# Clutha Delta flood hazard study

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*Prepared for*

Otago Regional Council

# Contents

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# Summary

This report describes investigations into flooding and erosion hazards in the Lower Clutha Delta region. Flooding is represented by inundation depths and erosion hazard by flow velocities. Flood sizes ranging from 2,900 m³/s to 6,600 m³/s are modelled in conjunction with three sea level scenarios and seven floodbank breach scenarios. A finer resolution model is used to investigate flooding of Balclutha township. The model runs indicate that a 50 yr ARI flood will inundate the Barnego Flats, the Balclutha aerodrome, the river loop west of Chicory Rd floodway, the Matau river loop at Mosley's Road and areas from opposite Kaitangata downstream. There will be low overtopping of floodbanks on the Koau NE of Otanomomo and on the Matau at Raumati. A  500 yr ARI flood will inundate most of the Clutha Delta including parts of Balclutha township. Without catastrophic floodbank failure, model results indicate that large floods will enter Balclutha from the downstream side. The level at which floods enter Balclutha depends on whether Koau Branch floodbanks breach or not. For floods around 100 yr ARI (or greater) damage to Balclutha town could be reduced by manually breaching the floodbanks south of Finegand.

# Caution

Particularly alongside Balclutha showgrounds and in the Lower Koau branch, the Clutha River bed, as surveyed in 2005, must undergo considerable vertical scouring during the rising stage of a large flood in order to pass floods such as the 1999 flood which was used to calibrate the models. Should future flood scouring evolve in a different manner to that indicated by the models, inundation levels different from those predicted by the models could result. Also, in several locations significant velocities occur against the stopbanks. While these locations are identified, failure of stopbanks from lateral scouring has not been considered in the present model runs and such failures could markedly change the predicted inundation extent. Results of the modelling investigation may become invalid if modifications are made to existing floodbanks. Finally, in consideration of the following report, it must be borne in mind that such model studies are simplifications of physical reality and consequently they cannot accurately represent all possible eventualities.

# 1. Introduction

This project is to produce inundation information to identify and quantify flooding and erosion hazards due to relevant river and coastal processes on the Lower Clutha Delta. Eight flood sizes are modelled and three scenarios combining sea level rise and storm surge are investigated. In addition various floodbank breach scenarios are examined. Hazards such as coastal erosion and tsunami are not included in this study. All elevations refer to the Dunedin Vertical Datum 1958.

Specific Project tasks were:

1. **To carry out a topographic survey of the Lower Clutha River bed, berms and floodbanks**

   - A re-survey of existing river cross-sections where the bench marks for these sections could be found.

   - A bathymetric survey of the Lower Clutha riverbed.

2. **To analyse and adaptat LiDAR data for the purpose of flood mapping**

   - LiDAR and bathymetric data are combined to give a Digital Elevation Model (DEM) of the Lower Clutha Delta.

3. **To assess and report on the impact of sea level rise and storm surge**

   - Inundation of the low lying coastal areas.

   - Boundary conditions for hydraulic model.

4. **To hydraulically model the Clutha River Delta and develop flood hazard maps**

   - The 2D hydraulic model includes three combinations of sea level rise and storm surge, three floodbank breach scenarios prescribed by Otago Regional Council (ORC) staff and eight design flow hydrographs specified by ORC.

5. **To hydraulically model inundation of Balclutha Township**

   - The model defines the potential extent and depths of flooding and velocities of floodwater flows in the Balclutha township for eight floods as specified above, associated with four different scenarios of floodbank breaching at

locations prescribed by ORC staff, and different degrees of floodwater overtopping of the floodbanks.

**6.      Output files**

- All coordinate information is in the New Zealand Transverse Mercator (NZTM) Projection and New Zealand Geodetic Datum 2000 (NZGD2000).

- The 106 maps derived from modelling are in Map Info compatible format. accompany this report on a CD

# 2.   Implementation

## 2.1.   Design hydrographs

Eight design flow hydrographs were specified by ORC. The hydrographs are identified by their Average Recurrence Interval (ARI) or peak flow as follows:

- 500 year ARI flood event

- 200 year ARI flood event

- 100 year ARI flood event

- 50 year ARI flood event

- 20 year ARI flood event and

- 10 year ARI flood event

- 5600 $m^3$/s

- 4000 $m^3$/s

These hydrographs are shown on Figure 1.
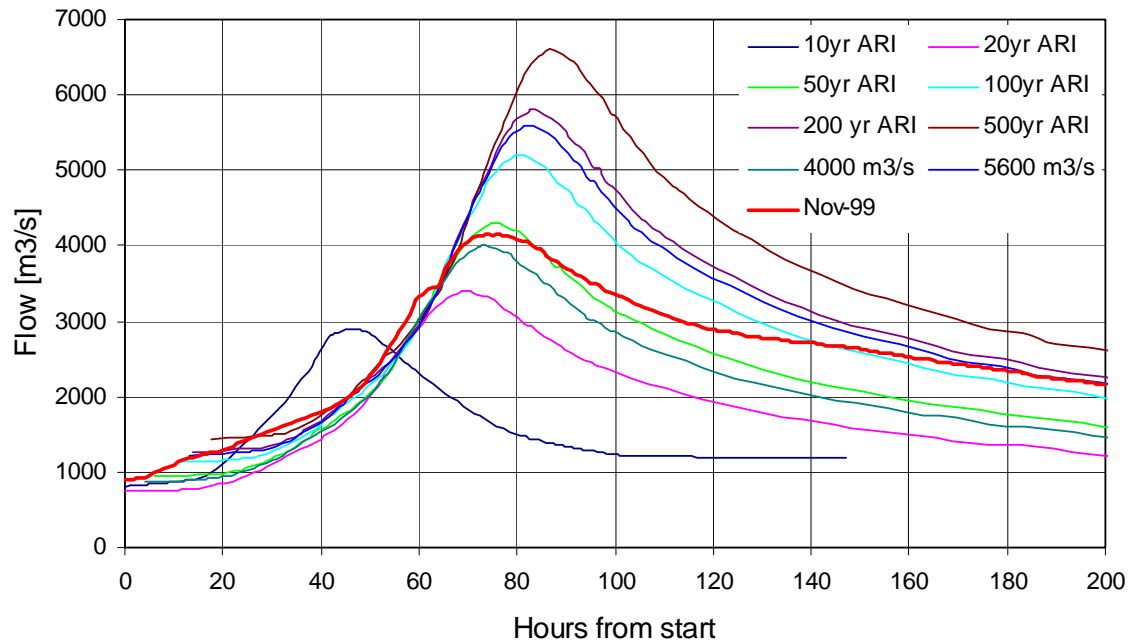
**Figure 1:** **Hydrographs used in inundation modelling.**

### 2.2. Sea level scenarios

Three different sea level scenarios were considered as shown in Table 1. The M2 tide is the lunar semi-diurnal tide. Tides calculated with this tidal component alone give a mean tide. When the S2 solar semi-diurnal tide is added to the M2 tide, tidal values for spring tides are obtained.

**Table 1:** **Sea levels used in inundation modeling**

| Scenario | Mean sea level used (m.a.s.l.) | Tide (amplitude) | Resulting max. water level |
|---|---|---|---|
| 1 | Present Mean Sea Level (0.12 m) | Standard M2 tide (0.77 m) | 0.89 m |
| 2 | Sea Level in year 2100 (0.62 m) | Spring tide M2+S2 (0.89 m) | 1.51 m |
| 3 | 100 yr Storm Surge (0.9 m) + Present MSL (0.12 m) **Or other combinations** such as: 10 yr SS (0.7 m)+ 40yr SL (0.32 m) | Spring tide M2+S2 (0.89 m) | 1.91 m |

Note. Scenario 1:  Present mean sea level has risen to 0.12 m above the m.s.l. datum.

Scenario 3: Different combinations of sea level rise and storm surge that add to 1.02 m are equivalent in terms of their downstream hydraulic effect on the model.

These sea level scenarios were implemented as dynamic downstream boundary conditions for the hydraulic model runs. Tides and hydrographs were synchronised so that high tide occurred at the time a flood peak reached the coast.

## 2.3. Topography

Topography for the model is derived from LiDAR scanning of the project area carried out on September 6-11 2004. The raw data were interpolated to a 10m grid **D**igital **E**levation **M**odel for the greater delta area and a 4m grid DEM for the Balclutha township area (Figure 2). Care was taken to preserve floodbank crest levels and flow paths in the data interpolation process. Some uncertainties over the accuracy of the geoid model have been expressed by ORC (a geoid model is used by the LiDAR mapping company to calibrate the LiDAR elevations to orthometric heights above the datum). As inundation levels are dependent on topography, any bias or trend in the LiDAR data will have an influence on the inundation results reported below.
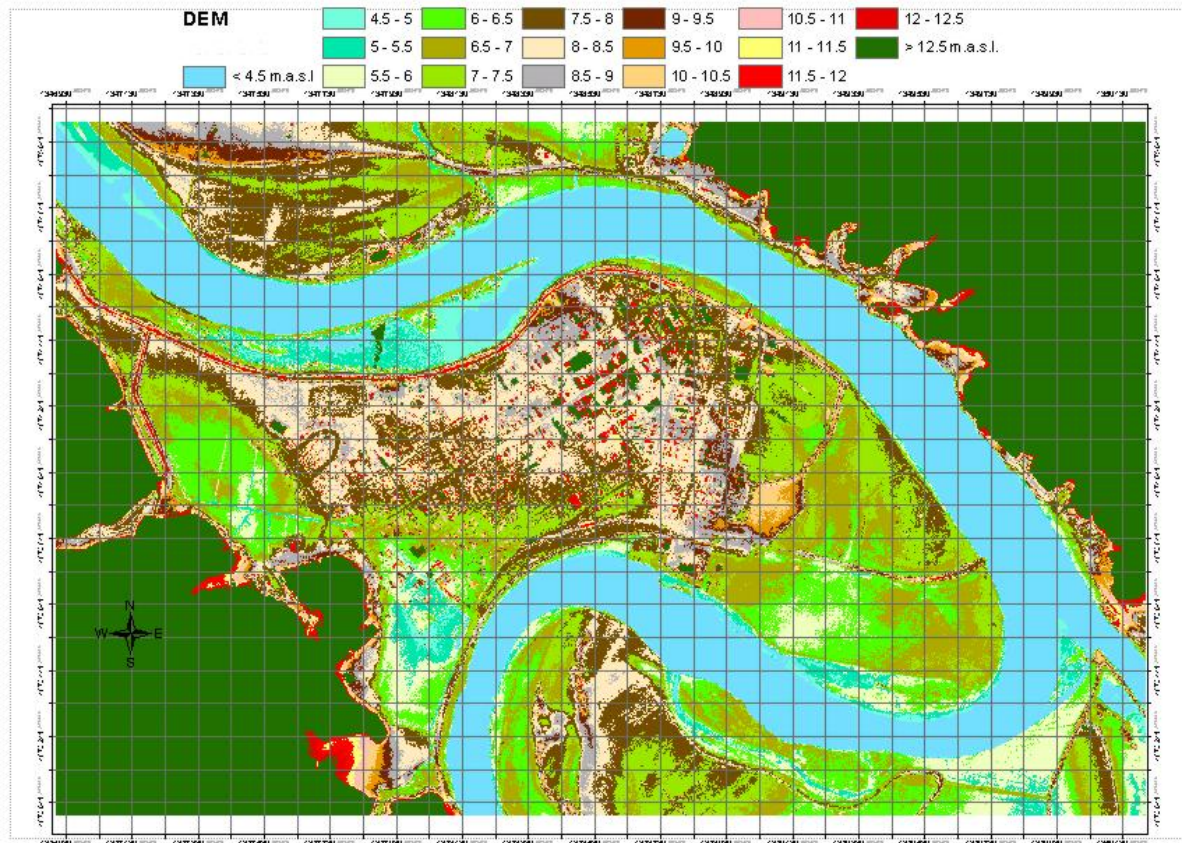


