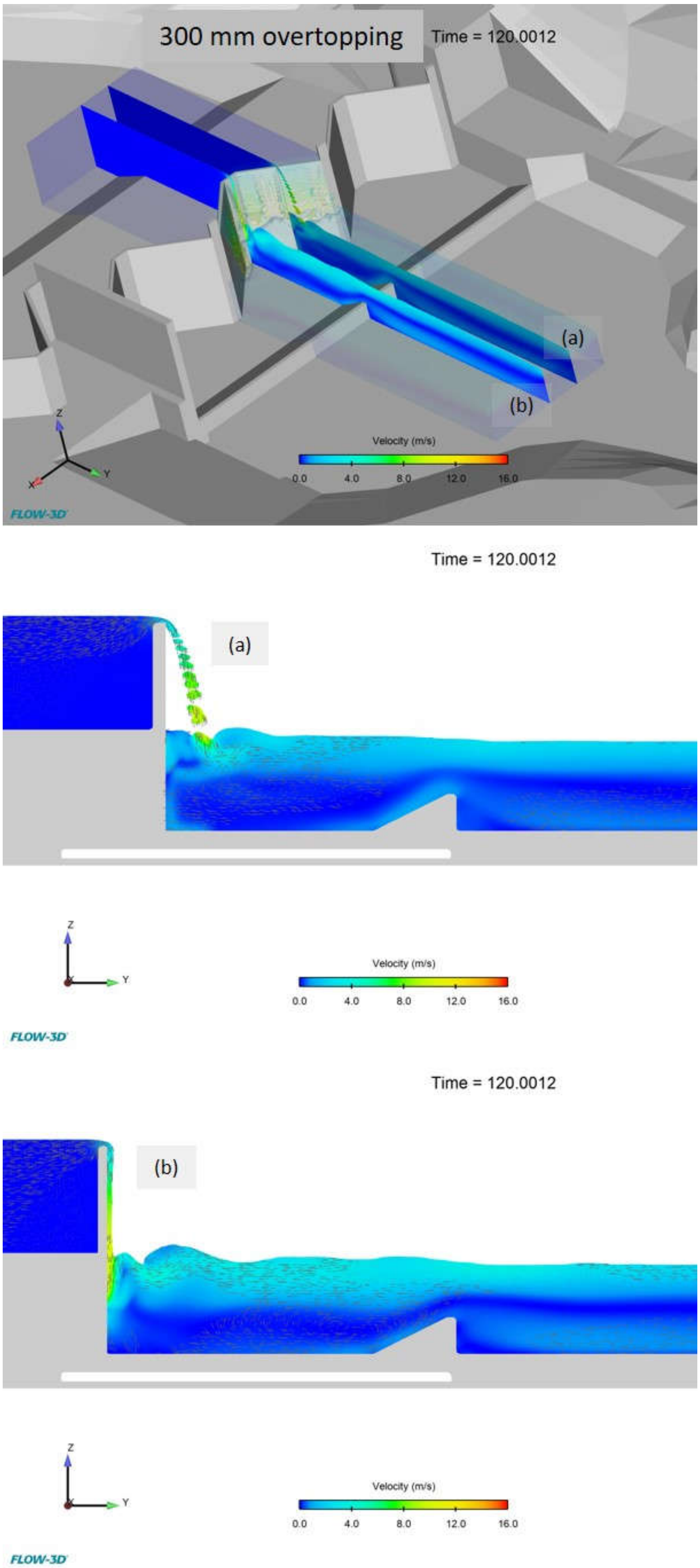

Figure 1. 300mm overtopping CFD model run slices through spillway section at an acute angle (a) and upstream apex section (b).

