July 2014

MANUHERIKIA CATCHMENT WATER STRATEGY GROUP

Dam Break Assessment - raised Falls Dam, full supply level of 588 m

Submitted to:
Manuherikia Catchment Water Strategy Group

Report: 1378110270_2000_214_R_Rev0_219

REPORT

Golder Associates

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List of Abbreviations

AADT	annual average daily traffic
amsl	above mean sea level
Aqualinc	Aqualinc Research Limited
CFRD	concrete faced rockfill dam
DEM	digital elevation model
FEMA	Federal Emergency Management Agency
FSL	full supply level
GIS	geographic information systems
MCWSG	Manuherikia Catchment Water Strategy Group
NZSOLD	New Zealand Society on Large Dams
OCRT	Otago Central Rail Trail
PAR	population at risk
PIC	potential impact category
RCC	roller compacted concrete
SH85	State Highway 85
XPSWMM	XP stormwater and wastewater management tool

1.0 INTRODUCTION

1.1 Overview

Golder Associates (NZ) Limited has been commissioned by the Manuherikia Catchment Water Strategy Group (MCWSG) to provide a feasibility level assessment of irrigation options in the Manuherikia catchment. Opus (2013) prepared an engineering prefeasibility study on options for raising Falls Dam. However, that study did not include a dam break assessment and recommended that such an assessment be completed as part of the feasibility study.

This report describes the findings of a dam break assessment of a roller compacted concrete dam with a full supply level (FSL) of 588 m above mean sea level (amsl) constructed immediately downstream of the existing dam. This assessment considers the effects that a dam breach may have on downstream areas and identifies a potential impact category for the dam. This assessment forms part of wider feasibility level investigations.

1.2 Objectives

The purpose of this study is to inform the wider feasibility level assessments of the implications of a dam break of the Falls Dam. In particular this assessment will:

1) Determine the Potential Impact Category (PIC) of the dam; this will influence the dam design parameters.

2) Assess the potential flooding hazard and risk in the event of a dam break, which is required during resource consenting of any dam.

1.3 Location

Falls Dam is located on the upper reaches of the Manuherikia River, approximately 60 km upstream of Alexandra, in Central Otago (Figure 1). The dam provides storage for four existing irrigation schemes (Blackstone, part of Omakau, Manuherikia and part of Galloway) which cover approximately 6,500 ha in the Manuherikia Valley. The Manuherikia River flows past several small townships to Alexandra, where it converges with the larger Clutha River.

Falls Dam is an existing concrete faced rockfill dam (CFRD) approximately 33.5 m high, with a FSL of 561.4 m amsl. The current feasibility study is evaluating increased storage options up to a FSL of 588 m amsl.

1.4 Report Limitations

Your attention is drawn to the document, “Report Limitations”, as attached in Appendix A. The statements presented in that document are intended to advise you of what your realistic expectations of this report should be, and to present you with recommendations on how to minimise the risks to which this report relates which are associated with this project. The document is not intended to exclude or otherwise limit the obligations necessarily imposed by law on Golder Associates (NZ) Limited, but rather to ensure that all parties who may rely on this report are aware of the responsibilities each assumes in so doing.

2.0 DAM BREAK INPUTS

2.1 Methodology

A dam break assessment simulates the release of stored water behind a dam over a specified failure time. Although the risk of failure of a suitably designed dam is very small, the New Zealand Dam Safety Guidelines (NZSOLD 2000) requires dams to be categorised according to their consequences of failure. These potential consequences include; loss of life, socio-economic, financial and environmental damage.

The general methodology for a dam break assessment involves:

