Copeton Dam: Performance of the Great Scour Case Study in the floods of 2022

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Erosion of the spillway at Copeton Dam in the 1970's captured worldwide attention. Much was published about the unexpected erosion, although studies considered only geological factors. Some remedial works were implemented, but erosion remained a critical concern. This paper provides an overview of historical scour issues including recent studies which considered hydraulic analysis and scour modelling.

In 2022, Copeton Dam Service Spillway experienced its flood of record, having not spilled for 40 years. An overview of the 2022 spill event is presented, leveraging modern surveying techniques to examine erosion, which allowed review of previous predictions and estimation of scour rate. Conceptual designs for scour protection measures for the Service Spillway are presented.

Keywords: *Spillway, scour, erosion, headcutting.*

Introduction

The extensive and unexpected erosion of granite in the unlined spillway of Copeton Dam in the 1970's captured the attention of the engineering world. Existing explanations for this erosion focus on the geological aspects of erodibility. In 2021 and 2022, the Service Spillway experienced spills, including the flood of record, some 40 years since its previous spill. This paper presents an overview of the erosion experienced during these events and presents some revised explanations and risk assessments of scour based upon hydraulic analyses which have previously remained unpublished.

Overview of Copeton Dam Spillway

Construction of Copeton Dam was completed in 1973 and included a spillway excavated through a ridge 600 m west of the main embankment. The 158m wide spillway channel released flows onto a steep natural hillside to return to the Gwydir River (Figure 1). A control structure for the spillway includes 9 by 14.63m wide bays into which radial gates were installed in 1976. The spillway experienced its first flows in 1976 during first filling (Figure 2) which resulted in extensive erosion of the granitic rock mass, including carving a defined slot at the location of the existing natural gully. In response to this unexpected erosion, a dividing wall was added in 1977 to demarcate a Service Spillway (Gates 6 to 9) and a Secondary Spillway (Gates 1 to 5) (Figure 3), the rationale being to operate the Service Spillway preferentially as the rock mass in this region was considered to offer better resistance to erosion. Concrete repairs were also done, including concrete works just below the apron of the Service Spillway (known colloquially as 'the swimming pool').

The spillway at Copeton Dam has historically not spilled often. Reservoir levels since 1976 are presented in Figure 4 with annotations showing flow events and when topographic surveys were undertaken.

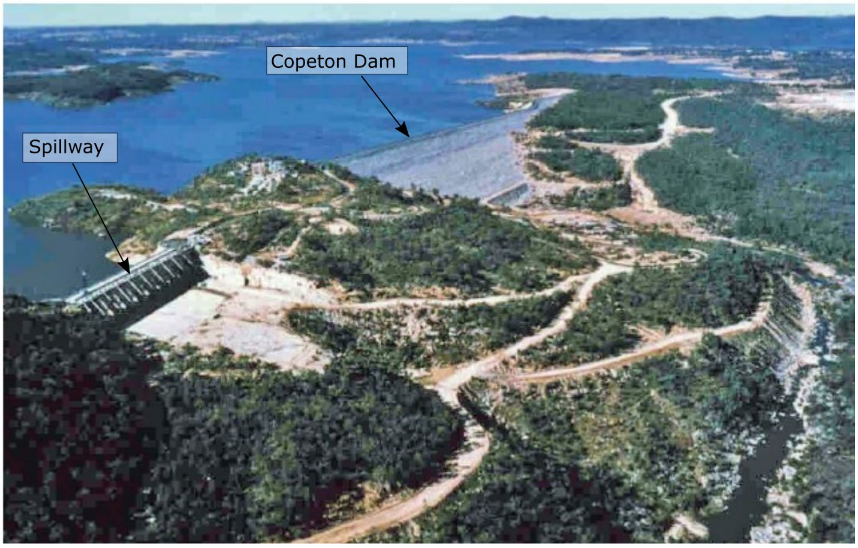

Figure 1 – Overview of Copeton Dam and Spillway after construction, c.1973

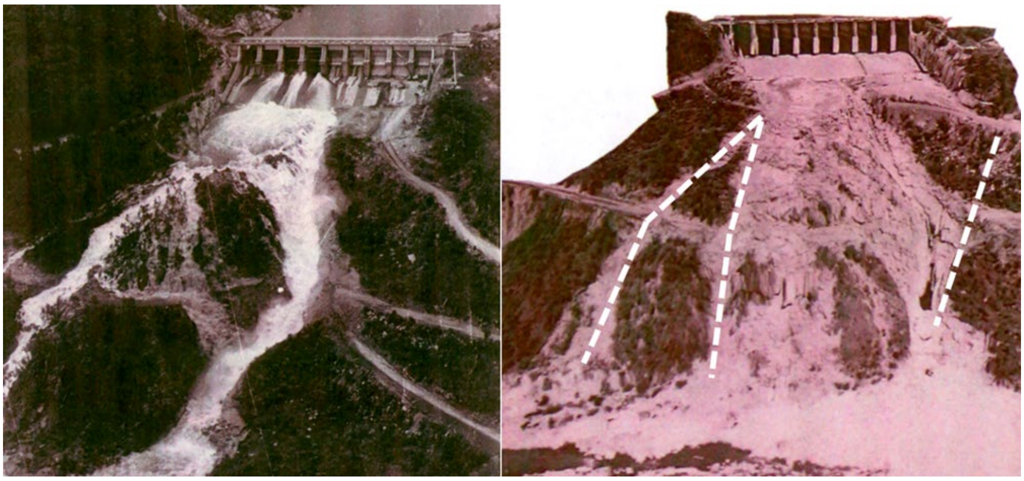

Figure 2 – Photographs of the spillway during and after the 1976 flood events. Weathered overburden was widely removed (right), and water falling into the natural gully (left) caused extensive erosion and formation of a deep slot. Some of the erosion has been interpreted to follow shear zones (right - white dashed lines)

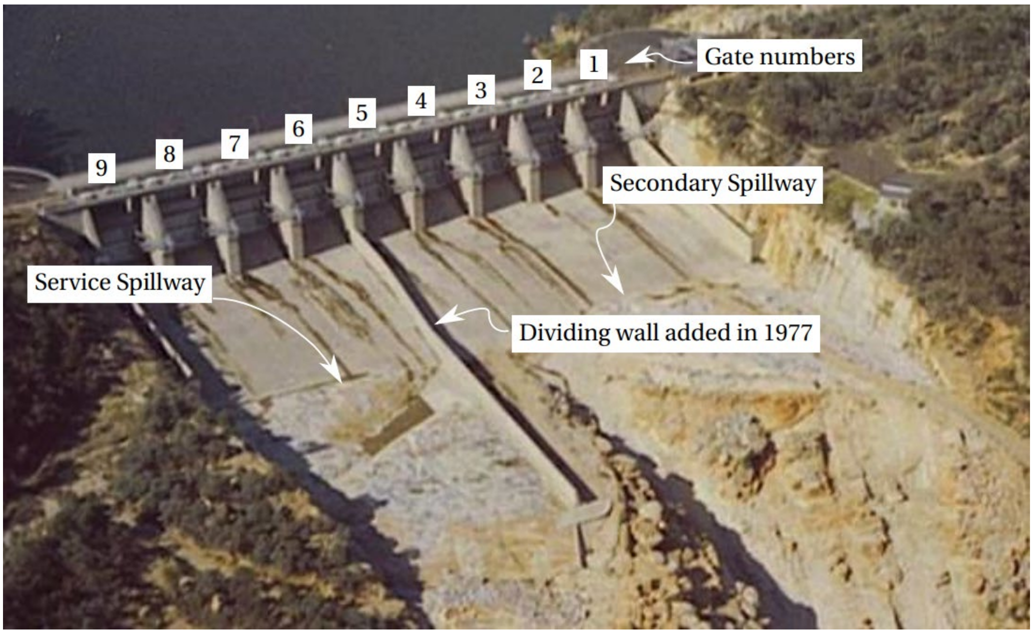

Figure 3 – Division of the spillway into Service and Secondary. Erosion was primarily in the (now) secondary spillway. Note repair work ('swimming pool') at the end of the slab in the Service Spillway.

