REPORT

Tonkin+Taylor

Western Catchment Flood Hazard Mapping

Model Build Report

Prepared for

Rotorua Lakes Council

Prepared by

Tonkin & Taylor Ltd

Date

March 2025

Job Number

1010988.9400 v2.0

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Document control

Title: Western Catchment Flood Hazard Mapping					
Date	**Version**	**Description**	**Prepared by:**	**Reviewed by:**	**Authorised by:**
06/09/2024	1.0	Draft for RLC and peer review	A. White	M. Pennington	L. Partner
27/03/2025	2.0	Final – including changes to section 2.1	A. White	M. Pennington	L. Partner

Distribution:

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Table of contents

1 Background

The RLC western catchment TUFLOW model was initially built by Tonkin & Taylor (T+T) in 2020 to support the Utuhina catchment master planning work for Rotorua Lakes Council (RLC). The model was further refined to support the Linton Park East dam design work in 2021. That version of the model was peer reviewed by Barnett & MacMurray Ltd in September 2021.

The most recent engagement with RLC is for the Infrastructure Acceleration Fund (IAF) project, and as part of this engagement T+T has further refined the TUFLOW model that covers the western part of urban Rotorua. This model was developed, and has been used, for assessments of flood performance of the urban drainage network. Future development scenarios have been considered and the model has been used to assess flooding effects from development and to conceptualise potential mitigation measures.

T+T is now engaged to refine the model further using rainfall and flow data collected by RLC then use this model to map flood hazard across the western portion of urban Rotorua for a range of scenarios and prepare a model build report. Accompanying this report is a series of flood hazard rasters. Model refinement has been undertaken through further calibration of the model from data recorded during a flood event dated May 2024, which builds upon previous model calibration exercises that were undertaken before this model update. Therefore, 'calibration' in this report is defined as the continuous process of model refinement as more data becomes available from recorded events.

T+T have also undertaken modelling of the eastern part of urban Rotorua, but this is using a separate model not covered in this report.

2 Purpose and scope

2.1 Purpose

The purpose of this work is to map flood hazards across the western part of urban Rotorua, using the TUFLOW western model and to document the building of the model in a report. It is understood that RLC intends to use the model outputs for flood mapping purposes and to identify areas exposed to potential flood hazard.

While this model has not been built for any other specific purposes, it may be used (with care) for a range of other outcomes. For example, if development levels are required at a property specific scale (not consistent with the model architecture), then model results can be used as one of many different considerations in setting such levels (model results should not be the only source of information accessed). Model results should be used in conjunction with a more detailed site specific assessment. This assessment should be carried out by an experienced stormwater engineer and include:

- Consideration of multiple flooding scenarios and flood level sensitivity
- A review of the model limitations (Section 2.2) and how they may affect the results at the specific site
- Consideration of site specific information such as recent surveys, public drainage network data, physical constraints around the site such as fences, buildings and walls and any recent development that has occurred.

2.2 Key model limitations

Listed below are a summary of limitations to the modelling work, described further in the following sections, that RLC will need to consider when interpreting any model outputs.

- Digital Elevation Model (DEM) derived from remotely sensed LiDAR survey data (refer Section 3.2). The limitations of accuracy of LiDAR data are well understood, and these limitations will apply to the model results obtained. In particular, LiDAR survey data and the resulting DEM will have lower accuracy in areas such as incised waterways, heavily vegetated areas and water bodies. Where ground levels have been changed since the LiDAR survey was captured, the DEM and hence the model will not recognise these changes and will be out of date.
- Direct rainfall methodology (refer Section 0) - A direct rainfall approach has been applied to this model, which can highlight accuracy deficiencies in input data by showing small “puddles” in predicted flooding. It is usual for flood depth results to be “cleaned” by removing puddles before publication or further analysis. T+T has presented cleaned model results in this report.
- Another limitation of direct rainfall hydrology is that runoff into the piped network relies on the modelled surface topography and roughness, while in reality, rainfall is intercepted by roofs and yards, with their own small-scale/private drainage systems that help to convey any runoff quickly and efficiently into the public stormwater system. It is impractical to model every private drainage and roof collection system, so the simplifying assumption is made that rainfall intercepted by the ‘bare earth’ terrain generated from LiDAR ground elevation data will travel to the receiving public (piped) stormwater system in much the same way. This is aided by depth varying roughness and TUFLOW sub-grid sampling. We note that there is no pipe flow or manhole level data that could be used in conjunction with rainfall gauge data in this catchment to validate this assumption. While a direct rainfall hydrology is adequate for the purpose of this project, it should be noted that there is a tendency for this modelling approach to underestimate capture into the stormwater network, and thus any use of the modelled pipe flows must bear this potential limitation in mind.
- Hydrological losses (refer Section 3.5) - The model has been built at a “city-wide” scale and as such several elements have been defined in the model at a city-wide scale. This is most obvious with regard to hydrological losses such as land use roughness zones that are based predominantly on the LCDBv5 national dataset, which is current as of December 2018. Where land use has changed since the latest update to this dataset, or where finer localised detail occurs, the model will not recognise these details (and will be out of date). This is also true of urban percentage imperviousness which has been estimated at city-wide scale.
- Stormwater infrastructure (refer Section 3.3) – Inclusions of pits, pipes, and other hydraulic structures as 1D elements in the model has been based on data extracted from the RLC GIS.

Given the points above, for areas where a high degree of accuracy in model outputs is required, or where there is a significant consequence associated with flood level assessment, or where ground levels are known to have changed, the recommended approach is a site-specific assessment instead of the city-wide scale modelling that has been undertaken as part of this scope of work.

2.3 Model build and mapping scope

The following steps were taken:

- Obtain the latest DEM ground surface available from the LINZ website. This was dated 2023.
- Check the new DEM. We have conducted checks to ensure that the new DEM meets our usual modelling quality requirements before being used in the model.
- Apply new DEM to the model. This involves replacing the existing with the new DEM, and requires that all connections in the model be checked.

- Drainage network updates. We have taken into account all known updates since the previous model build was completed, as provided by RLC.
- Calibrate the model using data from rainfall and flow monitoring sites. This is reported on in Section 5.

The model has been run for a series of different design events, as reported on in Section 6.

Mapped outputs have been produced to show maximum depth, water level and depth x velocity (D x V) product across the model domain, and are described in Section 7.

3 Hydraulic model

The model build scope agreed with RLC included the following considerations:

- A direct-rainfall hydrological approach with the use of design rainfall
- Soil infiltration losses using the initial and continuing loss method to represent catchment hydrological conditions
- A digital elevation model (DEM), derived from LiDAR data sources, to be applied to TUFLOW as a 1 m x 1 m (1 m^2) computational grid referenced to Moturiki 1953 Vertical Datum.

Model build details for the TUFLOW model are summarised in Table 3-1. Much of this section has been reported on previously as part of separate engagements, and this report is intended to be a combination of previous model build reports and the updates to provide a single model build report.

Table 3-1: Model build summary

Model element	Report section	Description
Model software		2023-03-AE TUFLOW HPC solver
Model overview		A 2D rain on grid model that includes some 1D hydraulic structures.
Time step		The TUFLOW HPC model applies an adaptive time step, based on maintenance of a Courant condition.
Eddy viscosity		Default WU viscosity coefficients for C3D and C2D (7.0, and 0.0 respectively).
Datums		Vertical: Moturiki 1953 (MVD53) Horizontal: New Zealand Transverse Mercator (NZTM) (NZGD2000)
Model extent	3.1	Two separate models have been developed, covering Western and Eastern areas respectively. This report only covers the Western model.
Model topography	3.2	A 1m x 1m (1 m^2) gridded DEM for ground level used in the model was provided by RLC. Outside of this area a 2 m x 2 m DEM was used.
Model cell size	3.2.1	Using the Quadtree solver, grid size is varied across the model domain.
Hydrology		Design rainfall depths were estimated using data from the National Institute of Water and Atmospheric Research (NIWA) High Intensity Rainfall Design System (HIRDS) V4 values. Direct rainfall hydrology.
Downstream boundary		Lake Rotorua level
Land use roughness	3.4	Land use zones defined by Landcare Research's Land Cover Database version 5 (LCDBv5). Roughness has been modified through the calibration process.
Soil infiltration	3.5	Initial and continuing loss method, with parameters attained through the calibration process.
Hydraulic structures	3.3	As-built information for relevant 1D hydraulic elements sourced from RL.

3.1 Model domain

This reporting covers the model extent as shown in Figure 3-1 below. The model extent covers the entire Utuhina Stream catchment, and it includes parts of the Waiowhiro Stream to the north, and Puarenga Stream to the south. The Puarenga Stream catchment is not modelled, instead inflows are applied at the model boundary where it meets the upstream end of the Puarenga Stream, these inflows have been provided by BOPRC.

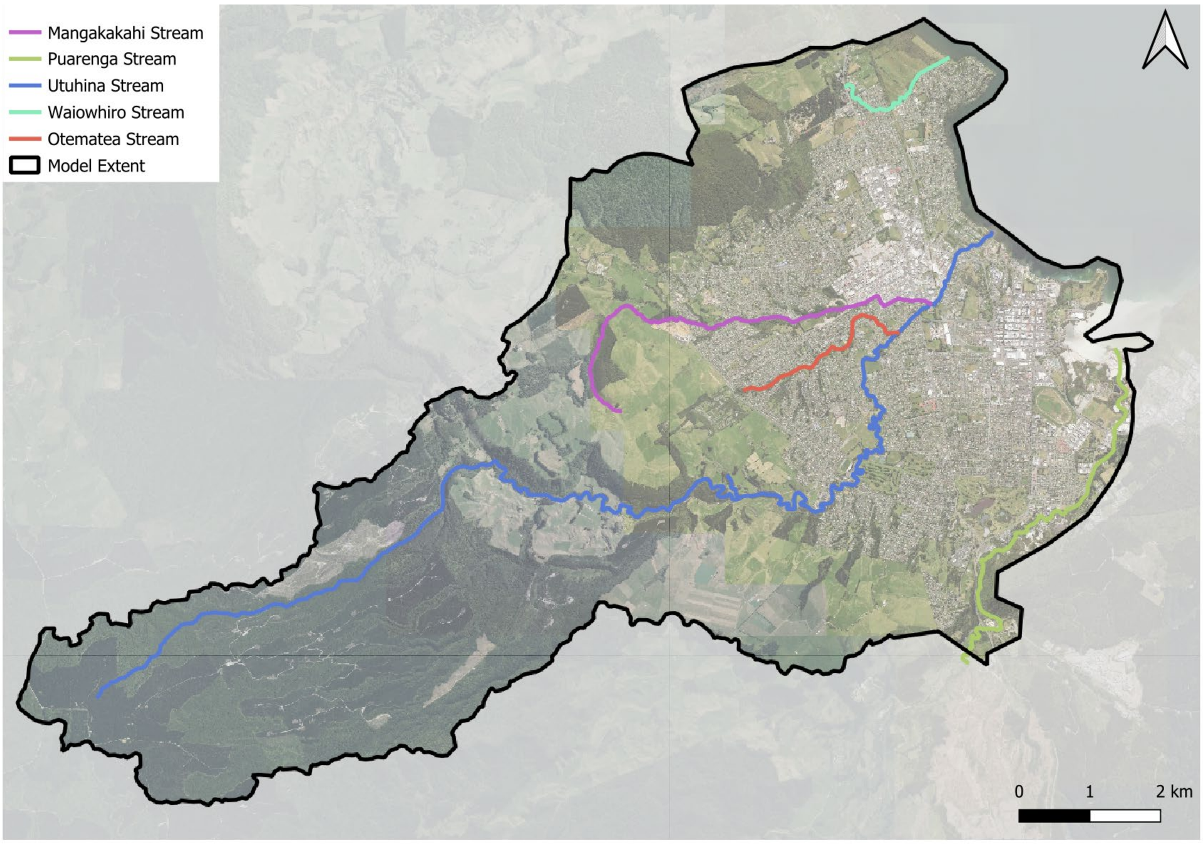

Figure 3-1: Model Extent

3.2 Digital Elevation Model

The main source of elevation data in the model is the Bay of Plenty LiDAR 1m DEM (2019-2022). The LiDAR within the model extent is dated 2020. This is a digital elevation model (DEM) derived from LiDAR sources, applied to TUFLOW as a 1 m x 1 m (1 m^2) grid referenced to MVD53. Despite the model cell size being larger (2 m x 2 m to 16 m x 16 m), TUFLOW's sub-grid sampling technology samples the underlying topography at a finer (1m x 1m) resolution.

