Styx Flood Modelling

TUFLOW HPC Model Build Report

Date 28/11/2025

STYX MODEL BUILD REPORT

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Project Manager	Avinash Chakravarthy
Author	Avinash Chakravarthy; Brad Scarfe
Additional technical contributors	Hamish Horan; Tony Trueman; Chusit Apirumanekul

VERSION	DATE	DESCRIPTION	AUTHOR	REVIEWED
v1.0	16/05/2025	Draft overview of calibration methodology and results for interim peer review	Avinash Chakravarthy; Brad Scarfe	Chusit Apirumanekul
v2.0	30/07/2025	Calibration / validation model Build report for peer review	Avinash Chakravarthy; Hamish Horan; Tony Trueman; Chusit Apirumanekul	Brad Scarfe
v3.0	06/10/2025	Updating Calibration / validation model results after peer review	Avinash Chakravarthy; Hamish Horan	Avinash Chakravarthy
v3.1	07/10/2025	Addition of Appendix B - Styx Recalibration Memo	Avinash Chakravarthy	Ben Fountain
v4.0	21/11/2025	Updated report after design model completed	Avinash Chakravarthy	Brad Scarfe
v4.1	28/11/2025	Updated after CCC internal review and Tonkin and Taylor peer review	Avinash Chakravarthy	Brad Scarfe

EXECUTIVE SUMMARY

The existing Styx River catchment stormwater and flood model was built in DHI MIKE FLOOD software version 2016 to represent the 2012 catchment situation but with some additional network information representing development in 2014. This legacy model was developed by GHD and Christchurch City Council (CCC) using the DHI MIKE software suite and updated with more information between 2020 and 2022. Awa Environmental (Awa) was engaged by CCC to update the existing DHI model and carry out design model runs for use by the Stormwater Asset Planning team.

The objectives of this study are to:

- review existing data and information including existing models to support model updates;
- develop a new TUFLOW model for the existing development (2024) state based on existing models and the updated information;
- calibrate the 2024 TUFLOW model with July 2022 event;
- validate the model using the December 2021 and June 2013 events; and
- run the 2024 TUFLOW model for design events and produce deliverables as described in the user deliverables requirements spreadsheet.

A range of model purposes for which this model can be used are:

- building design (especially floor level setting);
- building Consent requirements;
- other network infrastructure and earthworks planning and design (especially stormwater management infrastructure);
- definition of flood risk extents (e.g. high flood hazard area) and other District Plan requirements;
- expert evidence for establishing consents and supporting plan changes;
- input into rules, assessment matters, policies and consenting outcomes relating to waterway and flood management;
- ongoing operation of existing consents (e.g. CSNDC);
- planning and preparation for emergencies including response and recovery plans for Civil Defence groups; and
- multi-hazard planning and input into the Coastal Hazards Adaptation and Planning Programme.

A range of previous studies, input data and model build process is outlined in the report. Some key model characteristics are outlined below.

- 1D (one-dimensional) – 2D (two dimensional) coupling approach was applied for this model. The 1D components include stormwater network assets (pipes, culverts and pits) which are linked with the 2D domain. Open channels were modelled in the 2D domain.
- Coordinate system: New Zealand Transverse Mercator 2000.
- Vertical datum: NZVD 2016.
- TUFLOW HPC (Heavily Parallelised Compute) version 2025.1.2.
- TUFLOW's Quadtree and SGS features were applied in the model.

- An approach to groundwater was applied using an initial groundwater level layer to approximate the MIKE approach outlined in the CCC's flood modelling schema (Appendix L), however, some small amount of horizontal flow was implemented.

An approach taken to calibration was outlined and broadly follow these steps:

1. initial simulations of July 2022 event using a schema based approach;
2. verification of rainfall, soil, tide and groundwater datasets;
3. gained input from CCC experts and initial reviewer discussions;
4. implementation of GNS (White *et al.,* 2007) median discharges along stream network;
5. focus on calibration performance for water level and discharge at Radcliffe Road;
6. focus on calibration of water level at Harbour Road, including terrain editing to ensure channel outflow that was not represented by LiDAR;
7. sensitivity testing of key parameters including:
    a. roughness;
    b. infiltration;
    c. absence/presence of groundwater;
    d. rain on/off;
    e. groundwater level;
8. implementation of *"time varying groundwater discharges" (accounting for baseflow and interflow)* based on scaling GNS estimates to better represent groundwater response to rain as observed in groundwater monitoring sites; and
9. testing against smaller 2021 and medium sized 2013 validation events.

The results of the calibration and validation are described and discussed along with an overview of implications for the design model. A summary of the calibration quality is provided here.

- **2022 Calibration:**
    - Largest available event (22-year ARI)
    - Volumes have reasonable match.
    - Reasonable calibration achieved in discharge at Radcliffe.
    - Good calibration of water level at Harbour Road.
    - Radcliffe level ok and survey has been recommended around gauge as known DEM issues that will impact rating accuracy.
- **2021 Validation:**
    - Small event and discharge and level is over predicted at Radcliffe Road.
    - Good calibration of water level at Harbour Road.
- **2013 Validation:**
    - Medium event and Radcliffe Road validate reasonably
    - Harbour Road levels shape and range validate but are levels low. NWA tide forecaster as there was no monitoring available at that time. Climatic and stormwater impacts are not included in the boundary condition.

The existing model and significant new information have been used to develop a new flood model for the Styx catchment. It is considered a detailed, robust and validated model in line with good practice for flood models in New Zealand at the time of development. The model is consider fit for purpose for the stated model purposes in Section 1.3, and has been updated after a number of rounds of peer review. The model has now been used to successfully run various design scenarios.

The following recommendations are made for investigation and consideration in a future update of the Styx model.

- **Survey Enhancements at Radcliffe Road Gauging Station**
  Conduct a detailed survey of the concrete walls, the area behind the walls, and the cross-sections encompassing the expected flood zone during peak storm events (e.g., the 2022 event). This will support improved confidence in the rating used for calibration.
- **Review of Infiltration Parameters**
  Investigate and validate the default infiltration values used in the model to ensure they accurately reflect local soil and ground conditions.
- **Integration of Updated LiDAR Data**
  Incorporate the most recent LiDAR data into the model as it becomes available to better capture recent developments and topographic changes since the original model build.
- **Refinement of Soil Representation**
  Reassess the assumption that the current schema soil layer appropriately represents horizontal conductivity. Update the model with more accurate and detailed sub soil information as it becomes available.
- **Update Model with Turners Road Pump Station Details**
  Add information on the culvert and flap-gate configuration for the Turners Road pump station once more detailed data is obtained.
- **Use of Gauged Inflow Data at Boundary Locations**
  Replace the constant inflow boundary conditions currently used at the Waimakariri River, Kaiapoi River, and Kairaki Creek with gauged inflow data when such data becomes available.
- **Stormwater Network Update Management**
  Maintain a model backlog to capture any alterations or additions to the stormwater network, ensuring regular updates to preserve the model's accuracy and currency.
- **Improvement of Kerb Line Representation**
  Enhance the accuracy of kerb line data to improve the model's surface flow representation and drainage behaviour simulation.
- **Enhancement of Open Channel Survey Data**
  Improve survey data for open channels by integrating recent bathymetric survey data with LiDAR information. This will enhance the representation of below-surface channel geometry and align the model with current surveyed conditions.
- **Assessment of Groundwater Interactions**
  Investigate the potential for groundwater flow across surface water catchment boundaries—particularly upstream (north toward the airport) and near the Avon model boundary (around Prestons Road)—to determine whether these interactions significantly influence flood events.
- **Dataset size**
  The model has good computational performance but results in file sizes. To minimise issues with large model such as this, specify in future schema what groundwater depth, level and velocity (GWh, GWd, GWv) data should be stored. Consider only storing NetCDF format (.nc files) to be compatible will ArcGIS Pro without producing the standard TUFLOW XMDF files when not required.

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1. INTRODUCTION

1.1. BACKGROUND

The existing Styx River catchment stormwater and flood model (Styx model) was built in DHI MIKE FLOOD software version 2016 to represent the 2012 catchment situation but with some additional network information representing development in 2014. This legacy model was developed by GHD and Christchurch City Council (CCC) using the DHI MIKE software suite and updated with more information between 2020 and 2022.

Awa Environmental (Awa) was engaged by CCC to update the existing DHI model and carry out design model runs for use by the Stormwater Asset Planning team. In April 2024 Awa began to develop a new TUFLOW HPC model for existing development (2023-2024) in Styx using information in the existing MIKE model and additional updated information. This report outlines the model build, calibration and validation process as the interim step before design simulations are completed.

1.2. OBJECTIVES

The objectives of this study are to:

- review existing data and information including existing models to support model updates;
- develop a new TUFLOW model for the existing development (2024) state based on existing models and the updated information;
- calibrate the 2024 TUFLOW model with July 2022 event;
- validate the model using the December 2021 and June 2013 events; and
- run the 2024 TUFLOW model for design events and produce deliverables as described in the user deliverables requirements (CCC, 2025; Model Peer Review Template.xlsm) spreadsheet.

1.3. MODEL PURPOSE

CCC (2025) provides draft user requirements for Council catchment-wide flood models and typical internal model users:

- operations;
- consent compliance;
- asset management;
- technical services and design;
- transport;
- planning, including CHAP; and
- Civil Defence and Emergency Management;

CCC (2025) also lists a range of primarily functions that modelling supports. These are relevant to the purpose of the Styx model and include these functions:

- building design (especially floor level setting);

- building consent requirements;
- other network infrastructure and earthworks planning and design (especially stormwater management infrastructure);
- definition of flood risk extents (e.g. high flood hazard area) and other District Plan requirements;
- expert evidence for establishing consents and supporting plan changes;
- input into rules, assessment matters, policies and consenting outcomes relating to waterway and flood management;
- ongoing operation of existing consents (e.g. CSNDC);
- planning and preparation for emergencies including response and recovery plans for Civil Defence groups; and
- multi-hazard planning and input into the Coastal Hazards Adaptation and Planning Programme.

1.4. PREVIOUS STUDIES

Substantial information was provided to AWA to support the model development. The input information was reviewed by Awa to assess its relevance in filling any of the data gaps in the TUFLOW model. Table 1-1 summarises the previous modelling work referenced in this study.

Table 1-1. List of previous studies.

PREVIOUS STUDY	DESCRIPTION
MIKE 1D-2D coupled model GHD (2018)	MIKE 1D-2D coupled model: MIKE-based model components, M11, MU (the model was incomplete and had not been stabilised.)
Styx Model Build Requirements Report, GHD John McArthur (2020)	This document outlines the scope of work presently required to complete updating of the existing MIKE Flood (classic grid) Styx flood model to flexible mesh and a higher level of detail, to better reflect current and potential future catchment conditions.
Styx River calibration model report, Beca Roisin Blundell-Dorey, and Elliot Tuck (2023)	Christchurch City Council (CCC) are building a new hydraulic model for the Styx River catchment. River flow, water level, rainfall, weed growth, tide level and groundwater were investigated to select a recorded flood event within the Styx catchment to calibrate the new model.
Styx - Geometry Data Collection Review, WSP Thomas Nikkel, Ted Shu, and Matthew Murdock (2024)	WSP were engaged to undertake a gap analysis to confirm survey needs and a catchment wide inference and interpolation of missing asset data attributes across the Styx River catchment.

PREVIOUS STUDY	DESCRIPTION
Anticipated Baseflow and Water Balance Changes resulting from the Stormwater Management Plan for the Puharakekenui-Styx Catchment, PDP Caitlin Frazer, Madeline Inglis, and Guus Rongen, (2023)	Investigation to study the effects of the diversion and discharge of stormwater on baseflow and waterways and springs and details of monitoring.
Shallow Groundwater Levels Under Christchurch - APP Network Data Analysis Update, Aqualinc Julian Weir, Helen Rutter, Nick Dudley Ward, and Greg Hatley (2024)	Study covering the monitoring of shallow groundwater levels using a network of piezometers under the Automated Piezometer Programme (APP) network.
Data Quality and Accuracy Report (Machine Learning Impervious Surface), Lynker Analytics David Knox (2024)	The purpose of this work is to map impervious surfaces in Christchurch City.
Observations of Styx River Base Flow Water Level Changes with Time, CCC Graham Harrington (2009)	Analysis of weed growth and impact on flows in the Styx River.
Christchurch City Council – Styx River Survey, WSP Clinton O'Leary (2023)	This document is a survey report prepared by the Christchurch City Council that captures culverts, bridges, and cross-sections & longitudinal profiles of the Styx River catchment.

1.5. STYX CATCHMENT AND MODEL EXTENT

The Styx River catchment in Christchurch covers approximately 70 km^2 and extends for 22 kilometres, flowing from Harewood and Bishopdale to Brooklands Lagoon. It comprises a significant area containing a number of differing land-use types from semi-rural and urban land uses, including parks, reserves, lifestyle blocks, agriculture, residential areas, commercial spaces, and industrial zones. The catchment has multiple new and in progress subdivisions modifying land use and infrastructure.

The TUFLOW model boundary differs from the previous MIKE Flood model version as the model has been extended along the north-west boundary (Figure 1-1). This is to encompass the industrial/commercial development at the northern extent of the Christchurch airport and south of Lake Roto Kohatu.

An extension along the north-east edge also has been made to encompass the Waimakariri River in the 2D domain. This allows an inflow from the previous modelling (GHD, 2018: MIKE Flood model) to be released in the vicinity of the SH1 bridge to provide tailwater conditions in the Otukaikino Creek and Lower Styx River. Some other minor extent changes have been made to capture inflow into the catchment.

It is worth noting that while the model boundary extends to the coastal boundary to the east, the stormwater network associated with the Brooklands red zoned area has not been included in the model based on advice from CCC due to the removal of a majority of the residential dwellings in this location. It is also noteworthy that the model is a surface water catchment boundary and that the groundwater does have flow from the upstream of the catchment, as outlined in *Section 3.3 Assessment of Groundwater.*

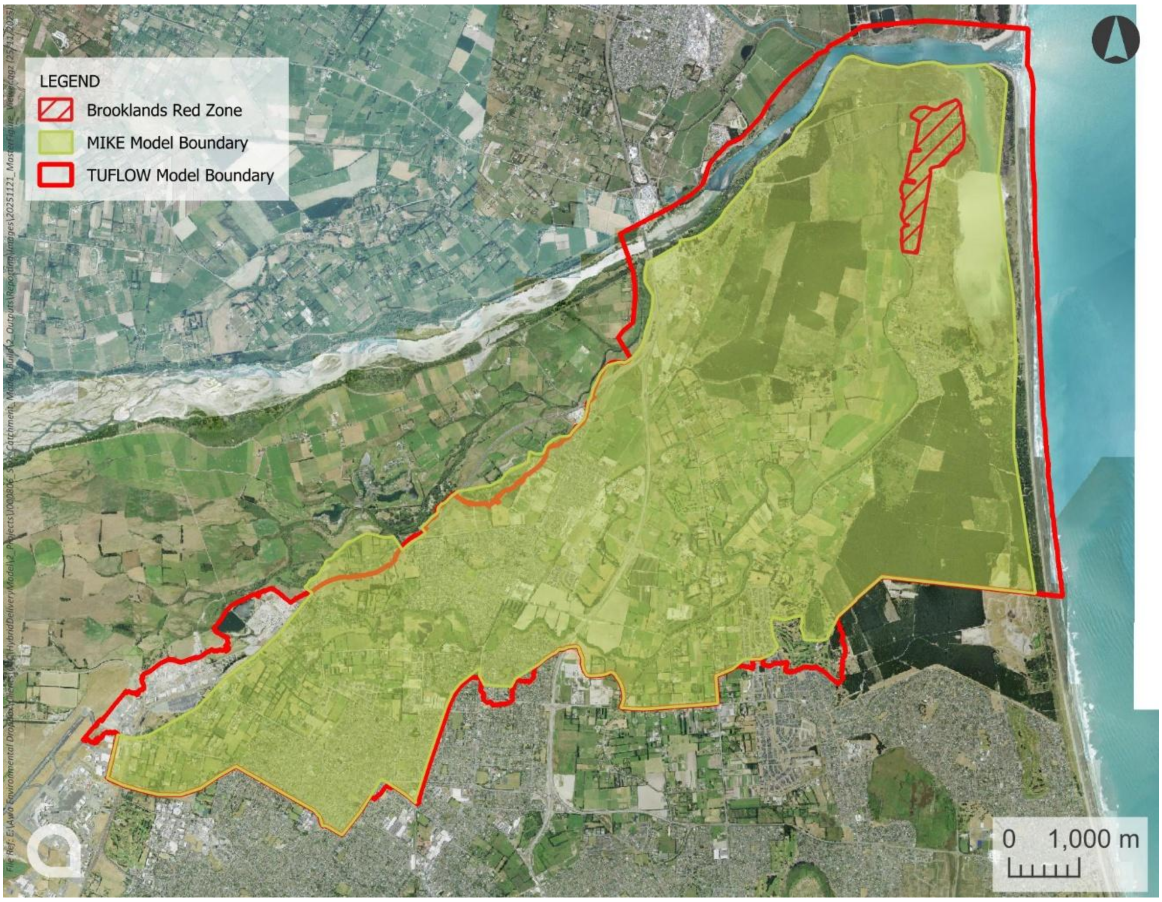


Figure 1-1. Styx catchment TUFLOW and previous model extents.

1.6. EXISTING LAND COVER

Existing land cover was classified into eight categories as shown in Figure 1-2.

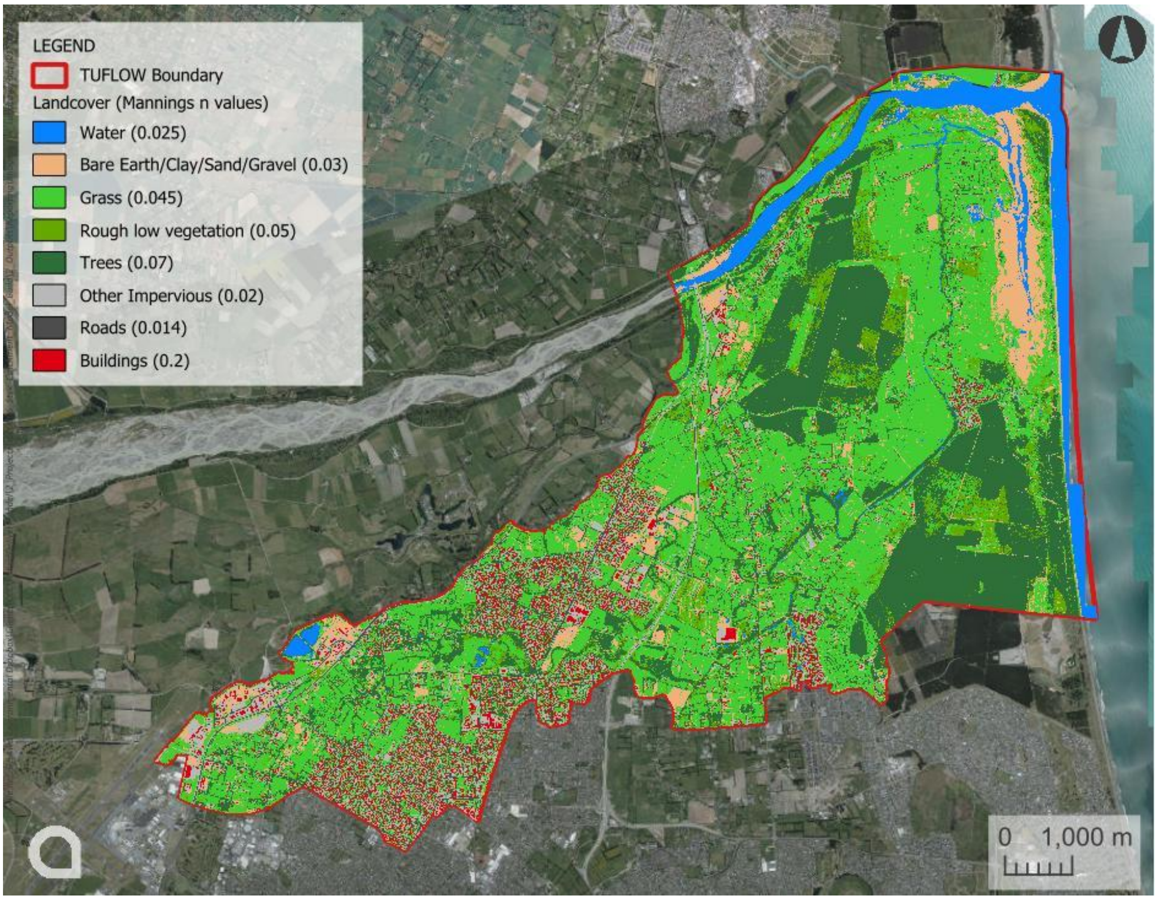


Figure 1-2. Land cover and associated roughness coefficients (Manning's n values) used in the model to represent the existing development.