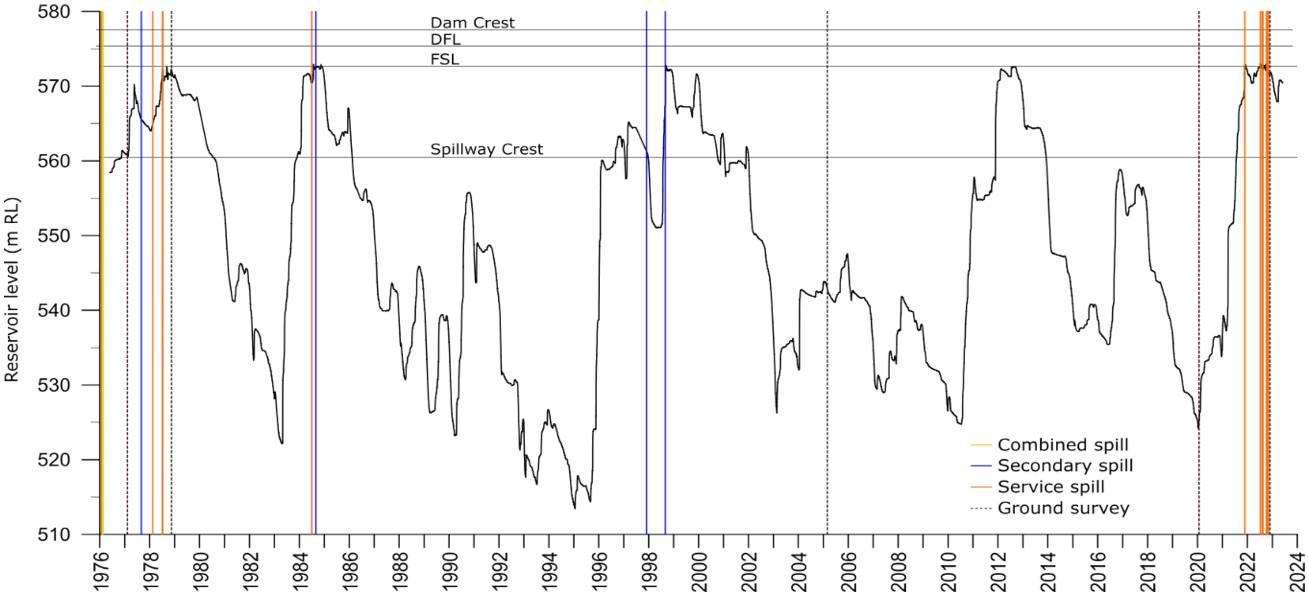

Figure 4 – Timeseries of reservoir levels at Copeton Dam showing times of spills and ground surveys

Historical Examinations of Scour

The erosion risks at Copeton Dam have attracted many technical studies since 1976. Earlier studies focussed exclusively on the geological facets of erodibility, noting regular subvertical joints and persistent horizontal sheet joints that arise from very high *in-situ* stresses over the entire spillway domain. The resulting large blocks of rock can be mobilised from hydraulic forces which penetrate the vertical defects and can slide and roll the blocks along the sheet joints. Examination of the large gully below the secondary spillway noted that *in-situ* stresses of 10 to 50 MPa (and larger) within the bed of the gully are of similar magnitude to the UCS of the rock mass, exacerbating closer sheet joint formation within the gully and associated smaller block sizes which may be more easily mobilised (Figure 5).

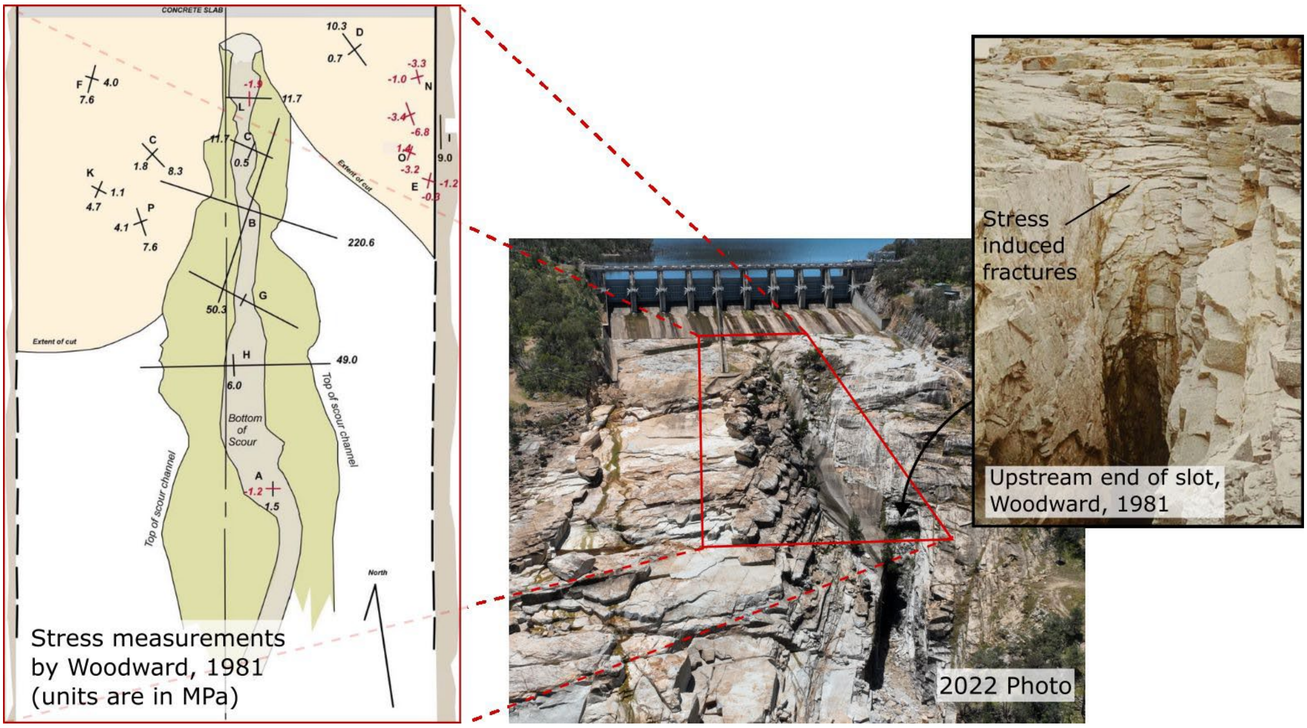

Figure 5 – Geomechanical mechanisms related to high insitu stresses have been interpreted to exacerbate scour

Studies by Pells (2016) and PSM (2021) considered both hydraulic and geological facets of scour for both the Service and Secondary spillways and included hydrodynamic modelling of historical and design flows (Figure 6). PSM (2021) presented four predictive scenarios based on selected moments in the 1000 AEP design event as shown in Figure 7. Also shown are the recorded levels and releases during the October 2022 event (discussed below). Prediction of scour risk made in 2021 using the Pells (2016) method are reproduced in Figure 8, showing Scenario 4. It is seen that concentration of flow into the gully resulted in extremely high specific discharge, which must also be seen as a mechanism behind observed scour.