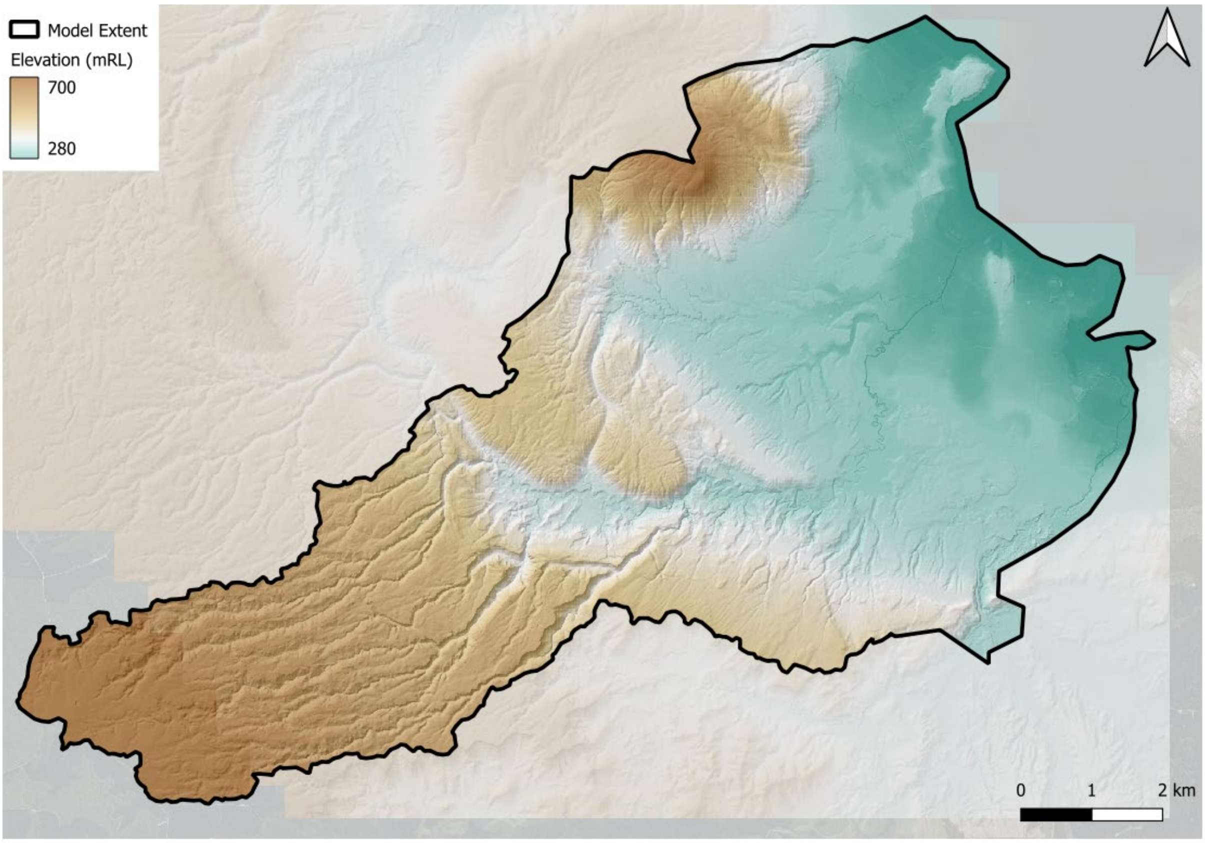

Figure 3-2: Model topography

3.2.1 Cell size

Computational speed of hydraulic models is influenced by the grid size used. Optimal model resolution ensures adequate model accuracy while maintaining run-time efficiency, so the largest grid size is sought that still provides adequate accuracy. To establish these criteria a grid size convergence is undertaken. This involves running a particular model scenario for a range of different grid sizes, to check results convergence. For this work, the following approach was used for grid size convergence:

- The model was run at the DEM resolution (2 m cell size) across the whole model domain. Model run times were unreasonable (~80 hours).
- Cell size convergence testing was undertaken in earlier iterations of the model build, where it was found that simulated flows and flood extents are within a relatively tight range from simulations using 16 m, 8 m and 4 m grid cells.
- We utilised TUFLOW's Quadtree nesting capability to vary the cell size across the model domain, as shown in Figure 3-3.
  - Where high model resolution was required in critical areas for conveyance such as roads and streams, a 2 m cell size was used.
  - A 4 m cell size was adopted in other urban areas.
  - A 16 m cell size was adopted in the upper Utuhina catchment in rural areas where model resolution requirements are less demanding.

- In increasing the cell size in different areas, checks were done to ensure that;
  - Flow hydrographs from the upper catchments did not change, especially in the upper Utuhina catchment as a result of a larger cell size.
  - Flood levels did not change as a result of a change in cell size, especially in the streams.

While areas of higher model resolution have been shown, this should not be inferred as higher model accuracy.

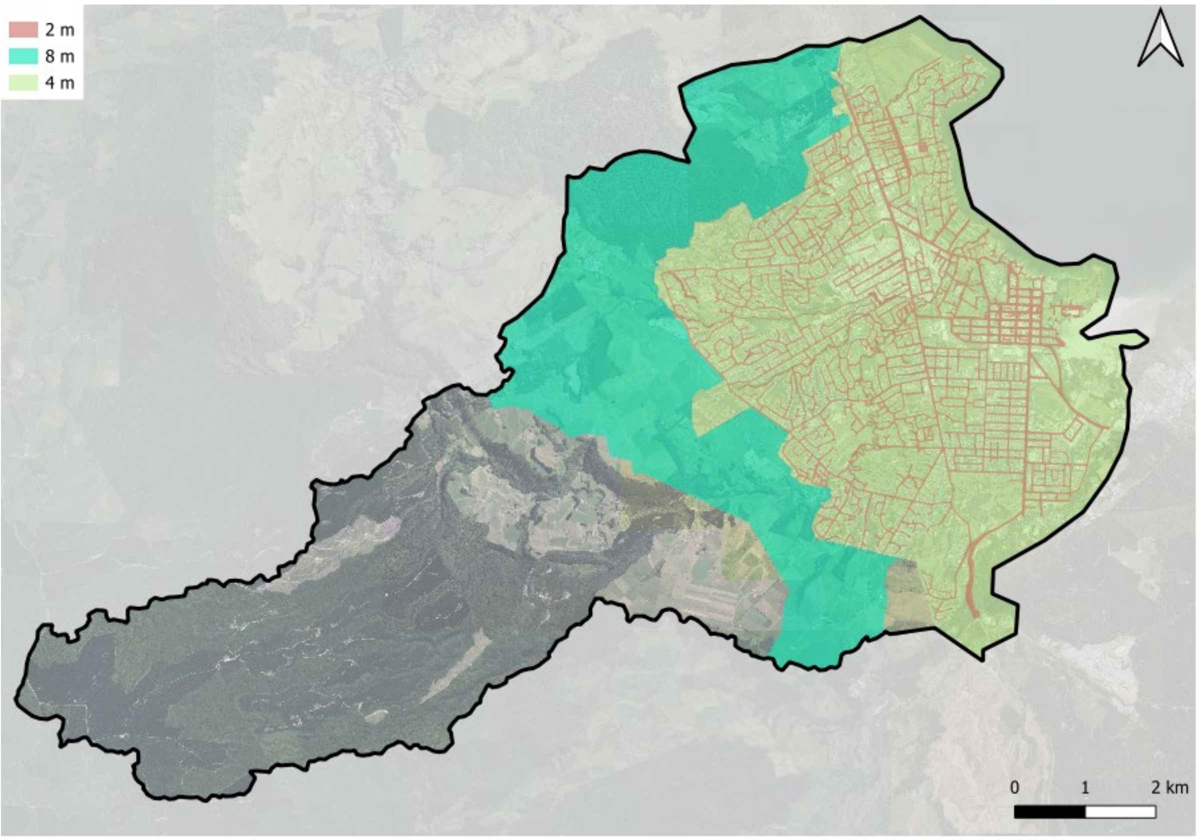

Figure 3-3: Cell size

3.2.2 Digital elevation model refinements

The LiDAR based DEM is a bare earth terrain model, meaning that above-ground features have been removed to show only ground levels. We have made some changes to the base DEM to develop the model topography as part of this build, including the following:

- The addition of building footprints as above ground elements in the DEM. As we were assessing flooding around buildings, it made sense to reintroduce the buildings into the DEM to give a more realistic picture of overland flow in urban areas (Section 3.2.3).
- Updating of the terrain around the Mangakakahi and Utuhina streams using cross section data to better represent stream hydraulics (Section 3.2.4).

Terrain updates are commented on in more detail in subsequent sections. Differences between the model terrain in the masterplan model and the updated enabling works model are shown in Figure 3-4 and Figure 3-5 respectively.

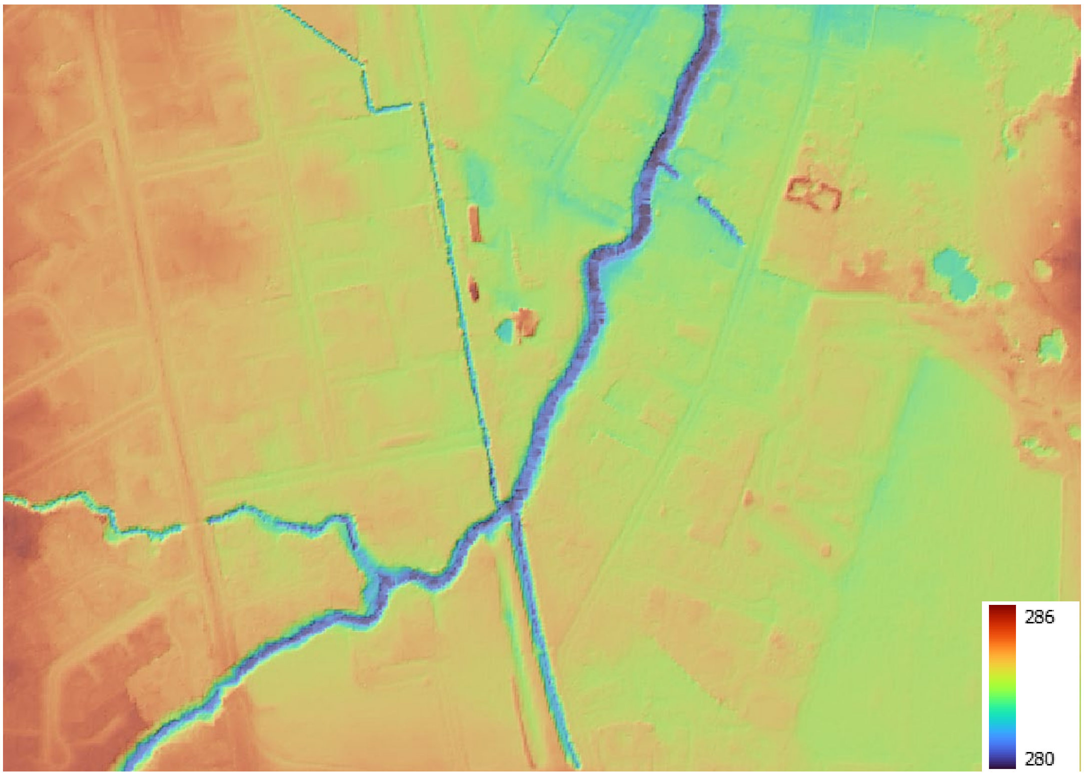

Figure 3-4: 2020 DEM without terrain modifications

Figure 3-5: Model topography with building footprints and stream cross section data added

3.2.3 Buildings

There are several methods to represent buildings within a floodplain. An investigation by Australian Rainfall and Runoff[1] into different methods showed that removing computational grid points under the building footprint, or raising the grid points in the topography under the building footprint above the highest anticipated flood level gave the best match with flow behaviour observed in a physical model.