1.7. STORMWATER SYSTEM

The stormwater network included in the TUFLOW model comprised elements from different sources including.

1. WSP 2023 node and pipe (inferred and interpolated data):

   The WSP 2023 node and pipe data is the output from WSP's assessment of the Styx stormwater network. The assessment included a gap analysis of the current dataset, collation of existing data, pre-processing of data, identification of overlapping network and interpolation of the physical geometry of the network. The interpolation and inference of missing asset data values used algorithms to attribute missing data and included a data flag system to highlight the interpolation method.

2. MIKE Urban & M11 components of the GHD Mike Flood model.
3. CCC's Spatial Open Data Portal.
4. Engineering plans of stormwater network.
5. Styx – Geometry data collection review.

6. Styx basin design details.
7. Expressway data.
8. Pump-station data.
9. KiwiRail culvert data.
10. Bridge data.
11. Lynker sump data; and
12. Assumptions based on engineering judgement.

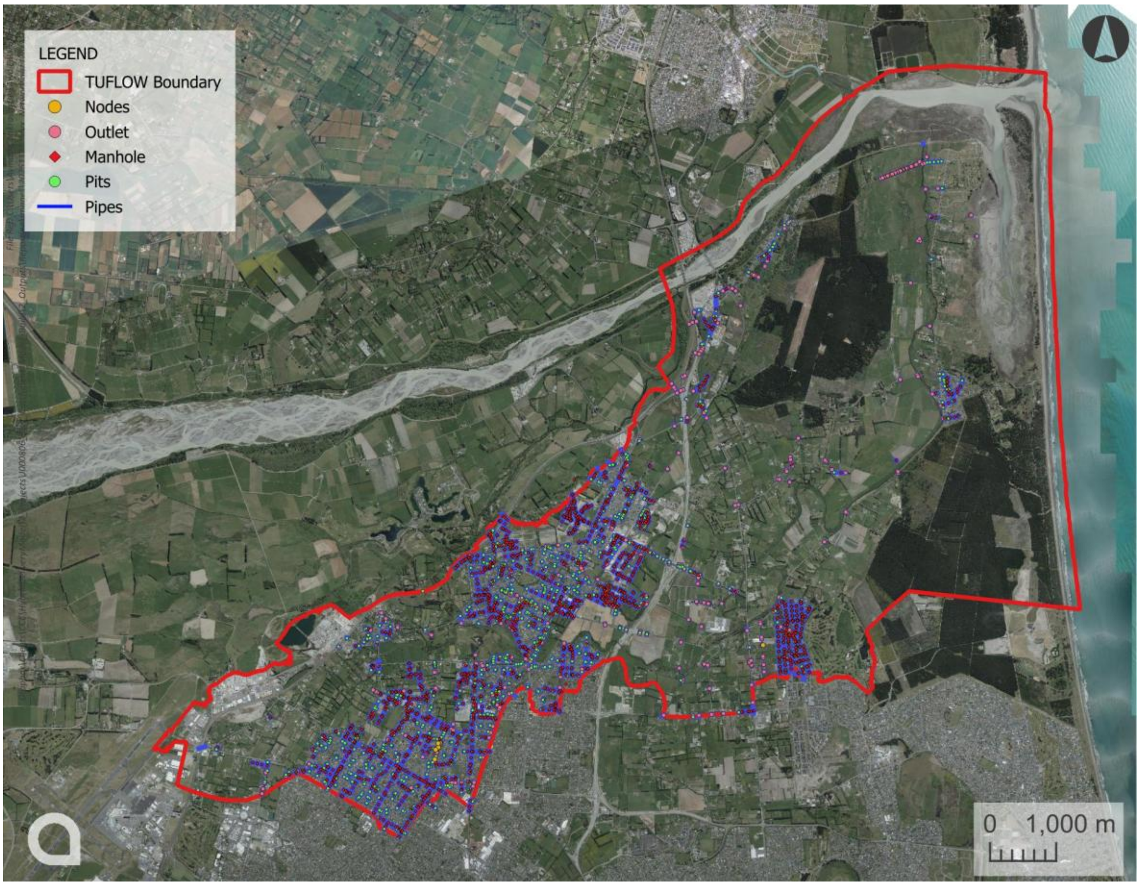
Table 1-2 compares the numbers of different asset types that constitute the TUFLOW and MIKE Urban models.

Table 1-2. Stormwater assets included in the TUFLOW model compared with the Mike Urban model.

STORMWATER NETWORKS	TUFLOW MODEL	MIKE URBAN MODEL
Nodes/Manholes	1536	1450 *
Catchpits	2256	631
Inlets/Outlets	713	162
Pipes	3883	2063

* Includes 343 nodes used to represent open drains

Figure 1-3 contrasts the baseline (2024) stormwater network included in the TUFLOW model with the stormwater network modelled in MIKE Urban.



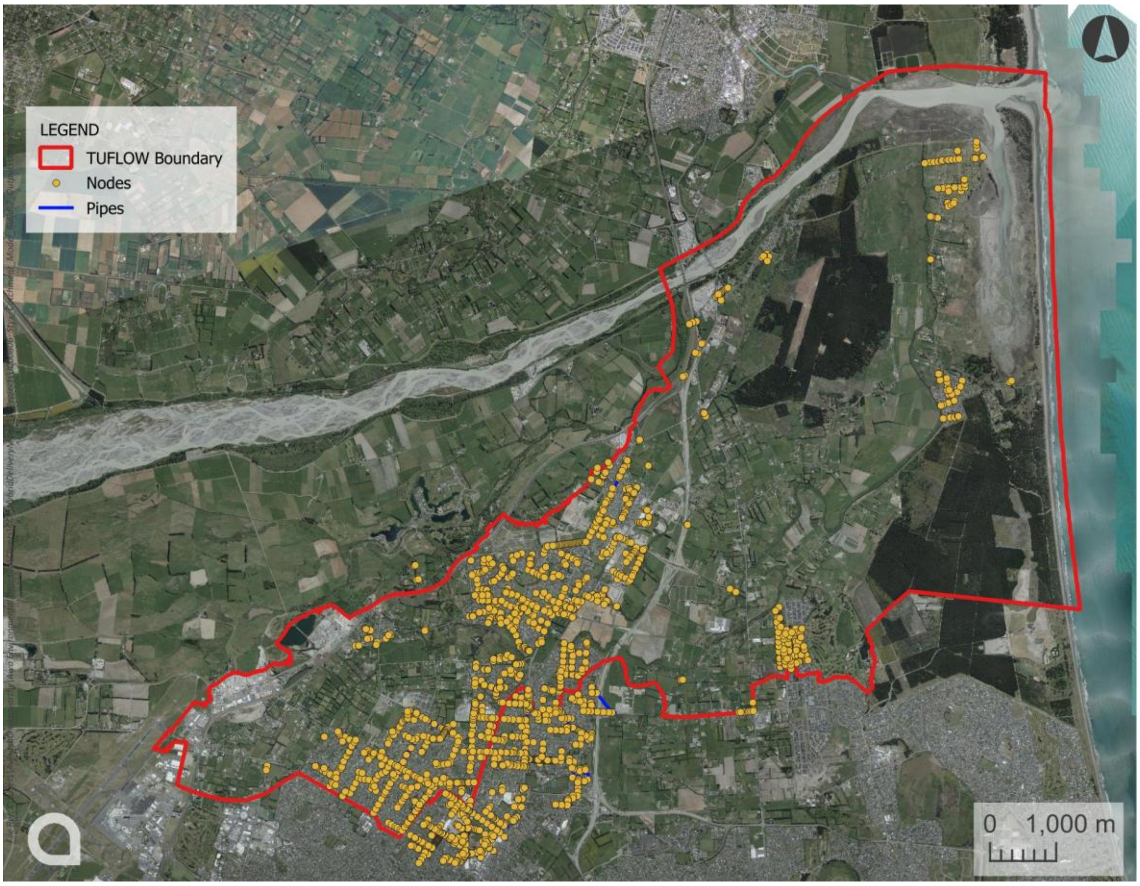


Figure 1-3. Stormwater networks included in TUFLOW model (top) and 2012 MIKE Urban model (bottom).

2. FLOOD MODEL BUILD

2.1. MODEL OVERVIEW

The following section defines the conceptual approaches that were used to represent the real-world characteristics of the Styx catchment. The CCC flood modelling Schema (rev7; GHD, Jul 2022) explains the methods, practices and standards used for the MIKE-based modelling system and it forms the basis for this TUFLOW model build where applicable. Table 2-1 summarises the key details of the TUFLOW model.

Table 2-1. TUFLOW model overview.

ITEM	DETAILS
Purpose	Provide CCC with the simulation capability to understand changes in the catchment and growth scenarios, and to plan for development. Details of model user requirements is outlined in *Section 1.3 Model Purpose.*
Software	TUFLOW HPC (Heavily Parallelised Compute) version 2025.1.2
Modelling approach	1D (one-dimensional) – 2D (two dimensional) coupling approach has applied for this model. The 1D components include stormwater network assets (pipes, culverts, pits and pump stations) which are coupled with the 2D domain and open channels were modelled in the 2D domain. The 2D soil layer has a thickness of 25 m to represent the shallow aquifer to supply applying an initial groundwater level. Sub-grid Sampling (SGS) approach was applied for more accurate representation of the topography and hydraulic conveyance in the 2D domain. This approach uses multiple points for grid cell elevations in a single cell) enabling a large grid cell size but sampling of terrain at the DEM resolution. A nesting of the grid cell (Quadtree mesh) was configured to allow higher resolution of grid cell size over focus areas and lower resolution in topographically or hydraulically simple locations. A modified version of the Schema “Appendix L – M21 infiltration with groundwater capacity” approach has been applied using an initial groundwater level. The modification achieves the infiltration capacity limiting approach of Appendix L but allows some horizontal groundwater conductivity (Kh) to partially represent this phenomenon in the catchment. The Kh values are minor as to not drift too far from the other schema model.
Coordinate system	New Zealand Transverse Mercator 2000.

ITEM	DETAILS
Vertical datum	Original information was provided in the Christchurch Drainage Datum (CDD). The CDD was converted to the Lyttelton 1937 and then converted to the New Zealand Vertical Datum 2016 (NZVD 2016). Refer to *Section 2.4* for more details.
Calibration	The TUFLOW model was developed to represent existing (baseline) conditions in 2024. The model has been calibrated to July 2022 event using observed flow and water level recordings along the Styx River main channel.
Validation	The model has been validated with two events as defined by CCC (15 Dec 2021 and 17 Jun 2013).
Design event model runs	Total of 58 scenarios were proposed, out of which 44 scenarios have been completed. 14 scenarios are missing required inflows from Avon catchment.

2.2. MODEL INPUT DATA

Various types of information were provided to Awa. The information was reviewed, and the findings were tested with CCC to agree on which information should be used for model development. Table 2-2 below details the key data used for model development.

Table 2-2. Data used for the model build.

DATA/ INPUTS	DESCRIPTION	SOURCE
Terrain	• 2020 LiDAR with 1 m resolution in raster format.	CCC, February 2024
Open channel	• Surveyed cross sections extracted from the 001_Styx_PostEQ_ED2014.xns11 MIKE11 model	GHD, 18 October 2023
	• Survey data for culverts, bridges, and cross-sections in Styx catchment	WSP, 14 December 2024
Building footprints	• Building classification was included in the land cover 2023 raster format from Lynker. • Roughness value (Manning's n coefficient) of 0.2 was applied for building footprints based on the Schema Rev7. • LINZ 2025 Building footprints	CCC, 09 May 2024 LINZ, 10 September 2025
1D stormwater networks	• The 1D stormwater network information on pipes, manholes and pits was mainly obtained from the WSP 2023 supplied dataset. • This was augmented with data from the (GHD, 2018) Mike Urban model.	WSP, February 2024 GHD, October 2023

DATA/ INPUTS	DESCRIPTION	SOURCE
	• CCC's open GIS data and from additional supplied datasets.	https://opendata-christchurchcity.hub.arcgis.com/ downloaded on 13 June 2024
	• Sumps that are not connected to the CCC stormwater network in the CCC Spatial Open Data Portal are not included in the model	Lynker, June 2024
Culverts and bridges along Styx	• Culvert and bridge information has been extracted from the 001_Styx_PostEQ_ED2014.nwk11 MIKE11 model provided by GHD and applied to the respective culverts in the TUFLOW model.	GHD, 18 October 2023
	• Survey data for culverts, bridges, and cross-sections in Styx catchment	WSP, 14 December 2024
Kerb line	Kerb line along road • Export_Surface Water Channels.zip (Surface Water Channel_LineString.shp)	RAMM (exported on 1 Feb 2024) CCC, 10 June 2024
Groundwater / infiltration	• Soil drainage classes in shapefile format • Associated constant infiltration rates and porosity from the Citywide Flood Modelling (Schema rev 7) Model Schematisation 2020 Update report (Table 3-4)	GHD, November 2023 GHD, July 2022
	• Design events apply the 85th percentile groundwater levels	Julian Weir (Aqualinc, February 2025).
Land cover / Roughness	• Land cover 2023, covering the entire citywide with 8 classifications, from Lynker was used to define roughness values. • Roughness values (Manning's n coefficients) for 8 land use classifications were from the Schema rev 7 report	CCC, 09 May 2024 Schema rev 7 report by GHD (July 2022)
Imperviousness	• Baseline – raster layer of imperviousness percentage for 2023 (ImperviousRasters.gdb) • Future – raster layer of imperviousness percentage for 2073 and 2103 (ImperviousRasters.gdb). Two impervious rasters (mitigated and unmitigated) were provided for each time horizon. The mitigated impervious raster represents the 10-year and 50-year ARI storm events while the unmitigated impervious raster represents the 200-year ARI storm event.	CCC, 29 October 24

DATA/ INPUTS	DESCRIPTION	SOURCE
Rain	• Rainfall for calibration and validation events (500-m resolution)	Beca, 15 December 2023
	• Design rainfall (citywide rainfall) in DFS2 format for future scenarios (500-m resolution)	Beca, 13 September 2024
Tide	• Gauged tide level from NIWA for calibration and validation events	Beca, 15 December 2023
	• Downloaded tide for 2013 event from NIWA tide forecaster	NIWA, January 2025
	• Tidal levels for design events generated using a spreadsheet calculator created by GHD (Generate Sea water level boundary conditions v2.xlsx)	GHD, 21 June 2024
Avon boundaries	• Design water level and flows were extracted from existing MIKE Avon model by DHI • A time series interpolation tool provided by CCC was used to interpolate water level and flow for some design scenarios	DHI, 29 August 2025

2.3. MODEL SCHEMATISATION

Details of the TUFLOW model components are described below.

2.3.1. HYDROLOGICAL APPROACH AND MODEL BOUNDARY CONDITIONS

Direct rainfall (rain-on-grid approach) was applied to the model extent depicted in Figure 2-1. Calibration and validation rainfall were provided by Beca in DHI DFS2 format in December 2023, and this has been converted to a TUFLOW acceptable input for these events respectively. Similarly, design rainfalls were provided by Beca in February 2024 in DHI DFS2 format. The rainfall events are triangular storms with a peak at 70% of the total storm duration, applied in a grid of spacing 500 m with units set to mm/day. These were converted to TUFLOW format by interpolating the storm in five-minute intervals based on conserving total volume (depth) over each interval.

Refer to Appendix M of the Schema rev 7 report for the definition of the triangular hyetograph with a peak rainfall intensity occurring at 0.7 of the event duration.

For TUFLOW, there is no interpolation between time steps when a gridded rainfall approach is applied (refer to 2023-03 manual), and thus the design storm was divided into individual rainfall depth grids for each 5-minute time step (mm/5 mins).

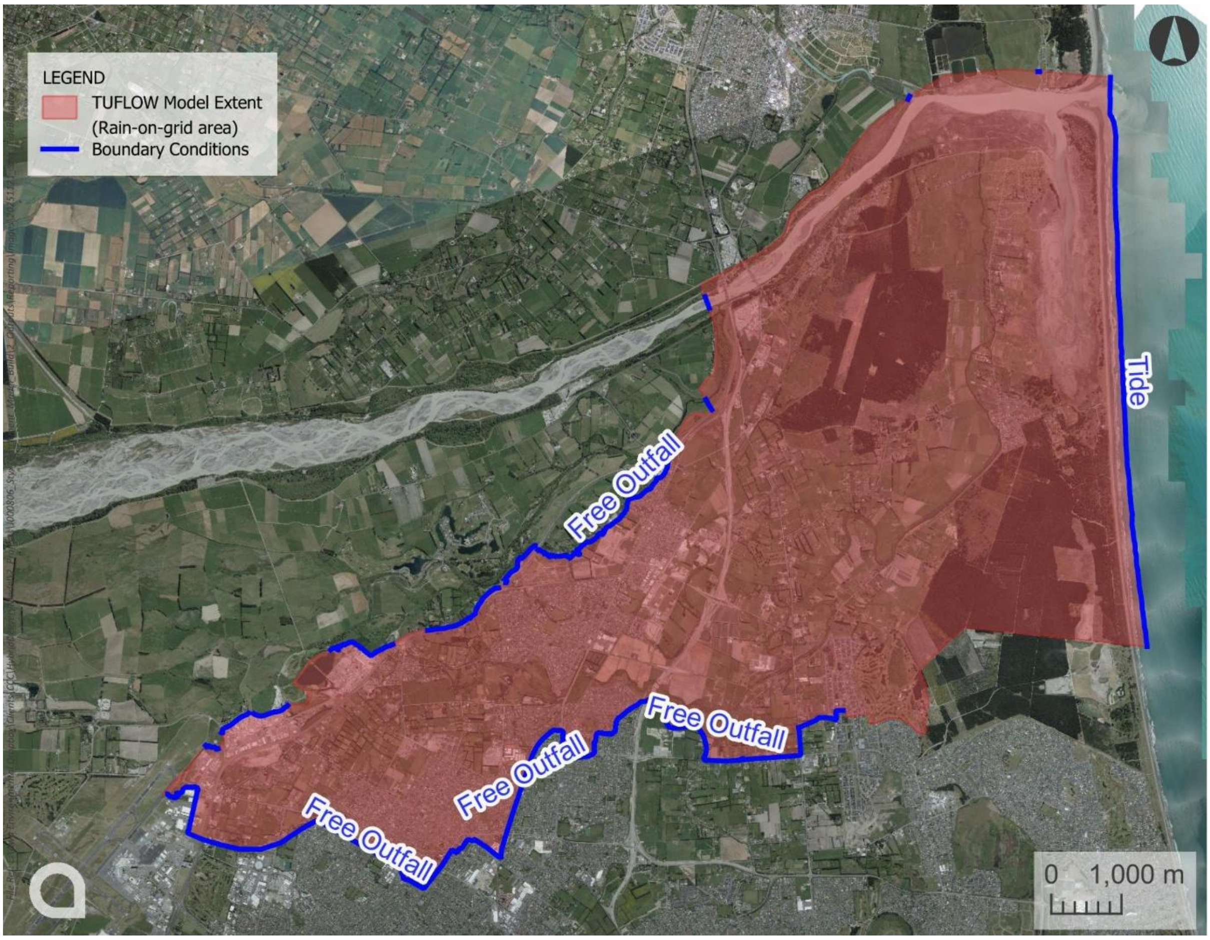


Figure 2-1. TUFLOW model extent with boundary conditions. The 'free outfall' boundaries upstream are to help avoid glass walling effect.

2.3.2. MODEL GRID APPROACH

The model uses two specific techniques to improve the representation of hydraulics in grid cells:

- SGS; and
- Quadtree.