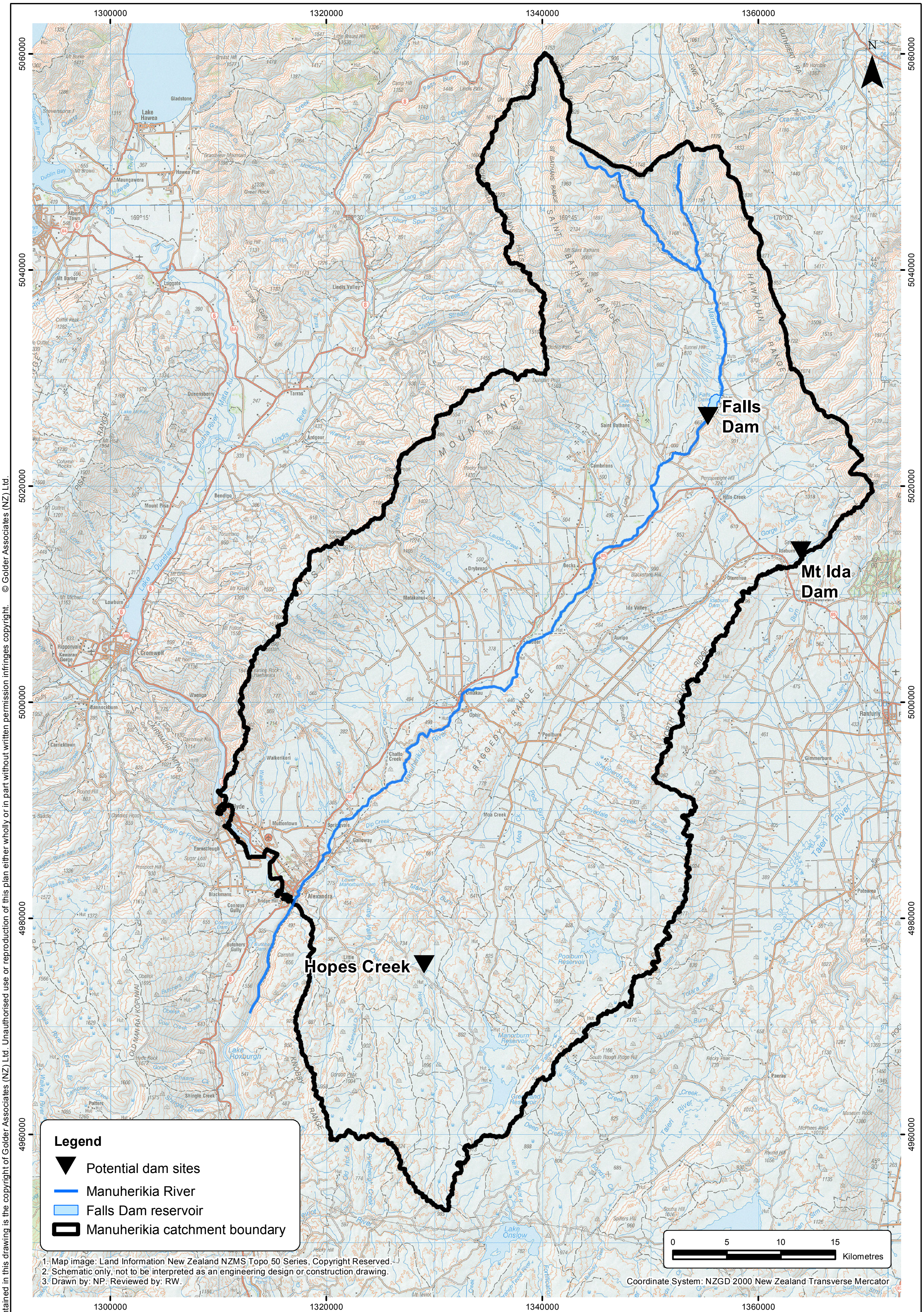
1) Determination of dam breach parameters.

2) Determination of breach discharge hydrograph.

3) Evaluation of the timing and extent of the flood wave.

4) Identification of the Potential Impact Category (PIC).

PIC classification is an important stage in dam design and evaluation because a number of the dam design criteria are dictated by the PIC.



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2.2 Breach Conditions

It is normal practice to undertake two dam failure scenarios; ‘sunny day’ and ‘rainy day’. The ‘sunny day’ scenario simulates a structural failure (i.e., earthquake, piping, etc.) under normal flow conditions, and the ‘rainy day’ scenario assumes that dam breach occurs during a flood event.

This evaluation considers a new Falls Dam constructed from roller compacted concrete (RCC). Concrete dam failures are typically modelled as structural failures (FEMA 2013). This construction type is very unlikely to fail due to overtopping as RCC is designed to overtop during flood events. Therefore, the ‘sunny day’ failure scenario is the most critical and the only scenario to be modelled in this assessment.

2.3 Breach Parameters

Dam breach parameters include the parameters needed to physically describe the breach (breach depth and width) as well as parameters that define the time required for breach initiation and failure. Time to failure plays a significant role in the determination of peak outflow from the dam breach. FEMA (2013) recommends a range of failure times for concrete dams from 6 to 30 minutes. An average of 15 minutes is applied in this model. A shorter time to failure gives the highest peak flows while the longest time to failure gives the lowest peak flows.