Building footprints were sourced from Land Information New Zealand (LINZ) which represents building footprints as of September 2024. The roof level (and thus the elevation) of each building footprint was defined as the maximum elevation value within the building footprint, plus 3 m (enough to raise the building out of the floodplain). The centroid of the building was then raised an additional 1 m to avoid ponding on large roofs. A schematic is shown in Figure 3-6.

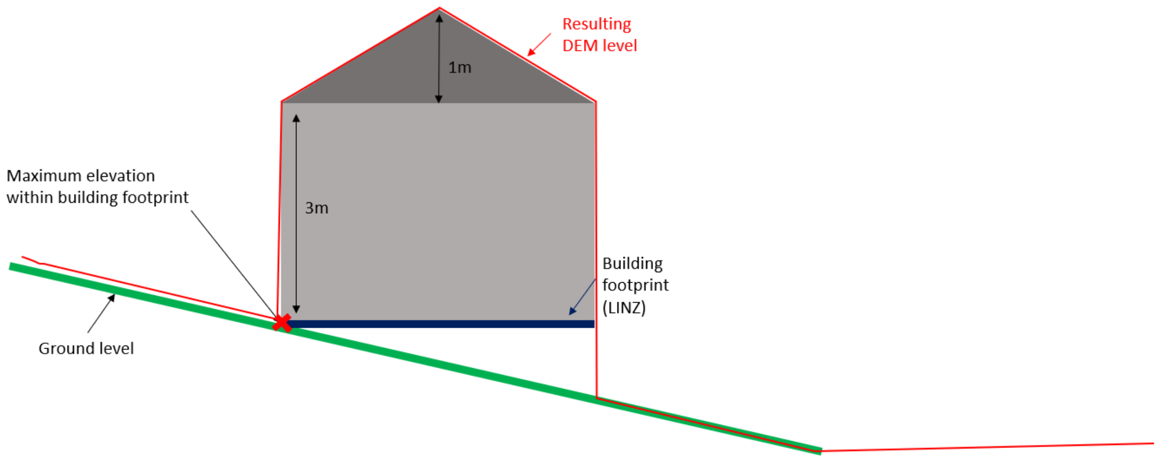

Figure 3-6: Modelling approach for buildings

3.2.4 Utuhina Stream cross section survey

Surveyed cross sections were able to be sourced from BOPRC[2]. These cross sections were used to create a representative 2D surface using the following methodology:

- Between known or surveyed cross sections, additional cross sections were interpolated at 5 m spacings using HEC-RAS software; and
- The elevation points from these cross sections were then triangulated to form a 3D surface.

The result of which is a 2D surface which is true to the surveyed cross sections where these were measured, and interpolated in between these sections. LiDAR often lacks the resolution to pick up key features of streams, i.e. stopbank crest levels and stream inverts, therefore this approach is more representative of the physical environment.

[1] Australian Rainfall and Runoff (2012) – Revision Project 15: Two dimensional simulations in urban areas – representation of buildings in 2D numerical flood models.
[2] Beca (2018) – Utuhina River – Catchment Field Surveys for Stormwater Hydraulic Modelling, prepared for Bay of Plenty Regional Council.

3.3 Hydraulic structures

3.3.1 Urban pipe network

The pipe and culvert information was supplied by RLC for this modelling and was projected to MVD53, consistent with the LiDAR-based DEM. We obtained this data directly from RLC's ICM model for catchments 7, 8, 9, 12, 14, 15 and 18 and directly from RLC Geyserview elsewhere. It is important to note that the available pipe network data for the Rotorua CBD area was not sufficient to include these pipes in the model, so these have been excluded.

The ICM datasets were complete and could be directly applied to the model. Elsewhere, it was noted that a large portion of network data was missing invert level information, and as such, it was agreed with RLC that an interpolation exercise would be undertaken to estimate invert levels where information was missing. This was done based on the following general sequence of assumptions:

1. If a node invert level is known, use it.
2. If a node invert of a connecting pipe is known, use it.
3. If the node is a catchpit/sump, set upstream invert level as the LiDAR DEM (ground level) and include an allowance for minimum cover.
4. If the node is a pipe inlet or outlet, use LiDAR DEM (ground level).
5. Following the above process, assign the remaining unknown inverts by 'searching' the upstream and downstream network for known inverts and linearly interpolating a value.

The modelled pipe network is shown in Figure 3-7.

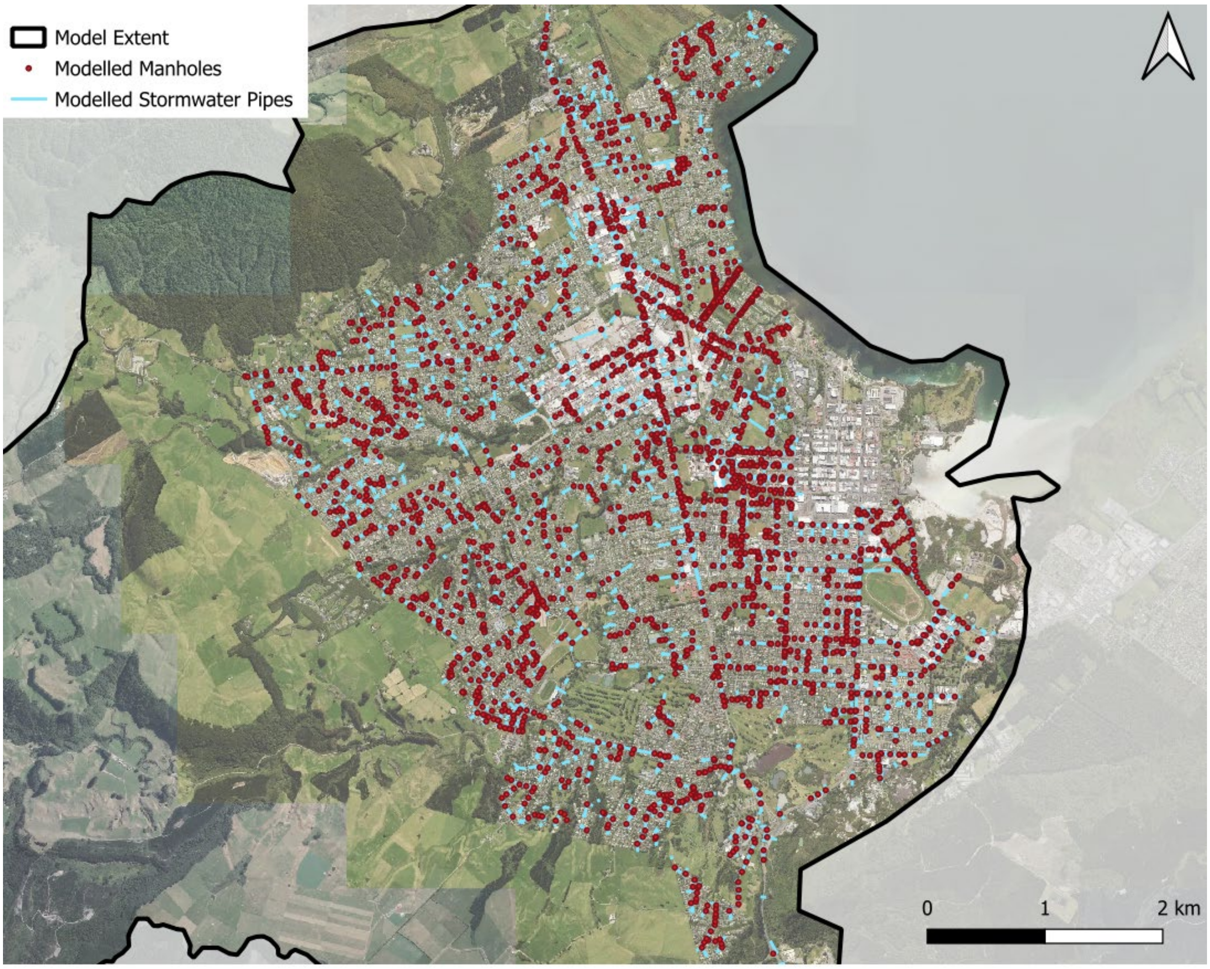

Figure 3-7: Modelled stormwater network elements

3.3.2 Bridges

In the Western Catchment model, TUFLOW 2D layered flow constriction was used to represent bridge structures at locations shown in Figure 3-8. Layered flow constriction allows blockages and form losses to be applied directly to the 2D model cells at different elevations to account for energy losses such as the bridge deck and handrails, while other losses, such as the contraction and expansion through the bridge structure are solved implicitly through the 2D solution.

River channel geometry through the bridge structures (below the bridge deck) and bridge structure dimensions (bridge deck, bridge deck soffit and handrails) were derived both from survey data, provided to T+T by BOPRC, and LiDAR data.