TUFLOW's SGS approach (using multiple points for grid cell elevations in a single cell) was applied for more accurate representation of the topography (such as open channels, small drainage ditches, etc.) and hydraulic conveyance. The traditional approach (non-SGS) applies a single elevation per cell centre and cell face as shown in Figure 2-2 below on the left versus the SGS approach on the right with multiple elevations. With SGS all four cell faces would be active for the same water level compared with only two faces without SGS. The benefit of SGS is focused on cells with variety of elevations within each cell. It also mitigates effects where cells are misaligned with the water flow direction (particularly in open channels) producing more realistic flow patterns

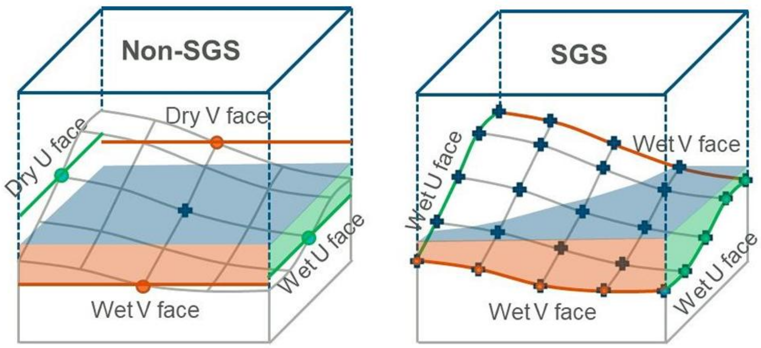


Figure 2-2 non-SGS (traditional) (left) vs SGS approach (right). Source: TUFLOW Classic and HPC 2020-01 Release Notes

The number of points at which the elevation datasets within a single cell are sampled can be defined. For instance, with a 4 m cell size and a 1 m SGS sample distance, the DEM is inspected using a regular 1 m grid, so 16 elevation points are used to define the volume vs elevation relationship within the 2D cell, and 4 points are used for defining the area-elevation relationship for the cell faces.

A Quadtree mesh (nesting of the grid cell) has been configured to allow higher resolution of grid cell size over key focus areas and lower resolution in topographically or hydraulically simple locations. The Quadtree feature allows recursive quad-tree cell subdivision (division of square cells into four equal-sized cells) to increase resolution in selected areas.

Quadtree feature allows combination of different computation cell sizes in 2D domain. The quadtree levels adopted for Styx catchment are as followed:

- 8-m cell resolution in general; and
- 2-m cell resolution for urban areas, roads, kerbs and the Styx River.

The largest cell size is 8 x 8 m as a good part of the Styx catchment covers rural areas, refined to 2 x 2 m for channels and roads. It is worth noting that reduction to 1 m in channels was found to significantly slow the model, but this is a parameter that can be configured for simulations where this additional resolution is required.

2.3.3. MODEL TERRAIN

Model terrain was primarily derived from the 2020 LiDAR data to best represent the 2024 baseline condition. The terrain is created by ordering a number of GIS raster and feature layers to build up a model DEM at run time while retaining the sources explicitly for auditing and future updates of layers. Examples of additional information incorporated into the DEM to improve the accuracy of terrain geometry included:

- surveyed cross sections of Styx River (2014);
- WSP Sept-Dec 2023 open channel survey;
- kerb lines;
- MIKE 11 cross sections (see *Section 2.3.4 Open Channels*);
- DEM lowering around inlets/outlets;

- inferred pond inverts (e.g. from pipes) as LiDAR picks up water level not invert levels; and
- stop bank enforcement lines

Due to lack of representation in the LiDAR DEM, along the coastal line the terrain was extended downward to 6 m RL CDD at a 2% slope as per Citywide model schema report (rev7; GHD, 2022), creating bathymetry under the tide level. The terrain in CDD was subsequently converted to NZVD 2016.

There is often a mismatch between 1D inlet/outlet elevations and LiDAR based DEM elevations. This was addressed by lowering the DEM elevation to match the invert levels of 1D elements. Terrain was lowered within a range from 50 mm to 100 mm to ensure that inlet/outlet levels are above the ground elevations and to reduce likelihood of instabilities (flow fluctuations) or pipes not conveying water.

Figure 2-3 shows the final terrain (or Digital Elevation Model – DEM) used in the TUFLOW model as a result of all the terrain modifications and the model DEM is written as a TUFLOW check during model initialisation (e.g. *C037_Styx_2013_DEM_Z.tif*).

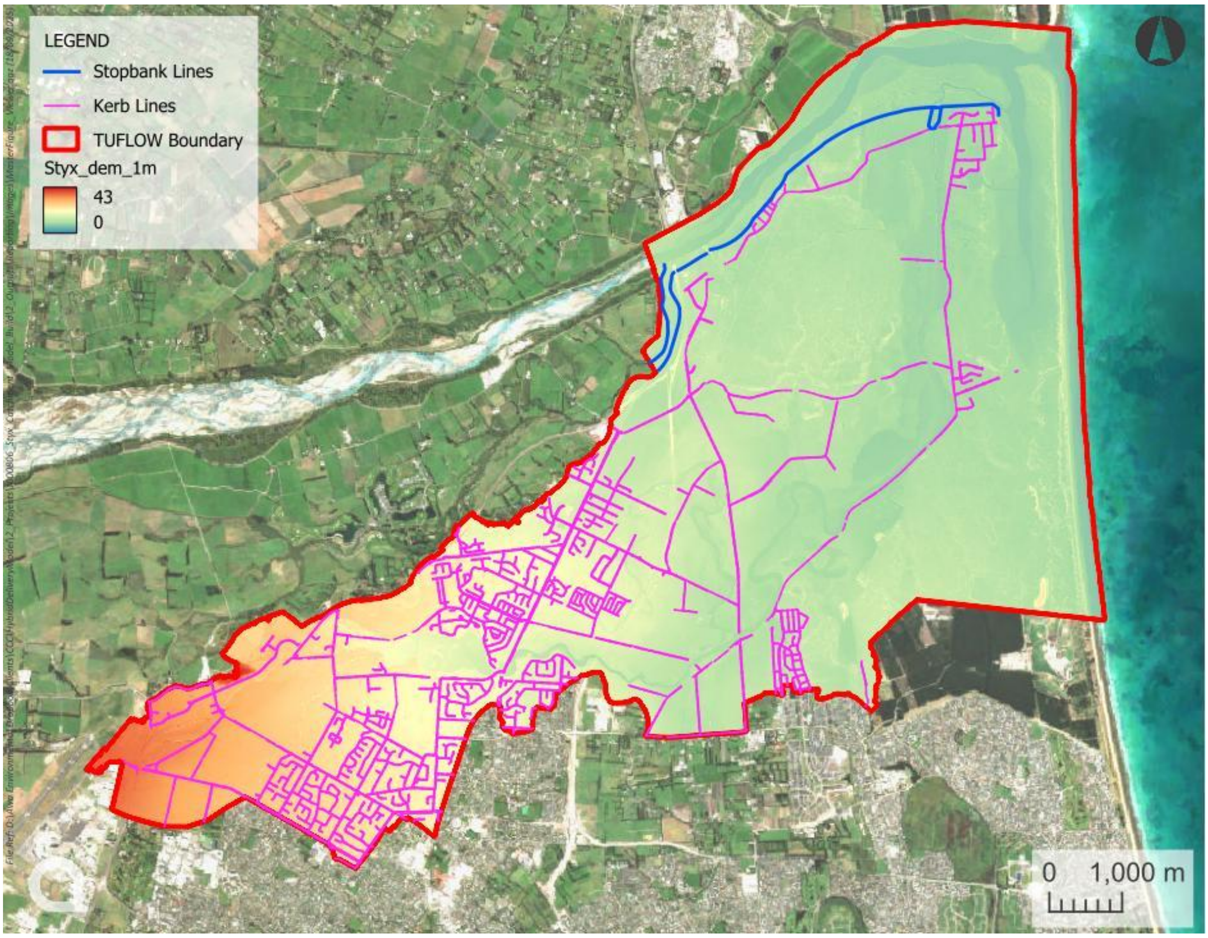


Figure 2-3. Digital Elevation Model (DEM) used in TUFLOW model.

2.3.4. OPEN CHANNELS

The Styx River and other open channels were previously modelled as a 1D component in the previous MIKE 11 model. As mentioned earlier, these have been incorporated into the 2D domain to provide improved visualisation of results and seamless open channel / flood plain integration. As several constructed drains are critical stormwater features of the Styx catchment (e.g. wooden lined drains), care was taken to represent these channels as terrain adjustments where information was available. There are three sources of open channel data used.

1. MIKE 11 network and cross-section data. This data was converted into a 2D layer using an open channel conversion tool. The output of this process was a raster of 0.5 m resolution, containing any level data that exists below the LiDAR layer. This usually only impacts bathymetry below the water surface but can also impact the banks if the MIKE 11 cross-section represents it in that way. This can lead to minor shifts in the position of the stop banks, but with minimal impact on model results.
2. Survey data for culverts, bridges, and cross-sections in Styx catchment provided by WSP. These were converted with the open channel conversion tool.
3. LiDAR 2020 retrieved from LINZ. This data is referenced to NZVD 2016 and represents bathymetry above the open-channel water surface; as a result, it does not accurately capture the bathymetry below the water surface. This is the last resort when no other data was available.

2.3.5. ROAD AND KERB LINES

Road and kerb lines were modelled in 2D domain applying the SGS technique with 3-level nesting (Quadtree), refining grid cell size to 2 m over the road. The SGS approach uses multi-point elevations from 1-m LiDAR (2020) for accurate representation of road terrain. To represent the drainage capacity of kerb lines, the terrain along the kerb lines was lowered by a further 100 mm to collect and direct rainwater away from road to the pits. Figure 2-4 shows the modified terrain along the kerb line on Northwood Boulevard. It is an example of disconnected kerb line along a roundabout. This study did not resolve gaps and issues with the kerb line layer and improvements in future are recommended.

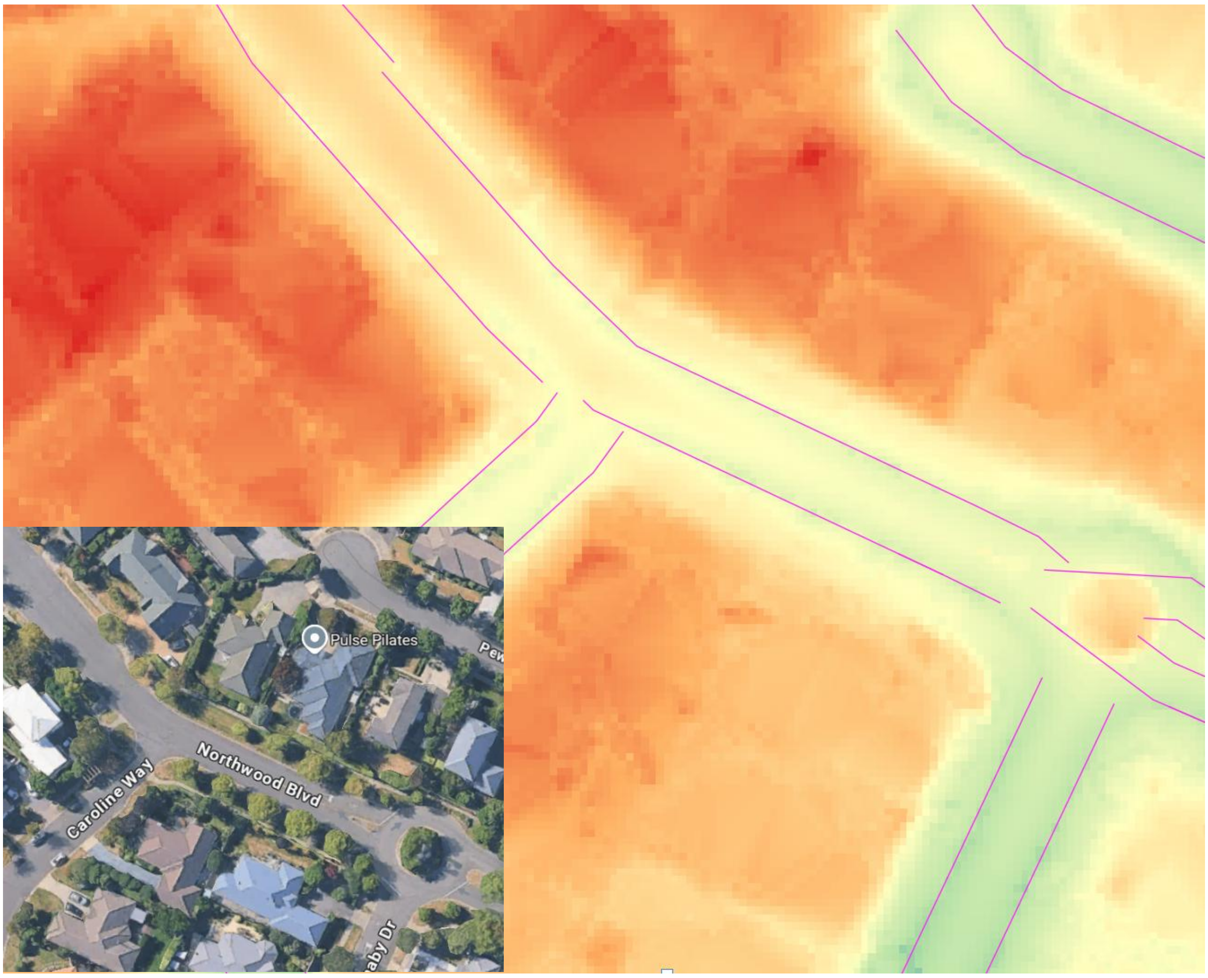


Figure 2-4. Kerb line along Northwood Boulevard (Google Street View).

Figure 2-5 displays the Quadtree areas (including road) and kerb lines for the model. The kerb line layer was provided by CCC and contains some gaps such as overlapping of kerb line and disconnected kerb line at intersections.

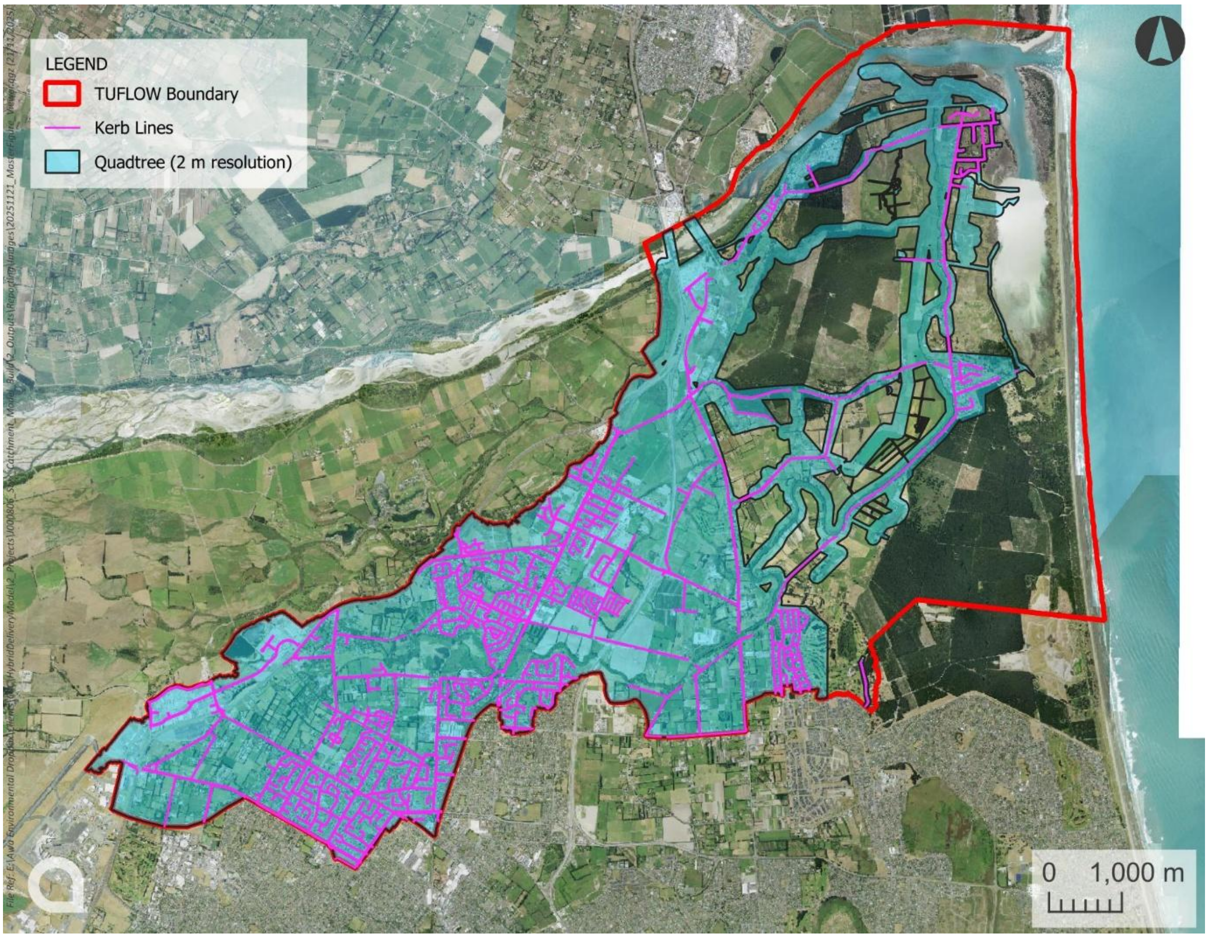


Figure 2-5. Modelling of road and kerb lines in the TUFLOW model, as well as Quadtree area. Areas outside of the Quadtree zone are modelled at an 8 m resolution.

2.3.6. BUILDING FOOTPRINTS

Building footprints were obtained from the land cover 2023 by Lynker. Manning's n value of 0.2 was applied over the building footprints to represent high flow resistance of buildings following the Schema rev 7 report. No increase in DEM elevation was made.

2.3.7. LAND COVER AND IMPERVIOUSNESS

Land cover and impervious areas from Lynker (2023) were mapped using the machine learning method by Lynker and the Christchurch 0.075 m aerial imagery from 2023. The 2023 Land cover was classified into eight types as shown in Table 2-3 below.

Figure 1-2 shows the land cover by Lynker (2023) with associated roughness values from the Schema Rev 7 report. The Schema rev7 report suggests roughness values for specific types of land cover which are different from the eight classifications by Lynker. During the peer review process with CCC, it was agreed that roughness values in the Schema rev7 report should be used. Roughness values from the Schema rev7 report were matched with the 2023 land cover classifications (Figure 1-2).

Table 2-3. Land cover classifications for 2023.

CATEGORY NAME	DESCRIPTION
Water	Water bodies including river, pond, lake and ocean
Bare earth/gravel/sand	Tilled land, bare earth, loose gravels and sand beaches
Grass	Open space without trees and shrubs
Scrub/shrub	Shrub species, rushes, low profile vegetation
High vegetation	Taller trees of all species
Other impervious	Driveways, carparks, footpaths and other paved areas
Road	Sealed and unsealed
Building	Commercial and residential

Impervious surfaces (raster format) were provided by CCC for baseline (2023) and future time horizons (2073 and 2103). It is assumed that the impervious rasters for 2073 and 2103 represent the time horizons of 2074 and 2124 for design events, respectively.

In TUFLOW, the fraction of imperviousness can be defined in overlying material type (land cover classification). This fraction is used to define the amount of water that is infiltrated from surface into the ground. The soil infiltration feature was using the infiltration rates defined for each soil drainage classification (section 3.3.8).

There were two source files for land cover and imperviousness: the 2023 land cover layer was provided in vector format (shapefile), while the imperviousness rasters were provided in raster format (2m cell size). TUFLOW incorporates the percentage of imperviousness in the land cover classification in a single materials layer. To combine the two inputs into a TUFLOW-consumable format, Awa mapped the spatially distributed imperviousness from impervious rasters to each polygon in the land cover classification layer.

This means that the classification of each material in the materials layer comprises unique combinations of land cover values plus a percentage imperviousness value.