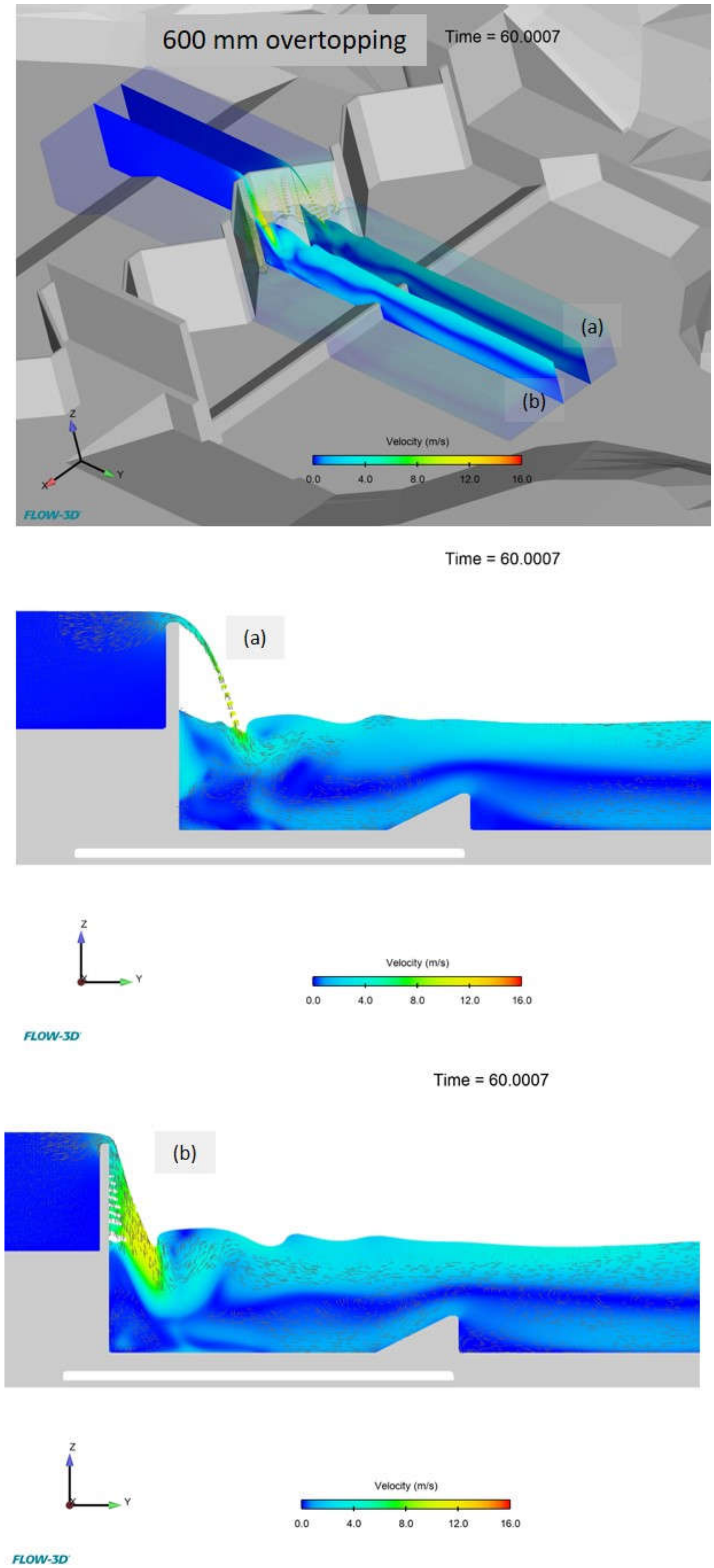

Figure 2. 600mm overtopping CFD model run slices through spillway section at an acute angle (a) and upstream apex section (b).