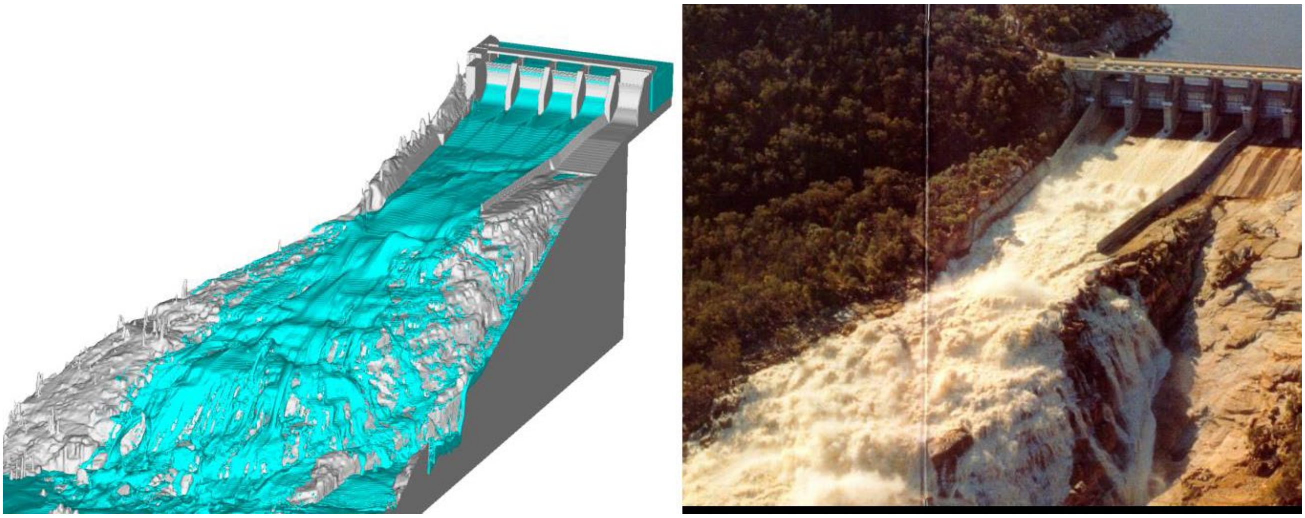

Figure 6 – Examples of hydraulic analyses from PSM 2021

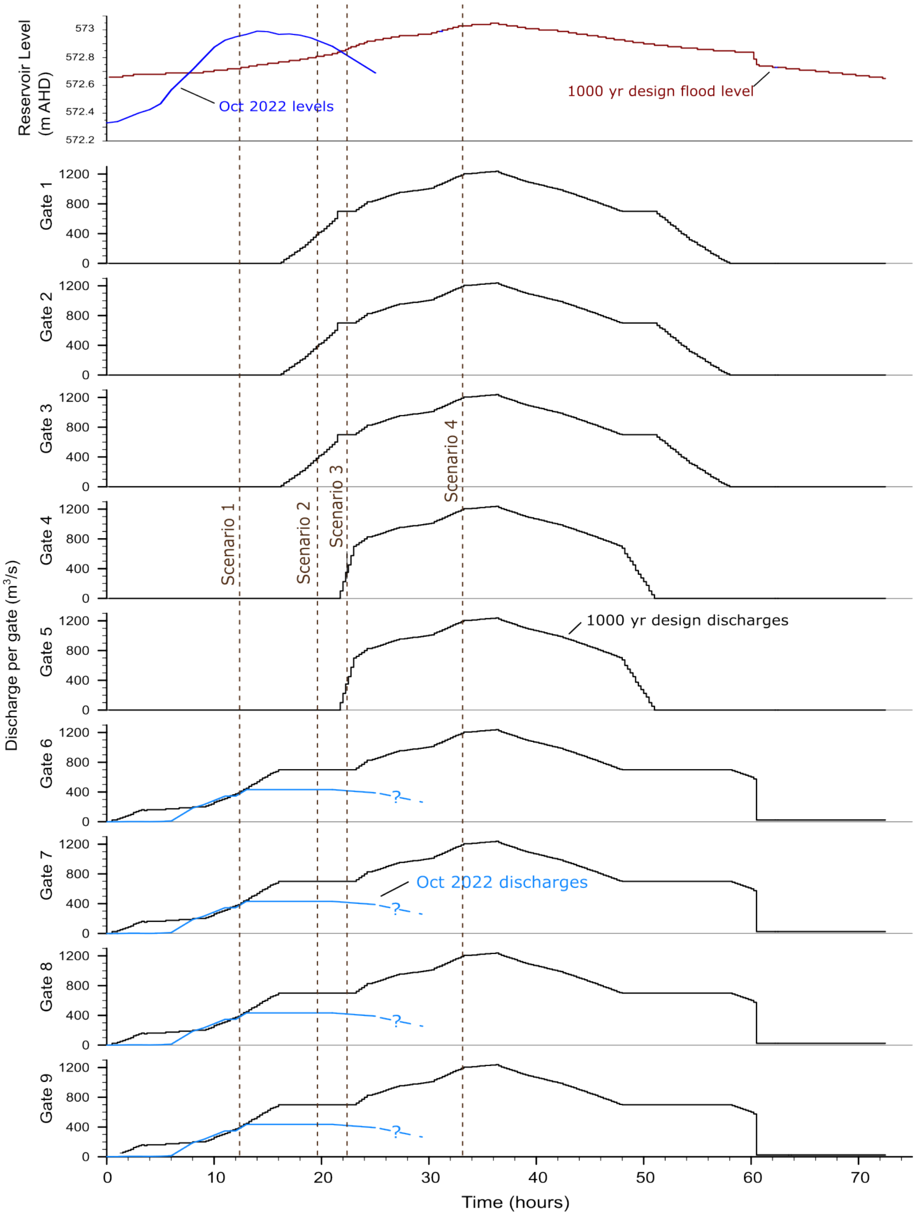

Figure 7 – 1000 AEP Design Event showing Scenarios 1 to 4 used to predict scour (2021), and October 2022 flows

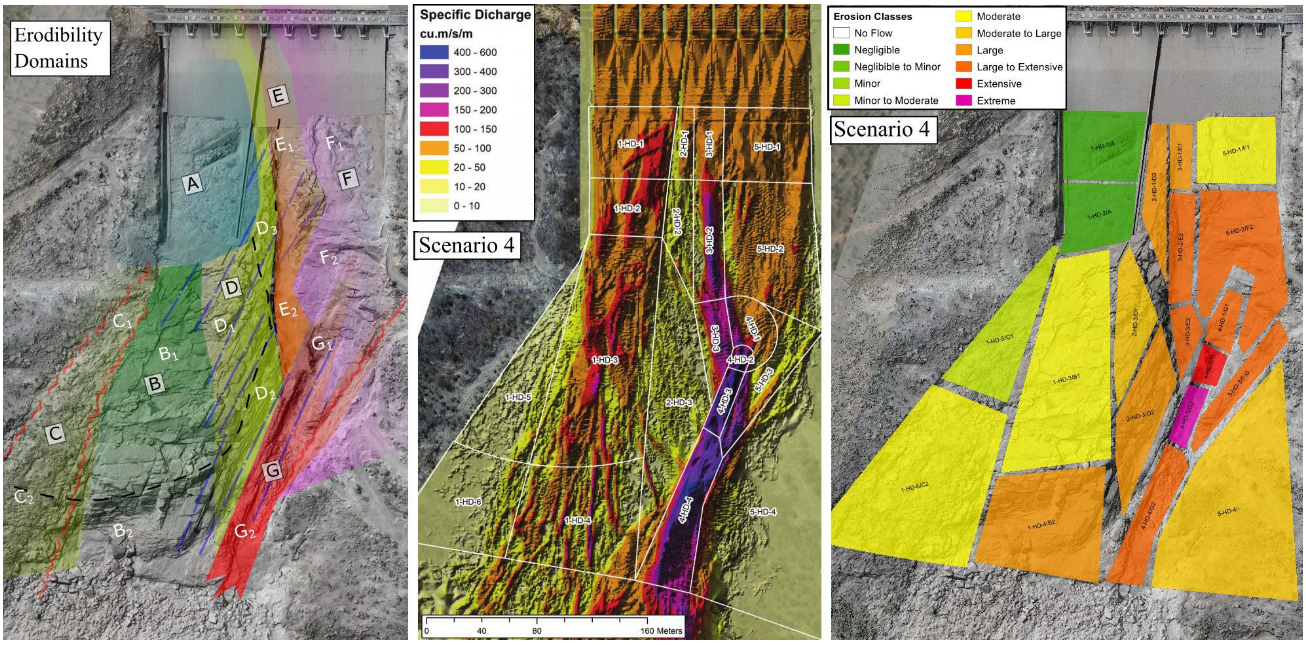

Figure 8 – Examples of scour predictions made in 2021 using the Pells (2016) method

Flood events of 2022

Spills and observed hydraulics

Selected operational records from 2022 were digitised to prepare the timeseries of the flow releases shown in Figure 9. In addition to a small spill in November 2011 (not shown), the records indicate 6 separate flood releases in July, August, September, October (two events) and November 2022. In total, there is approximately 300 hours of flow, with the latter event in 21/22 October peaking at approximately 1700 m^3/s (documented in operational records as 150 GL / day), which at the time of writing is the flood of record. The peak flow was maintained for approximately 8 hours and represents around 30% of the Service Spillway design capacity (or 14% of the entire spillway capacity). The October 2022 flood hydrograph is shown superimposed on the 1000 AEP Copeton Dam spillway design flow hydrograph in Figure 7. Note that in 2022 only the Service Spillway was operated.