Table 1: Falls Dam FSL of 588 m amsl breach parameters.

Parameter	Inputs
Construction materials	Roller compacted concrete
Impounded volume[A]	100 Mm^3
Crest length[A]	195 m
Breach width[B]	98 m
Dam height[C]	61 m
Breach depth[D]	61 m
Time to failure[E]	6 to 30 minutes

Notes: [A] Parameters derived from Opus (2013) report; [B] FEMA (2013) suggests an average breach width equal to half the entire length of the dam; [C] Based on a dam base level of 532 m amsl, a FSL of 588 m amsl and a 5 m freeboard allowance; [D] The bottom of the breach should generally be assumed to be at the foundation level of the dam; [E] FEMA (2013) suggests a range of failure times for concrete dams from 6 to 30 minutes.

2.4 Breach Discharge Hydrograph

To predict peak flow and the dam breach hydrograph, various methods can be applied including: a triangular hydrograph, level-pool routing, dynamic wave simulation, regression relationships, and comparative analysis to similar dams that have failed. All methods have shortcomings such as lack of data, lack of case studies and poor understanding of breach mechanics.

The breach discharge hydrograph was developed using the triangular hydrograph method. This is based on the dam impounded volume and time to failure. In this method, it was assumed that it would take 15 minutes from the start of the breach to the full extent of the breach to occur (time to failure), and the entire volume of the dam will be discharged in 30 minutes. Therefore, the area under the dam breach hydrograph is equal to the reservoir volume during the ‘sunny day’ event. The peak discharge in a ‘sunny day’ dam break scenario is estimated at 111,100 m^3/s (Figure 2).

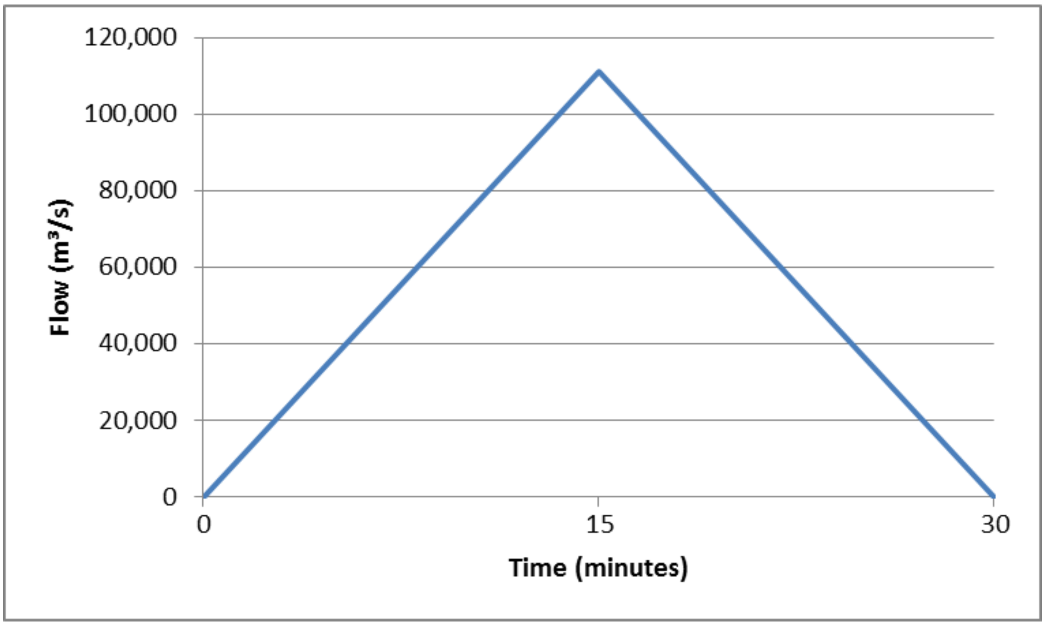


Figure 2: Dam breach hydrograph (Triangular method).

2.5 Hydrology

Flood routing of the dam breach discharge through the catchment requires an understanding of the catchment hydrology. The hydrology for the catchment has been assessed by Aqualinc Research Limited and is documented in two main reports (Aqualinc 2012a and 2012b). Aqualinc (2012a) states the following:

The Manuherikia River has a mean naturalised flow at the Clutha River confluence of 18.5 m^3/s. The major tributaries of the Manuherikia River are the Manuherikia above Falls Dam, the Pool Burn, Dunstan Creek, Manor Burn, Lauder Creek, Thomsons Creek and Chatto Creek. Collectively these tributaries provide almost 90% of the total catchment flow. Aqualinc (2012a) Page 4.