**Figure 2:**     **Digital Elevation Model of Balclutha area topography.**

### 2.3.1. Bathymetry

Riverbed topography in April 2005 was surveyed by GPS-located echo soundings as part of this investigation. An example of the bathymetry, interpolated to the modelling grid, is shown for the Balclutha region in Figure 3. Model runs of the 18 November 1999 calibration flood, which peaked at 4167 $m^3$/s, showed that it was not possible for the river to pass the 1999 flood with the bed levels surveyed in 2005. An investigation of the 1999 flood showed that bed shear stress levels indicated by the model were sufficiently high during this flood to cause substantial scouring of the channel bed and the model bed topography was consequently modified to encompass scouring. Scouring was deemed to be representative of the 1999 bed conditions during the flood when bed shear stress fell below levels required for entrainment of the larger bed particles and when peak water levels matched peak levels measured during the 1999 flood. Bed scouring in the vicinity of Balclutha is likely to be more accurate in the smaller Balclutha model because of the finer resolution.
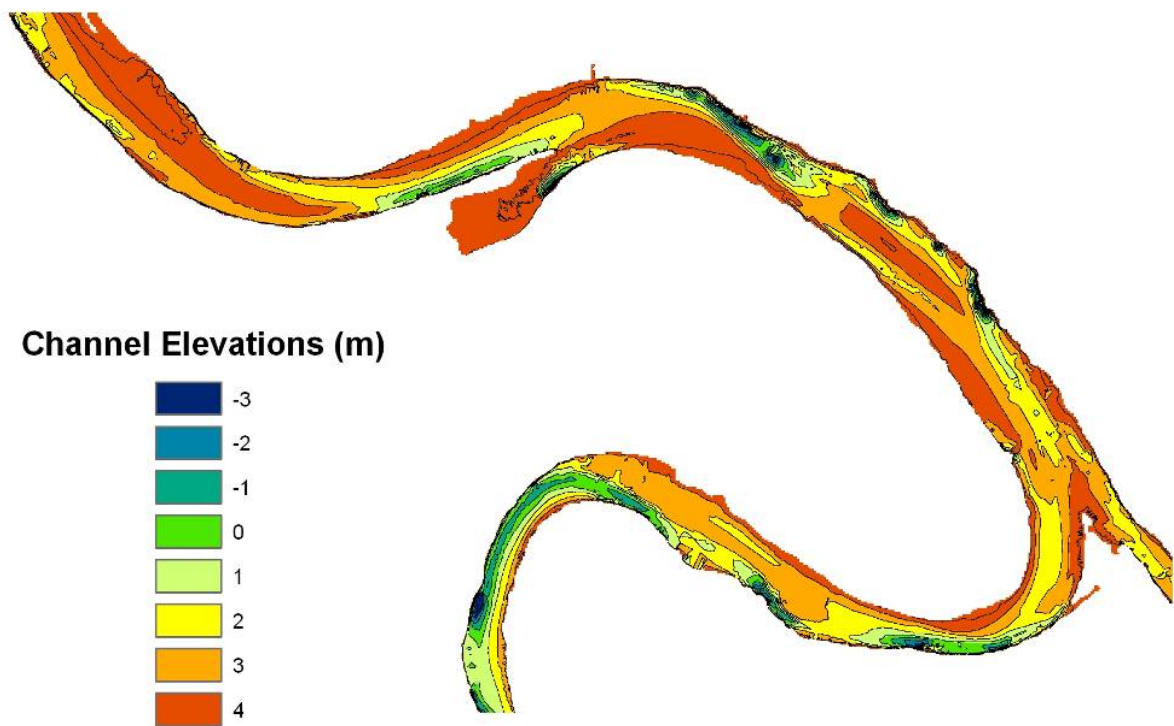


**Figure 3:** **Digital Elevation Model of river bed levels near Balclutha (surveyed in April 2005).**

### 2.3.2. Cross-sections

During the 2005 bathymetric survey, cross-sections were surveyed at locations of historic measurements. These data are supplied in associated files. An example of a cross section survey is given in Figure 4.
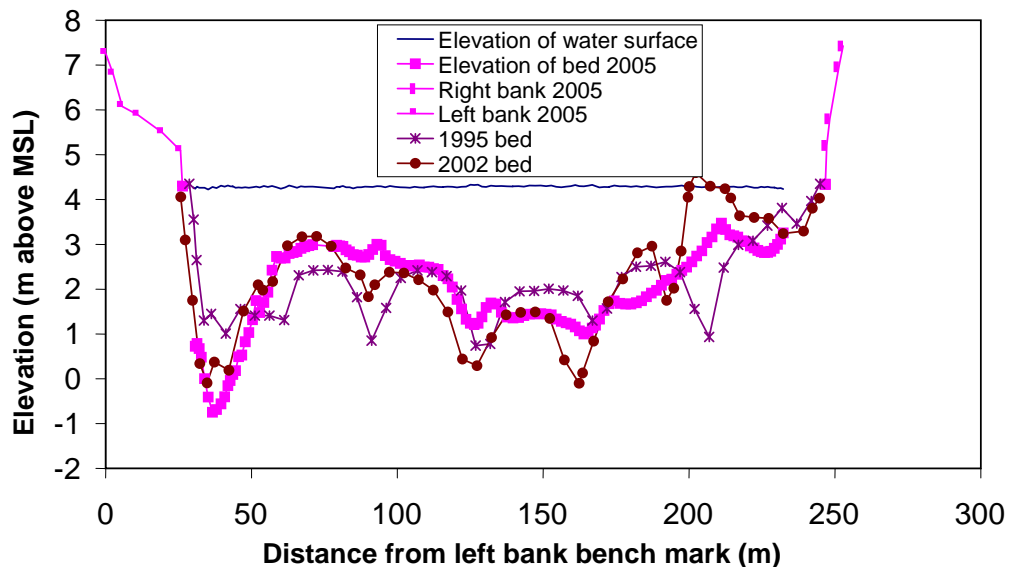


**Figure 4:** **2005 survey of a Clutha River cross section at the railway bridge compared to earlier measurements at the same location.**

### 2.3.3. Breach scenarios

For the Balclutha Delta region four breach scenarios were investigated. On the Koau, two breakout locations were permitted, #1 near the Finegand freezing works and #2 NE of Otanomomo near E 1350 000, N4869 000. The locations are shown on Figure 5. These two locations were combined as one scenario with breaching occurring wherever water depth over the prescribed locations exceeded 150 mm. This scenario was termed *Koau*. On the Matau Branch, breakouts were permitted near Mosley bend (#3) and at Lawsons (#4). These scenarios were termed *Mosley* and *Lawson*. Breaching occurred wherever water depth over the prescribed locations exceeded 115 mm. Breaching reduces floodbank levels to local ground level at a rate governed by the Meyer-Peter Mueller sediment transport formula.

Some uncertainty surrounds final inundation depth and extent following a breach (when a river is spilling out of its usual course) because steps would normally be taken
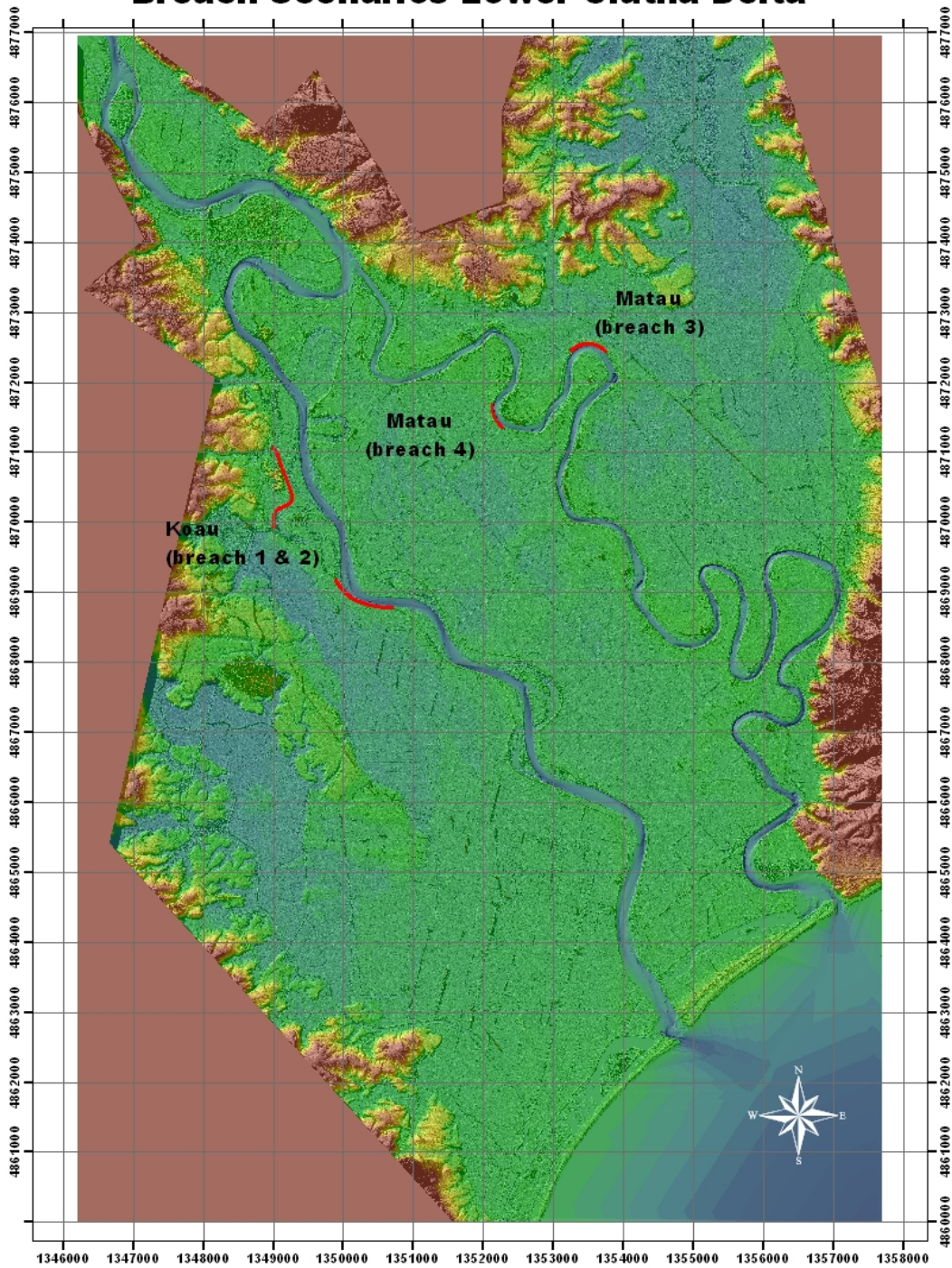
**Figure 5:** Locations on the Clutha Delta where breaching was invoked on stopbank overtopping

to plug a floodbank breach. For modelling of floods that took many days to recede (floods in excess of 5500 m$^3$/s), breaches were assumed to be repaired on a falling flood when inflows fell below 3800 m$^3$/s (rising floods overtop stopbanks at around 4300 m$^3$/s).