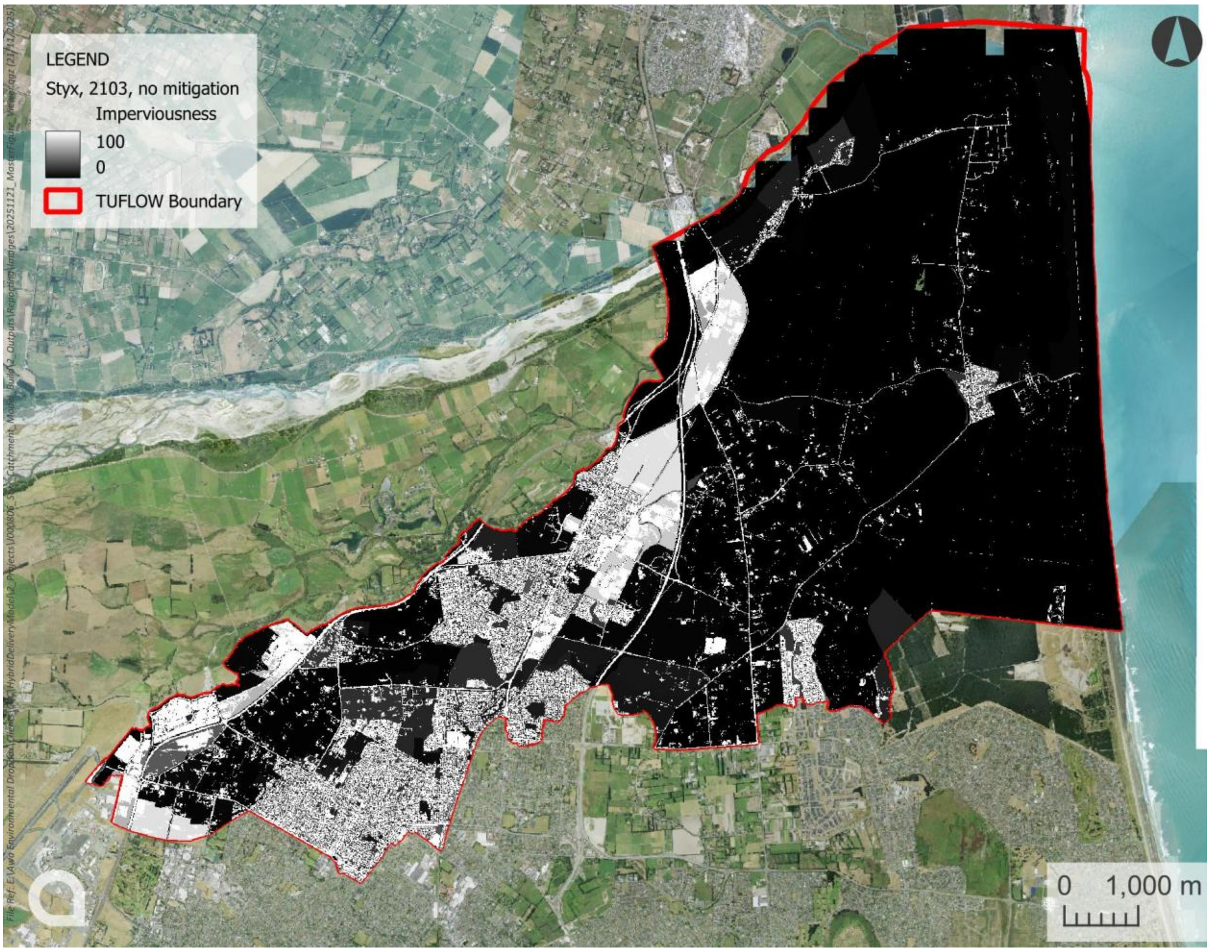


Figure 2-6: Imperviousness layer, future design scenario, no mitigation.

2.3.8. SOILS

The Schema rev 7 report (GHD, 2020) describes the infiltration methodology for MIKE21 models, and consideration of basic groundwater simulation. This TUFLOW model applied the same infiltration methodology, adapted to TUFLOW HPC, as summarized below.

- Infiltration using the constant rate of 75% of the final infiltration rate plus 25% of the initial infiltration rate from Horton's parameters for each soil type.
- Leakage to the saturated zone was assumed negligible as the slow leakage rate has little impact within the typical timescales of the flood events.
- Initial water volume was assumed null to represent unsaturated zone moisture using only porosity parameter

For the TUFLOW model, soil infiltration is applied by defining a soil classification with associated porosity, initial moisture and loss parameters. The Initial Loss/Continuous Loss (ILCL) approach was applied to the Styx model.

The following parameters were applied in accordance with recommended values related to the infiltration and groundwater capacity in the Schema rev 7 report.

- Initial loss = zero (null leakage to saturated zone).

- Initial soil moisture = zero (null initial water volume).
- Continuous loss (mm/hr) = constant infiltration rates for each soil type as defined in Table 2-4.
- Porosity = porosities for each soil type as defined in Table 2-4.

Note that the TUFLOW TSOILF file has horizontal hydraulic conductivity parameter empty, which equates to 0 mm/hr. This means groundwater acts as a limiting factor on infiltration, rather than groundwater moving through the catchment.

To date sands have been considered to have high infiltration rates consistent with the gravel drainage class. With the limits of Waterways, Wetlands and Drainage Guide knowledge, it is suggested that gravels and sands both coincided best with the same drainage class of 4.65 mm/hr infiltration rate (P. Tim, E-mail communication, August 18, 2024). It is noted though that these are low infiltration rates to increase runoff response for short term rain events.

Table 2-4: Parameters for infiltration and groundwater capacity for each soil type from the Schema rev 7 report.

Soil Classification	Soil Drainage Class	Capillary Rise (M)	Porosity (%)	Infiltration Rate (mm/hr)
Gravel (C)	Free draining	0.0125	14	4.65
Sand (M)	Moderately drained	0.135	15	3.85
Clayey Silts(F)	Imperfectly drained	1.055	10	3.35
Peat (P)	Poorly drained	0.5	15	2.55
Fill (X)	Very poorly drained	0.025	15	1.025
Dummy (W)		0	0	

Figure 2-7 shows the soil classifications in the Schema rev 7 report used in the model.

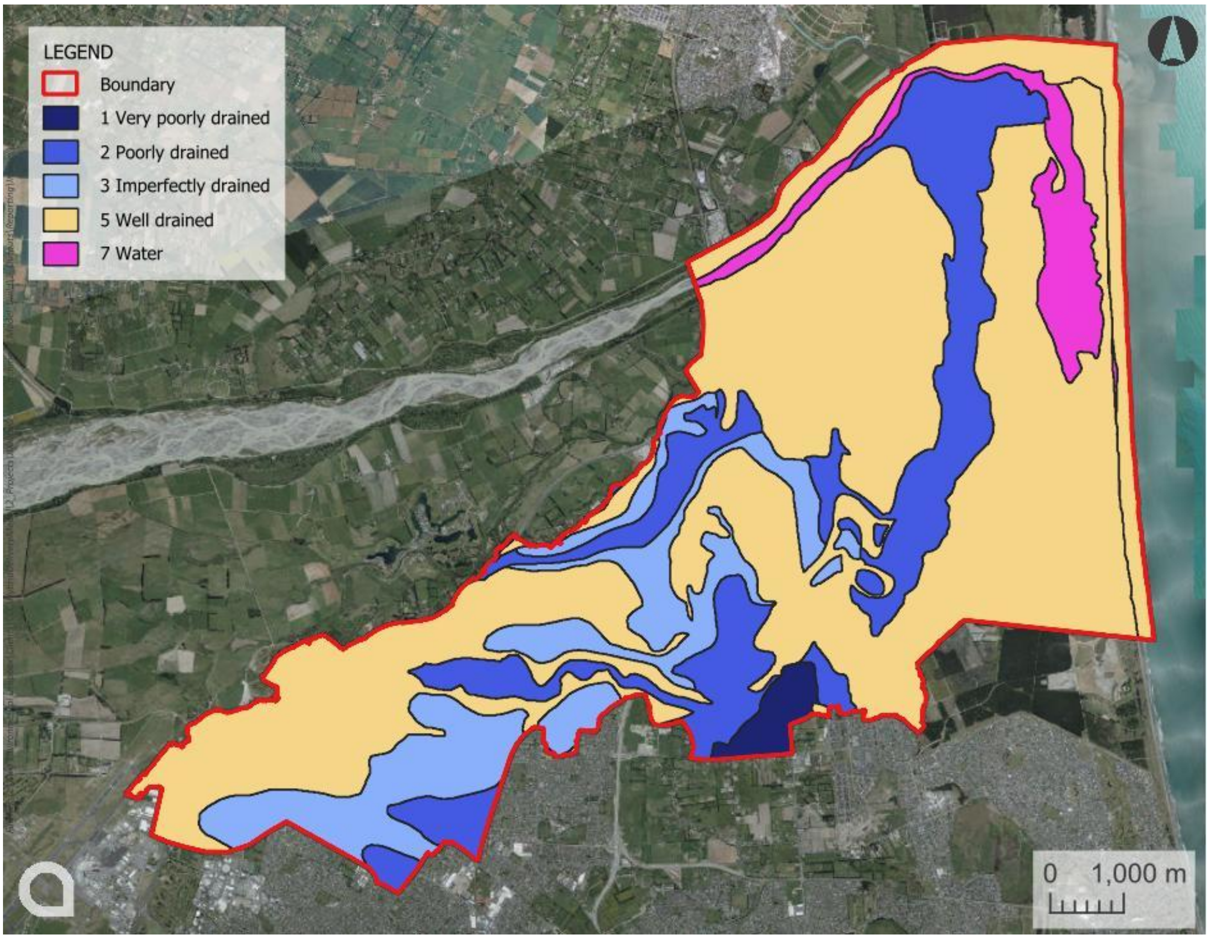


Figure 2-7. Soil classification based on the Schema rev 7 report for infiltration and groundwater capacity in TUFLOW model.

2.3.9. FOOTBRIDGES AND DRIVEWAYS

Previous MIKE-based modelling included culverts and bridges throughout the Styx model as culvert structures. Initially, the new TUFLOW model followed the same approach. However, the flows through some of the structures showed some flow fluctuations (instability issues) particularly along the structures that are wider than the channel/river width. This instability issue was discussed with the TUFLOW support team, who suggested to use bridge structures (layered flow constrictions) in TUFLOW which was adopted based on their flow obstruction characteristics as shown in Figure 2-8.

	
Radcliffe Road Bridge 2016	Harbour Rd Bridge 112 Harbour Rd bridge
	
Earlham Street Bridge Lower Styx 22 Dec 2009	Richards Bridge Lower Styx River 22 Dec 2009

Figure 2-8. Samples of bridges along Styx River where layered flow constrictions shapes (LFCSH) have been used.

Four flow constriction layers are used to model the structures within the Styx. Each layer has its own percentage blockage and form loss coefficient. The top (fourth) layer assumes the flow is unobstructed, representing flow over the top of a bridge while the first layer represents the flow beneath the bridge deck (Figure 2-9).

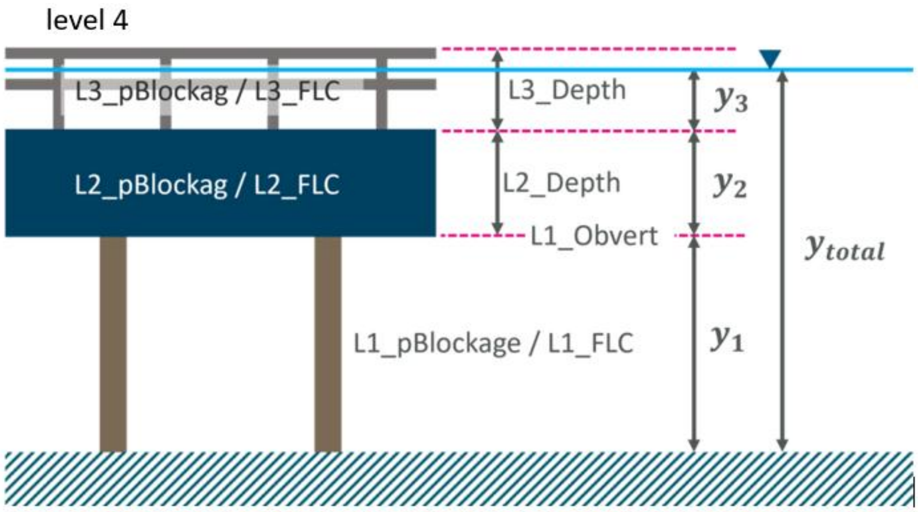


Figure 2-9. Layered flow constriction for modelling of bridges (driveways/footbridges) along Styx River.

Parameters of each layer (depth of each level, percentage of blockages of each driveway/footbridge) were estimated from street view and site visit images of the bridges. Usage of layered flow constrictions do not create instability issues, and the results show good agreement with flows upstream and downstream of the bridge structure.

2.3.10. 1D STORMWATER NETWORK

The 1D networks included in previous MIKE Urban models (2014 version and 2020 version) are considerably smaller than the available information in other datasets including the WSP network data and the CCC Open Data Portal, which represents the current state (2024) of the stormwater networks. The WSP 2023 node and pipe data represents the most complete dataset as it includes known CCC asset data and where there are data gaps the missing asset data values have been inferred using algorithms to attribute missing data and include a data flag system to highlight the interpolation method.

All relevant network assets in the CCC Open Data Portal and the WSP data were included in the TUFLOW model.

Awa reviewed all the available existing stormwater network data from the various available datasets and made use of them as required. While the WSP network data was complete it contained many locations where large parts of the stormwater network data had been interpolated as per the algorithms. To reduce the amount of interpolated assets AWA provided CCC with a gap analysis of these interpolated locations. CCC provided additional data from engineering drawings which were used to update the network data interpolated in the WSP dataset. The main areas where the WSP interpolated data was replaced with engineering drawing data is summarized in Table 2-5 below.

Table 2-5. Areas of WSP interpolated network and the engineering drawings used to update the data.

LOCATIONS OF WSP INTERPOLATED DATA	ADDITIONAL CCC SUPPLIED INFORMATION OR COMMENTS	OUTCOME IMPLEMENTED IN MODEL
A majority of the Glasnevin Drive pipe network invert level information is WSP interpolated data.	• Engineering drawing 13703-05 • Engineering drawing 13703-06 • Engineering drawing 13703-08 • Engineering drawing 13703-17 • Engineering drawing 13703-18 • Engineering drawing 14164-7	• Engineering drawing information used to update model
A majority of the Watermill Blvd and surrounds extended pipe network invert level information is WSP interpolated data.	• Engineering drawing 14234-32 • Engineering drawing 14534-13 • Engineering drawing 14534-15 • Engineering drawing 14694-01 • Engineering drawing 14694-02 • Engineering drawing 14694-03 • Engineering drawing 14780-02 • Engineering drawing 14780-03	• Engineering drawing information used to update model

LOCATIONS OF WSP INTERPOLATED DATA	ADDITIONAL CCC SUPPLIED INFORMATION OR COMMENTS	OUTCOME IMPLEMENTED IN MODEL
	• Engineering drawing 14850-01 • Engineering drawing 14850-05 • Engineering drawing 14910-01 • Engineering drawing 14933-01 • Engineering drawing 14933-02	
A majority of the Main North Road extended pipe network invert level information is WSP interpolated data.	• Engineering drawing 14234-35 • Engineering drawing 14234-37 • Engineering drawing 14460-05 • Engineering drawing 14460-06	• Engineering drawing information used to update model
A majority of the Saracen Ave extended pipe network invert level information is WSP interpolated data.	• Engineering drawing 14234-19 • Engineering drawing 14234-36 • Engineering drawing 14234-38 • Engineering drawing 14612-01 • Engineering drawing 14612-01a • Engineering drawing 14612-11 • Engineering drawing 14612-12 • Engineering drawing 14780-04 • Engineering drawing 14780-10 • Engineering drawing 14780-15 • Engineering drawing 14852-07 • Engineering drawing 14852-15	• Engineering drawing information used to update model
A majority of the Tyrone Street extended pipe network invert level information is WSP interpolated data.	• Engineering drawing 123971-01 • Engineering drawing 123971-02 • Engineering drawing 123971-03 • Engineering drawing 15198-09	• Engineering drawing information used to update model
A majority of the Murchison Avenue extended pipe network invert level information is WSP interpolated data.	• No additional data supplied	• Current WSP interpolated data used in model
A majority of the Mistral Ave extended pipe network invert level information is WSP interpolated data.	• Engineering drawing 14612-11 • Engineering drawing 14612-12 • Engineering drawing 14234-26 • Engineering drawing 14234-36 • Engineering drawing 14234-37	• Engineering drawing information used to

LOCATIONS OF WSP INTERPOLATED DATA	ADDITIONAL CCC SUPPLIED INFORMATION OR COMMENTS	OUTCOME IMPLEMENTED IN MODEL
		update model
A majority of the Radcliffe Road (commercial area) extended pipe network invert level information is WSP interpolated data.	• No additional data supplied	• Current WSP interpolated data used in model
A majority of the Station Road (commercial area) extended pipe network invert level information is WSP interpolated data.	• No additional data supplied	• Current WSP interpolated data used model
A majority of the Sawyers Arms Road pipe network invert level information is WSP interpolated data.	• No additional data supplied	• Current WSP interpolated data used model
A majority of the Springwater Avenue pipe network invert level information is WSP interpolated data.	• Additional data provided by CCC – Stormwater engineering plans, • Engineering drawing 14779-01 • Engineering drawing 14779-02 • Engineering drawing 14522-01	• Engineering drawing information used to update model
A majority of the Styx Mill Road pipe network invert level information is WSP interpolated data.	• No additional data supplied	• Current WSP interpolated data used model
Main North Road, Third Street and Richill Street – inconsistent network data causing negative grades.	• No additional data supplied	• Current WSP interpolated data used model
PS0221 Larch SW, PS0226 Larch SW & PS0223 Cherry SW missing pump-station data.	• Pump-station information supplied	• Pump-station information implemented in model
PS0228 Barnes SW missing pump-station data. If no data can be sourced pump-stations will need to be interpolated.	• No additional data supplied	• Pump-station information interpolated in model
PS0201 Turners SW * 2 missing pump-station data. If no data can be sourced pump-stations will need to be interpolated.	• Pump-station information supplied	• Pump-station information implemented in model

LOCATIONS OF WSP INTERPOLATED DATA	ADDITIONAL CCC SUPPLIED INFORMATION OR COMMENTS	OUTCOME IMPLEMENTED IN MODEL
Railway Culvert Data - currently interpolated in WSP data.	• Kiwi-rail survey data supplied	• Current WSP interpolated data used model
Bathymetry / Development inconsistencies. Sedge Street bathymetry is inconsistent with pipe network data causing negative grade in network due to inconsistent lid levels.	• Bathymetry has been modified to align with pipe network data	• Modified bathymetry used in model
Bathymetry / Development inconsistencies. Bellewood Avenue bathymetry is inconsistent with pipe network data causing negative grade in network due to inconsistent lid levels.	• This is only the end of the road, bathymetry has been modified to maintain the same level as design road	• Modified bathymetry used in model
Bathymetry / Development inconsistencies. Kirkland Crescent bathymetry is inconsistent with pipe network data causing negative grade in network due to inconsistent lid levels.	• Bathymetry has been modified to align with pipe network data	• Modified bathymetry used in model
Missing network within Summerset on Cavendish, does have pond and storage network	• Private, no further data to be collected	• Private network not included in model

2.4. DATA CONVERSION

CDD is based on the Lyttelton Vertical Datum 1937 with CDD having an offset of 9.043m higher than the Lyttelton 1937. The Lyttelton 1937 was converted to the NZVD2016 using the offset raster from Land Information New Zealand (LINZ)[1]. Below equation shows how CDD can be converted to NZVD2016.

NZVD2016 = CDD - 9.043 - Lyttelton 1937 offset

[1] The Christchurch Drainage Datum (CDD) was converted to Lyttelton Vertical Datum 1937 and then converted to New Zealand Vertical Datum 2016 (NZVD2016) using conversion factors from LINZ online data conversion (https://data.linz.govt.nz/layer/103958-lyttelton-1937-to-nzvd2016-conversion-raster/)

The Lyttelton 1937 to NZVD2016 conversion raster was obtained from the Land Information New Zealand (LINZ) Data Service[2]. For accurate conversion, LINZ suggests that the conversion raster grid must be downloaded in terms of NZGD2000 and then converted into a surface using bilinear interpolation (resampling to a small grid cell size, 1m in this case).

The asset data and terrain in CDD were then be selected and converted to NZVD2016 using the above equation.

2.5. KNOWN LIMITATIONS AND CONSTRAINTS

Table 2-6 includes a range of issues that should be considered when using the model or interpreting any outputs.

Table 2-6. Limitations and constraints.