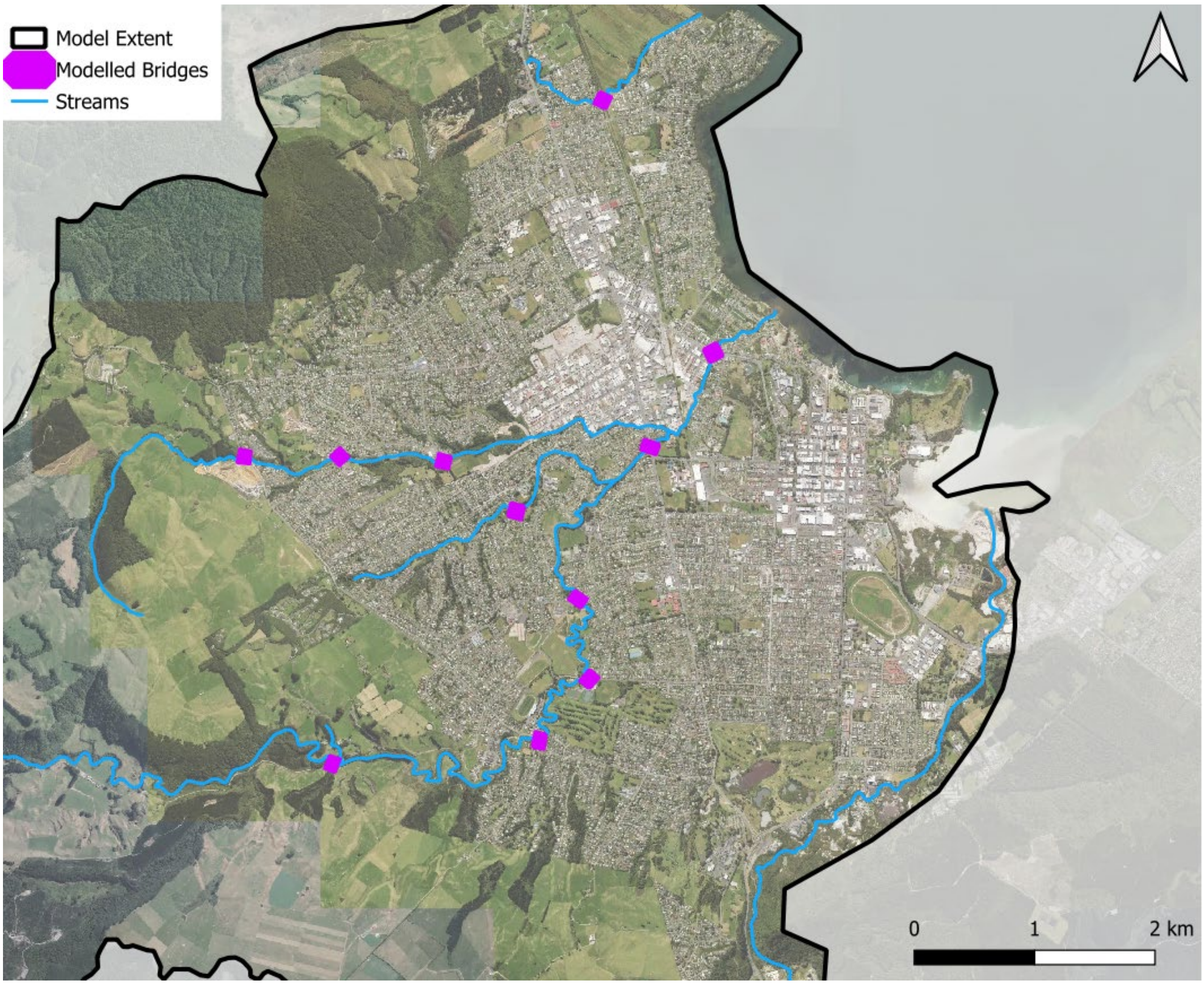

Figure 3-8: Modelled bridges

3.4 Roughness

3.4.1 Land use zones

The spatial distributions of various land cover used for each of the three scenarios was sourced from various land cover layers provided by RLC. Land Cover Database Version 5 (LCDBv5)[3], sourced from Landcare Research, has been used to define land uses in other areas of the model domain. This data is relatively coarse and does not differentiate micro scale roughness changes. For this reason, roads (not recognised in the LCDB data) were specifically differentiated from other land uses, mainly because many of these act as secondary flow paths under flood conditions that have been simulated.

Figure 3-9 shows the existing and proposed land uses for urban catchments areas applied to the model. For all model runs, we have based the land use on the Existing Development (ED) scenario, no future development (i.e. MPD) has been modelled.

[3] Source available online at https://lris.scinfo.org.nz/layer/104400-lcdb-v50-land-cover-database-version-50-mainland-new-zealand/

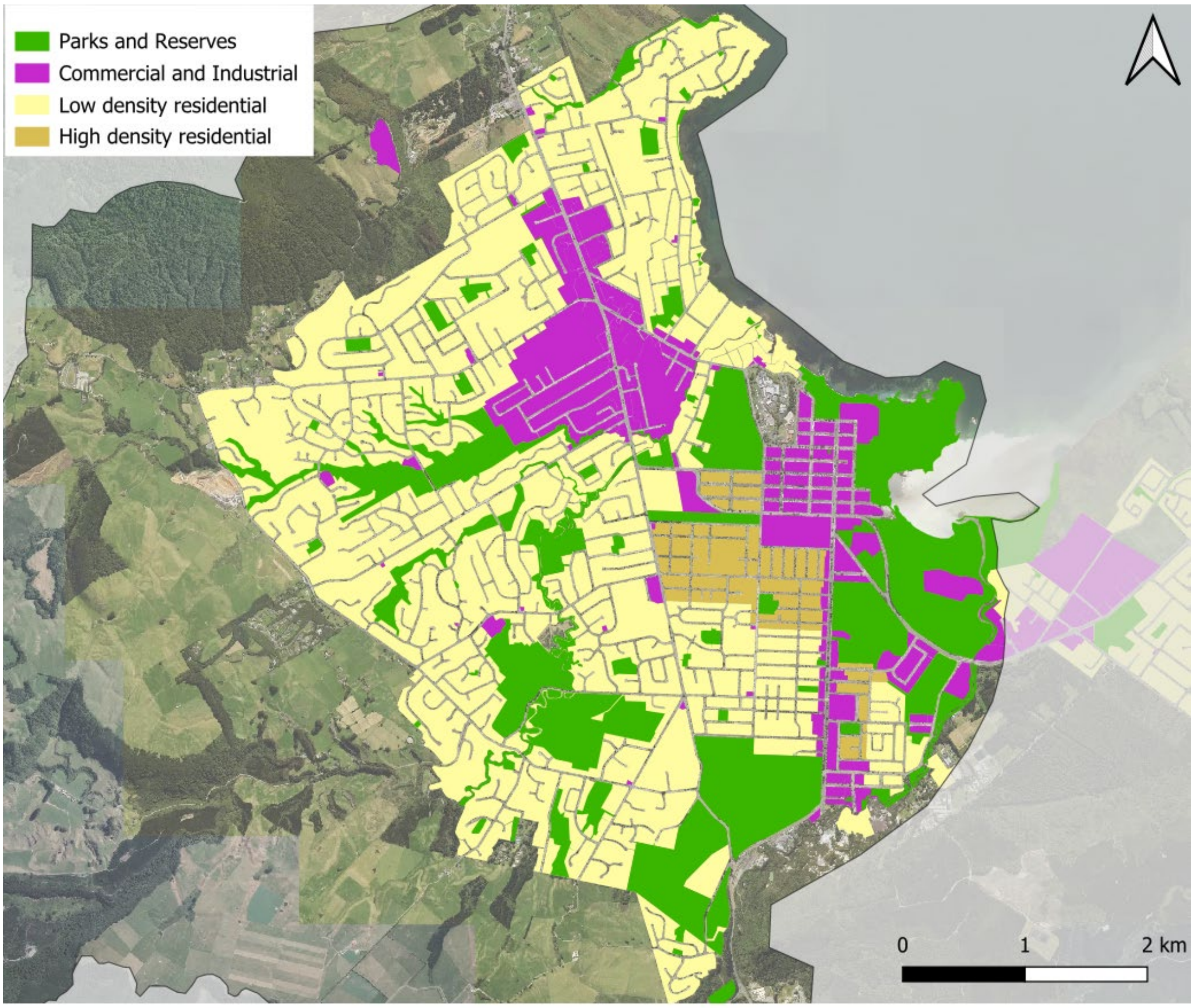

Figure 3-9: Land use zones

3.4.2 Roughness coefficients

Roughness coefficient is a hydraulic calibration parameter, which should be derived by matching model performance to observed performance. In the absence of suitable calibration data, roughness is often estimated using “look-up” tables that document ranges of calibrated roughness that have been found on other surface water systems. Throughout the calibration and validation process (described in Section 5), “look-up” values were first applied to the model as a starting point and adjusted (along with other parameters, such as hydrological losses) to provide a calibration to gauged flood events.

For the modelling undertaken, Manning n is the roughness parameter that has been selected. It is recognised that the Manning equation gives reliable results in fully developed, rough, turbulent flow (which generally occurs at high Reynolds number). This means that modelled behaviour may be closer to reality under high Reynolds number conditions (high combination of velocity and depth) and may be less accurate at lower Reynolds number. In this way, calibration is able to be achieved to peak flows (during conditions when Reynolds number is high), but is more challenging if using constant roughness at lower Reynolds number. Thus, if calibration seeks to match peaks only, then constant Manning n is a reasonable approximation. However, if calibration seeks to match an entire recorded hydrograph, there may be deviation in modelled performance at lower Reynolds number if constant Manning n was used. At lower Reynolds number, effective roughness will be higher than at high Reynolds number.

It should be noted that 2D roughness values do not necessarily equate to traditional 1D Manning's n roughness values used for open channel hydraulics, such as those published by Chow, (1949). There are multiple reasons for this, which have been recognised in publications such as Australian Rainfall and Runoff ARR[4] (2019). A major difference occurs where the 2D shallow Water Equations (used in the TUFLOW solver) approximate hydraulic radius with flow depth in a cell. This simplification suits wide, shallow flows but gives differences in incised channel areas.

Through earlier iterations of the calibration process, we initially applied roughness values, and then adjusted these initially applied values to match model outputs to the observed flood performance. These adjusted values have again been verified in the most recent round of calibration.

In order to achieve a calibration to gauged flood events (refer Section 5), Manning's n values applied to land use zones were increased beyond "look-up" 2D roughness values, such as those published in Australian Rainfall and Runoff ARR[5] (2019). Furthermore, it was found that applying depth varying roughness also improved model calibration, mainly to achieve goodness-of-fit with hydrograph shape and total runoff volume.

We have noted that application of direct rainfall modelling to highly pervious catchment areas is relatively untested. In online publications we have noted that similar approaches to roughness have been adopted in other similar catchments when using direct rainfall. An example of this is described in AWS (2021)[6], where the Welsh catchment response was described.

The roughness parameter applied to a direct rainfall model is often used to account for processes other than hydraulic friction loss at the rigid boundary. In some models, roughness is used to also account for turbulence losses, for bend losses and for losses through structures. In the case of the direct rainfall model applied to a highly pervious catchment, roughness is also used to account for rapid infiltration that emerges as surface runoff, delayed in time. If such rapid infiltration is applied as a hydrological loss, then the model has insufficient flow volume compared with the calibration response (i.e. the initial rapid infiltration is not a volume loss, but rather acts as temporary detainment of a portion of the initial rainfall). This is also discussed in Boyte (2014)[7].

Because of this, there was a need to apply depth varying roughness at low depth (as an indicator of low Reynolds number), and higher than typical roughness values is to compensate for interflow processes not represented explicitly by the initial and continuing hydrological loss approach (refer Section 3.5). An alternative to increasing catchment roughness would be to increase soil infiltration losses, however testing of this approach resulted in a significant loss of volume to the system that would otherwise emerge later in the flood event (refer Section 7) and resulted in a significant underestimation of flood volume compared to gauged flows.

In Table 3-2 the calibrated roughness's applied to the model are shown. For most surface types, roughness is high for cell inundation depth up to 50 mm to account for the interflow and low Reynolds number effects described above. Roughness then increases as depth increases to 100 mm and beyond 100 mm inundation depth, roughness remains constant. An exception to this is in built-up areas, where roughness is low at low depth and then increases as depth increases. The reason for this is that these areas are often comprised of roof and hardstand areas, both of which shed runoff

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[4] Ball J, Babister M, Nathan R, Weeks W, Weinmann E, Retallick M, Testoni I, (Editors)
Australian Rainfall and Runoff: A Guide to Flood Estimation, © Commonwealth of Australia (Geoscience Australia), 2019.

[5] Ball J, Babister M, Nathan R, Weeks W, Weinmann E, Retallick M, Testoni I, (Editors)
Australian Rainfall and Runoff: A Guide to Flood Estimation, © Commonwealth of Australia (Geoscience Australia), 2019.

[6] AWS (2021), *Is direct rainfall accurate?,* webinar hosted by Australian Water School, 17 February 2021.

[7] Boyte (2014), *The application of direct rainfall models as hydrologic models incorporating hydraulic resistance at shallow depths,* thesis submitted in partial fulfilment of Bachelor of Civil and Environmental Engineering degree at University of Queensland, 29 October 2014.

quickly as rain falls. The overland flow effect of using a bare earth terrain in these areas needs to be replicated, and is simulated using roughness effect.