For the Balclutha town model several scenarios for breaching were investigated. The proposed scenarios were initially: No Breach (1), Breach upstream of Balclutha on the bank protecting the Barnego flats (2), Breach opposite Balclutha on the bank protecting the Barnego flats (3), and Breach on the floodbank protecting the north of Balclutha town (4). Initial modeling runs showed that the Barnego flats were inundated during all floods greater than a 50 yr ARI and breaches in the surrounding banks only affected the rate at which Barnego flats were flooded and had little effect on maximum inundation depths. Modelling also showed that during high floods, Balclutha was back-flooded from the downstream southern side. It was decided that useful information would be achieved by modelling the following breach scenarios:

O.     No breach,

A.     North Balclutha overtopping leading to breach,

B.     North Balclutha piping (a forced breach whereby a 28 m long section of stopbank was assumed to fail suddenly at the 100 yr ARI flood peak 5200 m$^3$/s), and

C.     South Balclutha overtopping breach (stopbank removed on the downstream side of Balclutha town when it was overtopped by flow at least 150 mm deep).

These locations are shown on the Balclutha model domain in Figure 6. For the prescribed range of flood hydrographs, modelling showed that the banks on the north side of Balclutha were never overtopped and scenarios O and A gave the same result.

## 2.4.    Numerical model description

The computational model used was *Hydro 2de*. It was developed by Dr Cornel Beffa of Fluvial.ch, Switzerland. *Hydro 2de* is a non-interactive program that solves the depth-averaged shallow water equations on a cell-centred rectangular grid using a finite volume discretisation. It allows wet and dry domains; sub- and super-critical flow conditions, the specification of variable bed topography, variable hydraulic roughness, and dynamic boundary conditions. The salient features of *Hydro2de* are:

- explicit time integration (1st or 2nd order) with variable time stepping

- zero-equation turbulence models

- grid independent input (simulation on different grid sizes with the same input data)

- culvert flow (inlet- and outlet controlled)

- computational stability.

The *Hydro 2de* model is internationally recognised and has previously been used for flood and habitat studies on a wide range of New Zealand rivers.
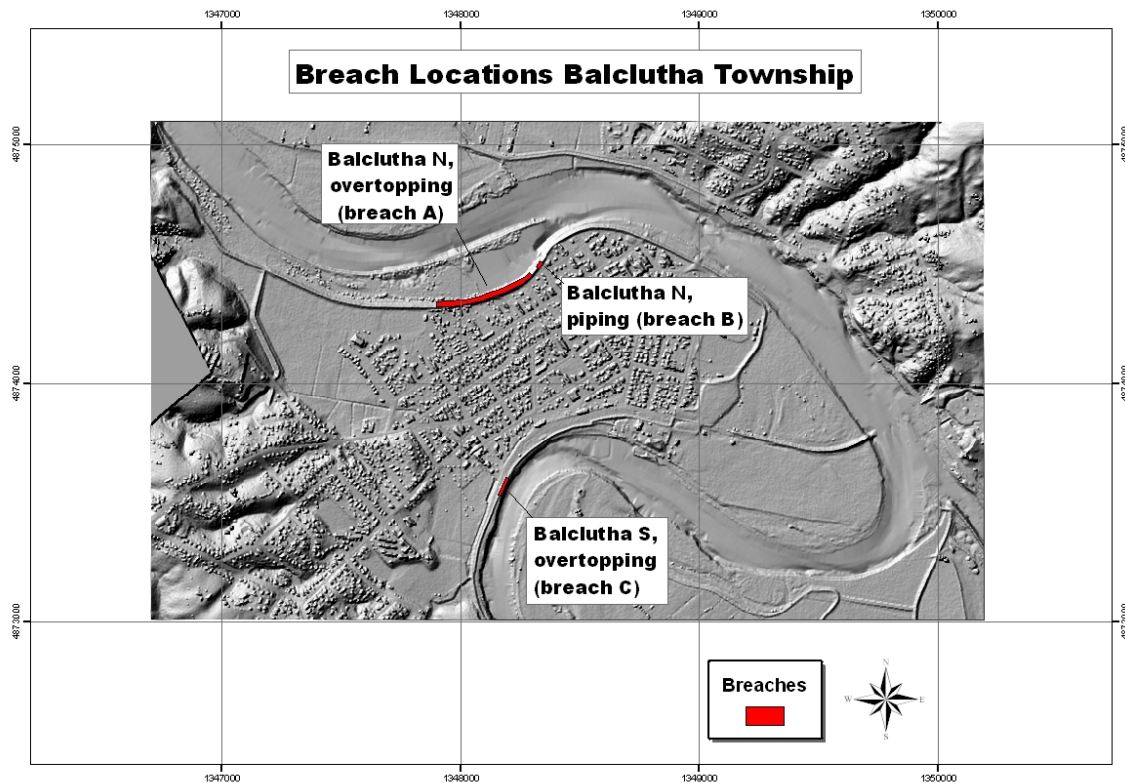


**Figure 6:** Locations North and South of Balclutha where floodbank breaching was possible.

### 2.5. Model assumptions and approximations

- Flow depths and velocities are calculated from the equations of depth-averaged shallow water flow as incorporated in the model. The inputs to the equations are derived from the supplied flow hydrographs, model boundary conditions, digitised topography elevations and the surface roughness. A log-law flow resistance equation is used to help overcome the problem of resistance coefficients changing with depth, as occurs with Manning's type equations (Smart 2002, 2004).

- Water depths calculated to be less than 50 mm are considered to be dry.

- Except at inflow boundaries, no assumptions are made on flow paths. The direction and velocity of flow are determined by bed topography, flow-resistance and the laws of hydrodynamics.

- The calibrated model provides mean water depth and depth-averaged velocities for each model cell. As these values are means for a cell, parameters for features smaller than the cell dimensions may not be accurately estimated. In the Clutha Delta model the cell size is 10m x 10m. In the Balclutha sub model the cell size is 4m x 4m. There are a total of 1.95 million cells in the Clutha Delta model and 461,000 cells in the Balclutha sub model.

- The model is a fixed bed model and any scour or deposition must be manually edited into the topography.

- Spillway gates were modelled as open above flows of 2710 $m^3$/s (ORC, May 2000).

- The model results are only as good as the data on which they are based. Potential causes of error include: topographical and roughness measurement errors, insufficient model resolution to represent small scale hydraulic effects, changes in topography and ground roughness between the calibration period and the time of a future flood, three-dimensional flow effects not represented in a 2-D model and morphodynamic effects such as unexpected scour and deposition in the river channel.

## 2.6. Model calibration

The flood used to calibrate the model occurred during November 1999 with a peak flow of 4167 $m^3$/s at Balclutha. This flood is close to the 4300 $m^3$/s magnitude of the prescribed ARI 50 year event and was the third highest event in 136 years of record (ORC, March 2000). The November 1999 flood was well reported with photographs taken on the day following the flood peak and maximum flood levels recorded at 28 locations within the model domain. The photographs and 23 more or less reliable levels provided an excellent basis for model calibration. Another factor aiding calibration was the knowledge that although the 1999 flood peak was estimated at 4167 $m^3$/s and the design flood for the majority of the stop banks was 4000 $m^3$/s, none of the floodbanks were significantly overtopped during the flood.

Boundary conditions used for calibration were the DEM measured in 2004, the 1999 flood hydrograph measured at the Balclutha water-level recorder and the ocean tide at the time, calculated using the NIWA NZ tidal model. There was no significant storm surge for the duration of the calibration flood. Hydraulic resistance of the channels was estimated from gauging records made in the Clutha, Koau and Matau channels. Out of channel (floodplain) roughness was based on interpretation of ground cover and, once classified, was not adjusted for calibration purposes. The surface roughnesses used are shown in Figure 7.

An initial attempt to calibrate the model gave predicted levels that were too high, even when the channel flow resistance was reduced within plausible limits. It was evident that locations of poor fit were typically associated with regions of very high bed shear stress. These bed stresses were sufficient to entrain large quantities of bed material and consequently the bed was artificially scoured (the DEM bathymetry was edited) at locations where scouring was indicated by the model. This technique was applied iteratively until bed shear reduced and the predicted peak water levels approached the field measured levels. The results of calibration for the Clutha Delta are shown at locations of measured flood marks in Figure 8. Considering that some flood marks can be imprecise and that the stated accuracy of the LiDAR derived elevations is ~ 0.15 m, the fit was judged to be satisfactory and most modelled water-levels were within 0.2 m of measured levels. A comparison of model-predicted water levels and an aerial photograph of the 1999 flood at the same location is given in Figure 9.

Various fixed bed conditions were consequently used for the different sized floods. For the Delta model:

- 10 yr ARI  -  River bed topography as surveyed in April 2005.

- 20 yr ARI  - April 2005 bed scoured according to bed shear stress.

- Calibration flood – Scoured to match water levels measured in the flood.

- 50 yr ARI and bigger – As for calibration flood (main channel shear does not increase significantly once floodbanks are overtopped).

For the high resolution Balclutha model the surveyed bed topography was used for the 10 yr and 20 yr ARI floods (a conservative assumption). The bed was scoured according to shear stress for the calibration flood and this bed was used for higher floods.

**Hydraulic Roughness Used for Calculations**

Roughness (in m)

| | | | | | | |
|---|---|---|---|---|---|---|
| 0.0015 | 0.003 | 0.0041 | 0.0061 | 0.029 | 0.115 | 1.2 |
| 0.0021 | 0.0031 | 0.0051 | 0.0101 | 0.058 | 0.385 | |

**Figure 7:** **Roughness length scales used for hydraulic modelling.**
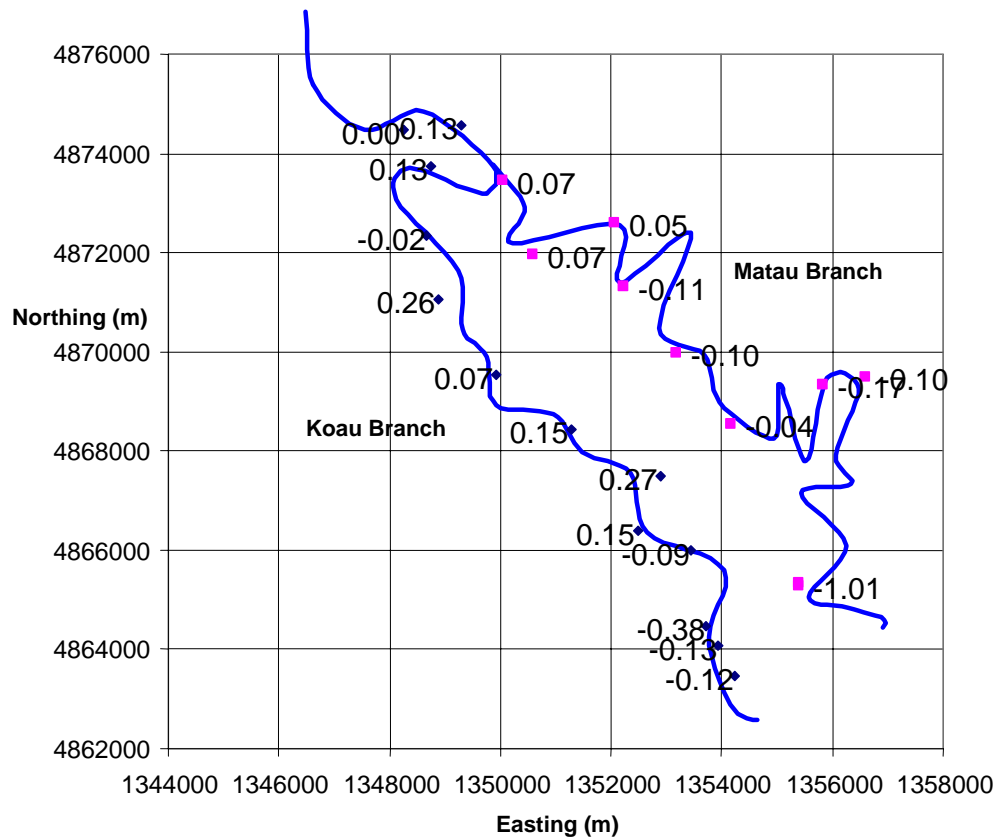
**Figure 8:** **Comparison of predicted water levels with flood marks measured after 1999 flood. Negative numbers indicate the model prediction is too low. Accuracy of the bottom right flood mark is suspect.**

### 2.7. Model runs

Modelling runs were carried out as prescribed in the contract and are listed in Appendix 1. For each of the runs there were two files produced, one containing maximum water depths (D) in metres and one containing maximum water velocity (V) in metres/second. Maximum depth and maximum velocity may have occurred at different times during the course of a flood.