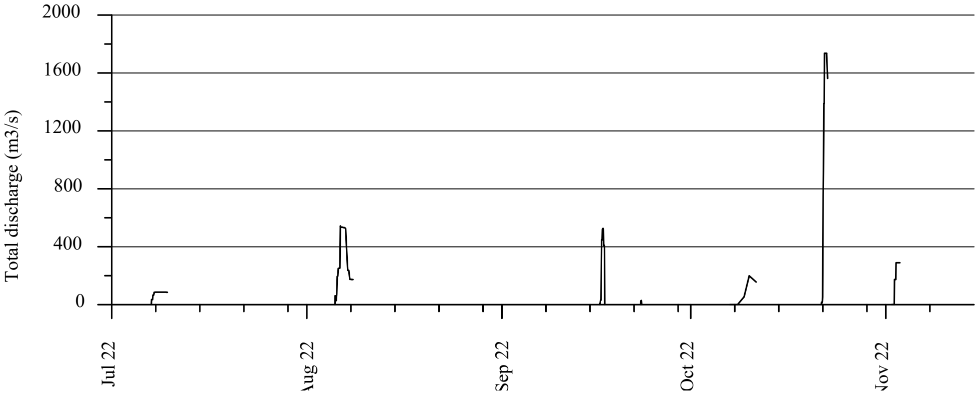

Figure 9 – Flow records from 2022 events, Service Spillway at Copeton Dam

Photographs taken by WaterNSW during the peak flow are shown in Figure 10 with annotations highlighting some observations. The guide wall that defines the left-hand side of the Service Spillway appears to nearly overtop under flows of 1700 m^3/s, and it therefore appears likely that it would be subject to significant overtopping from design flows, which are over 3 times greater. The orientation of the concrete works below the apron (the ‘swimming pool’) flip the flow upward and are evidently subject to very high energy. Lateral flows below the guide wall spill onto the Service Spillway. Under higher discharges, higher lateral flows would be expected. Whilst high energy supercritical flows are largely unable to turn a corner to follow an identified fault below the end of the right-hand wall, lateral spill is still likely to increase under higher flows.

Figure 10 – Photographs during peak flows in the October 2022 spill event

Observed Scour

Topographic surveys and aerial photographs were acquired using Unmanned Aerial Vehicles (UAV's) on 24 January 2020 and November 2022. The 2020 survey used photogrammetric techniques to resolve detailed topography, whereas the 2022 survey used Lidar techniques. Both surveys recovered detailed aerial photographs, and both were undertaken by HELImetrix (www.helimetrix.com.au). An oblique photo from each date presented in Figure 11 shows that large, loose blocks that were present in 2020 were swept away during the 2022 spills. An isopach map was calculated as the mathematical difference between 2020 and 2022 ground surface, which clearly highlights where erosion has occurred, as shown in Figure 12.

The rock mass within the excavated section of spillway (i.e., just below the apron) has previously been interpreted to be a Laumontite region of the granitic mass, and subvertical defects are less apparent, being either absent, less frequent, or more tightly welded. These characteristics create a mass of arguably higher erosion resistance. Numerous patches of dental concrete have been placed around this region, and erosion here comprised small locations of plucking out of isolated blocks.

Figure 11 – Oblique photos from Jan 2022 (top) and Nov 2022 (bottom)

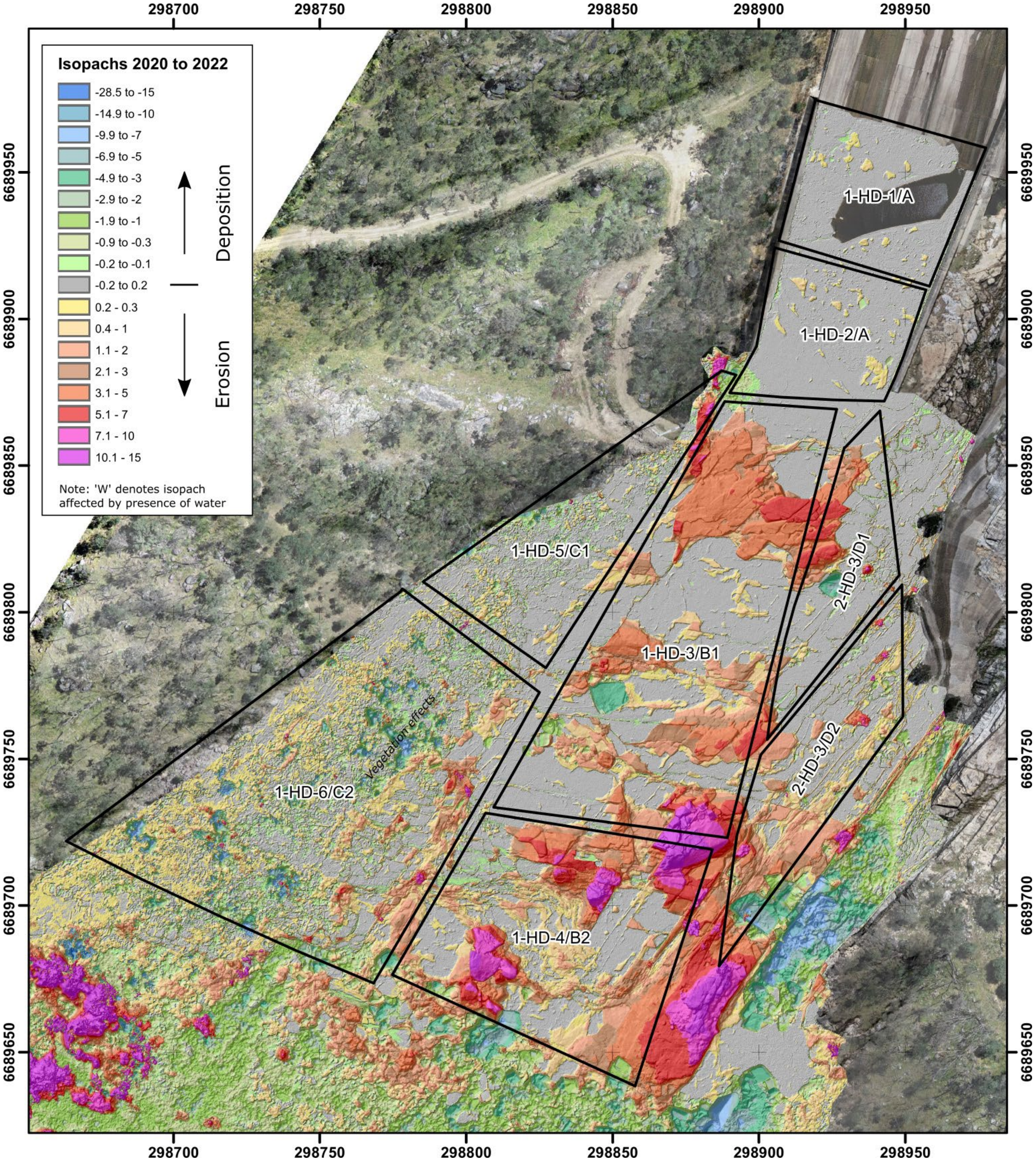

Figure 12 – Erosion isopachs, 2020 to 2022

Comparison to Predictions

Scour risks assessments made in PSM 2021 chose a discharge condition for Scenario 1 that happens to be representative of the October 2022 event – see Figure 7. This provided the opportunity to review the accuracy of the past assessment, conceding that observed erosion arises from a suite of events between November 2021 to November 2022 and not just from the October 2022 event. The 2021 analysis defined a series of 'scour domains', which are the polygons shown in Figure 12. A scour domain is a region that is interpreted to have common geological qualities and common hydraulic loading characteristics. For each scour domain, an 'erosion vulnerability class' was determined, based on geological and hydraulic analyses and application of the Pells 2016 method. Each of these classes are associated with erosion quantities, as presented in Table 1. For comparison, the measured erosion quantities from analysis of Figure 12 are also presented. The results are also presented graphically in Figure 13.