Mean naturalised flow in the seven main tributaries ranges from a high of 4.8 m^3/s for the Manuherikia above Falls Dam to a low of 0.7 m^3/s for Chatto Creek (Aqualinc 2012a). These tributary flows are very small (four to five orders of magnitude smaller) compared to the expected dam breach flows. Therefore flood routing of the dam breach discharge through the catchment will be largely insensitive to tributary inflows. To improve the runtime efficiencies of the flood routing model, tributary inflows were excluded from the model.

2.6 Flood routing

XPSWMM 2013, a hydraulic and hydrological modelling tool is used to route the flood wave downstream. XPSWMM uses the TUFLOW computational engine that links 1-D and 2-D modelling to simulate flood propagation.

The following are components of the hydraulic model:

- Digital Elevation Model (DEM) – developed by geographic information systems (GIS) based on 20 m contour data (LINZ 2014) combined with 5 m contour data (MWD 1976) around the Manuherikia River channel.
- Model extents – The Manuherikia River main stem is modelled from Falls Dam to the Ophir gorge.

- Downstream boundary condition – The downstream boundary condition is set to a shallow depth, forcing a critical depth to occur at the downstream end.
- Dam break hydrograph – The generated breach hydrograph is incorporated into the XPSWMM model as a flow boundary condition at the Falls Dam site.
- Tributary inflows – Flows from tributaries were not included in this model.
- Model nodes – A number of nodes are positioned throughout the model at the locations of infrastructure and towns. These nodes enable the modelled water depth, flow and velocity to be easily reviewed at these points of interest.
- Manning's roughness – The Manning's value can be expected to change throughout the reach of the Manuherikia River and its tributaries. However, for simplicity, a fixed value has been used. A Manning's value of 0.04 was selected as this is considered reasonable for a gravel-cobble river channel and surrounding pasture floodplains.
- 2D grid resolution – Grid size of 30 m was used.
- Time step – A time step of 0.5 seconds was used in the XPSWMM model.

For this dam break analysis, the downstream boundary of the XPSWMM model is the Ophir Gorge. An extended model to Alexandra was preferable, but a compromise exists between model extent and detail. In order to provide sufficient detail and accuracy to the model, the extent was limited to the reach of the Manuherikia River from Falls Dam to Ophir Gorge.

There are several hydraulic structures within the watercourse downstream of the dam. These include road and pedestrian bridges, irrigation siphons and intake structures. Due to the scale of the overall system model, these structures are largely ignored in terms of their impact on flood routing. Hydraulic structures are assessed in terms of their potential for damage due to inundation.

In any dam break model, calibration is difficult as peak flows of this magnitude rarely occur. Furthermore, the critical factor in the model is the time to failure and as such, errors associated with cross-sections, hydraulic structures and calibration will be less significant.