**Note: Flood depths from the model should be used only in conjunction with the corresponding DEM topography files supplied. Calculation of flood levels by adding model flood depths to other topographic measurements such as field R.L. measurements may produce erroneous results. To supply or export data for other uses, add local model depths to local ground levels from the model DEM (at the same resolution) and provide third parties with local flood levels.**
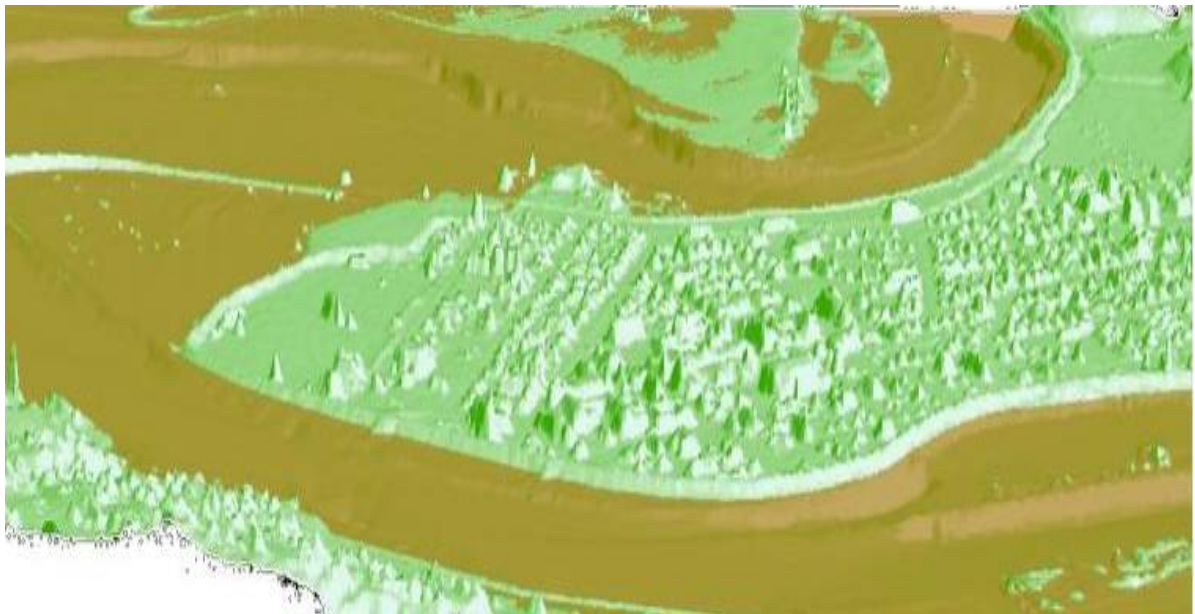
**Figure 9:** Comparison of 1999 flood photo (top) with model predicted water levels (below) for the Balclutha area.

# 3. Model results

As requested in the contract, output from the 106 hydraulic modelling runs has been provided for further analysis by the Council as MapInfo compatible files. Examples of the files are presented in this report to give an overview of results.

## 3.1. 2100 Sea Level with no flood event

Effects of a spring tide with the predicted 2100 sea level are shown in Figure 10. The floodbanks contain the inundation within the river channel, with minor out of channel flooding on the Matau Branch near the coast. Ponding behind floodbanks due to inadequate drainage could be extensive under these conditions but is not shown in this study.

## 3.2. 10 yr ARI flood event

In all scenarios no overtopping of floodbanks occurred.

## 3.3. 20 yr ARI flood event

In all scenarios no overtopping of floodbanks occurred.

## 3.4. 4000 m$^3$/s event

In all scenarios no overtopping of floodbanks occurred.

## 3.5. 50 yr ARI flood event

This event occurring at normal sea levels with no breaches is shown in Figure 11. There will be low overtopping of floodbanks on the Koau Branch NE of Otanomomo and on the Matau Branch at Raumati. This flood inundates the Barnego Flats, the Balclutha aerodrome, the river loop west of Chicory Road floodway, the Matau river loop at Mosley's Road and areas from opposite Kaitangata downstream. With a 100 yr storm surge affecting tide levels, stopbank overtopping NE of Otanomomo inundates the land between the Koau Branch and Kaka Point Rd and, if this floodbank breaches, the inundation extends inland to the Greenall Rd junction and south to the coast.
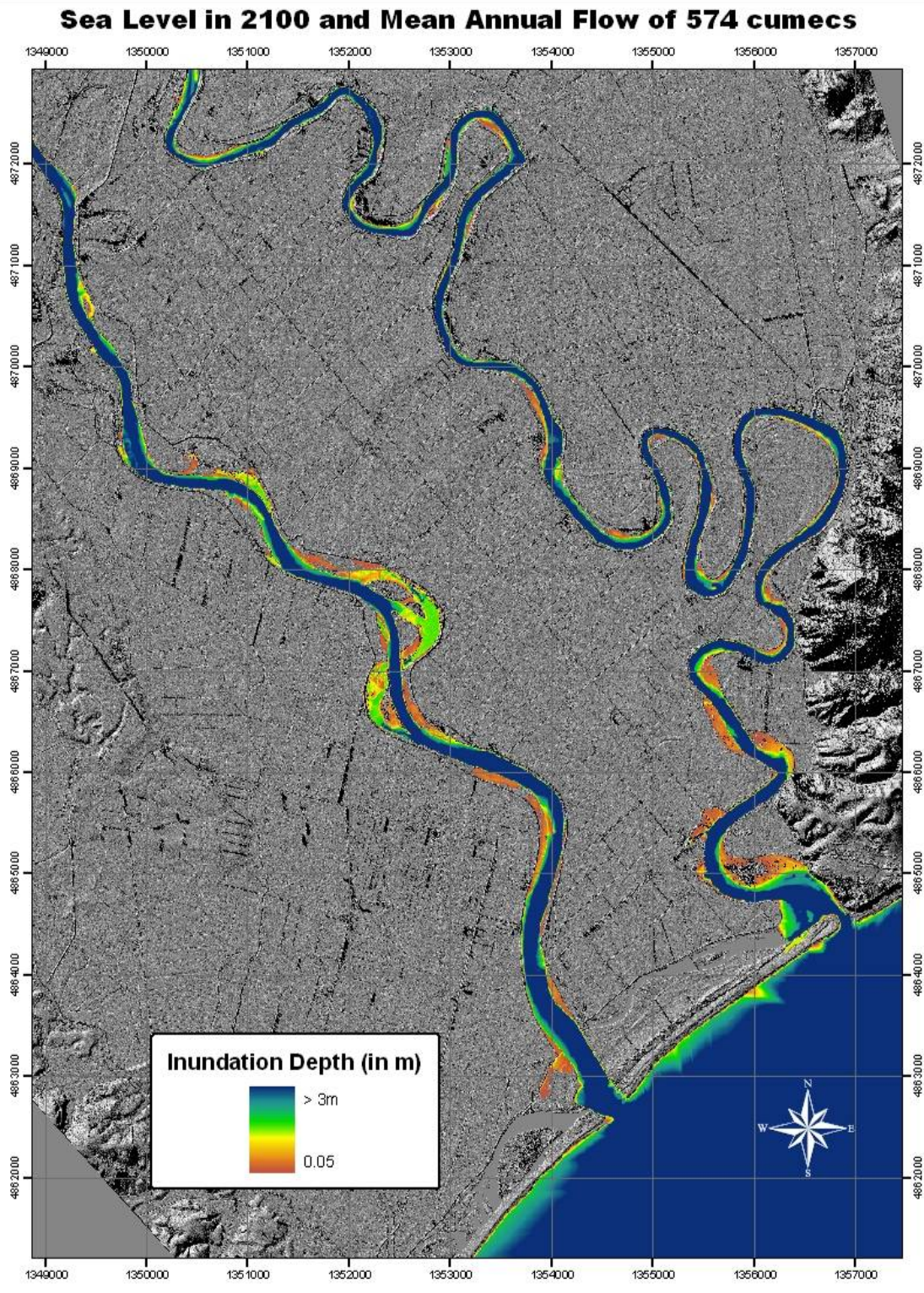
**Figure 10:** **Inundation for a spring tide, average river flow and anticipated 2100 sea level.**
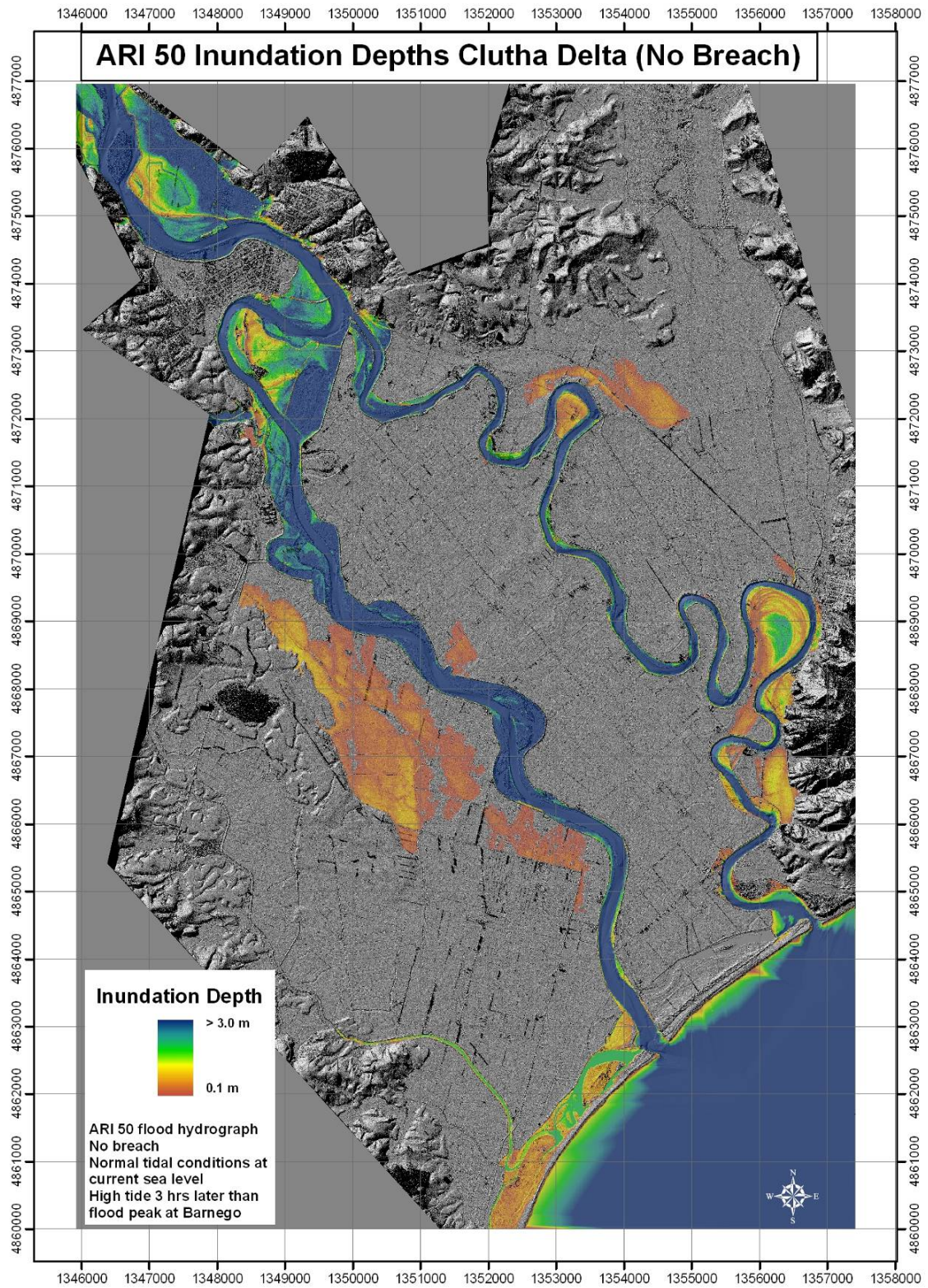
**Figure 11:** Inundation depths resulting from a 50yr ARI flood with no stopbank failure.