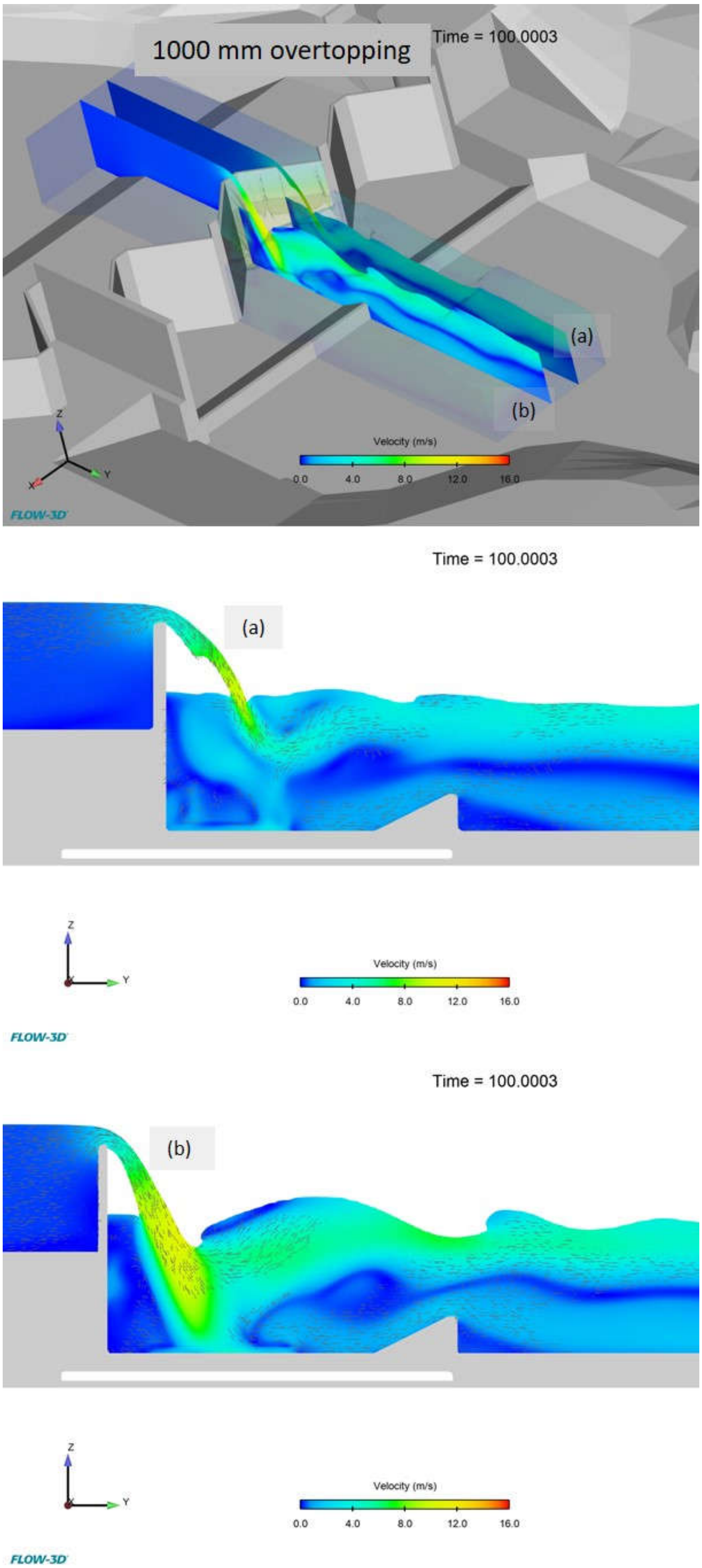

Figure 3. 1000mm overtopping CFD model run slices through spillway section at an acute angle (a) and upstream apex section (b).