LIMITATION / CONSTRAINT	DETAILS
2D surface	• Fine features that may influence the direction of flow such as, fences and walls, have not been resolved in the model. • Wetlands are presented from LiDAR DEM and with land cover information. No specific optimisation has been undertaken other than representation of structures when supplied. • Kerb lines input layer has gaps and some issues around intersections that were not resolved.
Groundwater	• The Styx catchment should be considered a reasonably high flow rate catchment in terms of groundwater flow (vertical and horizontal), and part of a larger groundwater catchment that has groundwater flow from upstream of the surface water boundary. However, no groundwater discharge occurs from upstream in the model, and any flow is limited to being from the initial groundwater condition and surface water infiltration.
Network data quality	• Private stormwater connections to buildings are not included in the model. • Soakage devices are not included in the model (private or public).
Representation of the rivers and channels	• Radcliffe Road gauge concrete walls and riverbank is not represented as well as it could be. It is based on survey and legacy MIKE11 and LiDAR under tree canopy which has been found to have issues.
Hydrological	• Schema based soil infiltration used provide consistency with other CCC models but are lower than recorded by Callander *et al.* (2023)

[2] https://data.linz.govt.nz/layer/103958-lyttelton-1937-to-nzvd2016-conversion-raster/

2.6. ASSUMPTIONS

The table below includes a range of assumptions that should be considered when using the model or interpreting any outputs. Some of these assumptions may be proven to be wrong if further information is obtained.

Table 2-7. Model assumptions.

TYPE	ASSUMPTION
Terrain	• MIKE11 cross section converted to 2D terrain are positioned correctly in XY coordinates to match LiDAR DEM. • The Radcliffe Road geometry is correct and doesn't affect the rating for calibration / validation.
Hydrological assumptions	• Schema infiltration values are appropriate for the model.
Hydraulic assumptions	• The LiDAR generated ground model is an accurate representation of catchment topography. • Sump lid levels can be adequately inferred from the DEM.
Stormwater network	• Pipes are sediment free, and inlets / outlets and sumps are sediment free and not blocked. • The network asset data is of a suitable standard for use in the model without additional survey. • Various data sources provided including WSP, CCC GIS and MIKE Urban pipe network are accurate where the data indicates it is from an original source and has not been interpolated. • The engineering drawings provided as part of the stormwater network update are an accurate representation of the in-ground stormwater network.
Groundwater	• Schema soil layer is appropriate for setting of soil representation of horizontal conductivity. This assumption may require updating with better soil information in the future. • The catchment has fast response to groundwater through surface water infiltration and interflow into streams. • The initial groundwater layer provided breached the DEM. It was assumed that where the groundwater breached the DEM that the groundwater level was the DEM level. It was found that setting the groundwater level to a surface water initial condition flooded the model in unrealistic fashion. • The low horizontal conductivity values are appropriate for the model even though the Aqualinc groundwater model values are orders of magnitude larger (also see Table 2-8).

TYPE	ASSUMPTION
Pond, dams and wetlands	• Ponds are filled with an initial water level condition at the start of the simulation to the downstream outlet level. This is to improve representation of storage in the ponds as they are not resolved by LiDAR. This is also important during the wet periods. If a pond does not have an outlet the ground level is dropped by half a meter and filled with half a meter of water.
Pump stations	• The Turners Road pump station connection to the Styx River has been assumed to be open and two ways. No additional details on culvert / flat gating were available, and the location is not easily accessible for site visit. • Pump-station data provided is an accurate reflection of pump operation including start/stop levels and pump capacity. Where data has not been supplied it has been assumed based on engineering judgement.
Buildings	• There is no modification of the terrain (using 2d_zsh layer) to represent building footprints. The schema has been used with a high roughness of 0.2 within the building footprints.
Waimakariri River, Kaiapoi River and Kairaki Creek.	• All the boundaries have constant inflow conditions rather than gauged inflow data.
South Avon/ Styx connection	• For the calibration scenario, the Horner's drain culvert has a tail water condition assigned to the upstream of the culvert, as per the previous MIKE model. This allows water to exit the model. In front of the culvert there is a 2D constant discharge coming in from Horner's drain, which is assumed to be a discharge calculated from measured water levels during the event. When applying a constant inflow of say 2 m^3/s, Radcliffe Road gauge was considered too high showing that a variable discharge through the event is required. • For the design scenarios, the design flows from the existing MIKE Avon model were used. • Walters Road inflow is a constant inflow into the 1d network. The outlet discharges a hydrograph that peaks in line with the schema value of 0.572 m^3/s but has the shape scaled from Horner's drains calibration inflows to represent discharge during event. • Marshland Road has a 1d boundary condition assigned to the network that removes water from the simulation up to the peak discharge specified within the schema.

2.7. SCHEMA DEPARTURES

This TUFLOW HPC model requires a range of departures from the MIKE Flood based schema. Some of these relate to the differences between the software approaches, but also some of them related to recommended departures due to Awa's advice on best outcomes for this specific catchment model. In general, efforts have been made to minimise departures and focus on essential changes only. It is also noted that not every change in method between the two software approaches has been reported here as that would be unpractical.

Table 2-8. Notable departures from the Schema in the Styx model.

TYPE	DEPARTURES
Software	• Using TUFLOW HPC rather than MIKE FLOOD comes with a range of departures including 2D representation of channels, Quadtree and SGS approaches to grid cells.
Groundwater	• The modified version infiltration with groundwater capacity outlined in Table 2-1. TUFLOW model overview. has been made where some horizontal groundwater conductivity (Kh) to partially represent this phenomenon in the catchment has been made. The Kh values are modest as to not drift too far from the other schema model. • The GNS (White et al., 2007) reach based groundwater baseflow for the main channels has been modified. It was found that the constant GNS values were too large for some of the simulations but also literature search and sensitivity testing demonstrated that a constant flow was not appropriate for the model. An approach where the GNS flow begin at 0% of the recommended inflow and scale proportional to the event size to represent event-based groundwater interflow. The scaling is 30 % for small events and up to 450 % of the GNS recommended value for large events and is outlined in Section 3.5. • Soil porosity was reduced on Aqualinc advice to about 1/3 of the schema values. The impact of this is that the groundwater response will be faster and the soil will become saturated, limiting infiltration.

2.8. PEER REVIEW

The peer review of the flood model was conducted by Tonkin and Taylor in two key stages. The first stage evaluated its accuracy and methodology in simulating flood scenarios for calibration and validation events. Once the design model was created, it was then reviewed for select design scenarios. After addressing concerns regarding model assumptions, outputs and accuracy, a consensus was reached on October 23, 2025, confirming the model's reliability for stated purposes in this report.

3. MODEL CALIBRATION

3.1. CALIBRATION METHODOLOGY

The approach taken to calibration broadly follow these steps:

1. initial simulations of July 2022 event using a schema based approach;
2. verification of rainfall, soil, tide and groundwater datasets;
3. gained input from CCC experts and initial reviewer discussions;
4. implementation of GNS (White *et al.,* 2007) median discharges along stream network;
5. focus on calibration performance for water level and discharge at Radcliffe Road (Figure 3-4);
6. focus on calibration of water level at Harbour Road, including terrain editing to ensure channel outflow that was not represented by LiDAR;
7. sensitivity testing of key parameters including:
    a. roughness;
    b. infiltration;
    c. absence/presence of groundwater;
    d. rain on/off;
    e. groundwater level;
8. implementation of *"time varying groundwater discharges" (accounting for baseflow and interflow)* based on scaling GNS estimates to better represent groundwater response to rain as observed in groundwater monitoring sites; and
9. testing against smaller 2021 and medium sized 2013 validation events.

It has been found that real world catchment phenomena relating to fast surface infiltration and rapid groundwater response to local rain resulted in an underestimation of stream flows. This report section details further the methodology followed, results and the rationale and impact of modifying the Schema approach by adding step 8 above to the configuration of this model.

3.2. JULY 2022 INITIAL CALIBRATION RESULTS

After the setup of the 2D domain and stormwater network, a setup using default schema values model simulation was completed (Figure 3-1 and Figure 3-2). It can be seen that there was a significant issue with the volume of flow at Radcliffe Road in the model, and to a lesser extent, in water levels at Harbour Road (which is located upstream of the tide gates). Harbour Road can be considered quite highly influenced by the tide, and so the tidal pattern is well represented, but it is too low, presumably due to lack of flows from upstream.

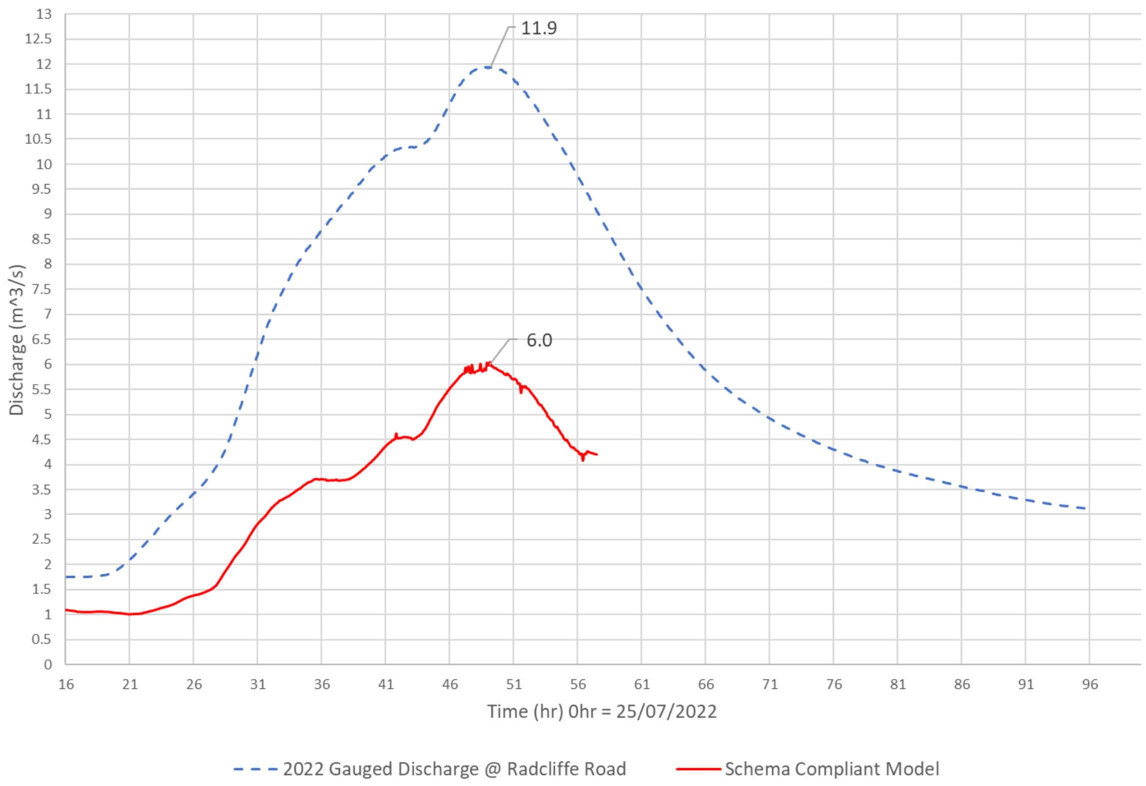


Figure 3-1. Comparison between observed flow and schema default values modelled flow at Radcliffe Road for 25-26 July 2022 event.

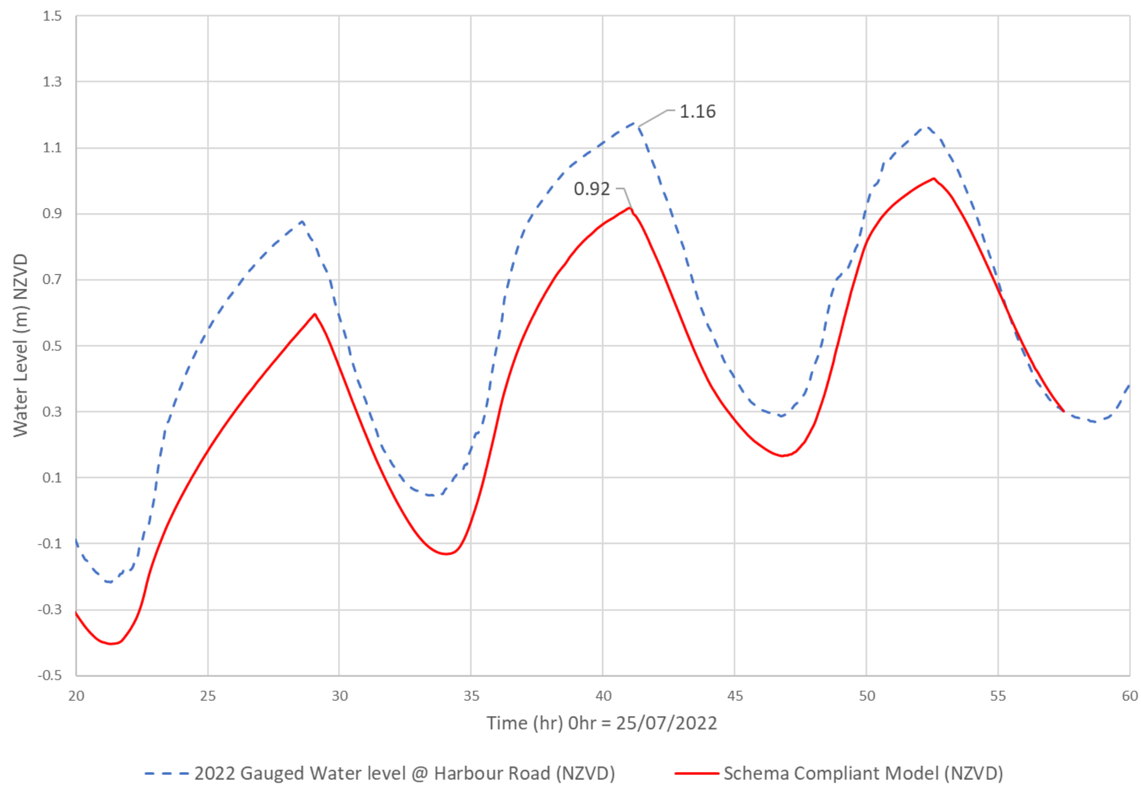


Figure 3-2. Comparison between observed water level and schema default values modelled level at Harbour Road for 25-26 July 2022 event.

After these initial results, dozens of model simulations each taking 24-36 hrs to complete, were run to test and unpick the relationship between different components and settings within model. The common calibration parameters, such as roughness and infiltration were varied, and while they had an impact, they were unable to effectively double the Radcliffe Road discharge while keeping within reasonable calibration values. Additional checking of the network, rainfall, bridges and terrain was also completed to ensure hydraulic conductivity from upstream reaches of the catchment with no major issues identified. Roughness values in the drainage networking (including wooden channels) as well as flow exchange with the Avon catchment have also been checked.

3.3. ASSESSMENT OF GROUNDWATER

The Schema approach to groundwater generally acts to limit the volume of infiltration possible from the initial and continuous loss method. This is achieved by setting an initial groundwater level that limits total storage. While this is a great advancement over many flood modelling methods in New Zealand that don't consider groundwater at all, it doesn't address the rapid response from horizontal of groundwater that could be generating baseflow in the Styx River.

Here we present an overview of groundwater investigations to support an approach to represent fast groundwater response as *time varying groundwater discharges* to match modelling results to measurement (outlined in *Section 3.5.2 Time Varying Stream Discharges)*. Based on interim peer review feedback on the approach, the scale of the discharges has been reduced in scale to make them a smaller component of the overall river flows.

3.3.1. GNS BASEFLOWS

The Schema method recommends 1D channels of MIKE11 models to implement a constant discharge based on GNS groundwater median baseflow discharges (White *et al.,* 2007; see Figure 3-3). It assumes that the baseflow is consistent with different flood flows and therefore the same baseflow can be applied to all model runs including calibration and design runs. Our findings in the *Section 3.2 July 2022 Initial Calibration Results* and *Section 3.3.3 Measured Responses* suggest that this is not the case in the Styx River.

The implementation of the GNS baseflows in TUFLOW is via *2d_sa* polygons representing the river channel for each reach in Figure 3-3. The incremental increase in discharge at each reach was applied additively so that the total discharge at the bottom matched the total discharge provided by GNS. This approach did not apply the values as presented in Figure 3-3 for each reach but the incremental difference between reaches to avoid double accounting for baseflows. Note that the ability to accurately identify exact boundaries between sections with different baseflow was difficult and assumptions were made, but this is considered adequate in context of the likely accuracy of the GNS values.

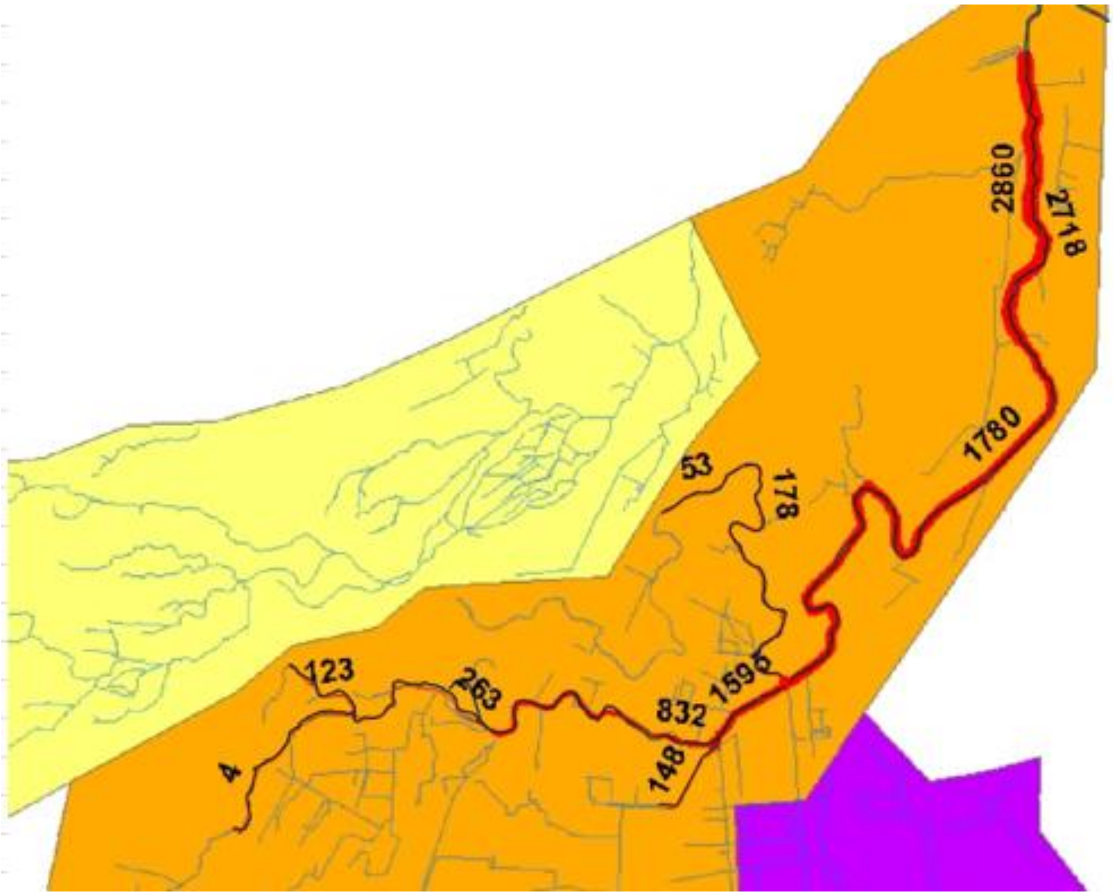


Figure 3-3. Median stream groundwater baseflow discharges into the Styx River and Kā Pūtahi/Kaputone Creek (White et al., *2007).*

3.3.2. AQUALINC MODELLED LEVELS

City wide modelled groundwater surfaces for the calibration and validation events were supplied by Aqualinc (Julian Weir, *pers. comms. February 7, 2025*). Developed based on interpolated bore records, these layers are considered extremely useful to enable representation of a critical phenomenon in the model. For example, the lower Styx River area and flood plain effectively have groundwater near or above the surface, increasing surface run off due to limits on infiltration from the low depth to groundwater.

Figure 3-4 shows the location of a long section (Figure 3-5) through the groundwater model layer, along with the location of two key bores discussed in *Section 3.3.3 Measured Responses.* What is particularly notable is that the groundwater body does not align with the surface water catchment boundary, meaning that groundwater will flow from outside of the catchment into the catchment. Also, over half the catchment profile is generally flat and low lying, where groundwater will naturally flow to, causing high groundwater levels.