### 3.6. 100 yr ARI flood event

The results indicate that the 5200 $m^3$/s 100-yr flood may overtop the Balclutha floodbanks which were designed to contain a 5600 $m^3$/s flood. Three possible explanations are suggested as to why the model predictions of water levels are higher than the design levels:

1.    The stopbank design was made on the basis of a 1-D model which does not incorporate water level changes across cross-sections or momentum effects on the outside of curves and/or other 2-dimensional flow effects which have been incorporated in the present inundation models.

2.    Greater channel capacity may have been anticipated during the 5200 $m^3$/s 100-yr flood than is indicated by the 4167 $m^3$/s calibration flood. Greater scour would produce water levels lower than those indicated herein.

3.    Floodbanks may not yet have been constructed on the Koau Branch or breaches of the Koau floodbank may have occurred during floods used to guide the design of the Balclutha floodbanks (see following).

The overtopping of the Balclutha floodbanks does not occur if breaches occur on the Koau floodbanks downstream of Balclutha as shown in Figure 12. When the downstream floodbanks are intact, overtopping of Balclutha floodbanks occurs on the downstream side of Balclutha as shown in Figure 13. Breaches of the Koau floodbanks downstream of Balclutha also prevent inundation of much of Inch Clutha between the Koau and the Matau Branches (compare Figures 12 and 13).

### 3.7. 5600 $m^3$/s event

Results are similar to the 200 yr ARI flood described below. For specific details on local water depths and velocities see the accompanying Map Info compatible files

### 3.8. 200 yr ARI flood

The situation with no floodbank breaches is shown in Figure 14. Serious inundation occurs over most of the Clutha Delta. Figure 15 shows that breaching of the Koau floodbanks no longer protects Balclutha from inundation. Details of inundation within Balclutha are best represented by results of the Balclutha sub model runs. The higher resolution of these models allows flow paths to be more accurately defined and inundation depths differ slightly from the 10m model predictions. An example from the Balclutha sub model is given in Figure 16, which shows inundation depths in the town during a  200 yr ARI flood with no downstream floodbank breaches.
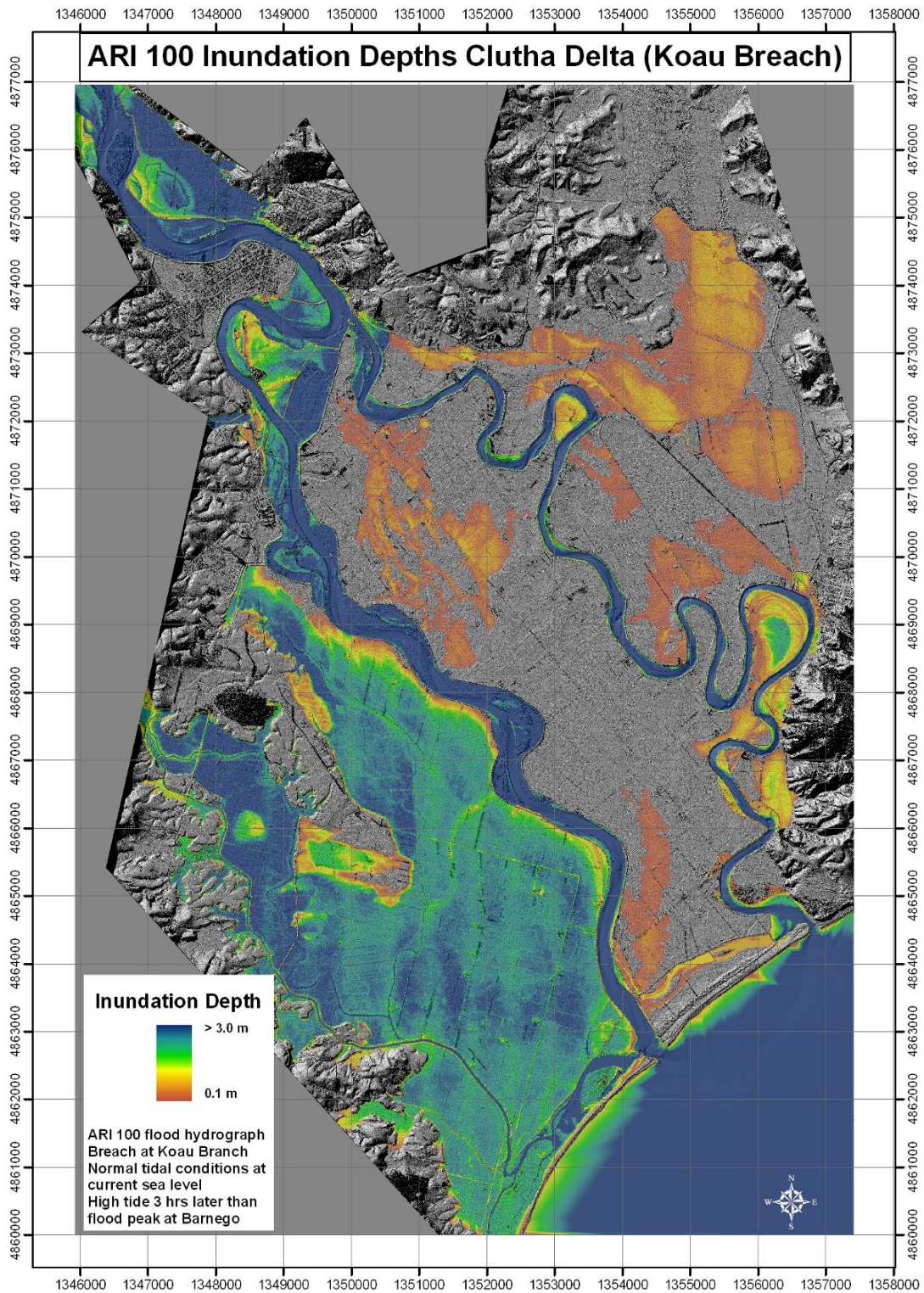
**Figure 12:** Inundation depths resulting from a 100yr ARI flood with breaching on the Koau branch.
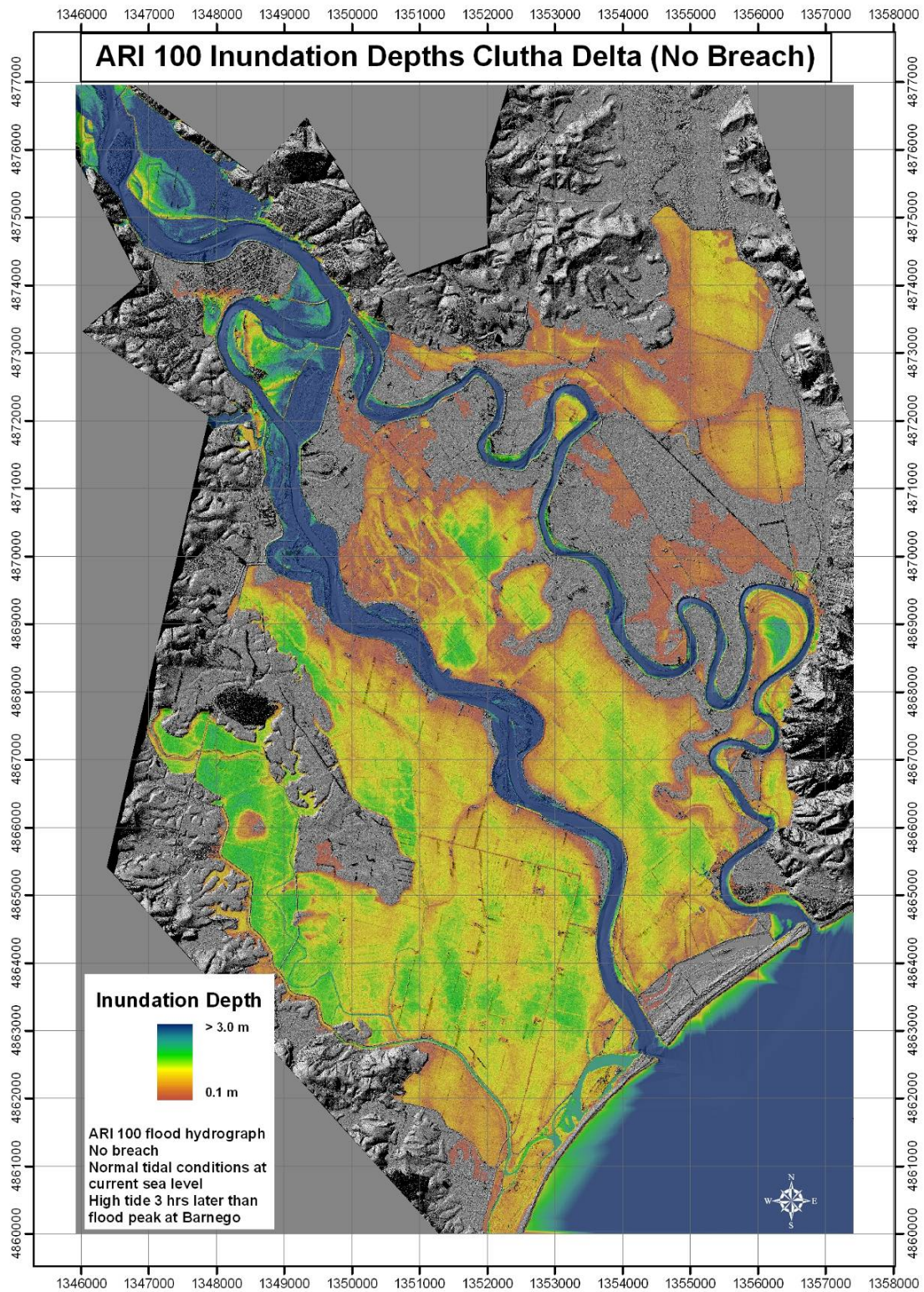
**Figure 13:** Inundation depths resulting from a 100 yr ARI flood with no breaching permitted.
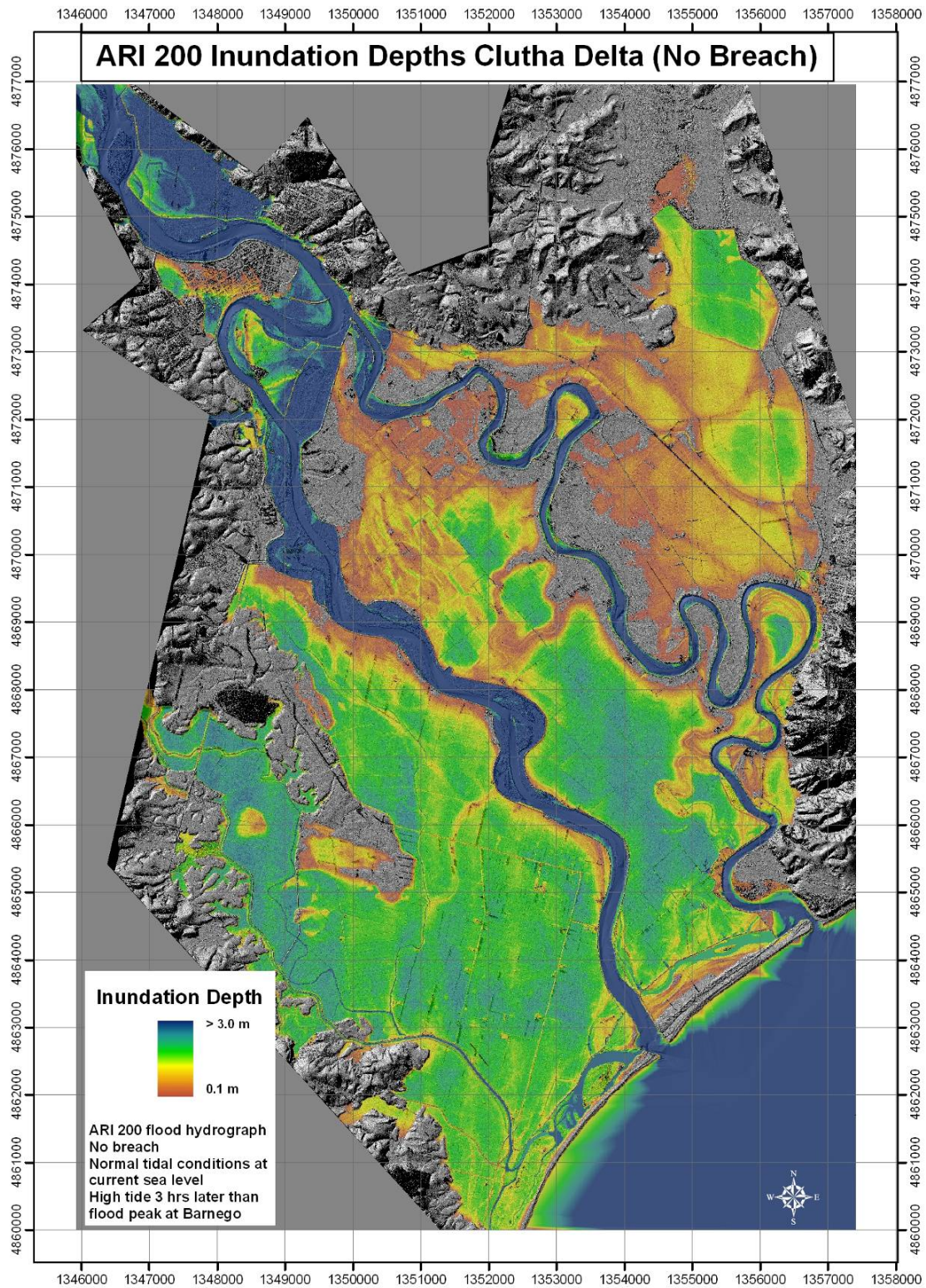
**Figure 14:** Inundation depths resulting from a 200yr ARI flood with no floodbank failure.
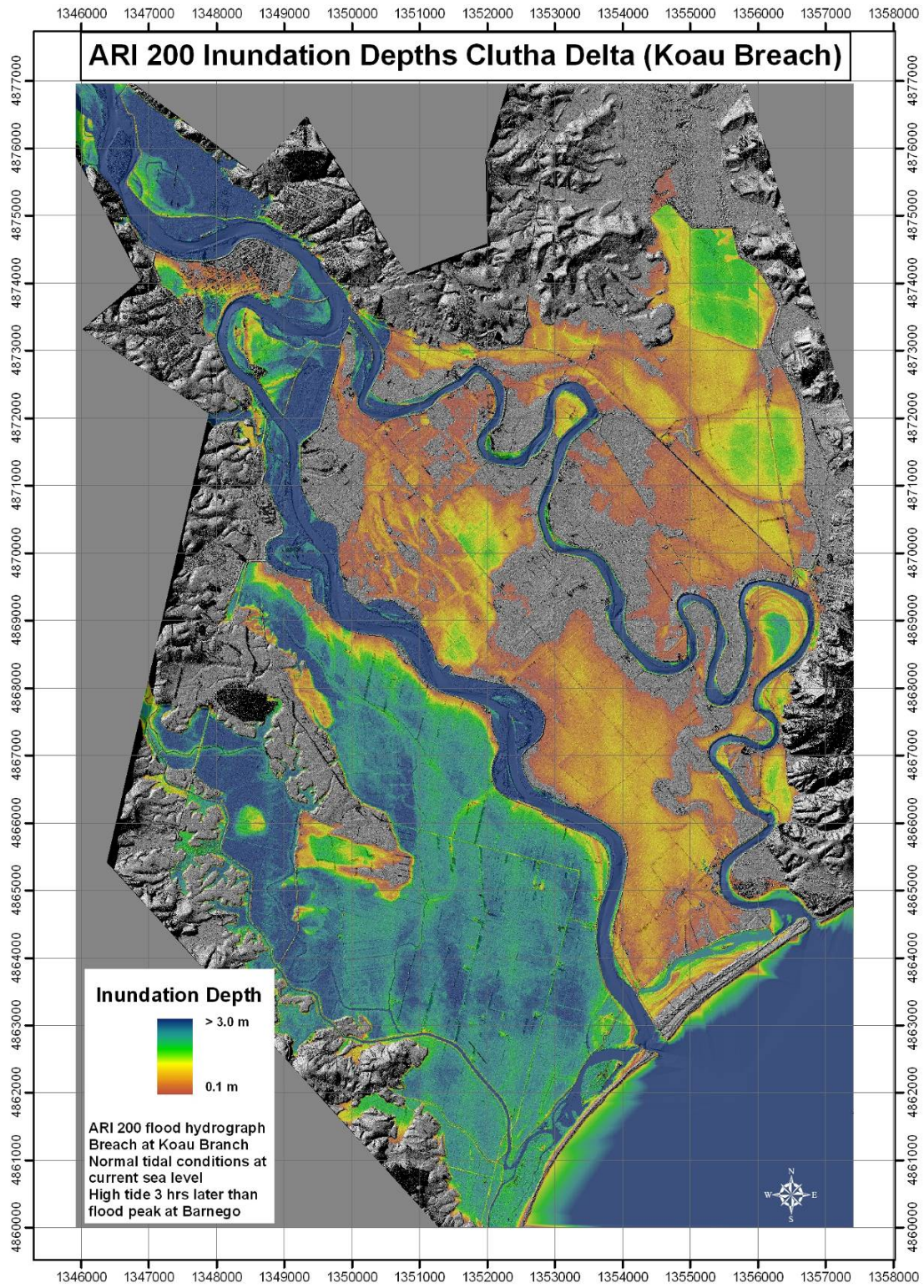
**Figure 15:** Inundation depths resulting from a 200yr ARI flood with breaching on the Koau branch.