Table 3-2: Manning's n roughness coefficients applied to land use

Material ID	Description	Water depth	Manning's n used in model	% Impervious	Manning's n from ARR (2019)
Non-urban landcover (LCDBv5)					
1	Built-up area	< 50 mm	0.015	50	0.1 - 0.2
		> 100 mm	0.2		
2	Urban Parkland/ Open Space	< 50 mm	0.66	0	n/a
		> 100 mm	0.066		
5	Transport Infrastructure	< 50 mm	0.32	95	0.02 - 0.03
		> 100 mm	0.032		
16	Gravel and Rock	< 50 mm	0.78	0	n/a
		> 100 mm	0.078		
20	Lake and Pond	< 50 mm	0.4	100	0.015 - 0.035
		> 100 mm	0.04		
21	River	< 50 mm	0.8	100	0.04 - 0.1
		> 100 mm	0.08		
30	Short-rotation Cropland	< 50 mm	0.2	0	n/a
		> 100 mm	0.02		
33	Orchard and Other Perennial Crops	< 50 mm	1	0	n/a
		> 100 mm	0.1		
40	High Producing Exotic Grassland	< 50 mm	1	0	n/a
		> 100 mm	0.1		
41	Low Producing Grassland	< 50 mm	1.8	0	n/a
		> 100 mm	0.18		
45	Herbaceous Freshwater Vegetation	< 50 mm	2	0	n/a
		> 100 mm	0.2		
51	Gorse and Broom	< 50 mm	2.5	0	n/a
		> 100 mm	0.25		
52	Manuka and or Kanuka	< 50 mm	2	0	n/a
		> 100 mm	0.2		
54	Broadleaved Indigenous Hardwoods	< 50 mm	2	0	n/a
		> 100 mm	0.2		
64	Forest Harvested	< 50 mm	3.2	0	n/a
		> 100 mm	0.32		
68	Deciduous Hardwoods	< 50 mm	2.5	0	n/a
		> 100 mm	0.25		
69	Indigenous Forest	< 50 mm	3	0	n/a
		> 100 mm	0.3		

Material ID	Description	Water depth	Manning's n used in model	% Impervious	Manning's n from ARR (2019)
Non-urban landcover (LCDBv5) continued					
71	Indigenous Forest	< 50 mm	3	0	n/a
		> 100 mm	0.3		
Urban landcover (% imperviousness based on Rotorua District Plan					
88	Roads	< 50 mm	0.4	100	0.02 - 0.03
		> 100 mm	0.04		
100	2D simulated pipes	< 50 mm	0.3	100	n/a
		> 100 mm	0.03		
101	Low density residential MPD	< 50 mm	0.015	80	0.1 - 0.2
		> 100 mm	0.2		
102	High density residential MPD	< 50 mm	0.015	100	0.2 - 0.5
		> 100 mm	0.2		
103	Schools Hospitals Airports ED and MPD same	< 50 mm	0.015	50	0.2 - 0.5
		> 100 mm	0.2		
104	Rural 2 Lifestyle ED and MPD same	< 50 mm	0.015	25	n/a
		> 100 mm	0.2		
105	Brent Block	< 50 mm	0.015	52	0.1 - 0.2
		> 100 mm	0.2		
106	Parks and reserves ED and MPD same	< 50 mm	0.015	5	n/a
		> 100 mm	0.18		
107	Commercial Industrial ED and MPD same	< 50 mm	0.015	100	0.2 - 0.5
		> 100 mm	0.2		
111	Low density residential ED	< 50 mm	0.015	50	0.1 - 0.2
		> 100 mm	0.2		
112	High density residential ED	< 50 mm	0.015	80	0.2 - 0.5

3.5 Soil infiltration

Soil infiltration has been applied as per the initial and continuing loss approach. Historically, soil infiltration values were set by comparing the gauged flows at the Utuhina at Depot Street to the modelled flows at the same location. The location of this gauge is shown in Figure 3-10 below, and has a period of record of more than 19 years. In initial modelling, it was found that using a continuing loss of 27 mm/hr matched the gauged flow for a 100 year ARI event. However, if this loss rate is applied consistently across all ARI events, the modelled peak flow in the smaller duration events was lower than what the gauge frequency analysis gave.

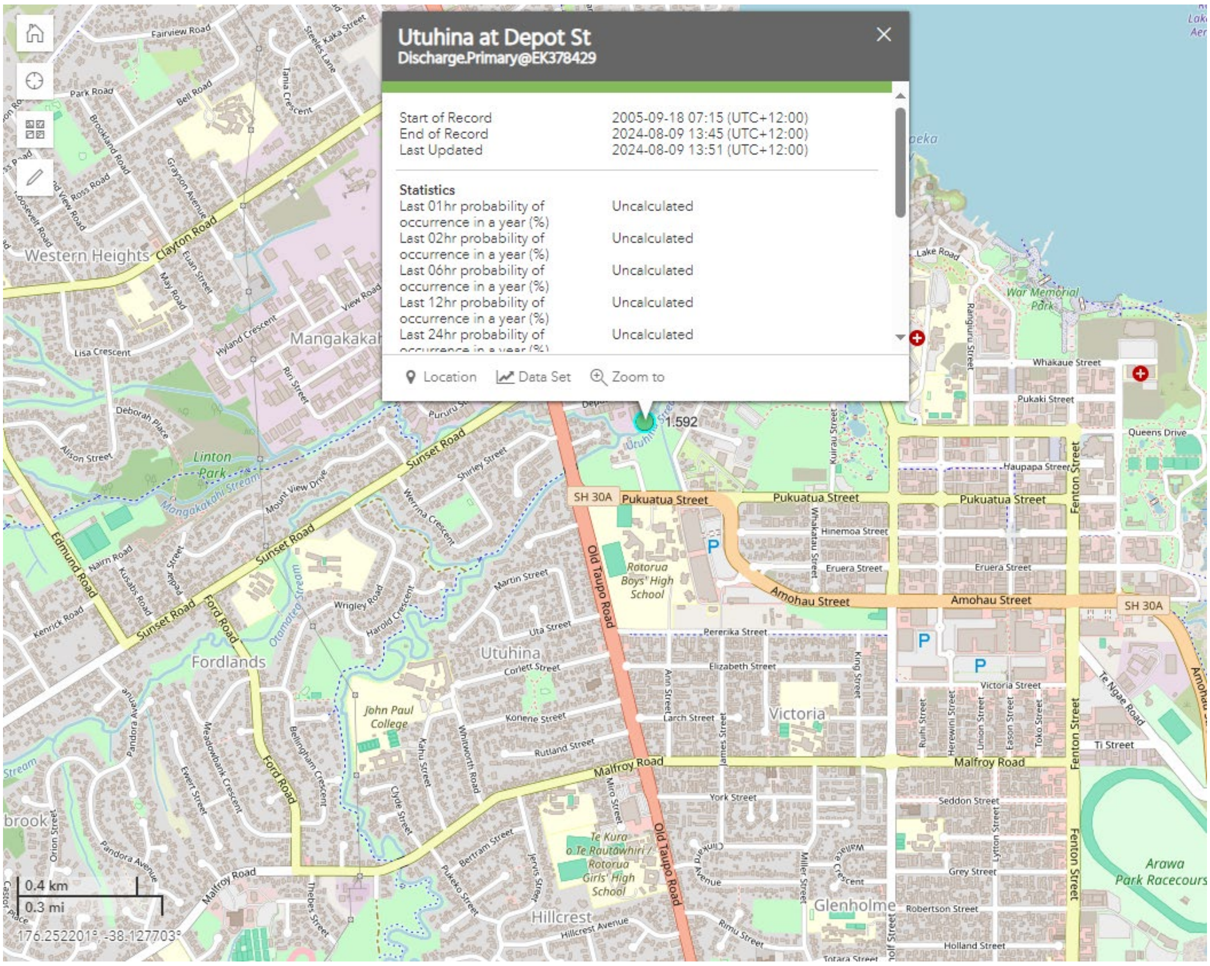


Figure 3-10: Utuhina at Depot Street Flow Gauge

From the most recent model calibration exercise undertaken using the May 2024 flow data, it was found that the soil infiltration rate needed to be lowered from 27 mm/hr to 12 mm/hr in order to match the observed flooding and flow gauge recorded at Utuhina at Depot Street, for the May 2024 event, with the recorded rainfall applied. The calibration event is described in more detail in Section 5.

This calibration exercise showed that a good calibration can be achieved if soil infiltration rate is varied with total rainfall, rather than being applied as a constant value across all rainfall events. For the model calibration event, and the 100 year ARI design event, it was found that soil losses needed to be around 8% of the total rainfall depth in order to achieve a match with the Utuhina at Depot Street gauge. That is, applying a proportional constant loss, where the actual loss through the model run is proportional to the total design rainfall depth. In the modelling, a greater rainfall depth will require a higher total soil infiltration loss (set by higher continuing loss rate). The continuing loss rate is set based on the event severity.

Figure 3-11 below shows the flow results as a plot, with the X axis being event ARI, and the Y axis being the peak flow at the Utuhina at Depot Street Gauge.

- The green line shows the NIWA flood frequency analysis flows, and the light blue line shows the T+T model flows with the constant 27 mm/hr losses. The results show that there is some convergence with the peak flow estimates in the 100 year ARI event, however the flows are underestimated in smaller events, and the lower the ARI, the greater this difference is.

- The dashed red line shows the T+T model flows using a proportional constant loss rate, consistent with Table 3-3. The results show convergence in all events with the peak flow estimates at the Utuhina at Depot Street gauge.

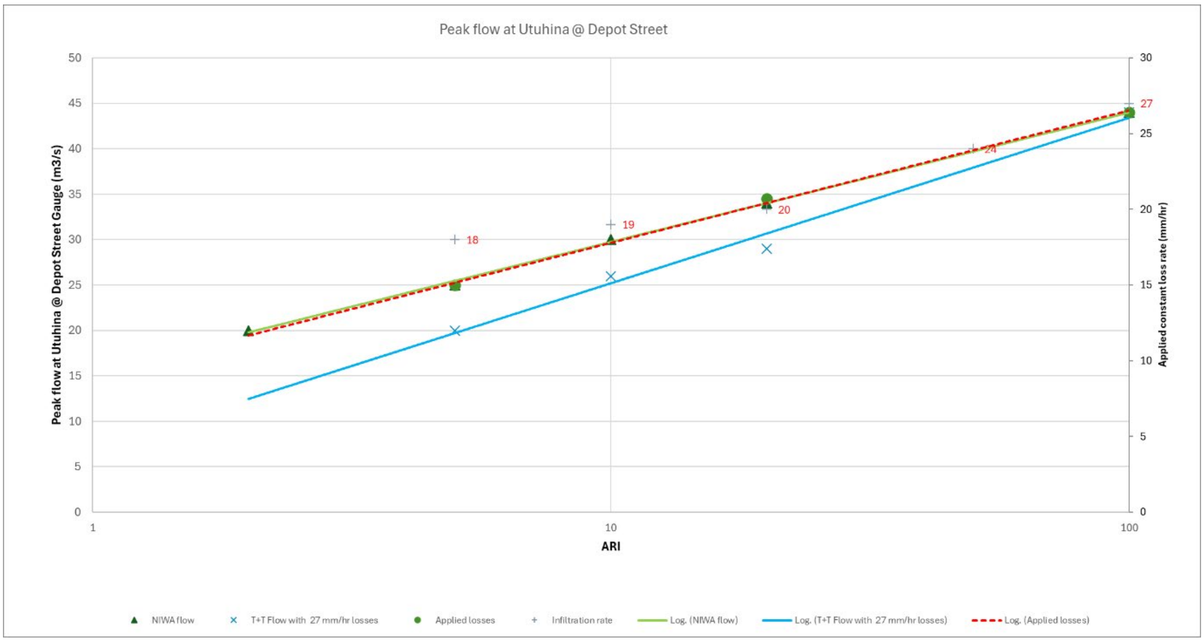


Figure 3-11: Modelled vs measured peak flows at the Utuhina at Depot Street gauge

The constant loss rates applied for each event are summarised in Table 3-3 below. The definition of event ARI is further discussed in Section 4.2

Table 3-3: Infiltration rates

Event ARI	Climate change RCP	Proportional constant loss rate (mm/hr)
5 year	Present Day	18
10 year	Present Day	19
20 year	Present Day	20
50 year	Present Day	24
100 year	Present Day	27
5 year	RCP 8.5 Projected to 2090	19
10 year	RCP 8.5 Projected to 2090	22
20 year	RCP 8.5 Projected to 2090	25
50 year	RCP 8.5 Projected to 2090	30
100 year	RCP 8.5 Projected to 2090	33

4 Design flood hydrology

4.1 Approach

Design events were simulated using the approach outlined in Figure 4-1. Initially the design event ARI is selected, land use state/condition is determined, and the appropriate rainfall profile is developed. The model purpose requires definition, and if it is to be used to reflect wet antecedent conditions (higher runoff conditions) then the appropriate infiltration rate is applied.