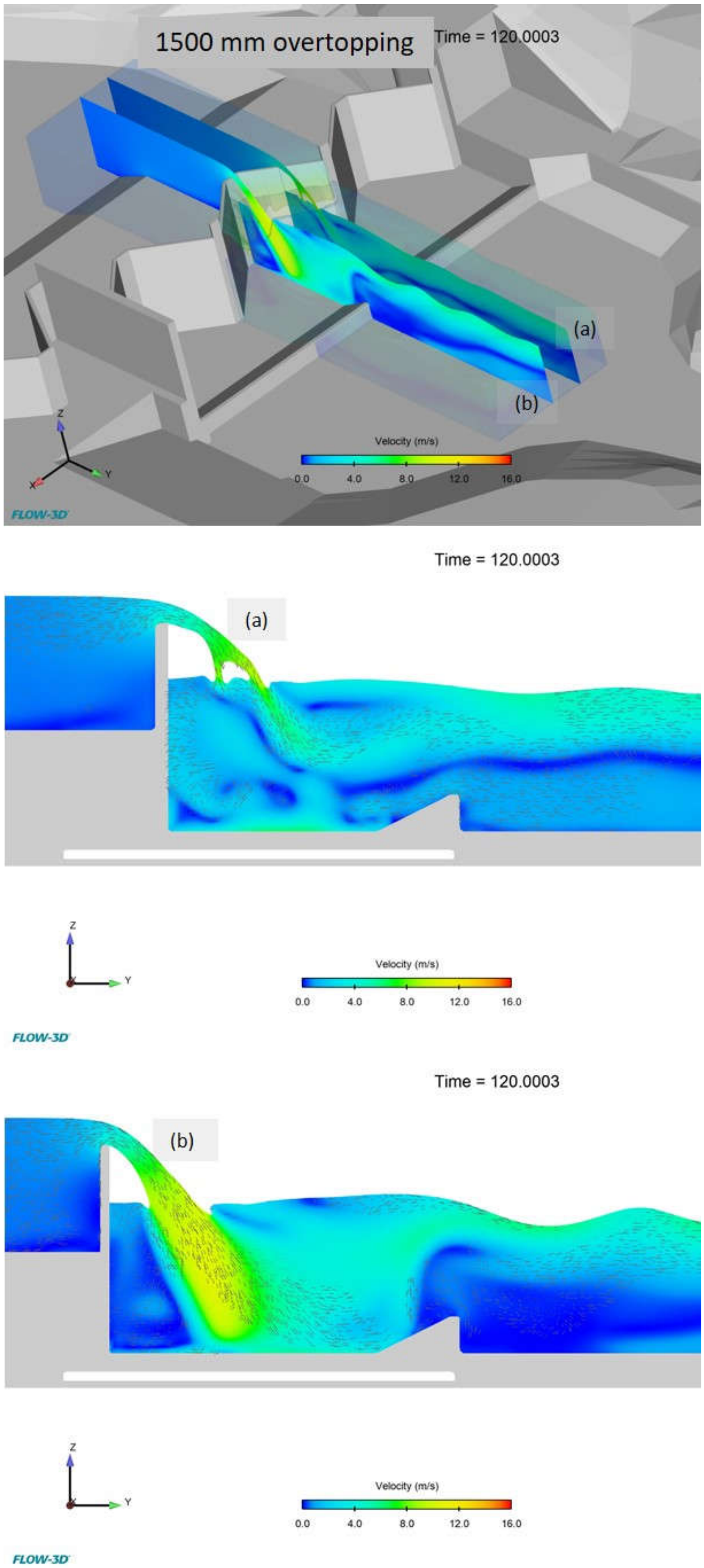

Figure 4. 1500mm overtopping CFD model run slices through spillway section at an acute angle (a) and upstream apex section (b).

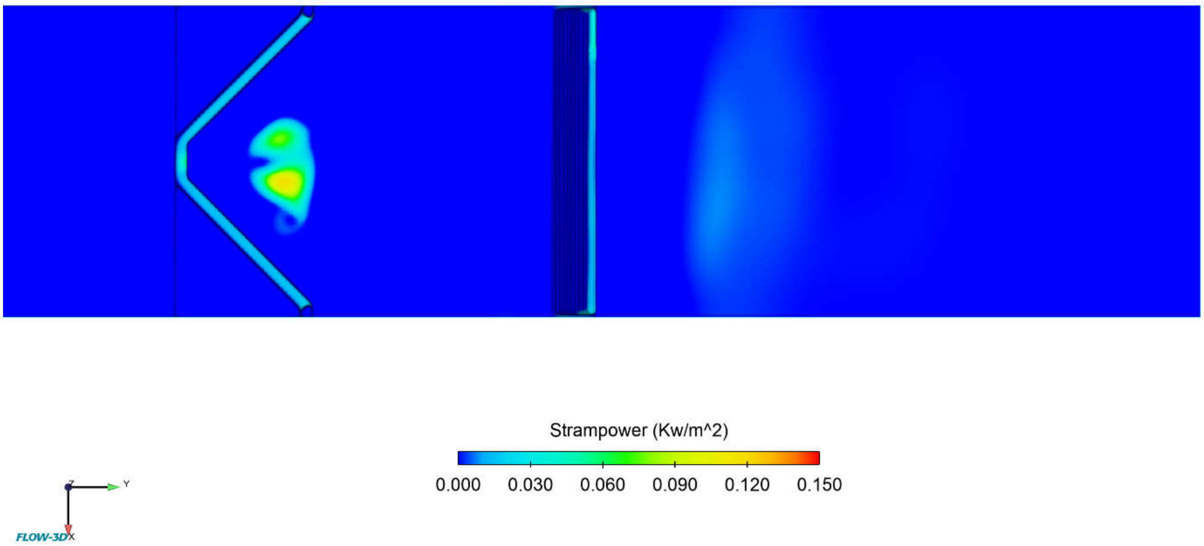

Figure 5. Plan view of CFD model run at 600 mm overtopping flow; showing impact on stilling basin floor caused by flows over the upstream apex section of spillway.