### 3.9. 500 yr ARI flood event

Except for some high ground beside the rivers and along the coastal strip, the entire Clutha Delta is inundated, including that part of Balclutha that is on the flat. The modelled 500 yr ARI flood overtopped floodbanks slightly later than the 200 yr ARI flood due to its slower early rate of rise. More specific details on local water depths and maximum velocities during the 500 yr ARI flood event are given in the accompanying Map Info compatible files.
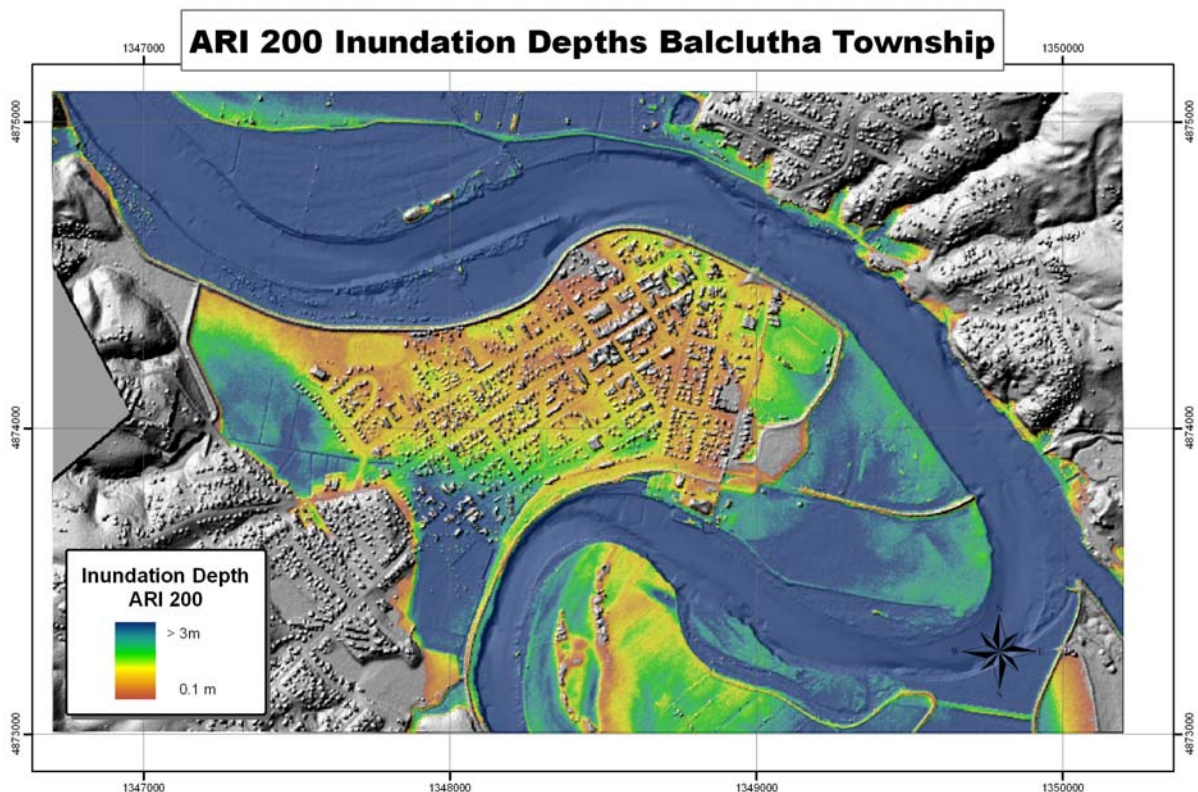


**Figure 16:** **Balclutha inundation predicted during a 200 yr ARI flood with no floodbank breaches.**

## 4. Hazard evaluation

A potential hazard exists if floodbanks do not meet the specifications of the project design. While it was not possible to check the original design specifications, low points in the present floodbanks have been detected at several locations. These are given in Table 2.

**Table 2:**     **Location of low points in the present floodbanks indicated by the LiDAR survey**

Balclutha Floodbanks:
E1348150 N4873510 to E1348245 N4873670

Matau Floodbanks:
E1352155 N4872440 to E1352140 N4872470
E1352815 N4870550 to E1352820 N4870620
E1352990 N4870060 to E1352900 N4870215
E1354115 N4869040 to E1354115 N4869100

Koau Floodbanks:
E1350000 N4868870 to E1349950 N4868890
E1349530 N4869300 to E1349520 N4869320
E1349925 N4869690 to E1349905 N4869765
E1351480 N4868330 to E1351510 N4868335
E1349915 N4868910 to E1349870 N4868950

Floodbank failure at the last of these locations prevents a 100 yr ARI flood from backing up into Balclutha township because the floodbank failure reduces upstream flood water levels. If the floodbank is resilient at this location or if it was raised, thus preventing a breach, the models indicate that parts of Balclutha would be flooded in a 100 yr ARI event.