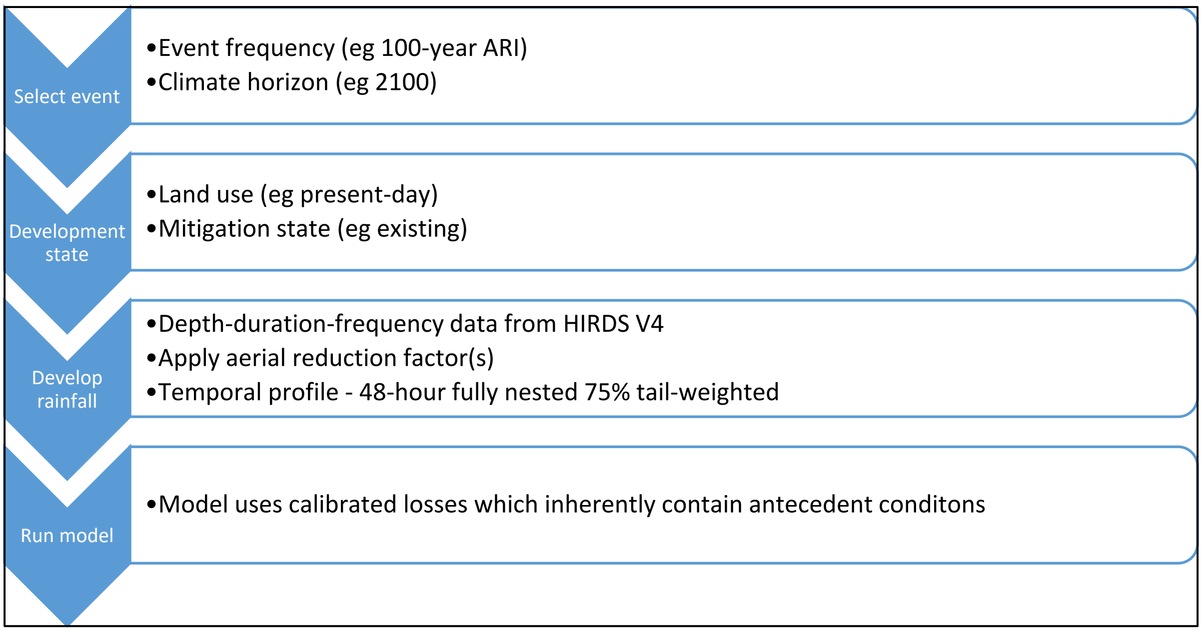


Figure 4-1: Design event simulation approach

4.2 Event definition

Previous iterations of the western catchment modelling have been focused on the flood performance of dams within the catchment. Given the lack of available calibration data at that time, the model hydrology was developed to be conservative when being used for dam design. This involved applying uniform rainfall across the entire catchment, at a single ARI.

Bay of Plenty Regional Council hydrological and hydraulic (BOPRC H&H) guidelines specify a design standard combination when modelling large catchments, referred to as 'joint probability'. This means that combinations of hydrological conditions in the lower and upper catchment, and the lake level, should be analysed to determine the critical case. An example snippet from the BOPRC H&H guidelines is shown in Figure 4-2 below to define a 10, 20, 50 and 100 year event.

Table 4.4 Design standard combinations for floods and sea level.

Design Return Period	Case 1	Case 2
100-year	$Q_{100} : L_{20}$	$Q_{20} : L_{100}$
50	$Q_{50} : L_{20}$	$Q_{20} : L_{50}$
20	$Q_{20} : L_{2}$	$Q_{2} : L_{20}$
10	$Q_{10} : L_{2}$	$Q_{2} : L_{10}$

Figure 4-2: Joint probability approach

The Utuhina catchment has been split into two hydrological zones – for urban (U) and upper catchment or rural (R) rainfall. This is also combined with a lake level (LL) scenario. As such, the design standard combinations have been defined in Table 4-1 below, for the extents shown in Figure 4-3.

Table 4-1: Event combinations

Design return period	Case 1	Case 2	Case 3
100 year ARI	U_{100}:R_{20}:LL_{20}	U_{20}:R_{100}:LL_{20}	U_{20}:R_{100}:LL_{20}
50 year ARI	U_{50}:R_{20}:LL_{20}	U_{20}:R_{50}:LL_{20}	U_{20}:R_{100}:LL_{50}
20 year ARI	U_{20}:R_{2}:LL_{2}	U_{2}:R_{20}:LL_{2}	U_{2}:R_{2}:LL_{20}
10 year ARI	U_{10}:R_{2}:LL_{2}	U_{2}:R_{10}:LL_{2}	U_{2}:R_{2}:LL_{10}

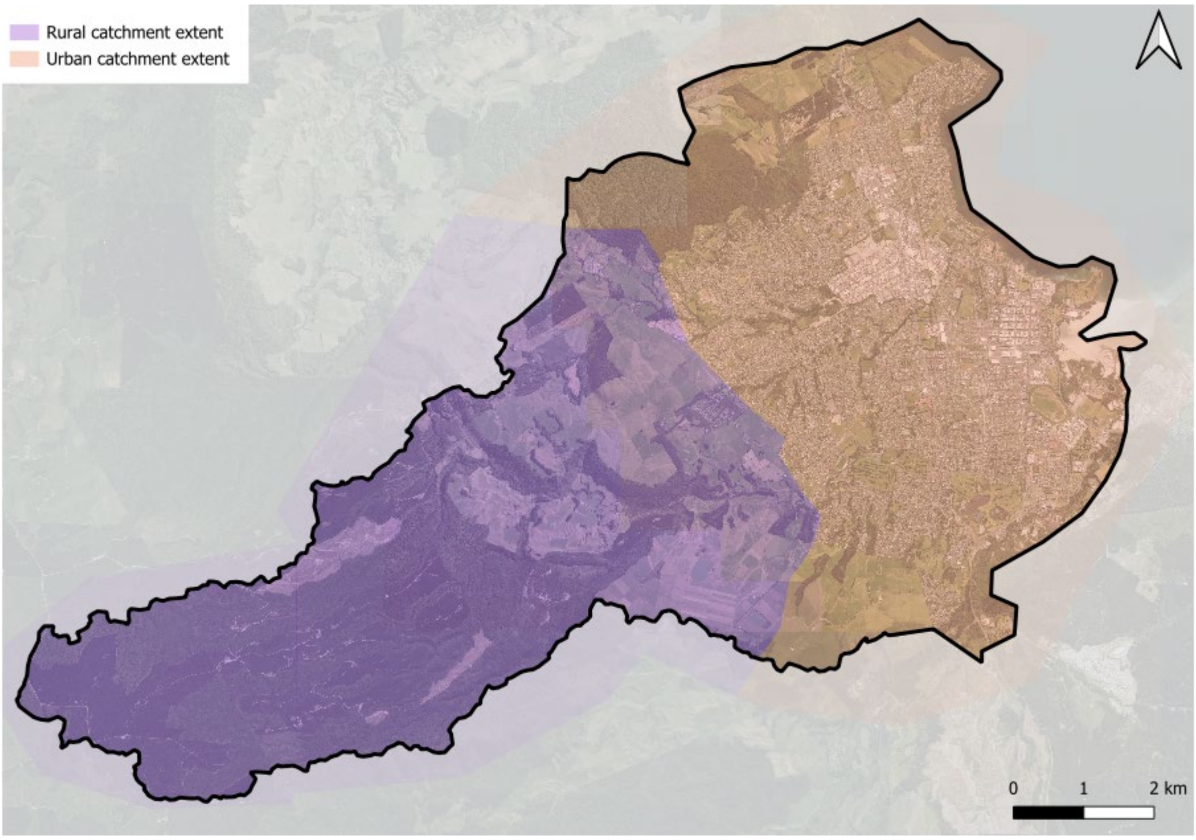


Figure 4-3: Rural and urban catchment rainfall split

4.3 Rainfall profiles

There has been prior agreement with RLC and BOPRC that the design rainfall input to the model should be the 48-hour fully nested tail-weighted (75%) rainfall, comprised of depth-duration-frequency data from HIRDS. It is recognised that adoption of other design rainfall profiles would result in different results, even for the same frequency event.

4.4 Event frequencies

For the modelling work described in this report and undertaken for this project, "event" frequency has been derived using the joint probability approach described above, with results being enveloped from the cases assessed. This means that, if plotting flood depth, the maximum flood depth from the cases assessed in each grid cell is reported.

4.5 Climate horizon

All present-day events simulated have no built-in allowance for climate change. All future climate scenarios have been based on a 100-year climate horizon (i.e. to the year 2130), using rainfall adjustments following the RCP 8.5 pathway.

5 Model calibration

5.1 May 2024 Calibration event

On 20 - 21 May 2024, the Utuhina Catchment experienced a significant rainfall event. Data from this event was captured by rainfall and flow gauges installed within the Utuhina Catchment as part of a separate RLC project in 2022. We have hindcasted the event in the TUFLOW model using the measured rainfall and calibrated the model to match observations at the flow gauges within the catchment.

The aim of the calibration exercise was to best match the modelling to the observed flooding and flow observations that were recorded in the catchment during the flood event. From this, we have modified certain model parameters to better match the flooding observed. By determining the relationship between the observed flooding and modelled results, we can gain confidence in the model outputs. To calibrate the model, we have used the following inputs:

- Rainfall and flow data recorded by the RLC gauges;
- Recorded flow at the Utuhina Depot Street flow gauge, managed by BOPRC;
- Flood observations provided by RLC during the event; and
- Surveillance footage at the Linton Park east dam primary spillway.

5.1.1 Model inputs

Where possible, we have used recorded data to capture the event and run it in the model. In general, we have applied the following:

- Urban rainfall has been applied as per the recording at the Tallyho Street rain gauge;
- Upper catchment rainfall has been applied as per the recording at the Upper Utuhina rain gauge; and
- Lake level has been applied as per the lake level monitoring gauge for Lake Rotorua.

This is shown schematically in Figure 5-1 below. For the purposes of this assessment, initially, the terrain and existing land uses as discussed in previous sections of this report remained the same.