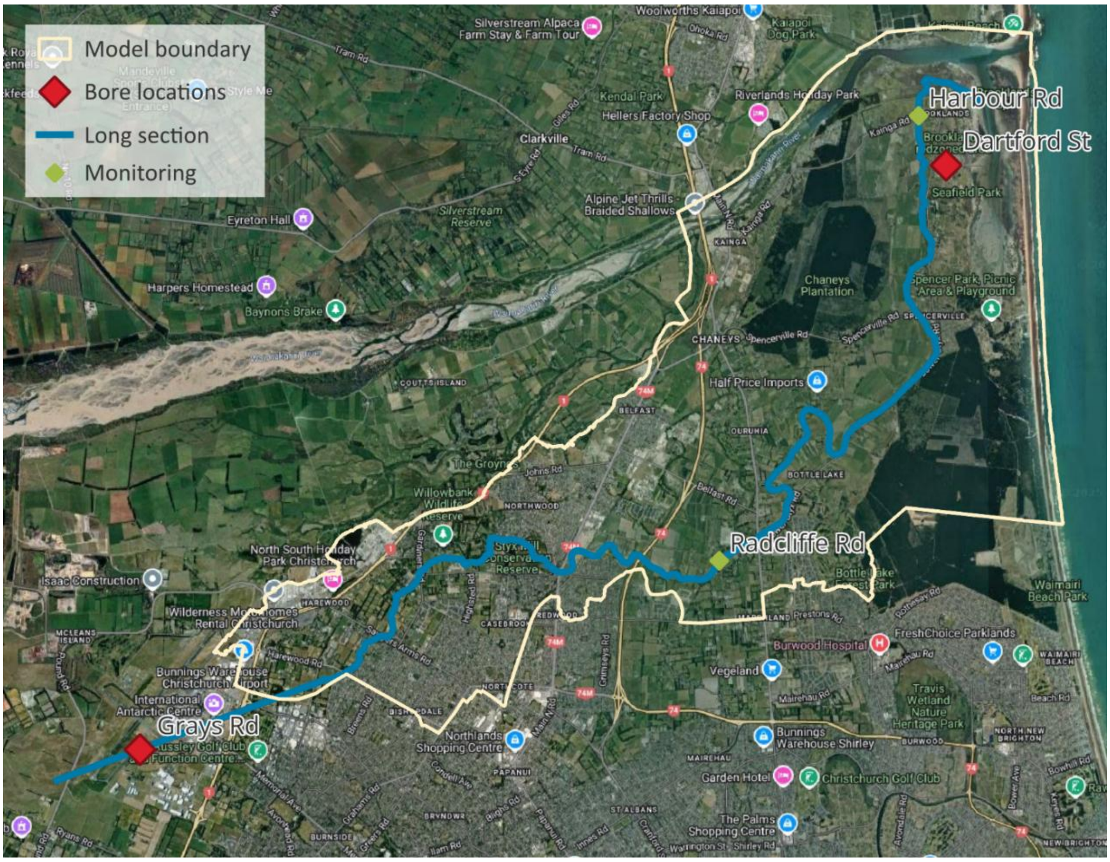


Figure 3-4. Long section location through catchment used for comparing groundwater layer to terrain model. The two key groundwater monitoring sites discussed in Section 3.3.3 Measured Responses are also identified in relation to the model boundary, as well as key river monitoring location used for calibration.

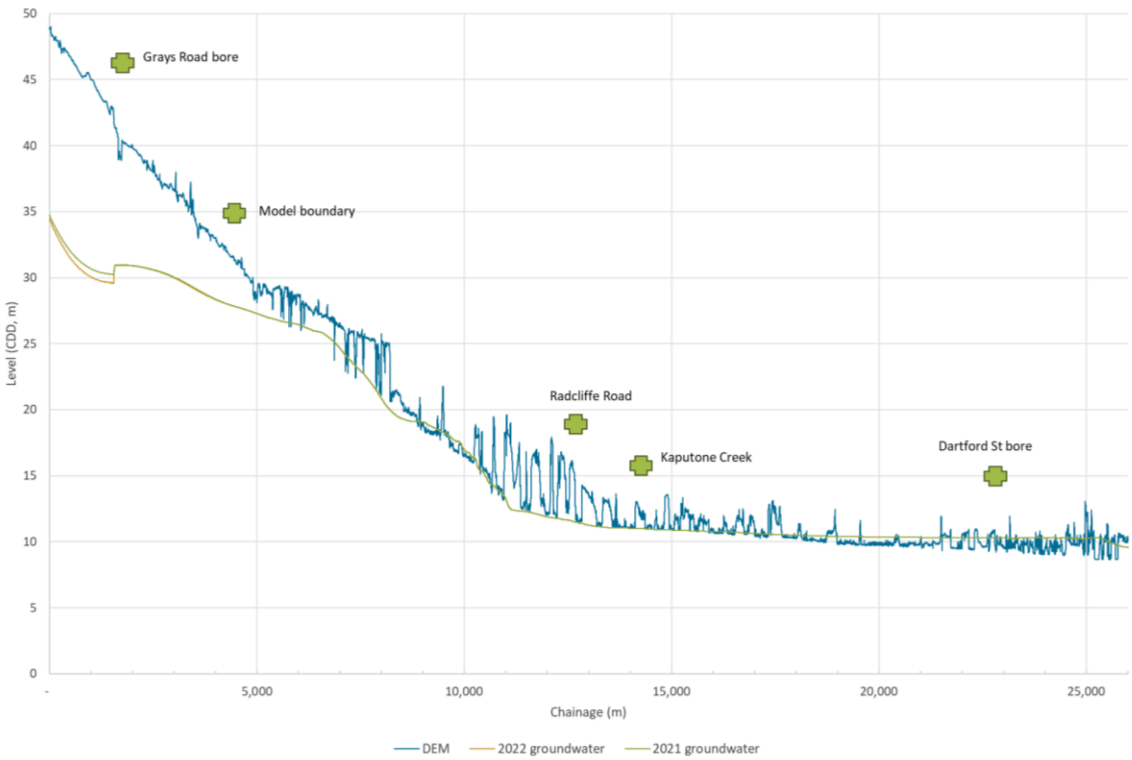


Figure 3-5. Long section through catchment with Aqualinc groundwater levels used as initial conditions for model.

Note that there are only minor differences between the 2021 and 2022 event levels in the data. This has not been queried to date, but comparison to measurements is discussed in *Section 3.3.3 Measured Responses.*

It is also clear in Figure 3-5 that the groundwater layer pierces the ground surface. Testing of applying this directly to the model as initial water levels was found to completely inundate areas of the model to unrealistic levels. To resolve this issue, a methodology was applied so that where any groundwater was above the ground level the area was set to the ground level using GIS techniques. This represents an assumption (reported in *Section 2.6 Assumptions*) that the groundwater level is very high at these locations.

An illustration based on TUFLOW model output data of how the ground, groundwater, and surface water interact is shown in Figure 3-6. This is a cross section through the Styx River near the Dartford St bore and it can be seen how groundwater levels change between time = 0 and 50 hrs. Areas of surface ponding are also observed from local rain, which then connect to the groundwater layer. This demonstrates that broadly the surface water / groundwater phenomena are being represented by the model.

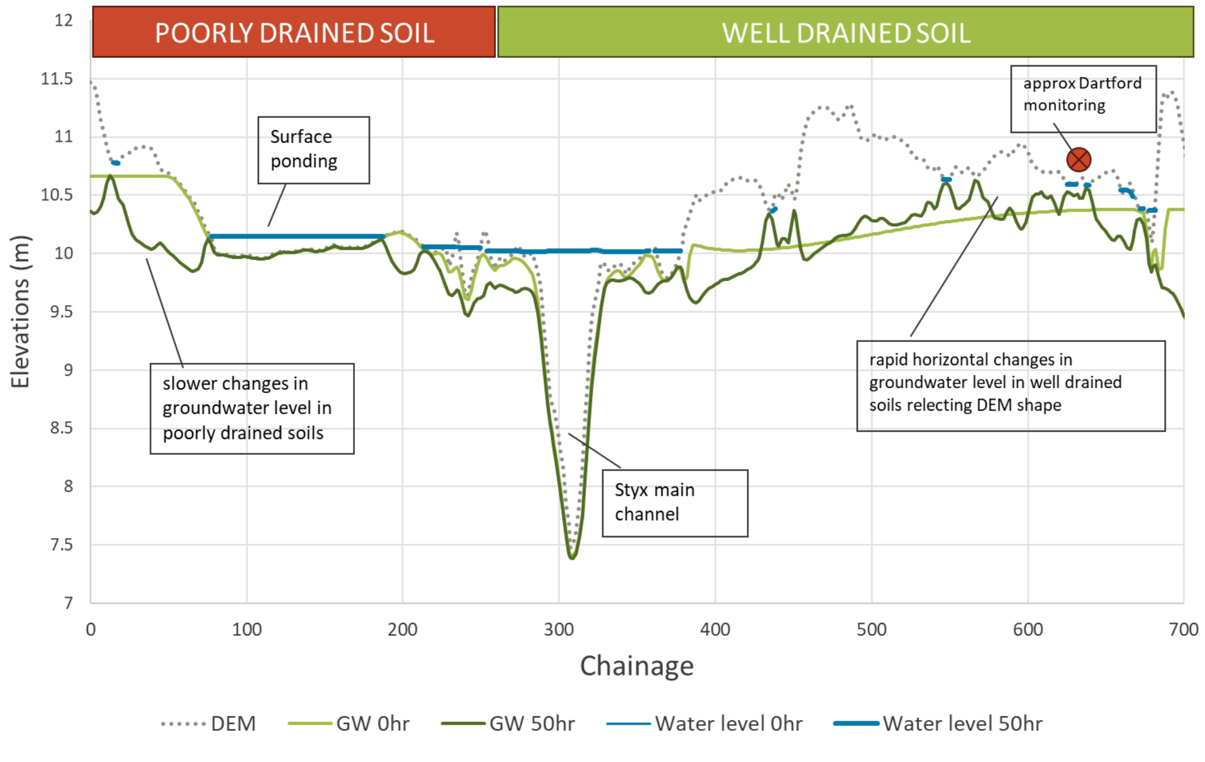


Figure 3-6. Analysis of modelled groundwater response in TUFLOW model through a cross section near the Dartford groundwater monitoring site. Note the change from time = 0 hr to time = 50 hr as the groundwater propagates through the model. The well drained soils are more responsive to surface water and exhibit a more undulating profile compared with the poorly drained soils. Note the water level at time = 0 is the same as time = 50 for this particular location.

3.3.3. MEASURED RESPONSES

Christchurch has an abundance of groundwater measuring sites. Unfortunately, only two sites (Figure 3-4) were identified to be useful for demonstrating the short-term response to rain of the groundwater. Many sites did not have frequent enough measurement resolution. There may be other sites, but they were not found at the time of writing. However, the two sites presented here show agreement in general behaviour.

DARTFORD ST (M35/5425)

The Dartford site is important as it has a high frequency sampling (5-minute intervals) since 2018. Both the 2022 and 2021 events (Figure 3-7) show what could be described as an immediate response to the rainfall during the simulation event. This suggests fast surface infiltration and transmission through subsoil layers in the area.

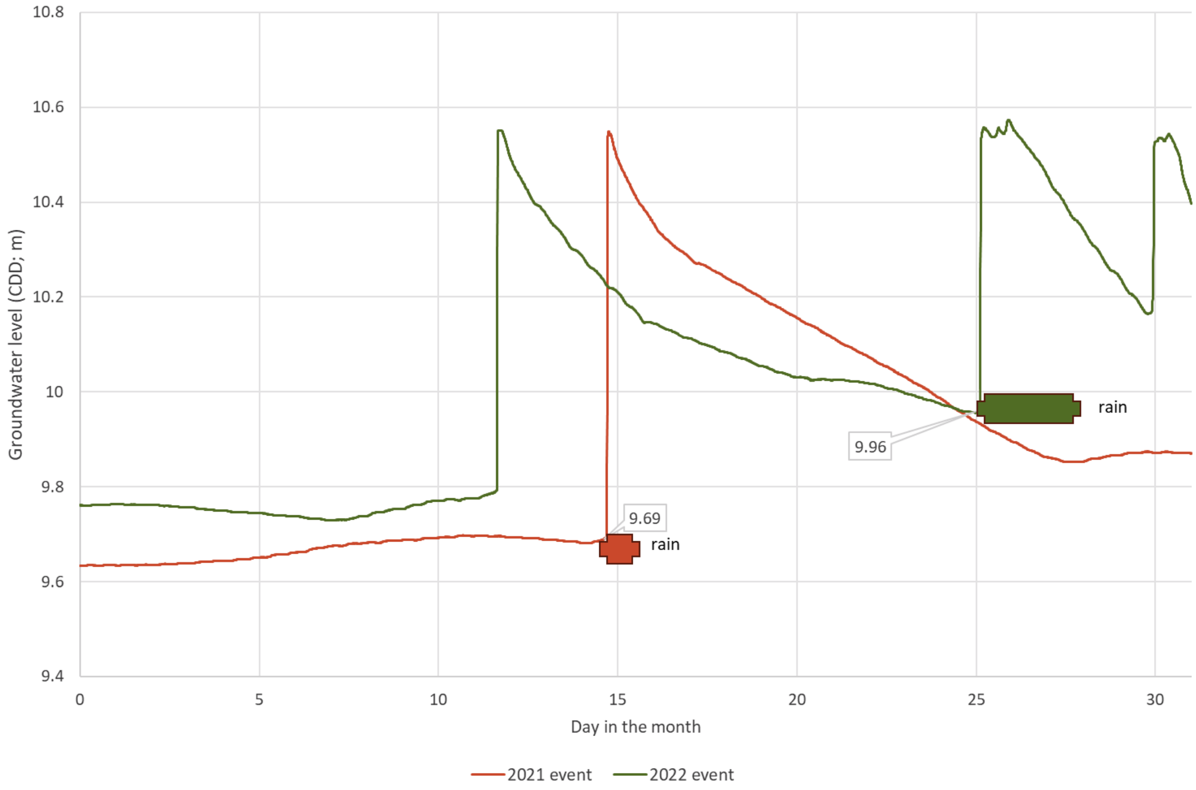


Figure 3-7. Measured groundwater response from high resolution (5 minute) groundwater monitoring at Dartford site (M35/5425) for July 2022 calibration and December 2021 event. Approximate timing of modelled rain events is also included for context.

When comparing the two events, they both begin the month with similar levels. However, the 2022 winter event has a preceding rain event that raises the groundwater about 0.30 m above the 2021 level. This means the 2021 event increases close to 0.90 m while the 2022 event raises 0.60 m. They both peak at a similar value due to this being effectively equal to the ground level.

The following check of the Aqualinc levels against the pre-storm measurements can be reported:

- 2021 measured = 9.66 m; Aqualinc modelled = 10.00 m (CDD); and
- 2022 measured = 9.96 m; Aqualinc modelled = 10.17 m (CDD).

Sensitivity tests by dropping the model initial groundwater level by 0.2-0.3 m level does show impact on initial pre-rain baseflow but less impact on the peak discharges. A test of this suggests some robustness in the model to stabilise discharges during model initialisation (first ~10 hrs). This model initialisation period is excluded from the data extracted from the results.

Figure 3-8 shows several data points from the measured and of the TUFLOW modelled groundwater levels at the Dartford St site. The minimum, maximum and average are statistics for the 2022 year, and rainfall rates are shown also for additional context. The maximum values top out as the groundwater is reaching the surface.

It can be noted in Figure 3-8 that the modelled groundwater response is much slower than the measured. This is likely due to the Schema approach to soils where a monolithic soil layer exists, with the low surface infiltration rates (without horizontal conductivity) being also applied to the sub soil layers. This is an example of this calibration taking a balanced approach between consistency with Schema and applying new approaches that might better match observations.

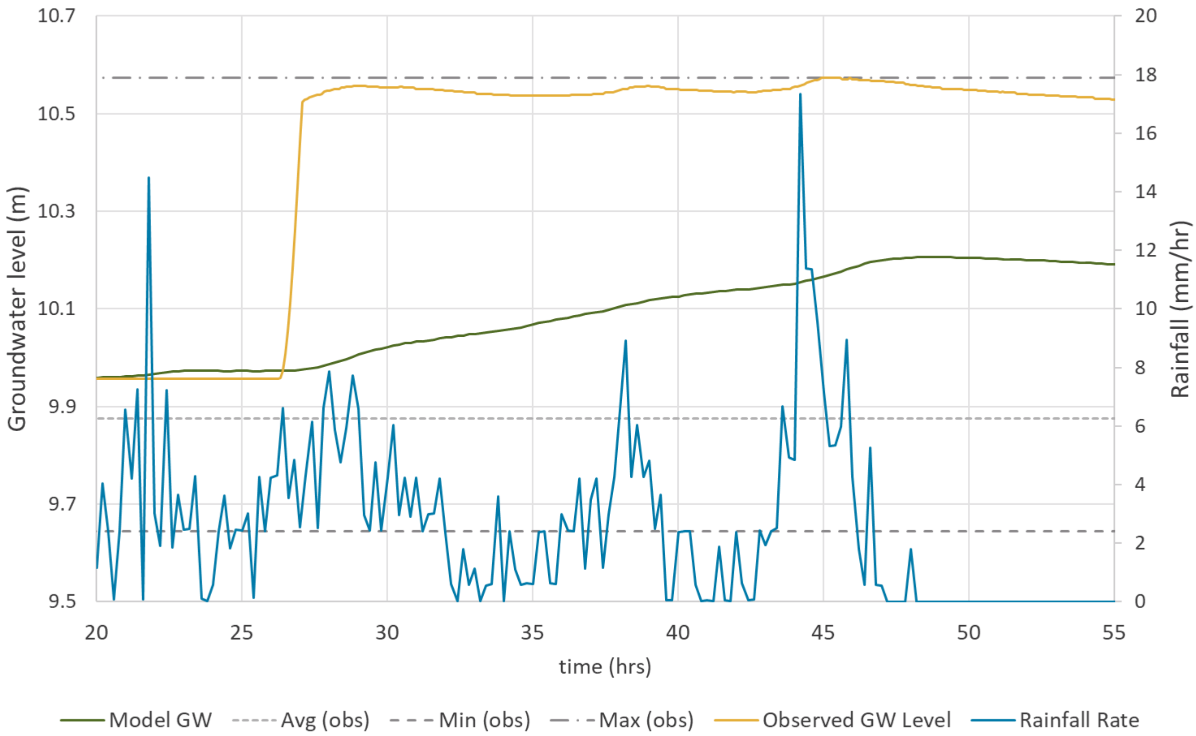


Figure 3-8. Measured groundwater response at Dartford site to rain event compared to model. The modelled response is less immediate due to the low surface infiltration rates. Minimum and maximum observed values are from the year 2022 as a guide. These compare with historical (since 1981) minimums of 8.50 and maximums of 10.87 m (CDD).

It was raised multiple times if the gauge is working as expected as it is close to a drain. This assessment was completed by Julian Weir of Aqualinc.

> *"It is a 3.2 m deep piezometer, 50 mm diameter, with the top of the piezometer at ground level at the side of the road, so there is a chance of inundation. Given its small size, I would expect it would fill up quickly if it was to be inundated at the surface. However, the water levels have never been measured as high as the land surface, so the fast response may not be due to inundation. The fast response is consistent throughout the whole record, even during events when antecedent groundwater levels are low. So, I suspect that it is a real*

groundwater response (groundwater can respond quite fast in places). Though I guess that can't be confirmed without further high-resolution monitoring."

GRAYS ROAD SITE (M35/3614)

This site, although it is only a daily depth to groundwater recording, provides data that cover the 2012-2022 events highlighted by Blundell-Dorey and Tuck (2023) as being of importance to the Styx model. This upper catchment record has been used to provide an estimate of the increase in groundwater level during the rain events for five key events of interest (Figure 3-9). Figure 3-10 and Figure 3-11 shows examples of more obvious responses, with the 2014 and 2012 response smaller or negligible, possibly due to the smaller size of the event.