Table 1 - Predicted erosion in the Service Spillway from 'Scenario 1' versus observed erosion from 2022 floods

Scour domain	Prediction made in June 2021				2022 observations	
	Erosion class	Erosion descriptor	Maximum erosion depth (m)	General erosion extent (m^3 / $100m^2$)	Maximum erosion depth (m)	General erosion extent (m^3 / $100m^2$) 1.
1-HD-1/A	I	Negligible	<0.3	<10	0.5	2
1-HD-2/A	I	Negligible	<0.3	<10	0.5	2
1-HD-3/B1	III	Moderate	1 to 2	30 to 100	6	149
1-HD-4/B2	IV	Large	2 to 7	100 to 350	13	204
1-HD-5/C1	II / III	Minor to Moderate	0.5 to 1.5	20 to 70	1	17
1-HD-6/C2	III / IV	Moderate to Large	1.5 to 5	70 to 230	11	25
2-HD-3/D1	II / III	Minor to Moderate	0.5 to 1.5	20 to 70	6	77
2-HD-3/D2	III / IV	Moderate to Large	1.5 to 5	70 to 230	8	80

1. Calculated in GIS as the total volume eroded in a domain / surface area of domain, x 100

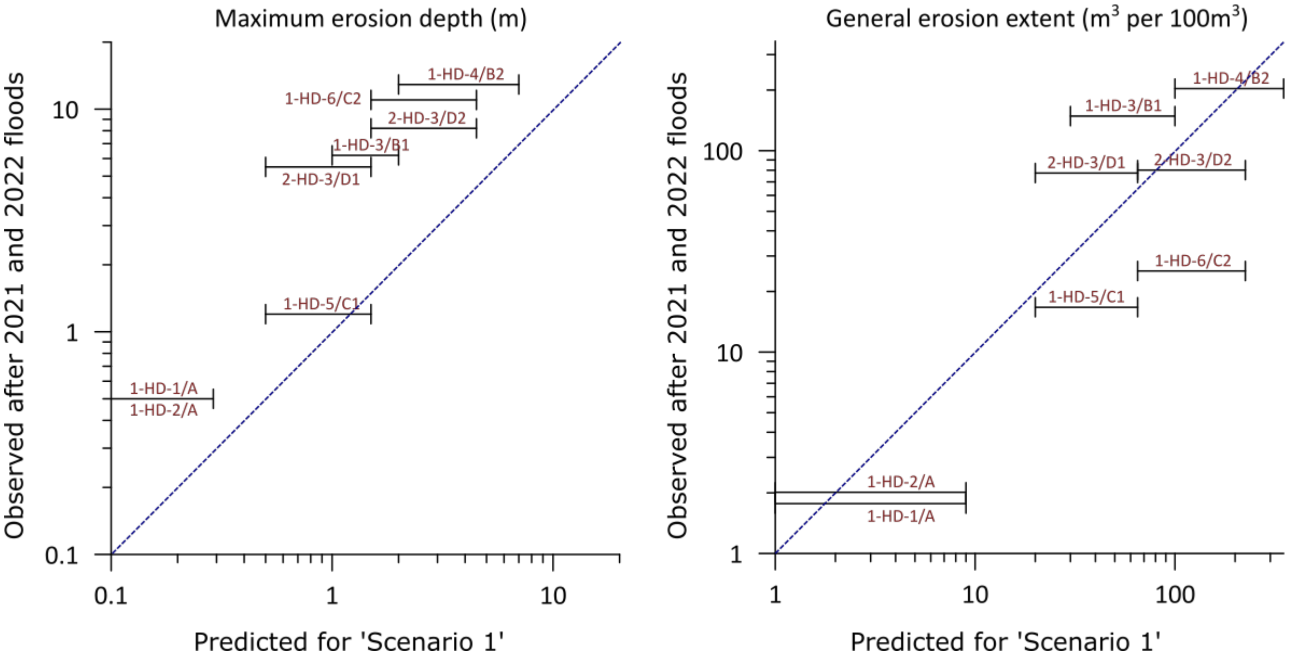

Figure 13 – Observed erosion from 2022 versus predicted erosion for 'Scenario 1'

Headcutting Rates

Erosion can often take the form of the upstream migration of a slope or 'knickpoint' (a step or a point of change in slope gradient). This upward migration, often referred to as 'headcutting' has been observed to take various forms. Ground surveys have been made of Copeton spillway in the past, as indicated in Figures 4 and 9. Cross-sections were prepared along multiple locations through the Service Spillway using ground survey data from 1966, 1977, 1978, 2020 and 2022. Examination of cross sections allowed interpretation the rate of upward migration of the rock slope below the Service Spillway between sequential surveys, for three types of interpreted 'types' of retreat, as defined in Figure 14. These broad estimates were made by hand, as per the example in Figure 15.