Flood depths, velocities and consequential hazard are available at any point in the modelled domain by delving into the output files that have been supplied to the Council. As it is not possible to report on all 106 model variants, the 100 yr ARI flood with present mean sea level is used as an example to illustrate the locations of potential hazards.

### 4.1.     Hazard due to water depth

Different degrees of water depth hazard are illustrated on Figure 17 for the 100 yr ARI flood. It is considered that water in the 0.3 – 0.6 range would enter many buildings and stall common modes of transportation. Water depths in the 0.6 – 0.9 m range would present some risk of drowning and water levels deeper than 0.9 m would cause serious damage to dwellings and present a higher risk of loss of life.

### 4.2.     Velocity hazard

Areas with high water velocities are shown on Figure 18. Velocities greater than 1 m/s present a risk to unsecured pedestrians, particularly if the water is deep. Velocities greater than 3 m/s indicate a strong likelihood of scouring of unprotected structures.

In several locations (usually on the outside of bends), significant velocities occur against the stopbanks. Failure of stopbanks from lateral scouring has not been considered in the present model runs and such failures could markedly change the inundation extent.

**ARI 100 Inundation Depths Clutha Delta**

**Inundation Depths**

- ☐ < 0.3 m
- 🟨 0.3 - 0.6 m
- 🟧 0.6 - 0.9 m
- 🟥 > 0.9 m
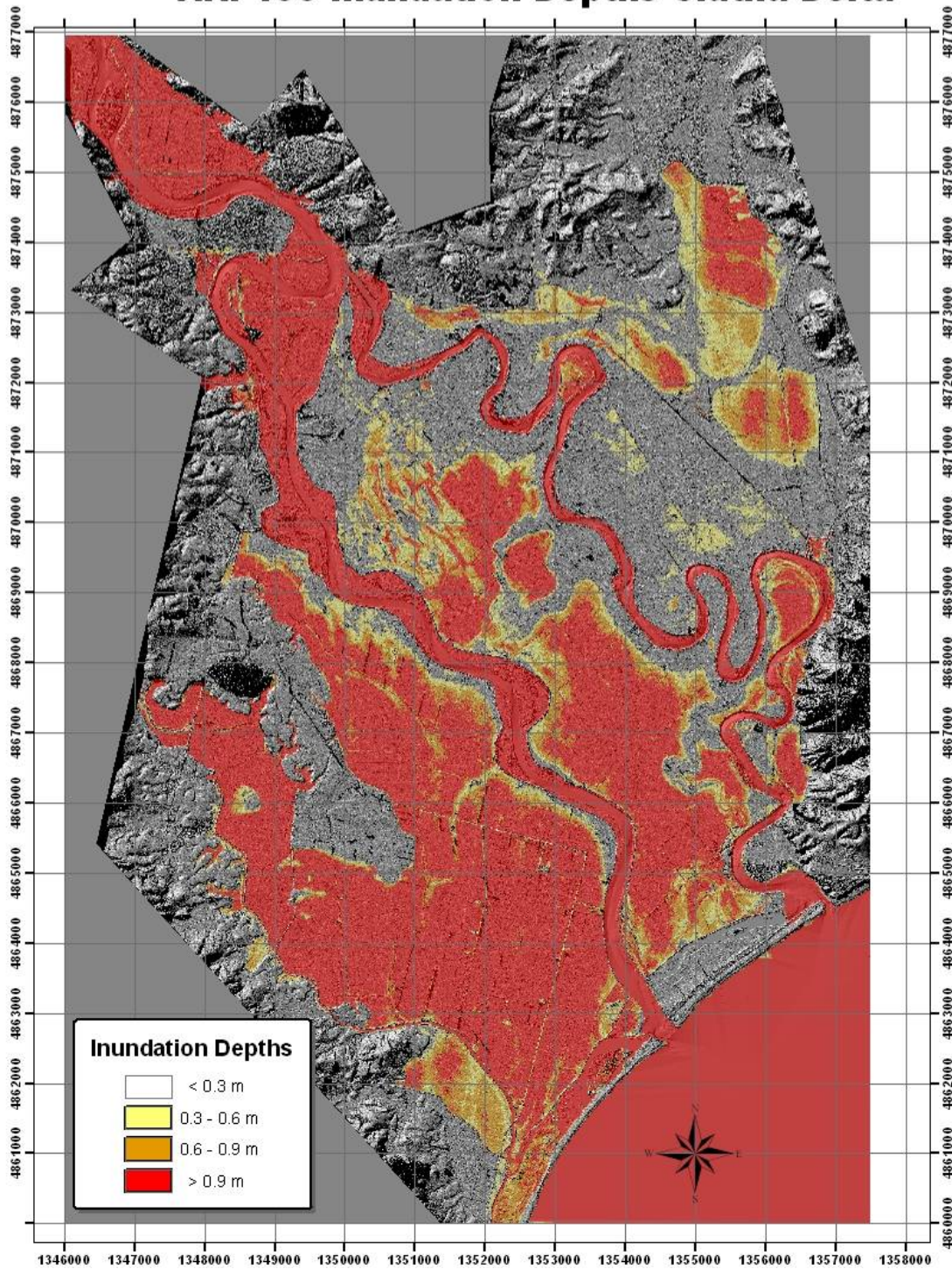
**Figure 17:** Hazardous locations due to water depth during a 100 yr ARI flood with present sea level.
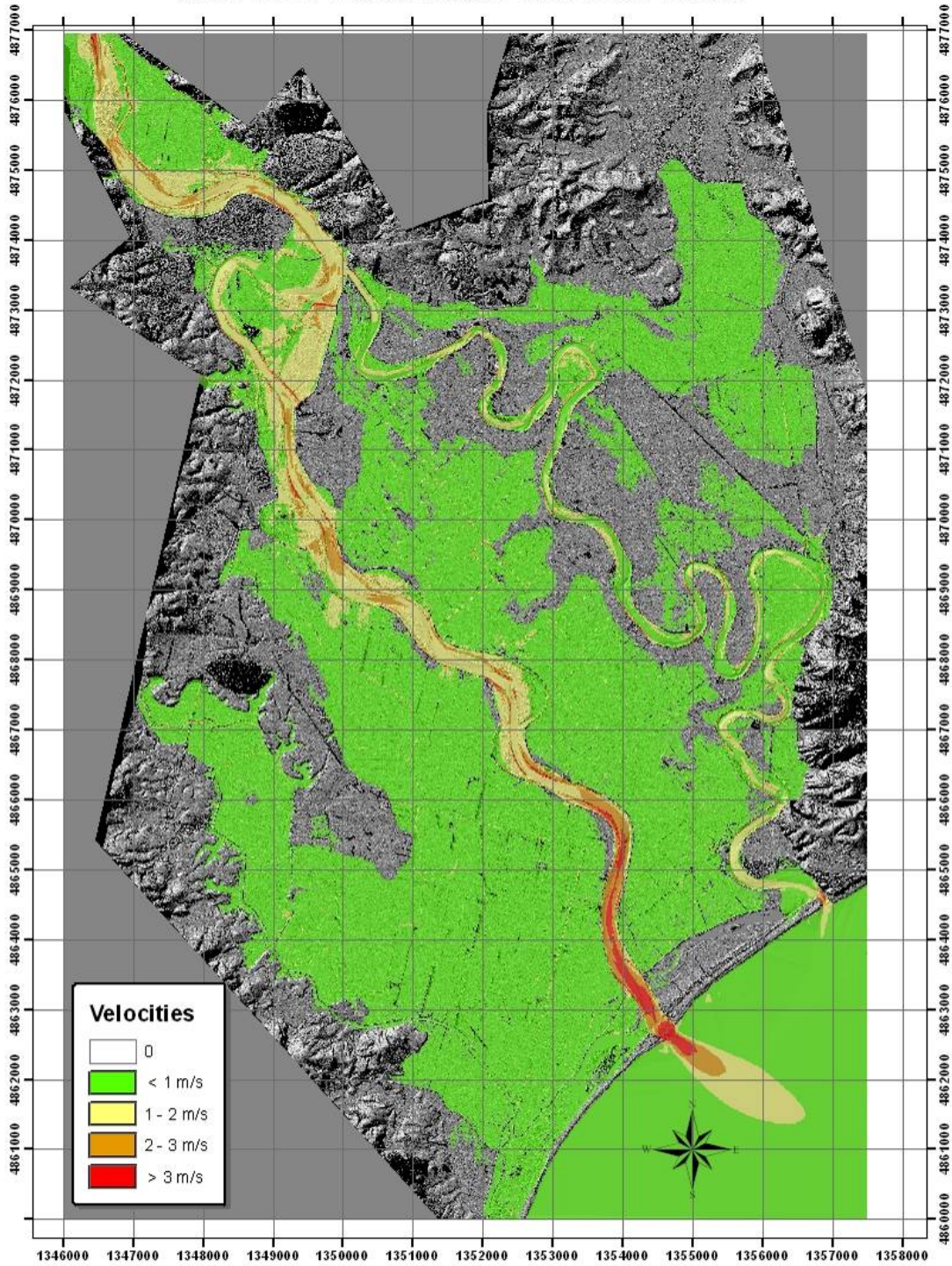
**Figure 18:** Hazard due to water velocities during an ARI 100 yr flood at present sea level

# 5.  Summary and Conclusions

A 10 m grid model of the greater Clutha Delta region and a 4 m grid model of the Balclutha township were developed and evaluated using the *Hydro 2de* numerical hydraulic model in conjunction with 8 design flood hydrographs, 3 sea-level scenarios and various floodbank breach scenarios.

The results show that overtopping of sections of the present floodbanks occurs from around a 50 yr ARI flood.

Depending on downstream conditions, a 100 yr ARI flood may or may not flood into Balclutha township from the downstream side. A breach of the Koau floodbanks downstream of Balclutha can help protect the township and also prevent inundation of much of Inch Clutha. A piping failure of the stopbank on the North side of Balclutha township would be catastrophic and cause great loss of life if the township were not evacuated. Details of local flood depths and velocities may be found in the Map Info compatible files supplied in conjunction with this report.

The bed, as surveyed in 2005, must undergo considerable vertical scouring to pass floods such as the 1999 calibration flood. Should future scouring not occur, or should it evolve in a different manner to that indicated by the models, inundation levels different from those predicted by the models could result.

# 6.  References

Otago Regional Council (March 2000). Clutha River Catchment Updated Flood Frequency Analyses Following the November 1999 Flood Event. ISBN: 1-877265-02-0, 20 p.

Otago Regional Council (May 2000). Lower Clutha Flood Control and Drainage Scheme, Operation and Maintenance Manual. 42 p.

Smart, G.M.; Duncan, M.J.; Walsh, J. (2002). Relatively Rough Flow Resistance Equations. *Journal of Hydraulic Engineering, ASCE 128(6)*: 568-578.

Smart, G.M. (2004). An Improved Flow Resistance Formula. Proceedings of River Flow 2004, A2-15, Balkema, Netherlands: 259-263.