By being able to quantitatively measure the groundwater response, this has enabled an initial estimate of the logarithmic relationship between the groundwater response and event return interval. In this case, it is an ARI representing a Gumbel analysis of maximum annual discharge at Radcliffe Road from 1992 to 2025 (see *Section 3.5*). This is important to the *varying groundwater discharges* approach outlined in *Section 3.5.2.*

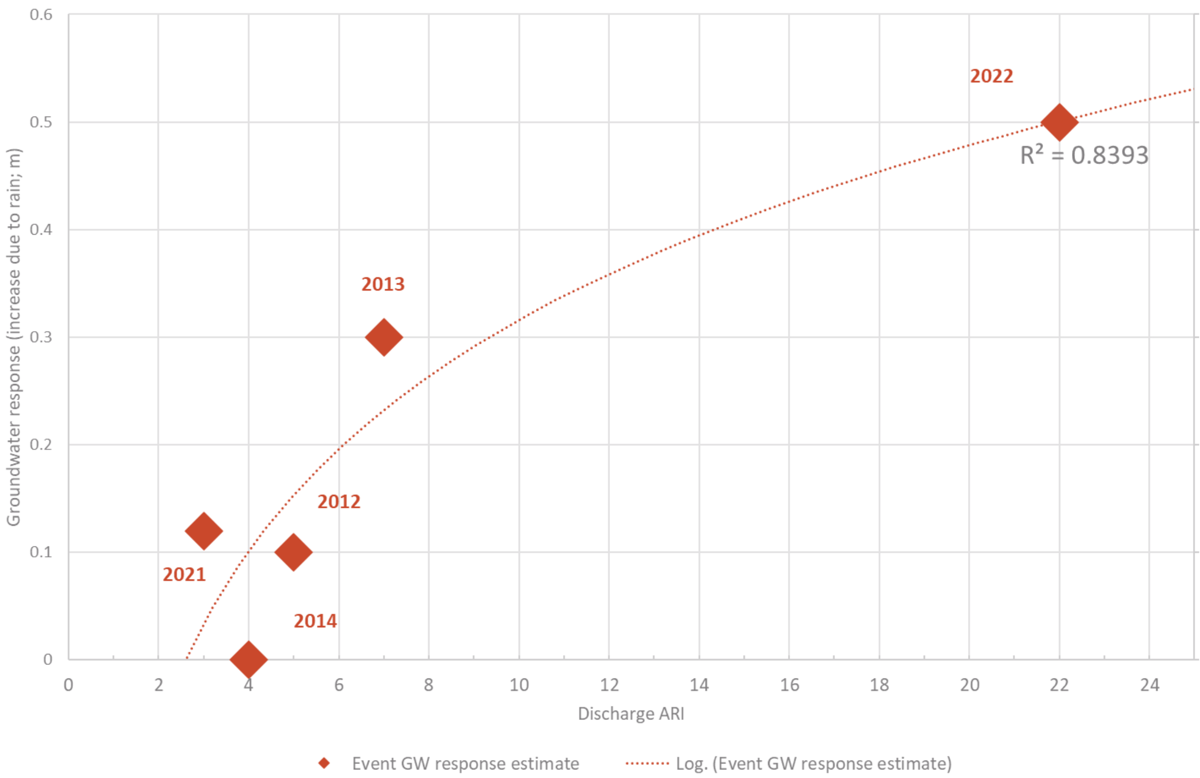


Figure 3-9. Comparison of estimated Grays Road groundwater response (increase in level) to different events with ARI for Radcliffe Road discharge.

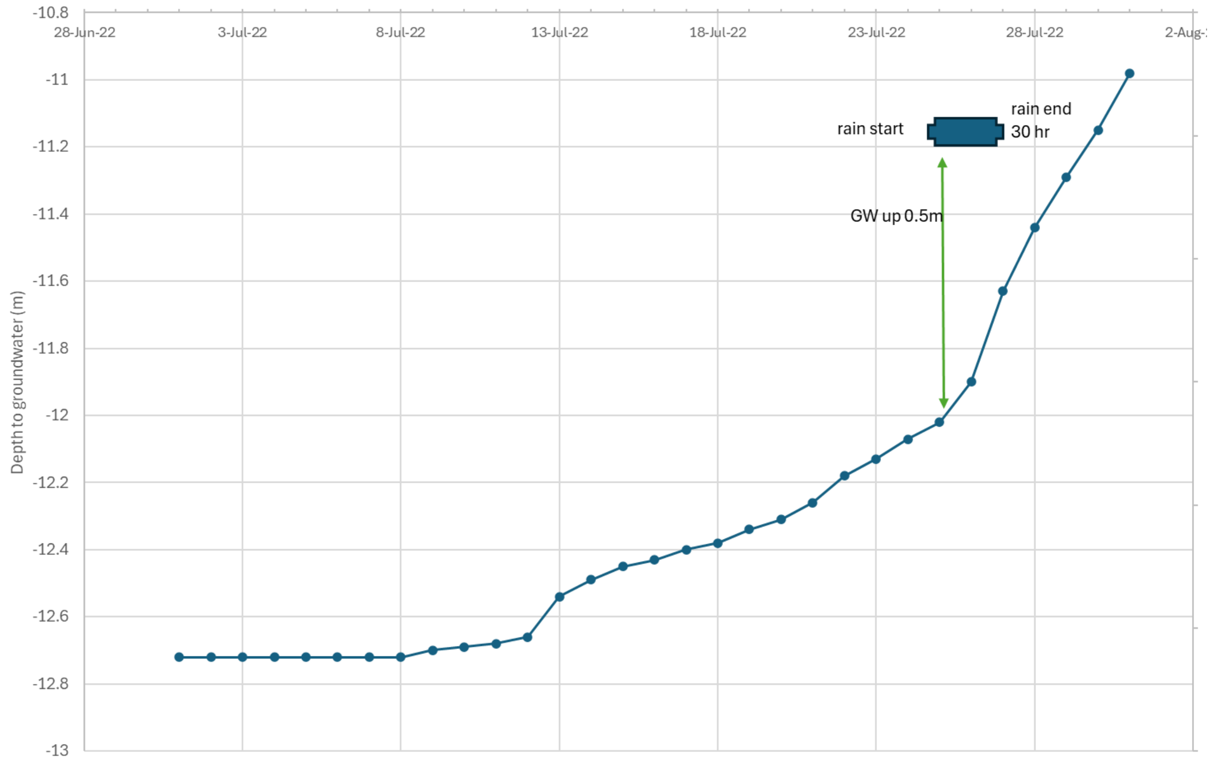


Figure 3-10. Groundwater level at Grays Road site during 2022 calibration event. Increase in gradient of groundwater level is noticeable.

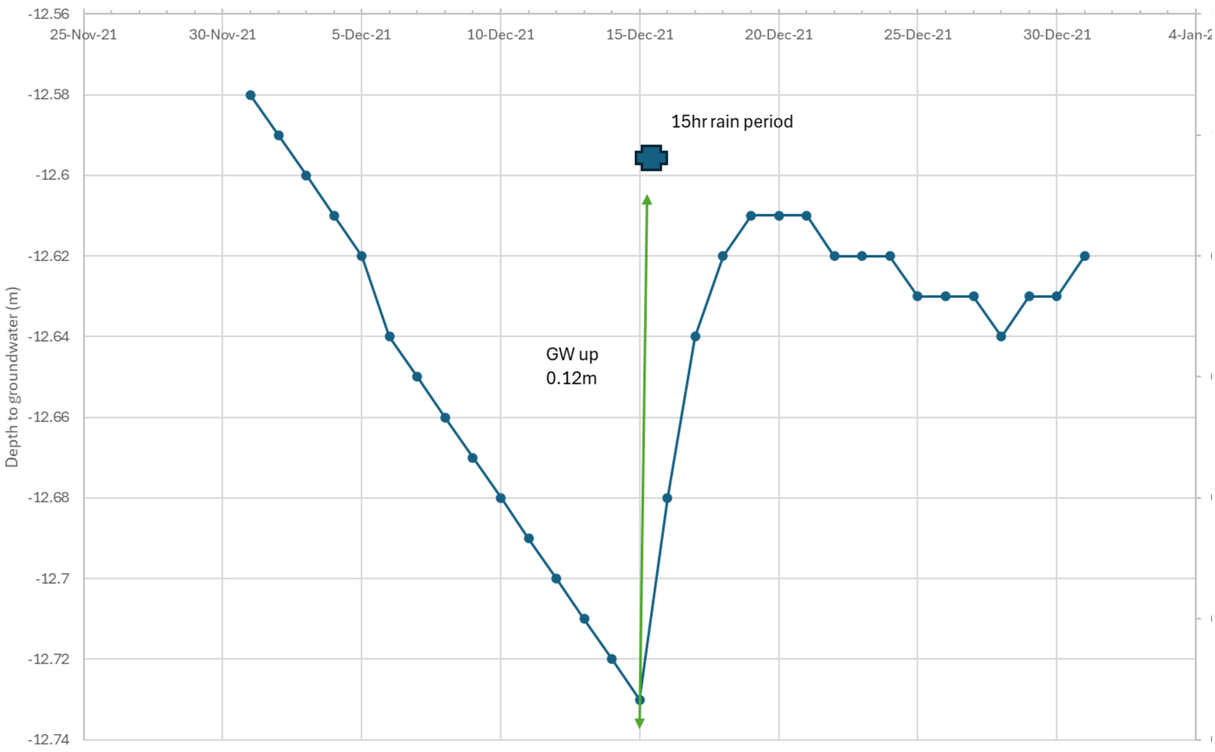


Figure 3-11. Groundwater level at Grays Road site during 2021 validation event. Increase in gradient of groundwater level smaller than 2022 event but pronounced.

3.4. BACKGROUND TO CALIBRATION SETTINGS

For reference, several key values for various parameters are described below in context of the Schema.

3.4.1. ROUGHNESS

A combination of roughness values from the Schema and other sources were documented in the memo “roughness values used for CCC catchment flood models” (Martell, 2024) appended in Appendix A – Roughness Values. The roughness values were agreed by CCC and were used as the starting point for the calibration. This assisted in mapping of land cover classifications to roughness values. Table 3-1 and Table 3-2 summarise these values.

Table 3-1. Manning’s n value for flood plains.

ID	LAND USE	SCHEMA VALUES	PROPOSED STARTING VALUES	REFERENCES
1	Water	0.025	0.025	CCC Schema report
2	Bare Earth/ Sand/ Gravel/ Clay/Rock	N/A	0.03	Waterways, Wetlands and Drainage Guide - Part B: Design
3	Grass*[3]	0.125	0.045	CCC, 2003
4	Rough Low Vegetation*	0.125	0.05	CCC, 2003
5	Trees*	0.125	0.125	CCC Schema report
6	Other Impervious	0.05	0.02	Values that Awa has used in models built for Kāpiti Coast District Council
7	Roads	0.014	0.014	CCC Schema report
8	Buildings	0.2	0.2	CCC Schema report
9	Wooden Open Channels	0.03	0.03	CCC Schema report
10	Rail	0.1	0.1	CCC Schema report

[3] The Schema has one land use classification named “vegetation” which has a Manning’s n value of 0.125 assigned (indicated by * in the tables above) and this classification is quite broad to cover the various types of land use that we have listed in *Table 3-1* and *Table 3-2*.

Table 3-2. Manning's n value for open channels.

ID	LAND USE	SCHEMA VALUES	PROPOSED STARTING VALUES	REFERENCES
1	Styx River	0.03	0.035	National Institute of Water and Soil, 1997
2	Light grass	0.03	0.03	CCC Schema report
3	Dense weeds* (depth of flow higher than weeds)	0.125	0.045	CCC, 2003
4	Light shrubbery on banks*	0.125	0.05	CCC, 2003
5	Heavy shrubbery on banks*	0.125	0.06	CCC, 2003
6	Weeds dense willow on banks*	0.125	0.125	CCC Schema report
7	Trees – little under growth, flood stage below branches*	0.125	0.05	Greater Wellington, 2021
8	Trees – little under growth, flood stage above branches*	0.125	0.125	CCC Schema report

Weed growth is a seasonal phenomenon that impacts water flow in the Styx. A weed clearing boat harvests and removes weed during the autumn / winter months after it develops over the summer months. The weed state changes channel roughness (Manning's n) in the lower and middle parts of the Styx River, and this is reflected in the model via a roughness (materials) layer that can be altered to represent different weed states for historic and design events.

Roughness values used in the model are based on the recommendations by Beca (Blundell-Dorey, R., and Tuck, E., 2023), which range between 0.04 (clean channel condition) and 0.15 (a channel with a heavily overgrown weed condition). A number of different tests on channel roughness were performed, and these settings have been used:

- 2022 event when weed growth was low and a value of 0.055 was used;
- 2013 event was when weed growth was medium to high and a value of 0.07 was used; and

- 2021 events when weed growth was medium to high and a value of 0.08 was used.

3.4.2. SOILS

The soils approach is aligned to the Schema required layer and shown in Figure 3-12. There are areas of more poorly drained soils aligned to the Styx River and flood plain, as well as large areas considered well drained. These categories are applied in the TUFLOW TSOILF file with number references 1 to 7 as seen in Table 3-3.

Table 3-3. TUFLOW HPC TSOILF parameters.

SOIL ID	INITIAL LOSS mm/hr	CONTINUING LOSS mm/hr	POROSITY	INITIAL MOISTURE	HORIZONTAL CONDUCTIVITY mm/hr	CLASSIFICATION
1	0	1.025	0.05	0	1	Very Poorly Drained
2	0	2.55	0.05	0	1	Poorly Drained
3	0	3.35	0.035	0	20	Imperfectly Drained
4	0	3.85	0.05	0	10	Moderately Drained
5	0	4.65	0.05	0	200	Well Drained
7	0	4.65	0.05	0	30	Water
99	0	4.65	0.05	0	50	Railroad

Significant amounts of sensitivity testing of these parameters has been completed. Comparison of these values to horizontal conductivity supplied by Aqualinc from the Christchurch groundwater model has also been made. It is recommended that a dedicated study on parameterisation be undertaken as part of future Schema development. Some summary comments are below.

- The Aqualinc groundwater model exhibits horizontal conductivities that are several orders of magnitude higher, along with soil patterns that differ substantially from those shown in Figure 3-12. Incorporating these values had a major impact on model calibration, and as a result, it was not feasible to continue the work in a way that aligned the two methods.
- This soil layer has been applied as a single layer rather than separated into surface and sub soil layers, as separating layers would be a significant departure from the Schema. However, consideration of a topsoil layer (e.g. top 0.5-1.0 m) and a shallow aquifer layer in better

representing the catchment should be considered in the future as closer to the physical characteristics of the catchment.

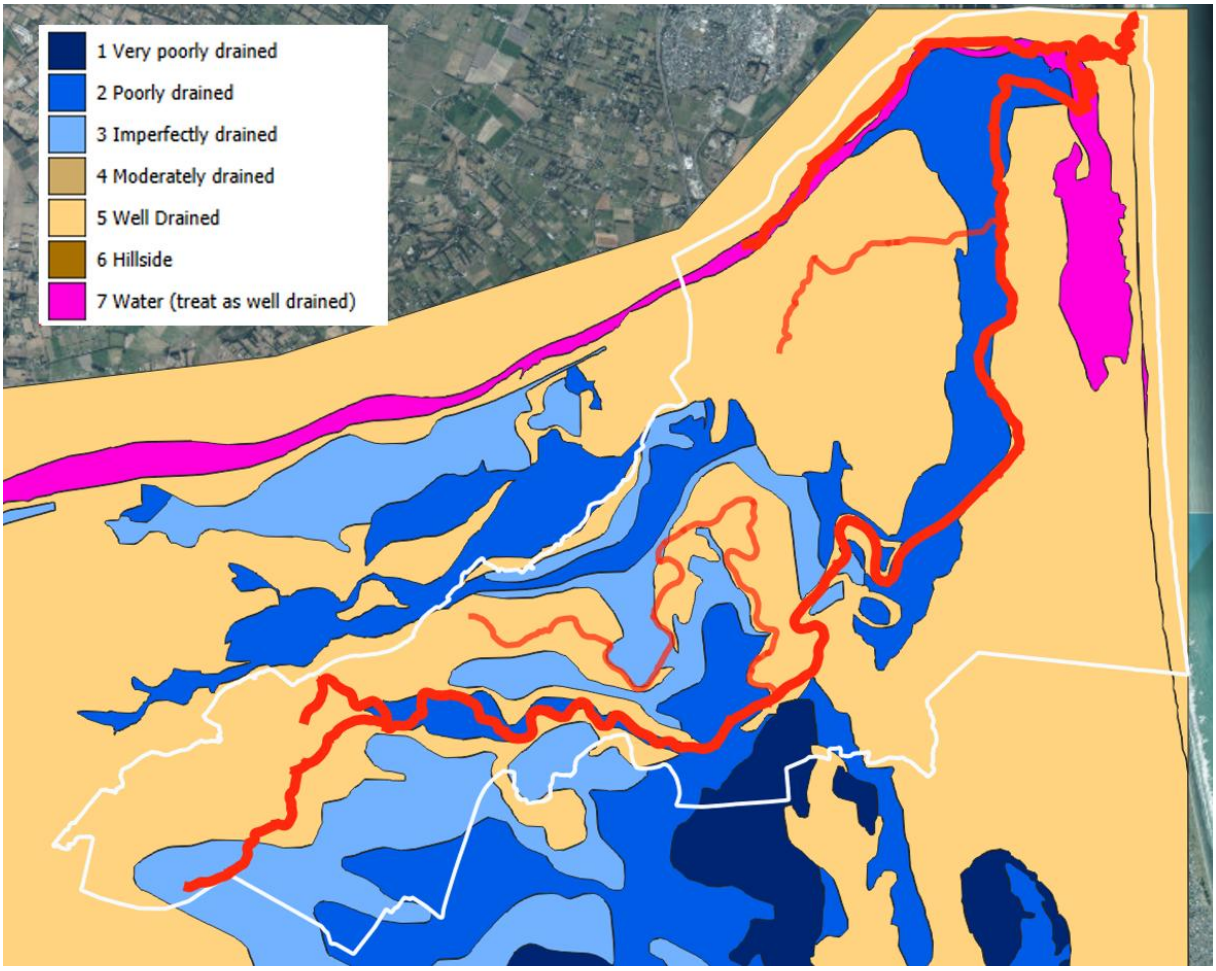


Figure 3-12. Soil classification used in the model with main water courses in red, and model boundary in white.

3.4.3. INFILTRATION

Infiltration is the process by which water on the ground surface enters the soil. In flood modelling, infiltration determines how much rainfall is absorbed versus how much becomes surface runoff. Infiltration approaches are important for predicting flood risks, designing stormwater systems, and managing water resources effectively. Model infiltration parameters can be adjusted during calibration to match observed runoff data and improve model accuracy.

The Schema values for infiltration (Table 3-4) were used for calibration. This was to align with the method used in other catchment models and avoid unrealistically using infiltration to force calibration without measurement (e.g. double ring infiltrometers testing). Tests with different infiltration settings were completed but it was concluded along with the soils and groundwater approaches, that more work is required on these areas before deviating from the default schema values.

Table 3-4. Citywide infiltration rates and derived constant infiltration rates (obtained from Schema Appendix L).

	Soils Drainage Class				
Parameter	Very Poorly Drained	Poorly Drained	Imperfectly Drained	Moderately Drained	Free Draining
Initial Infiltration (mm/hr)	1.7	3.6	5	5.5	6.6
Final Infiltration (mm/hr)	0.8	2.2	2.8	3.3	4
Horton Decay Rate k (s-1)	0.0015	0.0003	0.00006	0.00004	0.00003
Derived Constant infiltration rate (mm/hr) (75%/25% rule)	**1.025**	**2.55**	**3.35**	**3.85**	**4.65**

Considering much of the Styx catchment is well drained soils, Schema values can be low and encourage higher surface run off and conservative estimations of flooding as a result. However, the sub soil infiltration is likely to have much higher infiltration than the Schema values (e.g. potential 10’s to 100 mm/hr). This is demonstrated in a study conducted by Callander *et al.* (2023) in the upper portion of the Styx catchment that indicates that soil infiltration rates are highly variable. Ultimate (stabilised) infiltration rates were found to vary between 12 and 461 mm/hr with an average infiltration rate of 156 mm/hr. A comparison with the infiltration types in *Table 3-4* shows that the even the minimum measured infiltration rate (12 mm/hr) is still significantly higher than the highest infiltration rate (4.65 mm/hr) mentioned in the Schema. This warrants further investigation in future model versions especially since urban development and land compaction can cause highly variable infiltration across similar geologies.

With a surface water model where all infiltration is lost to the model, it has been traditional practice in New Zealand to use lower infiltration rates. The use of horizontal transmissivity in the groundwater component of the TUFLOW model results in infiltrated rainfall also being able to return to the surface via springs and stream baseflows. The use of low infiltration will increase the surface run off but reduce fast responses in groundwater recharge and then baseflow to streams during flood events which have been reported here. This has been a challenge for calibration in line with the schema.