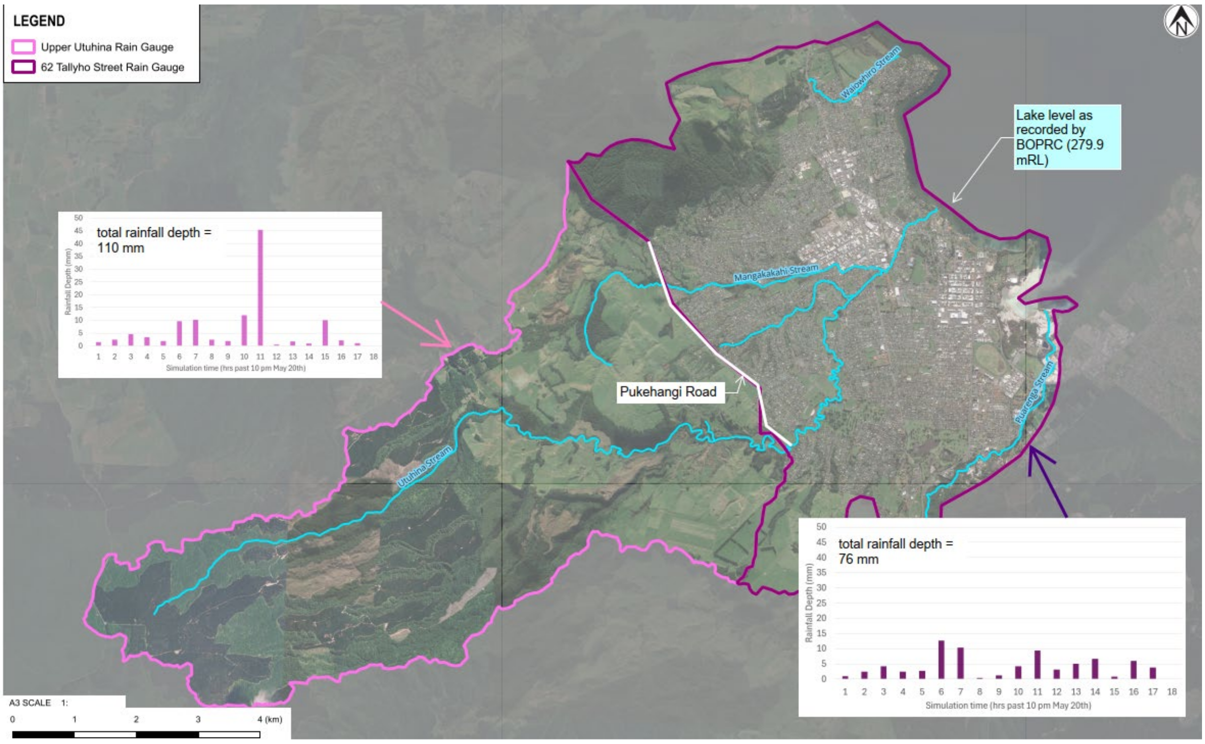


Figure 5-1: May 2024 calibration event rainfall

5.1.1.1 Comparison to BOPRC gauges

BOPRC have two rainfall gauges in the vicinity of the Utuhina catchment, shown in red in Figure 5-2 below compared to the RLC gauges in blue.

Figure 5-2: BOPRC and RLC rainfall gauges

The hourly totals for the upper catchment gauges are shown in Figure 5-3 below and lower catchments in Figure 5-4. This shows reasonable variation in the recorded data across the gauges, implying that there was spatial variation in the rainfall during the flood event.

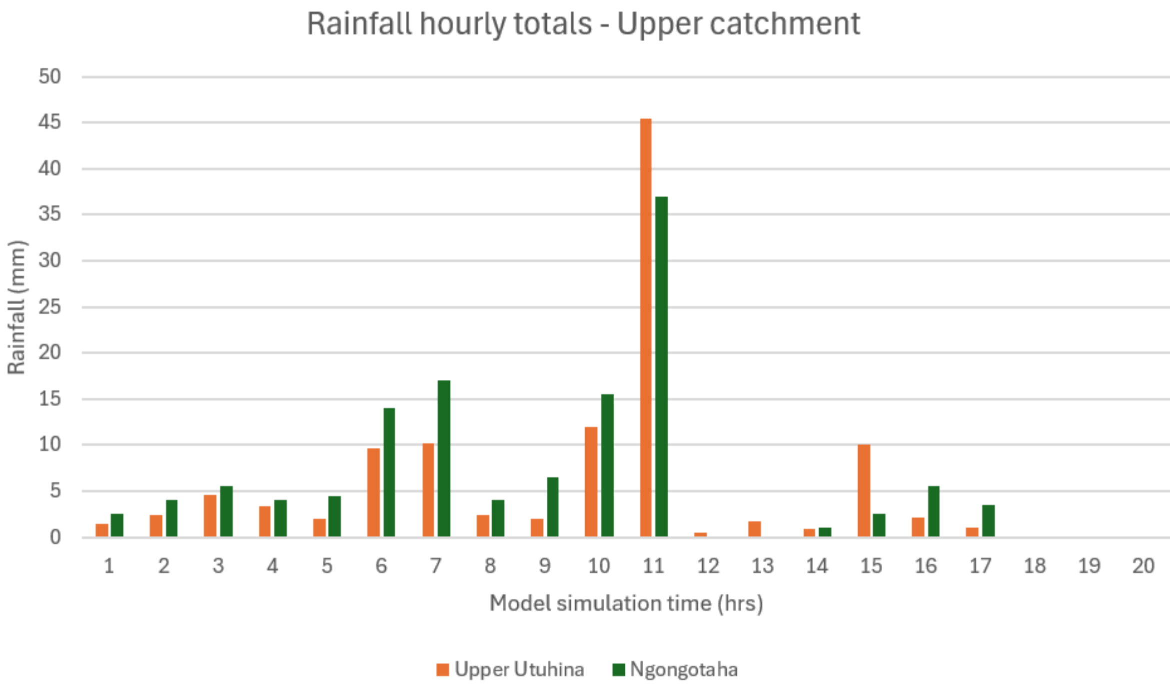


Figure 5-3: Comparison of upper catchment gauges

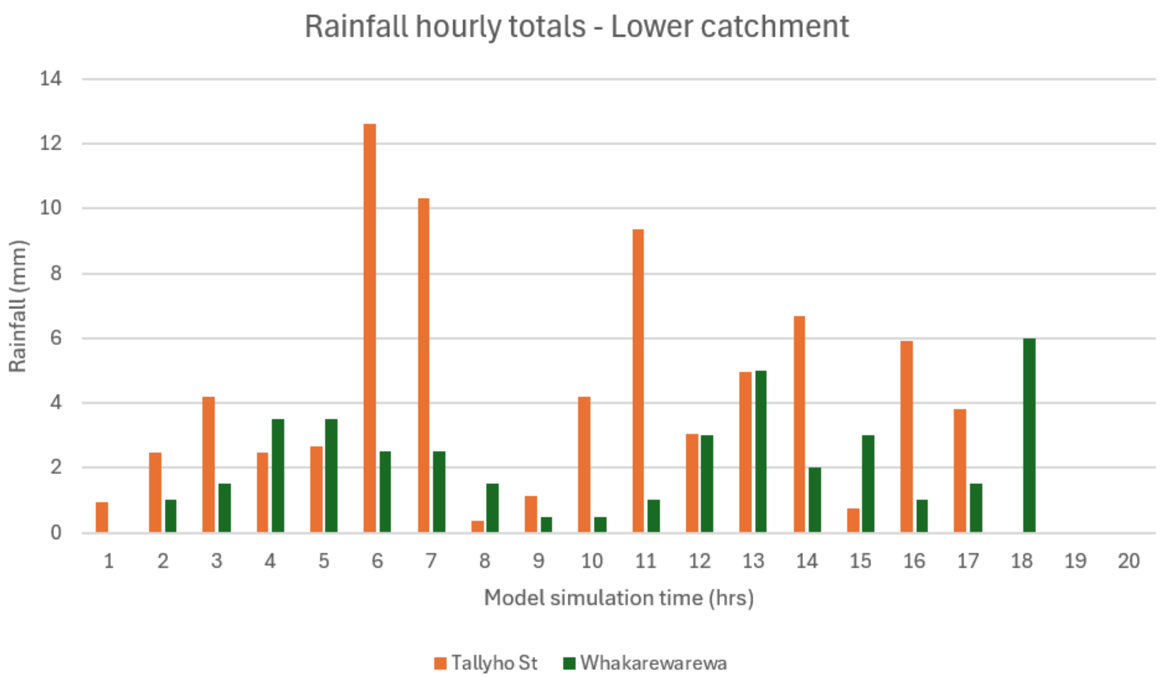


Figure 5-4: Comparison of lower catchment gauges

Total rainfall depths are shown in Table 5-1 below.

Table 5-1: Total rainfall depths over 18 hours

Gauge	Total rainfall depth (mm)
Upper Utuhina	112
Tallyho St	76
Whakarewarewa	40
Ngongotaha	127

5.1.2 Model runs

The model was run with the updated terrain and with existing land use. The results were compared to the Utuhina at Depot Street gauge, which recorded a peak flow of 26 m^3/s. The model matched best with observations when using a constant loss rate of 12 mm/hr. This resulted in a peak flow at the gauge location of 25.5 m^3/s.

Figure 5-5 below shows the hydrograph comparison at the Utuhina at Depot Street gauge for the modelled and observed flows. Observations are as follows:

- There is a lack of baseflow in the initial few hours of the model that causes the flow estimates to be slightly lower than observed.
- The peak of the flood event occurs approximately 2-3 hours earlier in the model compared to the observed flows.
- The peak flow modelled is only 0.5 m^3/s lower than the observed flow. We found through the calibration process that model results were highly sensitive to infiltration rate, therefore this is considered a reasonable match.

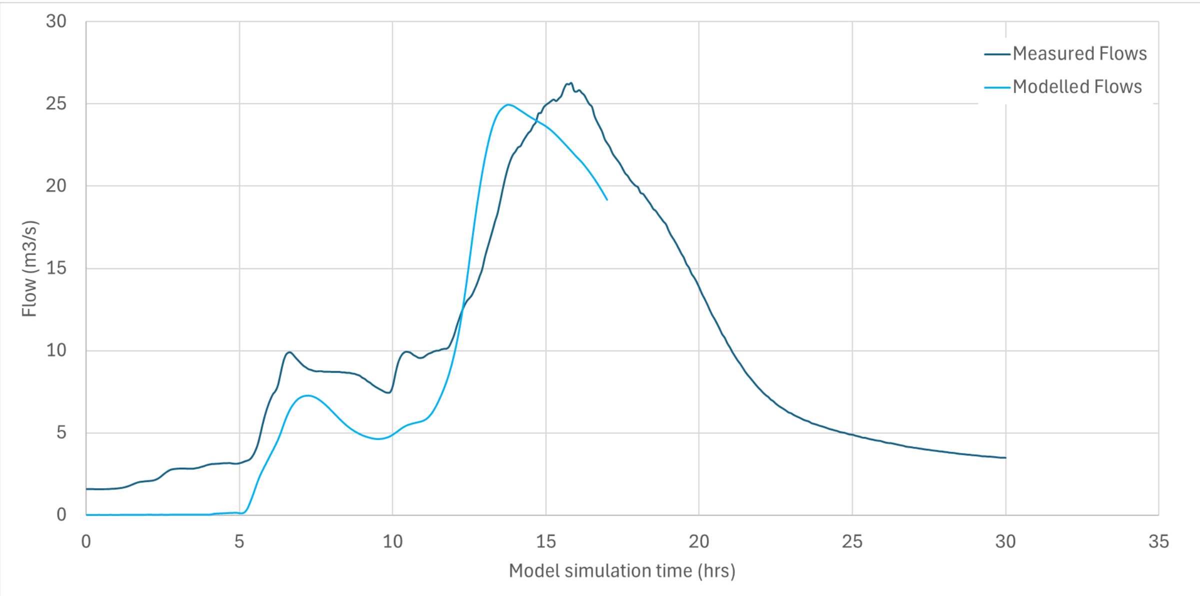
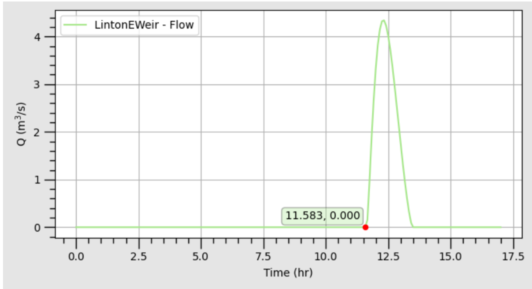
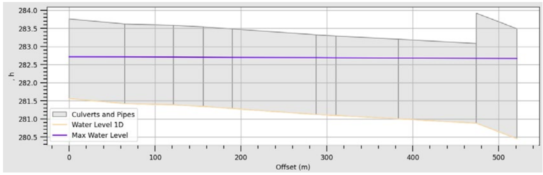


Figure 5-5: Modelled vs observed flows

There were also a number of flood observations that were reported during and after the flood event, summarised in Table 5-2 below. There is a reasonable match between the flood observations and the model results.