# Appendix 1:    Clutha Delta model and Balclutha model

**Clutha Delta Model (10m resolution)**

| File name | Flood | Sea level | Breach | Constraints |
|-----------|-------|-----------|--------|-------------|
| Calibration1999.zip | 1999 | actual | nil | Calibration flood |
| MeanFlowSL2100.zip | Mean flow | 2 | nil | 2100 sea level, no flood |
| | | | | |
| ARI10br12.zip | ARI 10 | 1 | Koau | 2005 bed bathymetry |
| ARI20br12.zip | ARI 20 | 1 | Koau | 2005 bed bathymetry |
| ARI50br12.zip | ARI 50 | 1 | Koau | Scoured bed used |
| ARI100br12.zip | ARI 100 | 1 | Koau | Scoured bed used |
| ARI200br12.zip | ARI 200 | 1 | Koau | Scoured bed used |
| ARI500br12.zip | ARI 500 | 1 | Koau | Scoured bed used |
| 4000br12.zip | 4000 $m^3$/s | 1 | Koau | Scoured bed used |
| 5600br12.zip | 5600 $m^3$/s | 1 | Koau | Scoured bed used |
| | | | | |
| ARI10SL2100br12.zip | ARI 10 | 2 | Koau | 2005 bed bathymetry |
| ARI20SL2100br12.zip | ARI 20 | 2 | Koau | 2005 bed bathymetry |
| ARI50SL2100br12.zip | ARI 50 | 2 | Koau | Scoured bed used |
| ARI100SL2100br12.zip | ARI 100 | 2 | Koau | Scoured bed used |
| ARI200SL2100br12.zip | ARI 200 | 2 | Koau | Scoured bed used |
| ARI500SL2100br12.zip | ARI 500 | 2 | Koau | Scoured bed used |
| 4000SL2100br12.zip | 4000 $m^3$/s | 2 | Koau | Scoured bed used |
| 5600SL2100br12.zip | 5600 $m^3$/s | 2 | Koau | Scoured bed used |
| | | | | |
| ARI10SSbr12.zip | ARI 10 | 3 | Koau | 2005 bed bathymetry |
| ARI20SSbr12.zip | ARI 20 | 3 | Koau | 2005 bed bathymetry |
| ARI50SSbr12.zip | ARI 50 | 3 | Koau | Scoured bed used |
| ARI100SSbr12.zip | ARI 100 | 3 | Koau | Scoured bed used |
| ARI200SSbr12.zip | ARI 200 | 3 | Koau | Scoured bed used |
| ARI500SSbr12.zip | ARI 500 | 3 | Koau | Scoured bed used |
| 4000SSbr12.zip | 4000 $m^3$/s | 3 | Koau | Scoured bed used |
| 5600SSbr12.zip | 5600 $m^3$/s | 3 | Koau | Scoured bed used |
| | | | | |
| ARI10br3.zip | ARI 10 | 1 | Mosley | 2005 bed bathymetry |
| ARI20br3.zip | ARI 20 | 1 | Mosley | 2005 bed bathymetry |
| ARI50br3.zip | ARI 50 | 1 | Mosley | Scoured bed used |
| ARI100br3.zip | ARI 100 | 1 | Mosley | Scoured bed used |
| ARI200br3.zip | ARI 200 | 1 | Mosley | Scoured bed used |
| ARI500br3.zip | ARI 500 | 1 | Mosley | Scoured bed used |
| 4000br3.zip | 4000 $m^3$/s | 1 | Mosley | Scoured bed used |
| 5600br3.zip | 5600 $m^3$/s | 1 | Mosley | Scoured bed used |
| | | | | |
| ARI10SL2100br3.zip | ARI 10 | 2 | Mosley | 2005 bed bathymetry |
| ARI20SL2100br3.zip | ARI 20 | 2 | Mosley | 2005 bed bathymetry |

| File name | Flood | Sea level | Breach | Constraints |
|---|---|---|---|---|
| ARI50SL2100br3.zip | ARI 50 | 2 | Mosley | Scoured bed used |
| ARI100SL2100br3.zip | ARI 100 | 2 | Mosley | Scoured bed used |
| ARI200SL2100br3.zip | ARI 200 | 2 | Mosley | Scoured bed used |
| ARI500SL2100br3.zip | ARI 500 | 2 | Mosley | Scoured bed used |
| 4000SL2100br3.zip | 4000 $m^3$/s | 2 | Mosley | Scoured bed used |
| 5600SL2100br3.zip | 5600 $m^3$/s | 2 | Mosley | Scoured bed used |
| | | | | |
| ARI10SSbr3.zip | ARI 10 | 3 | Mosley | 2005 bed bathymetry |
| ARI20SSbr3.zip | ARI 20 | 3 | Mosley | 2005 bed bathymetry |
| ARI50SSbr3.zip | ARI 50 | 3 | Mosley | Scoured bed used |
| ARI100SSbr3.zip | ARI 100 | 3 | Mosley | Scoured bed used |
| ARI200SSbr3.zip | ARI 200 | 3 | Mosley | Scoured bed used |
| ARI500SSbr3.zip | ARI 500 | 3 | Mosley | Scoured bed used |
| 4000SSbr3.zip | 4000 $m^3$/s | 3 | Mosley | Scoured bed used |
| 5600SSbr3.zip | 5600 $m^3$/s | 3 | Mosley | Scoured bed used |
| | | | | |
| ARI10br4.zip | ARI 10 | 1 | Lawson | 2005 bed bathymetry |
| ARI20br4.zip | ARI 20 | 1 | Lawson | 2005 bed bathymetry |
| ARI50br4.zip | ARI 50 | 1 | Lawson | Scoured bed used |
| ARI100br4.zip | ARI 100 | 1 | Lawson | Scoured bed used |
| ARI200br4.zip | ARI 200 | 1 | Lawson | Scoured bed used |
| ARI500br3.zip | ARI 500 | 1 | Lawson | Scoured bed used |
| 4000br4.zip | 4000 $m^3$/s | 1 | Lawson | Scoured bed used |
| 5600br4.zip | 5600 $m^3$/s | 1 | Lawson | Scoured bed used |
| | | | | |
| ARI10SL2100br4.zip | ARI 10 | 2 | Lawson | 2005 bed bathymetry |
| ARI20SL2100br4.zip | ARI 20 | 2 | Lawson | 2005 bed bathymetry |
| ARI50SL2100br4.zip | ARI 50 | 2 | Lawson | Scoured bed used |
| ARI100SL2100br4.zip | ARI 100 | 2 | Lawson | Scoured bed used |
| ARI200SL2100br4.zip | ARI 200 | 2 | Lawson | Scoured bed used |
| ARI500SL2100br4.zip | ARI 500 | 2 | Lawson | Scoured bed used |
| 4000SL2100br4.zip | 4000 $m^3$/s | 2 | Lawson | Scoured bed used |
| 5600SL2100br4.zip | 5600 $m^3$/s | 2 | Lawson | Scoured bed used |
| | | | | |
| ARI10SSbr4.zip | ARI 10 | 3 | Lawson | 2005 bed bathymetry |
| ARI20SSbr4.zip | ARI 20 | 3 | Lawson | 2005 bed bathymetry |
| ARI50SSbr4.zip | ARI 50 | 3 | Lawson | Scoured bed used |
| ARI100SSbr4.zip | ARI 100 | 3 | Lawson | Scoured bed used |
| ARI200SSbr4.zip | ARI 200 | 3 | Lawson | Scoured bed used |
| ARI500SSbr4.zip | ARI 500 | 3 | Lawson | Scoured bed used |
| 4000SSbr4.zip | 4000 $m^3$/s | 3 | Lawson | Scoured bed used |
| 5600SSbr4.zip | 5600 $m^3$/s | 3 | Lawson | Scoured bed used |

**Balclutha Model (4 m resolution)**

| File name | Flood | Breach | Constraints |
|---|---|---|---|
| BalARI10.zip | ARI 10 | No breach | 2005 bed bathymetry |
| BalARI20.zip | ARI 20 | No breach | 2005 bed bathymetry |
| BalARI50.zip | ARI 50 | No breach | Scoured bed used, no breaches of delta banks |
| BalARI100.zip | ARI 100 | No breach | Scoured bed used, no breaches of delta banks |
| BalARI200.zip | ARI 200 | No breach | Scoured bed used, no breaches of delta banks |
| BalARI500.zip | ARI 500 | No breach | Scoured bed used, no breaches of delta banks |
| Bal4000.zip | 4000 $m^3$/s | No breach | Scoured bed used, no breaches of delta banks |
| Bal4000.zip | 5600 $m^3$/s | No breach | Scoured bed used, no breaches of delta banks |
| | | | |
| BalARI10breachA.zip | ARI 10 | Barnego Island | 2005 bed bathymetry |
| BalARI20breachA.zip | ARI 20 | Barnego Island | 2005 bed bathymetry |
| BalARI50breachA.zip | ARI 50 | Barnego Island | Scoured bed used, piping breach |
| BalARI100breachA.zip | ARI 100 | Barnego Island | Scoured bed used, piping breach |
| BalARI200breachA.zip | ARI 200 | Barnego Island | Scoured bed used, piping breach |
| BalARI500breachA.zip | ARI 500 | Barnego Island | Scoured bed used, piping breach |
| Bal4000breachA.zip | 4000 $m^3$/s | Barnego Island | Scoured bed used, piping breach |
| Bal5600breachA.zip | 5600 $m^3$/s | Barnego Island | Scoured bed used, piping breach |
| | | | |
| BalARI10breachB.zip | ARI 10 | Barnego Road | 2005 bed bathymetry |
| BalARI20breachB.zip | ARI 20 | Barnego Road | 2005 bed bathymetry |
| BalARI50breachB.zip | ARI 50 | Barnego Road | Scoured bed used, potential overtopping breach |
| BalARI100breachB.zip | ARI 100 | Barnego Road | Scoured bed used, potential overtopping breach |
| BalARI200breachB.zip | ARI 200 | Barnego Road | Scoured bed used, potential overtopping breach |
| BalARI500breachB.zip | ARI 500 | Barnego Road | Scoured bed used, potential overtopping breach |
| Bal4000breachB.zip | 4000 $m^3$/s | Barnego Road | Scoured bed used, potential overtopping breach |
| Bal5600breachB.zip | 5600 $m^3$/s | Barnego Road | Scoured bed used, potential overtopping breach |
| | | | |
| BalARI10breachC.zip | ARI 10 | Town NW bank | 2005 bed bathymetry |
| BalARI20breachC.zip | ARI 20 | Town NW bank | 2005 bed bathymetry |
| BalARI50breachC.zip | ARI 50 | Town NW bank | Scoured bed used, potential downstream breach |

| File name | Flood | Breach | Constraints |
| --- | --- | --- | --- |
| BalARI100breachC.zip | ARI 100 | Town NW bank | Scoured bed used, potential downstream breach |
| BalARI200breachC.zip | ARI 200 | Town NW bank | Scoured bed used, potential downstream breach |
| BalARI500breachC.zip | ARI 500 | Town NW bank | Scoured bed used, potential downstream breach |
| Bal4000breachC.zip | 4000 m$^3$/s | Town NW bank | Scoured bed used, potential downstream breach |
| Bal5600breachC.zip | 5600 m$^3$/s | Town NW bank | Scoured bed used, potential downstream breach |

## Appendix 2: River Cross Sections Supplied.

| Clutha River file names | Koau Branch file names | Matau Branch file names |
|---|---|---|
| C1.xls | K9.xls | M5.xls |
| C2.xls | K10.xls | M6.xls |
| C3.xls | K10A.xls | M7.xls |
| C5.xls | K11.xls | M8.xls |
| C6.xls | K12.xls | M9.xls |
| C7.xls | K13.xls | M10.xls |
| C8.xls | K48.xls | M11.xls |
| C9.xls | K54.xls | M12.xls |
| C10.xls | K64.xls | M94.xls |
| C11.xls | K67.xls | M99.xls |
| C12.xls | K84.xls | M128.xls |
| C13.xls | | M140.xls |
| | | M147.xls |
| | | M154.xls |
| | | M195.xls |
| | | M202.xls |
| | | M223.xls |