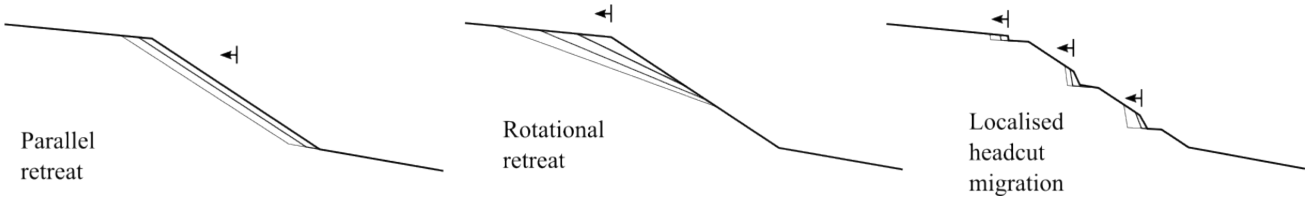

Figure 14 – Types of headcutting

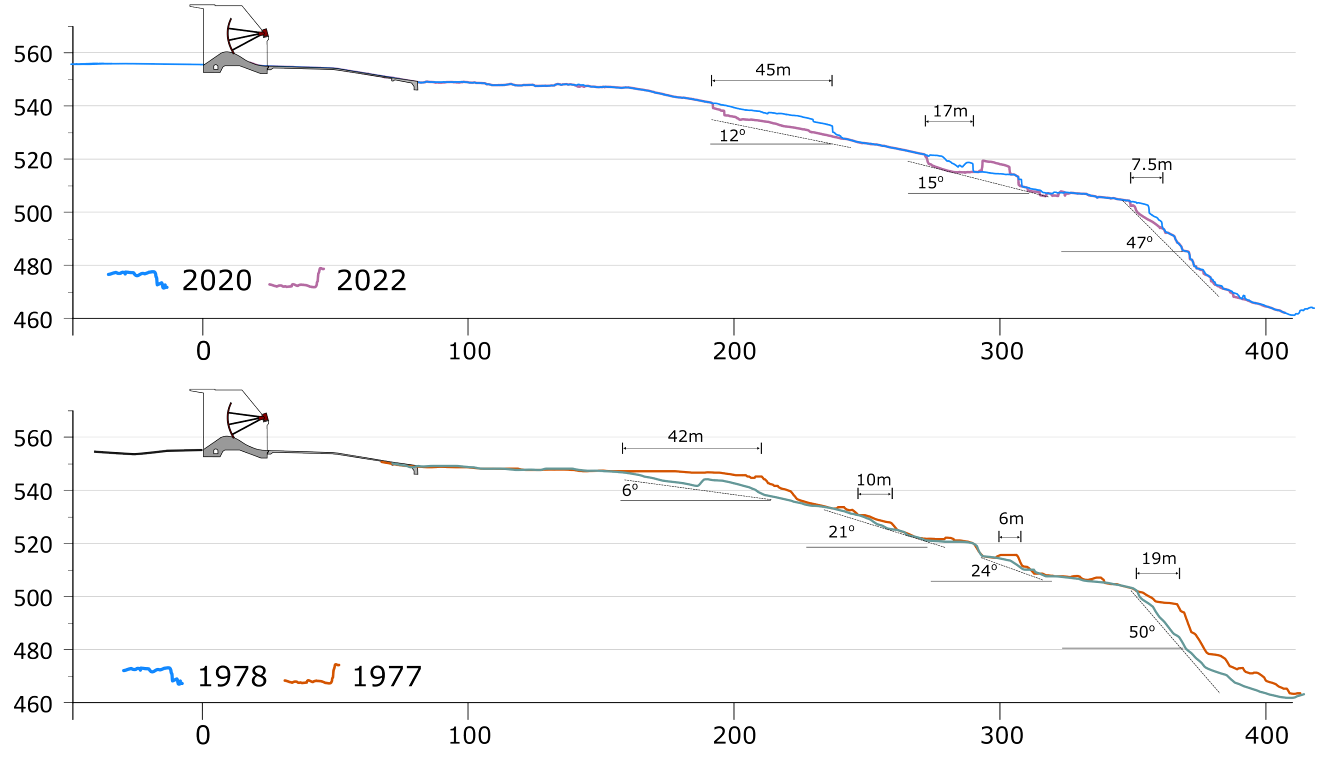

Figure 15 – Example of estimates of headcutting between sequential ground surveys

Flows that have passed through the Service Spillway were concatenated into periods of time between sequential ground surveys, as shown in Figure 16. In each case, the rate of headcutting between two sequential ground surveys was estimated as the observed headcut depth divided by the duration of concatenated flows between the sequential ground surveys. A note was also made to interpret if the geology was highly weathered (being representative of first flows over vegetated spillway) or moderate to fresh (for areas previously eroded).

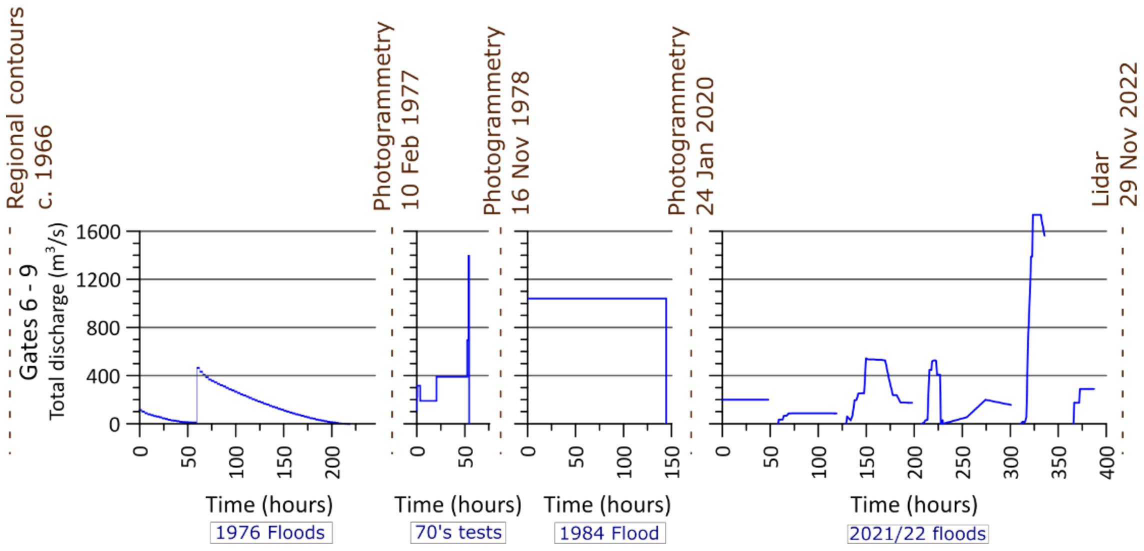

Figure 16 – Flow records in Copeton Dam Service Spillway since construction, concatenated between sequential ground surveys

A corresponding estimation of unit stream power dissipation was made for each of the identified erosion locations. Unit stream power dissipation Π_{UD} is defined the product of the water density ρ (1000 kg/m^3); gravity g (m/s^2); the specific discharge q (m^2/s), and the energy gradient s_f (-). For this exercise, a very approximate estimation of Π_{UD} was made by assuming:

- a constant discharge to approximate each of the concatenated flow records between sequential ground survey dates (for example, the 2022 flows were represented as a discharge of 400m^3/s for a duration of 400 hours).
- the flow width was estimated through review of historical photographs and CFD modelling.

- the energy gradient was taken as equivalent to the ground slope in the region of the interest.

Plots showing the results are presented in Figure 17. It is noted that the data is noisy, as may be expected by the nature of the interpretation and as is often the case for headcut data. There is a paucity of such data published, and these plots at least provide some approximate point of reference.

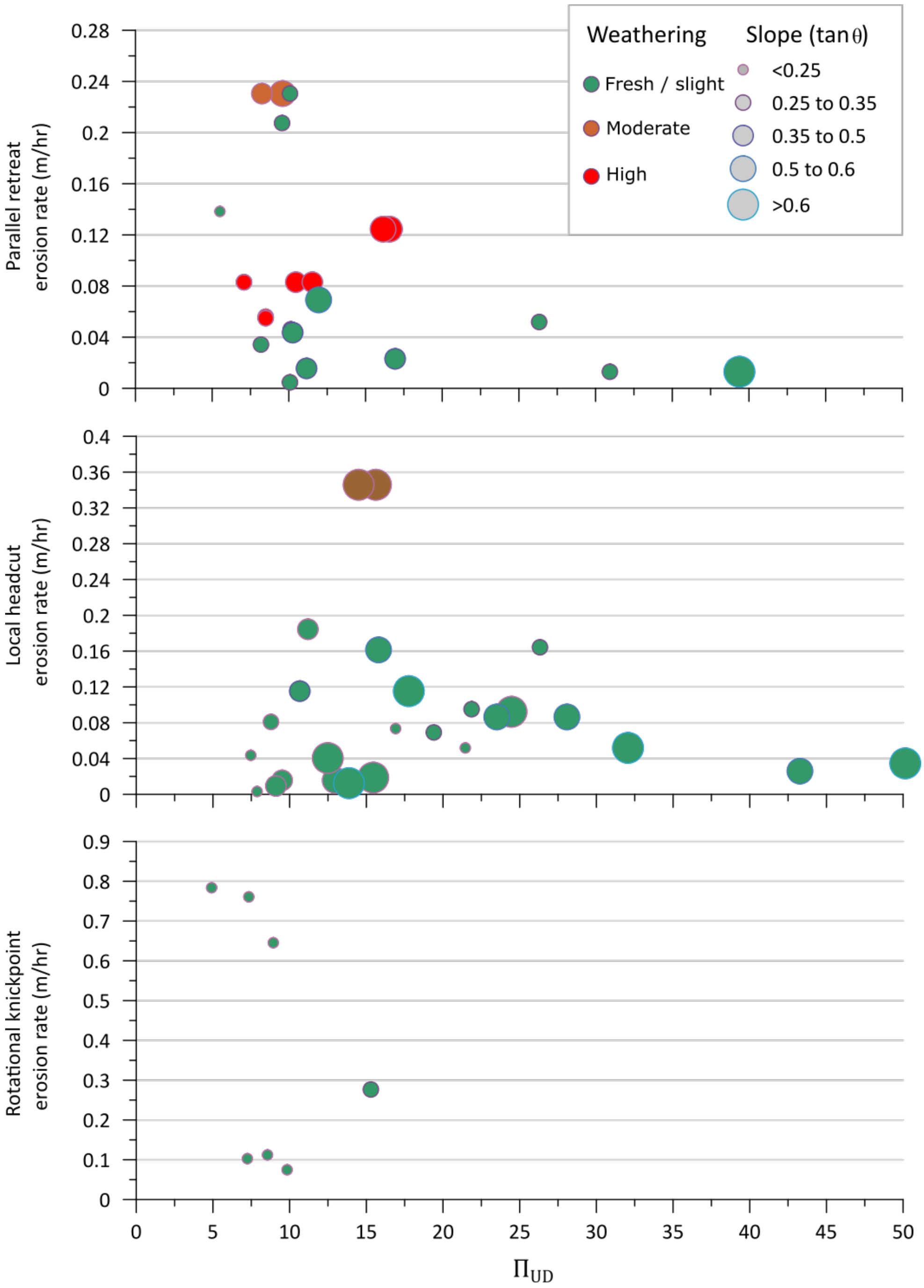

Figure 17 – Dataset of interpreted headcut rate (m/hr) versus unit stream power dissipation (kW/m^2)