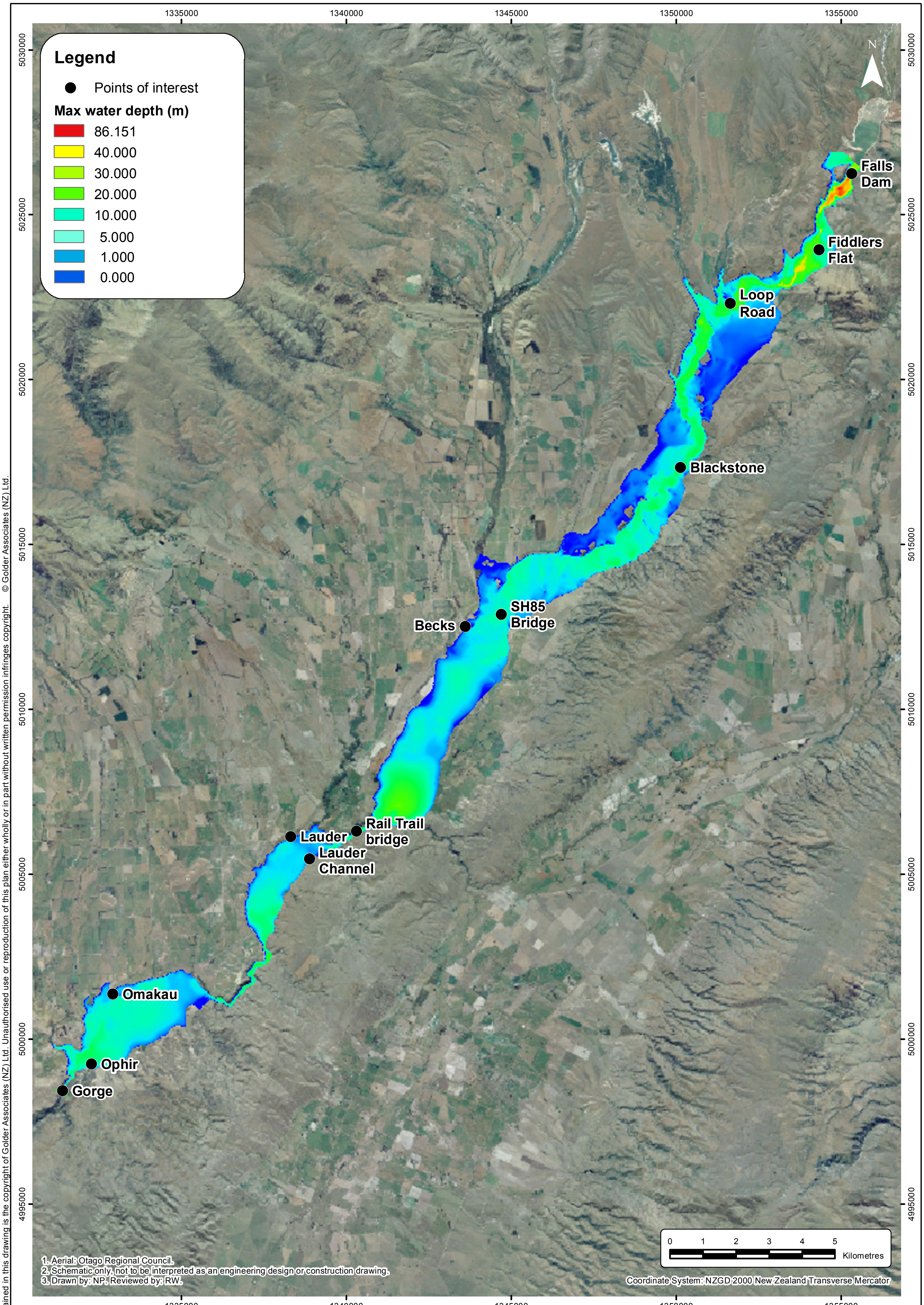
3.0 DAM BREAK MODELLING

3.1 Model Results

The modelled maximum flood extent and water depth is shown in Figure 3. Overall there is significant out of channel flooding throughout the length of the modelled Manuherikia River reach. The exceptions to this are where the river flows through gorges: north of Lauder, north of Omakau and south of Ophir.

Table 2 summarises the timing, depth, flow and velocity of the dam break flood flow at points of interest in the catchment. The towns of Becks, Omakau and Ophir are expected to suffer inundation to varying degrees, however Lauder is located just beyond the extent of the flooding.

The wetted front of the dam break flood travels through the modelled catchment within 3 hours. However, it takes almost 8 hours for the peak flood depth to travel from Falls Dam to the gorge at Ophir. Flood flows and velocities generally decrease throughout the river reach. The dam break peak flow of 111,100 m^3/s is estimated to dissipate to a peak of 1,600 m^3/s by the time it reaches the gorge at Ophir.



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TITLE

FALLS DAM BREAK (FSL OF 588 m amsl)
MAXIMUM FLOOD EXTENT

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Table 2: Summary of dam break results for Falls Dam with a FSL of 588 m amsl.

Location	Distance downstream (km)	Time to arrival of wetted front [A] (hr:min)	Time to arrival of maximum depth (hr:min)	Maximum depth of water (m)	Maximum flow [B] (m^3/s)	Maximum velocity [C] (m/s)	Wetted floodplain width (m)
Fiddlers Flat	2.9	0:05	0:24	27.6	89,000	16	1,000
Loop Road	6.6	0:17	0:28	4.8	74,000	2.0	2,050
Blackstone	12.7	0:27	0:36	6.7	65,000	5.6	1,250
SH85 Bridge	22.0	0:47	0:53	10.8	51,000	7.4	1,500
Becks	22.0	0:50	0:54	0.6	51,000	1.3	1,500
Rail Trail Bridge	30.5	1:12	1:42	11.4	8,200	1.7	170
Lauder channel	32.7	1:18	1:44	1.8	8,100	2.7	800
Lauder	32.7	-	-	0.0	8,100	0.0	800
Omakau	42.7	3:45	7:47	4.7	4,600	0.13	1,800
Ophir	44.0	2:55	7:48	11.3	3,200	0.30	1,400
Gorge	45.4	-	-	-	1,600	-	-