Table 5-2: Flood observations 20 May 2024

Location	Description	Model results
Linton Park Spillway	The Linton Park primary spillway operated over around 2 hours starting at 10:00 am on May 21, according to surveillance footage. 	Spillway operates for approximately 2 hours, starting at approximately 9:30 am in the model. 
Mitre 10 pipe	RLC correspondence on the 21st of May stated that the pipe below Mitre 10 "inspected the mitre 10 culvert today and apparently at its peak the water was just about stationary, so this confirms the back flow up our mitre 10 pipe, as the Utuhina river started dropping, water was able to start moving through"	The hydraulic grade line in the culvert is almost completely flat at the peak of the event, and there was little to no flow through it at the peak. 
Flooded houses at 156 and 134 Riri Street	Flood complaints were recorded at 152 and 134 Riri Street.	The houses are shown to be floodable according to the model hindcast (red buildings). 
Peak flood depth at Utuhina Stream at Pukehangi Road bridge	The gauge records the distance from the bridge soffit level to the water surface level. Recording shows the water level increased about 3 m during the flood event.	Water level rise at the bridge was approximately 2.5 m.
Peak flood depth in the Mangakakahi Stream at the Edmund Street gauge	The gauge records the distance from the bridge soffit level to the water surface level. Recording shows the water level increased about 1.8 m during the flood event.	Water level rise at the bridge was approximately 1.5 m.

6 Design event simulation

The model has been run for a 100 year ARI design event with an allowance for climate change. A joint probability approach has been applied as recommended by BOPRC in the hydrological and hydraulic guidelines to flood hazard investigations. The full run matrix is shown in Appendix A. For all model runs:

- Vertical datum is Moturiki 1953.
- Projection is NZTM.
- Roughness derived from BoPRC H&H Guidelines.
- Rainfall depth-duration-frequency data from HIRDS V4.
- Aerial reduction applied to rainfall nested elements as per BoPRC H&H Guidelines.

Model outputs, represented as "peak of peak" maximum modelled flood depths for each of the simulated ARI events, have been provided in raster form accompanying this report. "Peak of peak" outputs are the enveloped maximum flood depth reached at any one cell in the model domain across the joint probability events and provide a "worst-case" estimate of peak flood depth. The "peak of peak" overlays do not come from any single event simulation, but are compiled from all event simulations for a given ARI and climate change projection.

7 Flood model results processing

The flood model outputs prepared are maximum flood depth, maximum flood level and the Depth x Velocity (DxV) related flood hazard.

To plot flood depths, a mapping threshold of 100mm was adopted. This means that any cells with modelled maximum flood depth less than 100mm have been removed from any mapping. In addition, small "puddles" (areas of flooding not connected to the main flood area) of up to 50 m^2 have also been removed.

DxV gives an indication of areas where the combination of flood water depth and flow velocity as a combined product poses a safety risk. Australian Rainfall and Runoff (ARR) specifies a hazard index that we have post processed through the model.

Hazard Classification	Description (and defined limits)
H1	Relatively benign flow conditions. No vulnerability constraints. (D < 0.3 m, V < 2.0 m/s, or V x D < 0.3)
H2	Unsafe for small vehicles. (D < 0.5 m, V < 2.0 m/s, or V x D < 0.6)
H3	Unsafe for all vehicles, children and the elderly. (D < 1.2 m, V < 2.0 m/s, or V x D < 0.6)
H4	Unsafe for all pedestrians and vehicles. (D < 2.0 m, V < 2.0 m/s, or V x D < 1.0)
H5	Unsafe for all pedestrians and vehicles. Buildings require special engineering design and construction. (D < 4.0 m, V < 4.0 m/s, or V x D < 4.0)
H6	Unconditionally dangerous. Not suitable for any type of development or evacuation access. All building types considered vulnerable to failure. (D > 4.0 m, V > 4.0 m/s, or V x D > 4.0)

Figure 7-1: ARR Hazard index

7.1 Results extent

The results are provided for the extent shown in Figure 7-2 below, as shown in red. Note there are excluded parts of the Rotorua CBD as the network detail is of insufficient quality for this area to be modelled accurately, and the upper catchment flood depths have been removed as agreed with RLC.

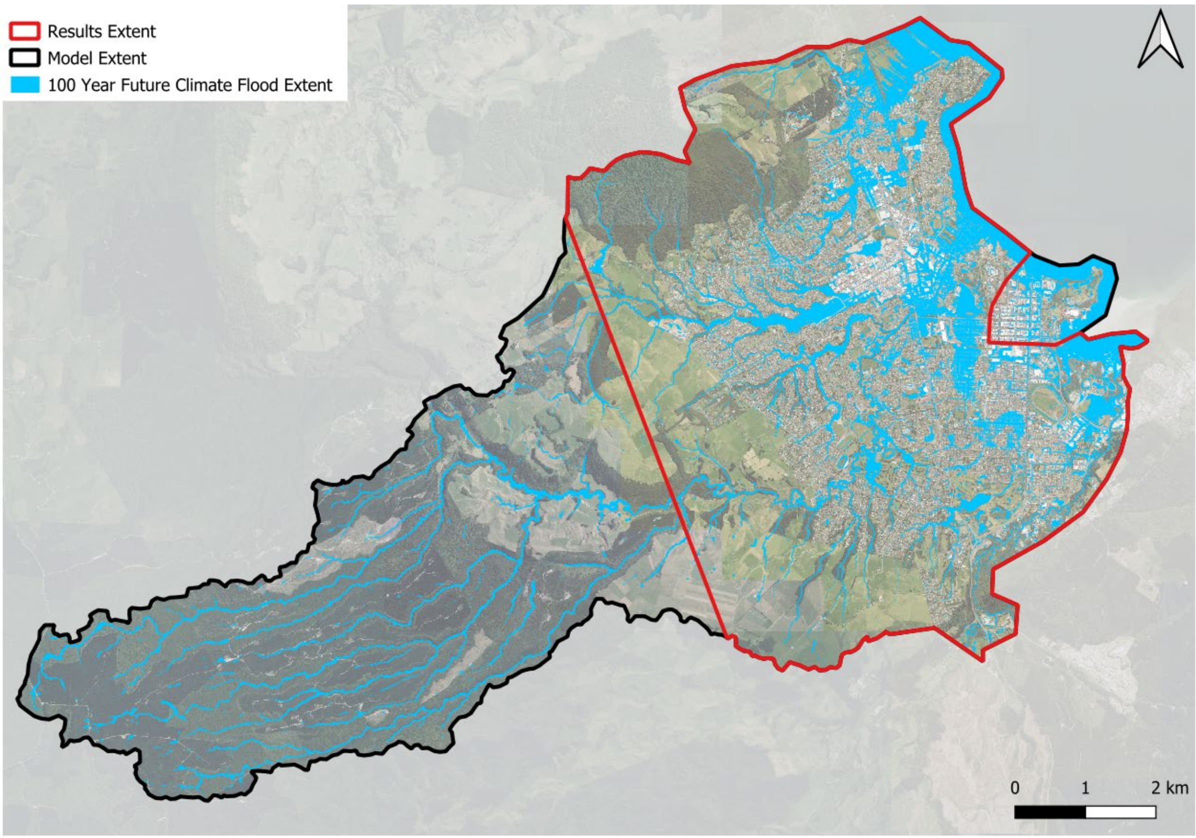


Figure 7-2: Results extraction extent

8 Conclusion

The western catchment TUFLOW model for Rotorua has been updated and calibrated in order to provide flood hazard maps. The model has been run for various combinations of urban, rural rainfall and lake level in order to provide two enveloped sets of results to define the 100-year ARI event for two climate change projections, defined as present day and future climate (RCP 8.5 projected to 2100). For all model runs, the land use is based on the Existing Development (ED) scenario, no future development (i.e. MPD) has been modelled.

The outputs have also been 'cleaned' to remove small flood depths and ponding areas which are the consequence of the modelling approach we have used, and may not be considered realistic. The outputs comprise a series of flood depth results, for the 100-year ARI flood event, covering all of the model domain.

9 Applicability

This report has been prepared for the exclusive use of our client Rotorua Lakes Council, with respect to the particular brief given to us and it may not be relied upon in other contexts or for any other purpose, or by any person other than our client, without our prior written agreement.

Tonkin & Taylor Ltd
Environmental and Engineering Consultants

Report prepared by:	Authorised for Tonkin & Taylor Ltd by:
....	....
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Water Resources Engineer	Project Director

Technical review done by Mark Pennington

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Appendix A Model run matrix

Run #	ID (TBC)	Model Build			Rainfall									Tailwater boundary		
		Landform	**Land use data source**	**Roughness data source**	**DDF data source**	**Upper catchment ARI (years)**	**Lower catchment ARI (years)**	**Temporal profile**	**Rainfall duration**	**Climate horizon**	**Approach (lumped or RoG)**	**Loss model**	**Loss parameters source**	**Lake level ARI**	**Boundary source**	**Purpose**
1		Existing	LCDB5	H&H guidelines	HIRDS v 4	100	20	Fully nested, tail weighted	48	Present day	RoG	Initial continuing	Proportional	20	BOPRC	Merge runs 1 - 3 to establish base 1%AEP scenario for present day climate against which sensitivity can be tested
2		Existing	LCDB5	H&H guidelines	HIRDS v 4	20	20	Fully nested, tail weighted	48	Present day	RoG	Initial continuing	Proportional	100	BOPRC	
3		Existing	LCDB5	H&H guidelines	HIRDS v 4	20	100	Fully nested, tail weighted	48	Present day	RoG	Initial continuing	Proportional	20	BOPRC	
4		Existing	LCDB5	H&H guidelines	HIRDS v 4	100	20	Fully nested, tail weighted	48	Future Climate	RoG	Initial continuing	Proportional	20	BOPRC	Envelope runs 4-6 to establish base 1%AEP scenario for future climate against which sensitivity can be tested
5		Existing	LCDB5	H&H guidelines	HIRDS v 4	20	100	Fully nested, tail weighted	48	Future Climate	RoG	Initial continuing	Proportional	20	BOPRC	
6		Existing	LCDB5	H&H guidelines	HIRDS v 4	20	20	Fully nested, tail weighted	48	Future Climate	RoG	Initial continuing	Proportional	100	BOPRC	