Prognosis

Floods of 2022

The floods in 2022 resulted in operation of the Service Spillway at Copeton Dam on various occasions, resulting in further erosion of the unlined rock mass. The nature of erosion followed expectations and included: the removal of looser large boulders at the end of the excavated section; development of various headcuts throughout the lower sections of spillway, and relatively little erosion within the excavated section just below the apron – although some pockets of erosion here of up to 0.5m were perhaps larger than expected. Just below the excavated section, the erosion has aligned with persistent sheet joints, creating a smoother surface that is perhaps more resistant to further erosion due to the absence of adverse steps or protrusions. This offers some degree of comfort as such smoothed surfaces have demonstrated good resistance to further erosion (e.g., Hartesbeespoort Dam, as documented in Pells, 2016). Notwithstanding this, observations of the 2022 flood events raised five points of concern.

1. The guide wall that defines the left-hand side of the Service Spillway appears to nearly overtop under flows of 1700 m^3/s, and it therefore appears likely that it would be subject to significant overtopping from design flows, which are over 3 times greater.
2. Photos of the 2022 flows shows that concrete repair works just downstream of the apron (the 'swimming pool') flip the flow upward and are evidently subject to very high energy. The orientation of these concrete works suggests that they cover-over a lower quality rock mass associated with a geological structure. Failure of these concrete repairs would expose the lower quality rock masses and be subject to high hydraulic energy, and therefore likely result in serious erosion near the structure and associated serious consequences. Risk assessments should consider review of the details of these repair works.
3. Lateral flows below the guide wall spill onto the Service Spillway over a region of rock mass which is perceived to be vulnerable to erosion, due to open subvertical fractures which run parallel to a steep slope, and sheet jointing that dips toward the steep slope. Under higher discharges, higher lateral flows may mobilise this rock, causing erosion and potentially undermining the end of the guide wall – which would in turn increase lateral flows and further erosion.
4. Significant undercutting of the slope below the end of the wall on the right-hand side of the spillway is observed, which appears to be at the head of a previously identified fault line. Whilst high energy supercritical flows are largely unable to turn a corner to follow this fault, lateral spill is still likely to increase under higher flows. Ongoing erosion here may progress upstream into the flow field, capturing more flow and potentially causing development of a gully along this geological structure that could potentially advance further the flow field.
5. Whilst the erosion has created a smoothed surface below the excavated section that is favourable to resist erosion, it would be optimistic to assume that observed headcutting would not eventually progress upstream into the excavated section.

Overall assessment of scour risks

It is considered that the scour potential at Copeton Dam has the potential to result in reputational damage, financial impacts as well as dam safety and life safety risks. WaterNSW applied risk assessment and risk informed decision making to guide the appropriate response to the scour potential at Copeton Dam. This was found to be a difficult endeavour and problematic to assess. This is generally due to the following:

- Uncertainty in the prediction of scouring and progression of scouring, especially where lines of defence of present, such as concrete lining, anchoring or other control measures.
- Time and duration aspects of the scouring. When is action required?
- Non-life safety, operational risks dominating the risk exposure, such as reputational impacts of significant scouring or economic decision making of control measures done 'now' to save future expenditure.
- No broad risk acceptance criteria supported by industry bodies, guidelines, or regulations.
- ALARP/SFAIRP considerations and if this thinking is applicable to non-life safety risks.

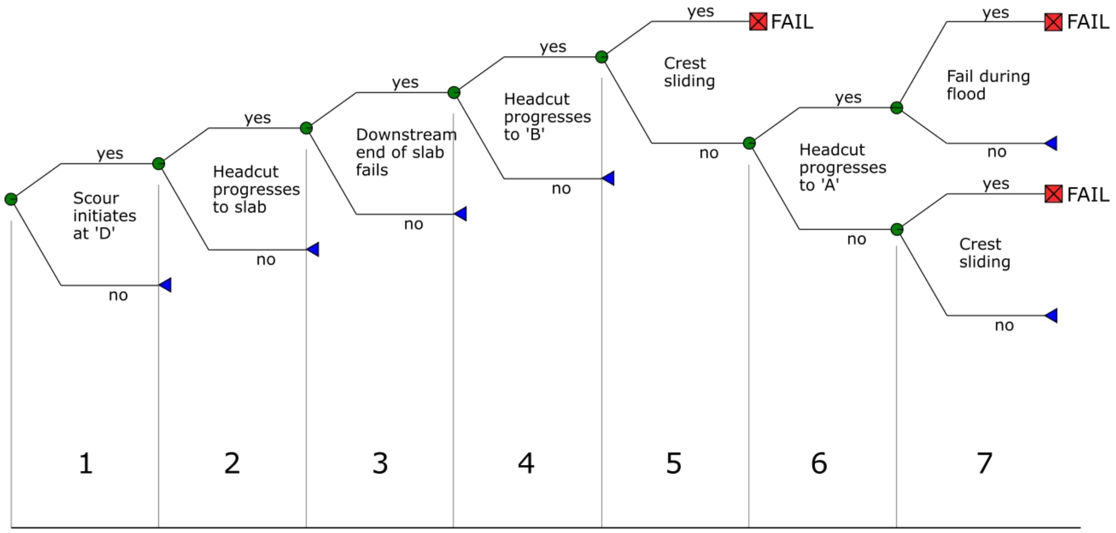

Figure 18 – Event tree layout for scour risks

These challenges were successfully overcome for Copeton Dam via taking the following approach:

1. Traditional risk assessment using expert elicitation and engineering inputs resulted in an event tree layout as shown in Figure 18. This individual failure mode was integrated into the overall risk profile for the facility, which noted an elevated societal risk profile. This elevated risk position required controls to be assessed.
2. Understanding of uncertainty, which was found to be approximately 1-order of magnitude due to difficulty of the engineering inputs to assess head cut scouring to undermine concrete slabs without physical hydraulic modelling information.
3. Operational style risk assessment using WaterNSW's corporate consequence matrix to investigate the risk exposure of financial and reputational risks.
4. Risk Management Planning to identify interim or structural risk controls.

The outcomes of this approach were that:

1. Dam breach, life safety risks were below the safety threshold yet not yet deemed SFAIRP without further works to justify. It was observed that significant uncertainty remains as potential 1-order of Magnitude.
2. Non-Breach, reputational and financial risks were far more likely to occur and resulted in 'low' to 'medium' risks. With the rock scouring progressing yet stopping at the concrete lining being considered the highest risk and most likely outcome.