Notes: [A] Time to an inundation depth of 0.1 m. [B] Maximum flow across floodplain cross section. [C] Locations vary between points in the main river channel and points of interest in the floodplain, refer to Figure 3.

4.0 DAM BREAK CONSEQUENCES

4.1 Population at Risk

The population at risk (PAR) is defined as the number of people occupying the dam failure floodplain prior to the issuance of any warning. The population at risk varies throughout the day and throughout the seasons (USBR 1999). The number of people undertaking recreational activities outdoors in and around the Manuherikia River will change depending on whether it is summer or winter and the distribution of the population will vary between day and night.

4.2 Population at Risk for Falls Dam – FSL of 588 m amsl

The PAR downstream from Falls Dam was estimated based on the inundation area from the dam break analysis. Population and census data was used to estimate permanent residences in the inundation area. The population per residence in the inundation area is based on a projected average of 2.5 people per household (Statistics NZ 2014) and an inspection of aerial imagery to determine number of residences inundated by a dam failure. For the towns of Omakau and Ophir, where the flood map indicates the whole town is likely to be inundated, population estimates were adopted (CentralOtagoNZ 2014).

The Otago Central Rail Trail is a 150 km long cycling trail from Clyde to Middlemarch. The trail travels up the Manuherikia Valley from Clyde and crosses into the Ida Valley near Lauder (approximately 40 km) (Otago Central Rail Trail 2014). It is estimated that approximately 10,000 - 12,000 people cycle the trail each year (ODT 2011). The majority of the users are likely in the warmer months (November to April) which results in 66 users per day during the summer. Assuming 5 % of the Otago Central Rail Trail could be affected (7.5 km), approximately 3 cyclists would be at risk.

State Highway 85 (SH85) follows the Manuherikia River through the catchment and at times is located very close to the river channel. Other rural roads may also be inundated. However traffic rates on these roads are too low and the population at risk is estimated to be very low. There is an estimated annual average daily traffic volume (AADT) of 500 on SH85 near Lauder (Transit 2006). Assuming 10 % of the Manuherikia River length of SH85 (6 km) could be affected by inundation from a dam break over a 6 hour period, approximately 12 vehicles would be at risk. This could equate to approximately 25 people at risk on the roads.

The rivers and lakes in the Manuherikia catchment are popular trout fisheries. Other recreational uses of waterways include game bird hunting, kayaking and swimming (MCWSG 2013). Assuming access may be gained to the Manuherikia River primarily around the locations of road bridges and townships, it is estimated that 10 people could be at risk during a dam break event during summer.

The estimated population at risk for various downstream locations are presented in Table 3.

Table 3: Estimated population at risk at various locations downstream from Falls Dam.

Location	Distance downstream (km)	Estimated Population at Risk (PAR)			
		Properties	OCRT	Roads	Recreation
Falls Dam to Fiddlers Flat	2.9	3			
Fiddlers Flat to Loop Road	6.6	5			
Loop Road to Blackstone	12.7	5			2
Blackstone to SH85 Bridge/Becks	22.0	20		6	2
SH85 Bridge/Becks to Rail Trail Bridge	30.5	55	1	6	
Rail Trail Bridge to Lauder	32.7	3	1		2
Lauder to Omakau	42.7	45	1	6	2
Omakau to Ophir	44.0	140[2]		6	2
Ophir to Gorge	45.4	40[2]			
Estimated PAR		**353**			

Notes: Property estimates based on a projected average of 2.5 people per household (Statistics NZ 2014), and an inspection of aerial imagery to determine number of residences. [2] Based on Central Otago Population Statistics for Omakau and Ophir (CentralOtagoNZ 2014). OCRT – Otago Central Rail Trail.

5.0 GUIDELINES AND LEGISLATION

New Zealand Building (Dam Safety) Regulations 2008 (amended 2010) identifies a damage level, based on damage to homes, critical infrastructure, natural environment and community recovery time (Table 4). A subsequent dam classification is based on the damage level and the population at risk (Table 5).

Table 4: Determination of damage level (DBH 2008).

	Residential houses	Critical or major infrastructure		Natural environment	Community recovery time
		Damage	Time to restore to operation		
Catastrophic	>50 houses destroyed	Extensive and widespread destruction of and damage to several major components	>1 year	Extensive and widespread damage	Many years
Major	4 – 49 houses destroyed	Extensive destruction of and damage to more than one major component	Up to 12 months	Heavy damage and costly restoration	Years
Moderate	1 – 3 houses destroyed	Significant damage to at least one major component	Up to 3 months	Significant but recoverable damage	Months
Minimal	Minor damage	Minor damage	Up to 1 week	Short-term damage	Days to weeks

Table 5: Determination of dam classification (DBH 2008).

Assessed damage level	Population at risk			
	0	**1 to 10**	**11 to 100**	**More than 100**
Catastrophic	High	High	High	High
Major	Medium	Medium/High	High	High
Moderate	Low	Low/Medium/High	Medium/High	Medium/High
Minimal	Low	Low/Medium/High	Low/Medium/High	Low/Medium/High

The New Zealand Society on Large Dams (NZSOLD) provides initial screening advice regarding the PIC of dams, related to broad dam height and storage volume parameters. NZSOLD also indicates potential impact categories in terms of failure consequences (life, financial, environmental and socio-economic) (Table 6).

Table 6: Potential impact categories for dams in terms of failure consequences (NZSOLD 2000).

Potential Impact Category	Potential incremental consequences of failure	
	Life	**Socio-economic, financial and environmental**
High	Fatalities	Catastrophic damages
Medium	A few fatalities are possible	Major damages
Low	No fatalities expected	Moderate damages
Very low	No fatalities	Minimal damages beyond owner's property

6.0 POTENTIAL IMPACT CATEGORY

The purpose of a PIC is to understand the potential consequences (loss of life, socio-economic, financial and environmental) of failure of Falls Dam with a FSL of 588 m amsl.

Based on an inspection of aerial imagery within the floodplain, an estimated 126 residences would be inundated to some degree. The level of damage to these properties would vary, but according to Table 4, this would be considered a 'major' to 'catastrophic' damage level.

At least 6 road / pedestrian bridges span the Manuherikia River between Falls Dam and Ophir Gorge. Other critical infrastructure in the floodplain includes; the 1.2 MW capacity hydropower scheme located at the base of Falls Dam; at least 3 pieces of significant irrigation infrastructure (major intakes and siphons); community electricity distribution networks and various other local community infrastructure. The consequences of a dam break would be considered as widespread and extensive damage to several infrastructure components, and likely to be described as 'catastrophic' damage according to Table 4.

Dam break modelling indicates an expected peak flow of 1,600 m^3/s at the Ophir Gorge. This is almost twice the estimated 1 in 500 year return period peak flow for the Ophir site of 940 m^3/s (Aqualinc 2012b). This large flood event, and the large floodplain width, indicates significant damage to the natural environment. According to Table 4 this would likely be considered a 'moderate' to 'major' damage level.

Large tracts of agricultural land would suffer inundation, and community infrastructure and facilities would be damaged or destroyed. With a failure of Falls Dam, potentially 21,000 ha of land would lose its supply of irrigation water. This would have a major impact on the livelihoods of farmers and the community economy. As the area consists of small, rural communities, the time to repair and reconstruct communities would span years and would likely be considered as 'major' to 'catastrophic' damage according to Table 4.

Overall, based on Table 4, the assessed damage level for a dam break of Falls Dam with a FSL of 588 m amsl would be ‘major’ to ‘catastrophic’. When combined with the estimated population at risk of 353 (Table 3), Table 5 determines the dam to be of High PIC classification.

With regard to the NZSOLD guidelines (Table 6), a PIC classification of High is also estimated. The flood wave travel time to the properties closest to the dam is very short (<15 minutes) and the flood water depths are significant (over 25 m high near Fiddlers Flat) making evacuation difficult. The water will also be moving quickly and evacuation routes are limited. The flood wave travel time to the more populated areas (Becks) is still under an hour and still moving quickly, potentially making warning and evacuation difficult. Due to the proximity of the population at risk and the high flood wave velocity, fatalities are probable. Combined with the previously discussed catastrophic damages to infrastructure, communities and the environment, a High PIC is concluded.