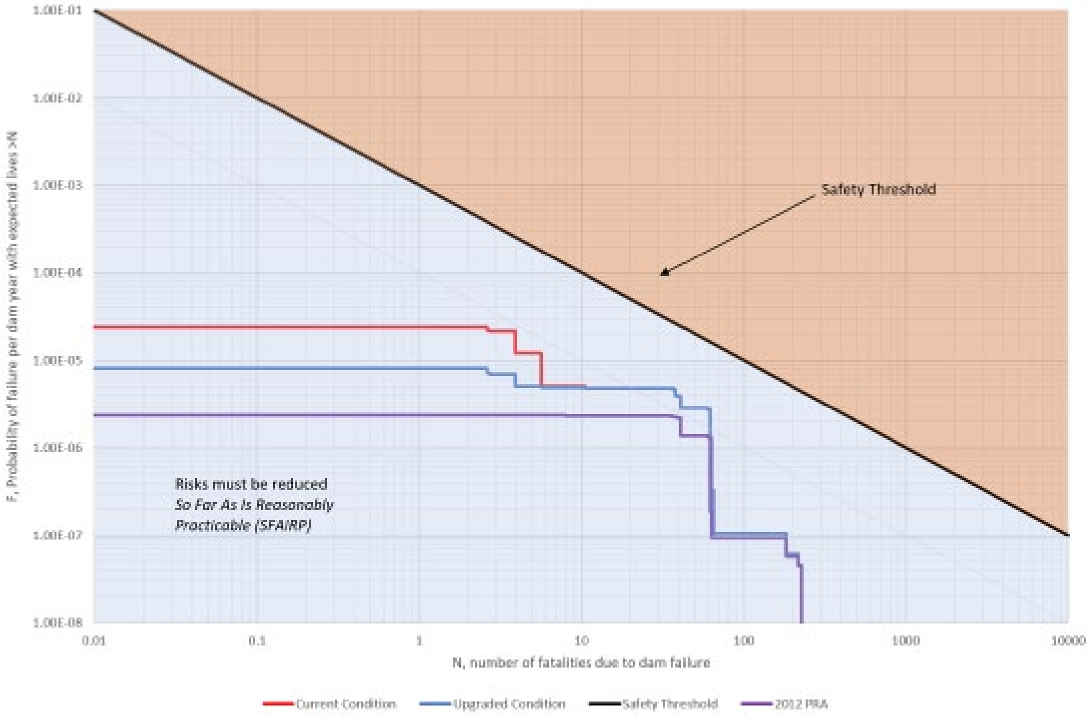

Figure 19 – Risk profile for Copeton Dam with spillway scouring risk included

Recommendations

Concepts for design works to decrease risks from erosion of the Service Spillway have been proposed for further discussion and review. Works that may be considered are shown conceptually in Figure 20 and include:

1. raising of the guide wall to prevent overtopping during design flows.
2. review of the details of design and construction of repair works below the apron slab (the 'swimming pool') and, if necessary, assessment of its adequacy against hydraulic forces from the design flows. Consideration may be given to augmentation of these concrete repairs to increase their strength and to reduce the 'flipping' effect on flows, which may promote overtopping of the guide wall.
3. extension of the guide wall to lower lateral overflow onto the secondary spillway
4. extension of the right-hand side concrete wall to protect against further bank erosion and potential erosion along fault structures.
5. construction of an anchored concrete plinth at the end of the excavated section, at the location of the current headcut, to discourage further upstream movement of the headcut (Figure 21). Consideration may be given to addition of flow splitters / flip buckets to promote flow energy dissipation.

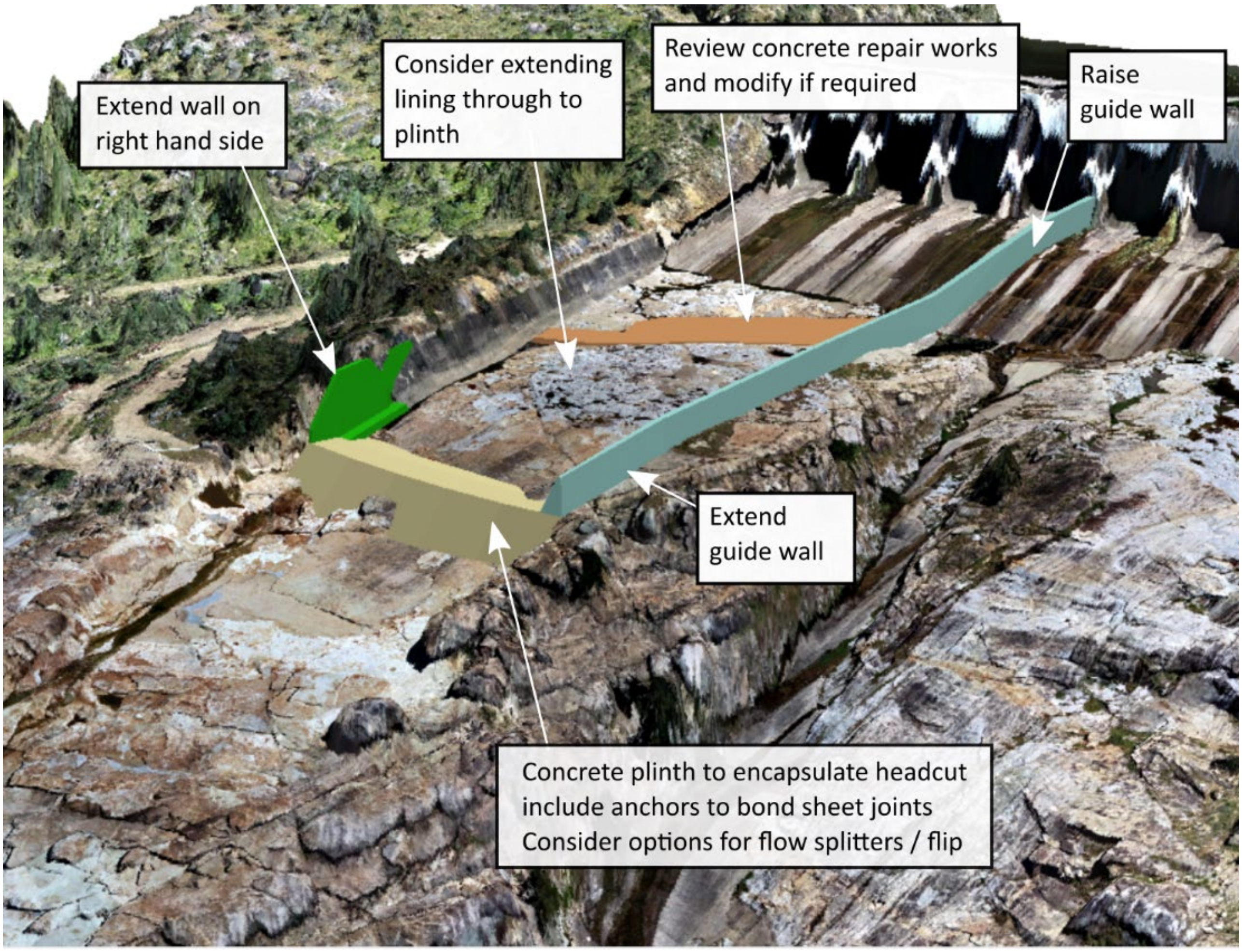

Figure 20 – Concept of works to reduce erosion risks

In consideration of these works, it may be pragmatic and reasonable to consider extension of the apron slab up to the location of the proposed concrete plinth, so that all the new concrete works can be tied in together. It is also noted that spot-erosion within the excavated section was higher than expected, and this alone may warrant consideration of an extended slab.

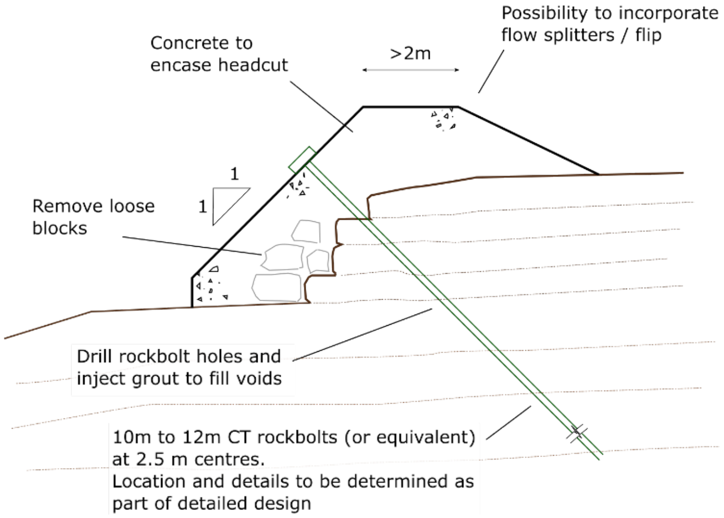

Figure 21 – Concept of plinth to control headcutting

It was recommended that the necessity for, and effectiveness of, these designs may be tested and optimised through further hydraulic modelling. It is recommended that this includes physical hydraulic modelling but may be augmented by CFD modelling that is calibrated against physical hydraulic models.

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