7.0 MODEL LIMITATIONS

A sensitivity analysis has not been undertaken and there are limitations to the accuracy of the model output. Model limitations are noted below:

- Natural flows in the Manuherikia River and its tributaries have been ignored in the model. This is to increase model runtime efficiencies.
- A Manning’s value of 0.04 was applied as a constant value across the entire river channel and floodplain. However, differing vegetation in the channel and floodplain could cause this to vary.
- Due to the magnitude and speed of the breach flow, some water appears to flow upstream (north and west of Falls Dam) down a small gully. This flow is lost to the model, but the volume lost is not considered of significance.
- Due to the extent of the modelled area, a model grid of 30 m was applied. This grid size limits the accuracy of the model in narrow areas such as gorges downstream of Lauder and downstream of Ophir. The model may be creating additional backwater effects which would have the following effects:
  - increasing the time to inundation of downstream infrastructure, and
  - decreasing the magnitude of inundation of downstream infrastructure.

  As the areas of the model which receive the largest and most rapid inundation are upstream of these gorges, it is not considered to have a significant impact on the results of the model. However, it should be considered in future modelling for evacuation planning purposes at detailed design stage.
- The underlying ground elevation data for the model was compiled from a number of sources including 20 m topographical data (supplied electronically) and 5 m topographical data (only available on hard-copy maps). There are a number of limitations on this data:
  - Alignment of data between sources.
  - Delineation of hard-copy topographical maps into an electronic version.
  - Age of the data sources (some map sources from 1976) and potential river channel changes.
  - River channel depth was ignored.
  - Truncation of the topographical data due to the model grid size.

It is recommended that the model is refined during detailed design once the dam configuration is confirmed.

During final design is it suggested that the terrain model be refined through site specific topographic surveys and a sensitivity analysis, possibly varying channel roughness (Manning's n), hydrograph, grid size, and other variables. Extending the model to the confluence of the Clutha River is also recommended. This may require an increase in the processing capability of the modelling software.

Even though only the dam break of Falls Dam with a FSL of 588 m amsl was analysed, a similar PIC is estimated for smaller RCC raises. Flood extents, depths, and velocities may be reduced for a smaller dam raise but major to catastrophic damages are still expected to critical infrastructure and the population at risk will not likely be reduced significantly (>100). If a concrete faced rockfill dam is selected for final design, the PIC is again not expected to change. The critical failure mode will likely become a rainy day failure which would result in a more water being released downstream if a failure were to occur. This increase in flows is likely to offset the longer breach formation but this should be confirmed during final design.

8.0 CONCLUSIONS

The resulting PIC for Falls Dam with a FSL of 588 m amsl is High. Various dam options are currently being assessed and final dam configuration (size and type) will not be confirmed by the MCWSG until after the current feasibility study. This dam breach assessment has been completed using standard methodologies based on the potentially worst case scenario of a maximum storage volume and a dam type (RCC) that results in a rapid failure mode.

9.0 REFERENCES

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APPENDIX A

Report Limitations

REPORT LIMITATIONS

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Africa	+ 27 11 254 4800
Asia	+ 86 21 6258 5522
Australia & NZ	+ 61 3 8862 3500
Europe	+ 356 21 42 30 20
North America	+ 1 800 275 3281
South America	+ 55 21 3095 9500

solutions@golder.com
www.golder.com

AUCKLAND

Tel +64 9 486 8068
Fax +64 9 486 8072

Level 2
Nielsen Centre
129 Hurstmere Road
Takapuna
Auckland 0622

PO Box 33-849
Takapuna 0740

HAMILTON

Tel +64 7 859 2356
Fax +64 9 486 8072

Room 31 in the Homestead
Ruakura Research Centre
10 Bisley Road
Hamilton 3214

PO Box 19-479
Hamilton 3244

NELSON

Tel +64 3 548 1707
Fax +64 3 548 1727

Level 3
295 Trafalgar Street
Nelson 7010

PO Box 1724
Nelson 7040

CHRISTCHURCH

Tel +64 3 377 5696
Fax +64 3 377 9944

Level 1
214 Durham Street
Christchurch 8011

PO Box 2281
Christchurch 8140

DUNEDIN

Tel +64 3 479 0390
Fax +64 3 474 9642

Level 9A
John Wickliffe House
265 Princes Street
Dunedin 9016

PO Box 1087
Dunedin 9054

Golder Associates