Through July 2022 leading to the event on 25-26 July, there was widespread rain in the catchment. The antecedent moisture conditions as a result mean the infiltration of water to the ground is further reduced.

The Bay of Plenty Regional Council hydraulic modelling guidelines (BOPRC, 2024) have some useful considerations for considering antecedent moisture conditions including:

- increased soil moisture contributes to elevated groundwater and stream baseflows;
- reduce the initial and continuing loss for wetter periods; and
- wetter periods will influence the actual return period of the flood event.

Taking the various considerations into account, the calibration goal was to increase discharges to the stream. As a result, after several tests we reduced the infiltration rate by 20 % below the Schema infiltration values. While this has made improvements to the calibration, it is out of out of alignment with research we have undertaken in other costal catchments such as in Kapiti (Figure 3-13) and the Callander *et al.* (2023) measurements. This is considered acceptable as a balance between the Schema groundwater approach and a fully functioning surface water / groundwater model, which is capable with TUFLOW HPC as it continues alignment to other catchment methodologies.

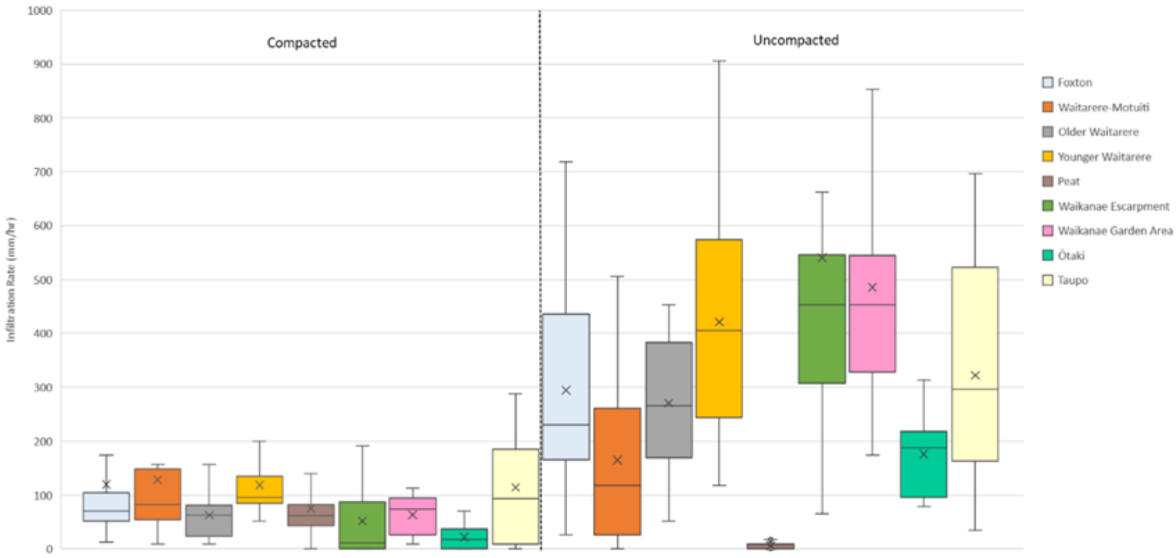


Figure 3-13. Infiltration rates of compacted and uncompacted soils in Kāpiti Coast district. Left side shows the compacted soils while the right side shows the uncompacted soils. The [X] in the graph refers to the mean while the box show the 25th - 75th percentile range, and the line in the box refers to the median.

Infiltration rates were reduced as a test by lowering by 30 % for high infiltration soils then again by 30 % for low infiltration soils. Figure 3-14 shows that subtle changes in the balance of where peaks occur could be made by changing which soils infiltrated more. With the lower infiltration soils often being situated in the stream channels and flood plains, we were looking to see the system response to changes in inflation in these different areas. While interesting, this was not found to be consequential to the calibration but is an example of a fine-tuning mechanism.

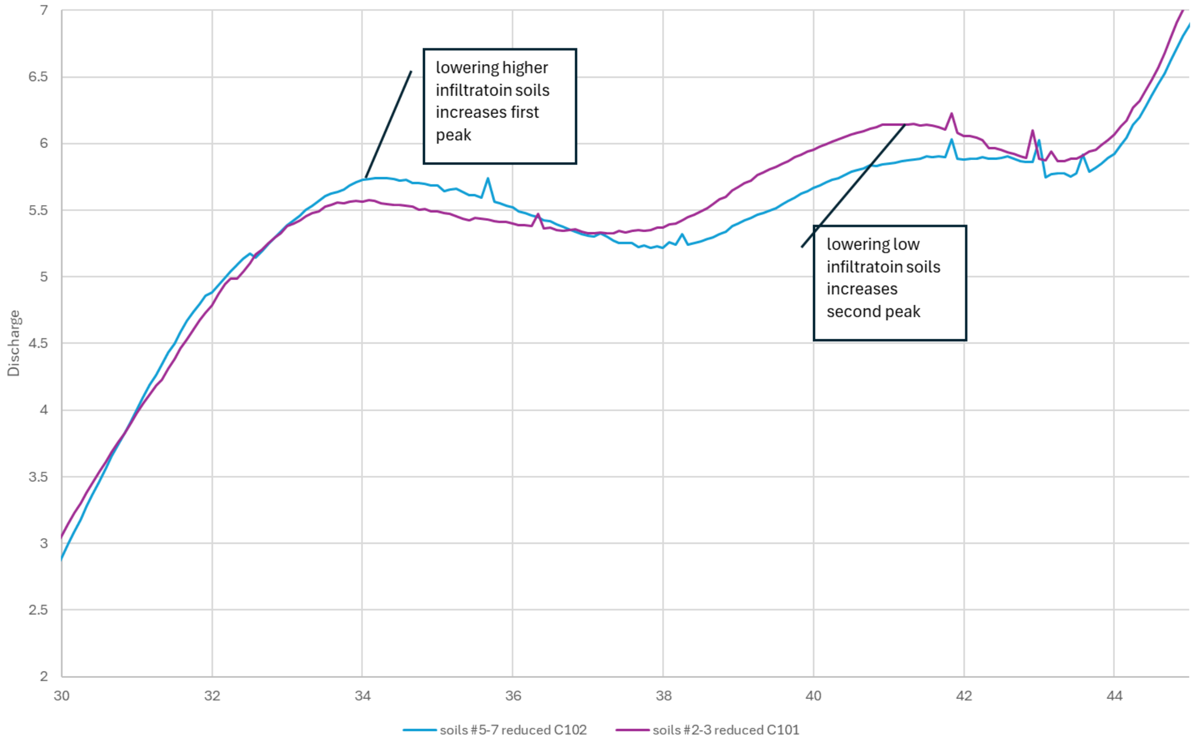


Figure 3-14. Example of applying lower infiltration rates (30 %) to higher infiltration soils (id's 5-7), and lower infiltration soils (id's 2-3). The impacts were found to be subtle in the shape of the profile.

3.4.4. CHANNEL FROM GATES TO OCEAN

The LiDAR used in this model has measured the water surface downstream of the flood gates, through the estuary and Waimakariri River entrance and therefore the channels are not well defined by the LiDAR. Several different tests were completed to estimate the channel shape better and a channel was implemented via *2d_zsh* terrain adjustments. The invert of the channel was set to -2.1 m (NZVD 2016) to match the existing channel that had geometry available.

Results of some of these tests at the coastal gate can be seen in Figure 3-15. It was proven that connectivity through the Waimakariri channel and inlet was required to enable the correct hydrograph shape to be modelled. Examples such as gentle, moderate and extreme cuts were made between the gates and the Waimakariri to see the effect. The use of a moderate cut approach was made which continued a similar channel to what was in the MIKE11 channel cross sections downstream of the gates.

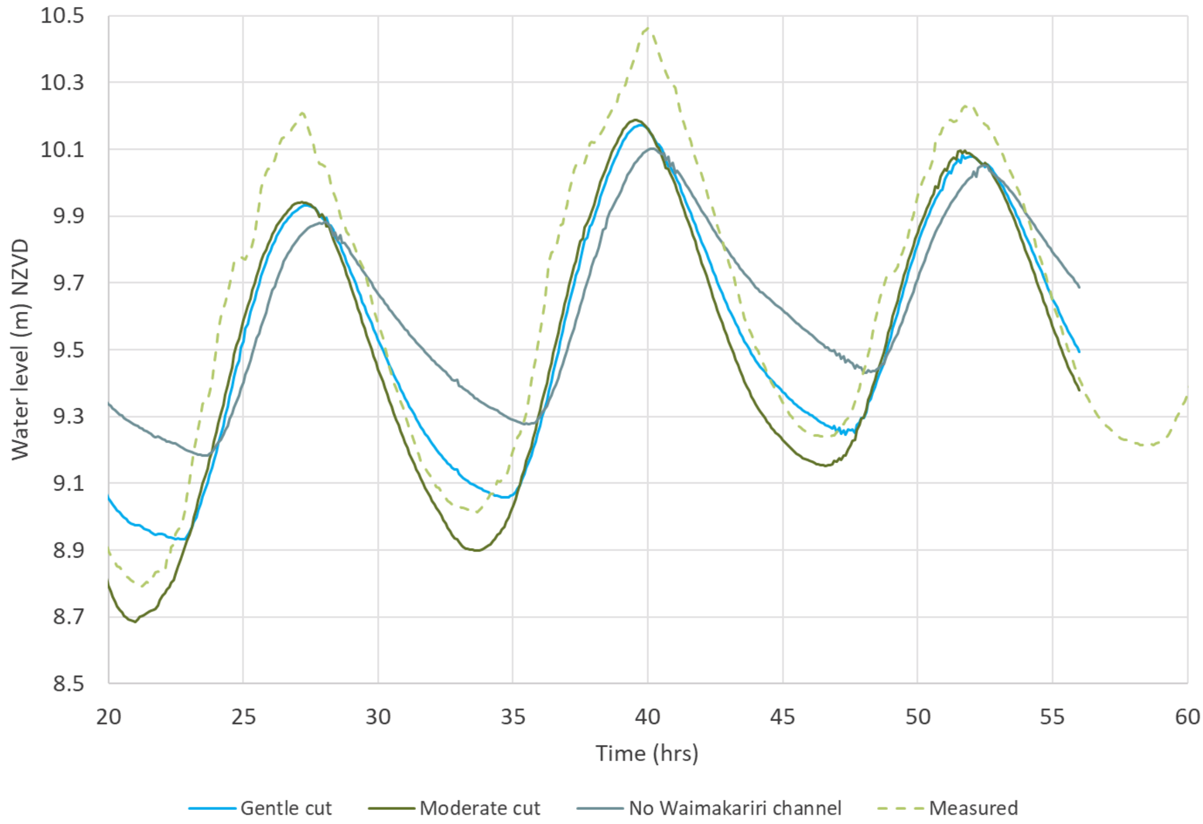


Figure 3-15. Hydrograph results at Harbour Road for testing of different channel geometry to connect the lower Styx River to the open coast.

3.5. APPROACH TO DESIGN MODEL

3.5.1. RADCLIFFE ROAD DISCHARGE ARI ANALYSIS

As mentioned earlier, Blundell-Dorey and Tuck (2023) assessed the historic events suitable for the Styx model build process. Some additional analysis is provided here that involved the Radcliffe Road discharges since 1992 being assessed to understand relative discharge scales for different ARIs as part of developing the approach to the design model.

A Gumbel analysis (Table 3-5) was conducted where the largest discharge from each year was analysed to understand how the Radcliffe Road discharges change with ARI. This was done as a simple approach and other analysis methods are available. This is important as part of creating an approach for design models in *Section 3.5.2 Time Varying Stream Discharges*. Measured discharges are compared to the Gumble estimate, and a possible issue with the Blundell-Dorey and Tuck (2023) 7-year ARI classification for the 2013 event may exist as the variance is -2.08 m.

Table 3-5. Gumbel analysis of Radcliffe Road discharge.

HISTORICAL EVENT	ARI	GUMBLE Q	MEASURED Q (m3/s)	VARIANCE (m)
	1.43	4.2		
	2	5.6		
2021 validation	3	6.9	6.7	0.16
2014	4	7.7	8	-0.30
2012	5	8.3	8.1	0.21
2013 validation	7	9.2	11.3	**-2.08****
	7.14	9.3		
	10	10.1		
	20	11.9		
2022 Calibration	22	12.1	11.9	0.23
	50	14.2		
	100	15.9		
	200	17.6		
	300	18.6		
	500	19.8		

*** red = planned design event ARI**

** variance is high and ARI classification by Blundell-Dorey and Tuck (2023) may contain an error

3.5.2. TIME VARYING STREAM DISCHARGES

Implementation of the Schema approach to groundwater flows using the GNS method was found to be too simplistic and results in a poor calibration (Figure 3-1; Figure 3-2). We believe that a conceptual model such as outlined in Figure 3-16 is a more realistic representation an environment where fast (and large) groundwater responses in streams occur as a result of large rainfall events. Similar types of models of hydrographs are described in numerous hydrological research studies such as Curtis *et al.* (2020) and He *et al.* (2016).

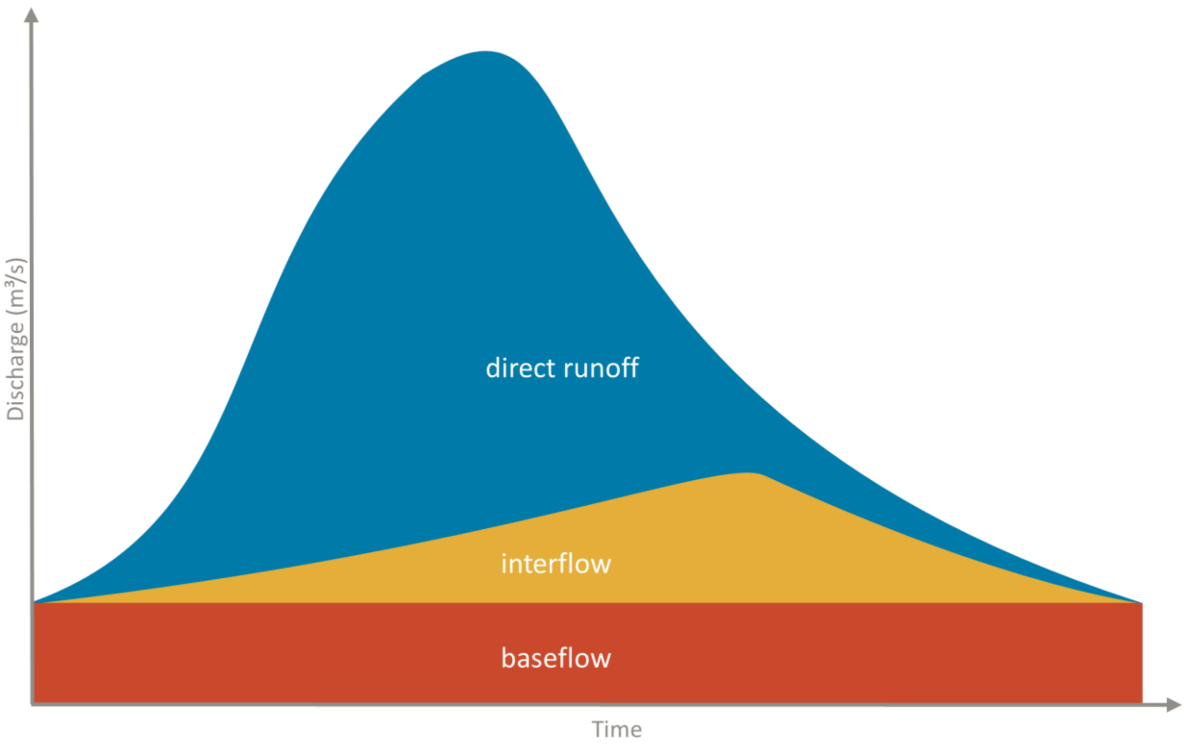


Figure 3-16. Proposed conceptual model of the components that make up a typical discharge hydrograph in locations such as Radcliffe Road (adapted from Curtis et al.*, 2020).*

Curtis et al. (2020) proposes that *"interflow should not be explicitly lumped with either the fast (direct rainfall) or slow (baseflow) components of streamflow"* and proposed partitions of streamflow into three subcomponents defined by the timescales of hydrologic response (e.g., fast: direct runoff, intermediate: interflow and slow: baseflow; Figure 3-17). The Schema approach with direct runoff and baseflow is effectively a two-partition approach, and the measured intermediate/interflow response has been shown to be actually quite fast for the Styx River as shown in Section 3.3).

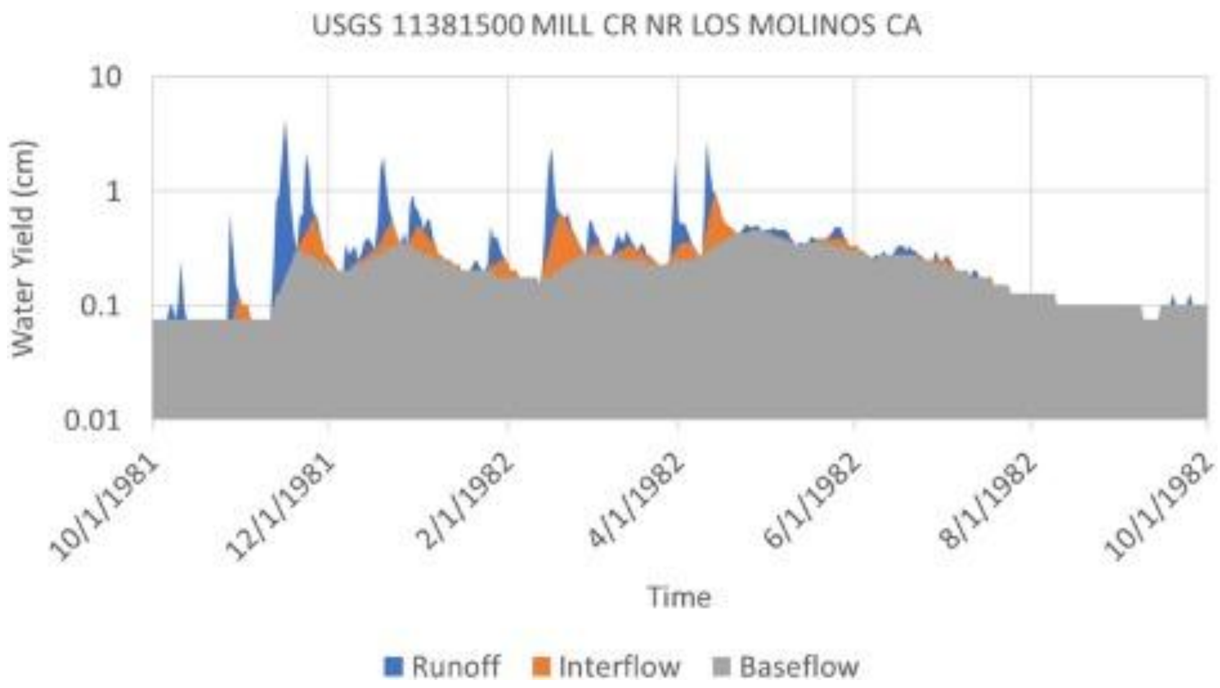


Figure 3-17. Example of real-world hydrograph-separation results from Curtis et al. (2020), estimated using a three-component metric for assessing hydrologic response. Fast-runoff (blue area), intermediate-interflow (orange area) slow-baseflow (grey area) are presented.

This sort of conceptual model breaks a discharge in different components that can be considered separately during model schematisation and calibration. Using the terms from Curtis *et al.* (2020), definitions are provided below to help with interpretation:

- **direct runoff** = the discharge created from surface run off that reaches the Styx River by overland flow, tributaries or the stormwater network;
- **interflow** = additional flow in the stream sourced from local rain being transmitted through the surface, to groundwater and into the river; and
- **baseflow** = groundwater flow into the stream from previous rain events and/or upstream groundwater bodies.

What this means for the Styx model calibration is that the Schema based approach:

1. produces the **direct runoff** driven component of the discharge;
2. does not produce the storm driven **interflow** response to rain from groundwater; and
3. produces the constant **baseflow**.

To address the gap in the storm driven interflow (#2), a time varying groundwater discharge has been applied in the calibration, validation and design models.

By way of evidence, an example of the magnitude of a storm driven groundwater **interflow** is outlined in Doyle (1994) and Martell (1996). While a completely different region and geology, these studies showed that the **interflow** rise rate in these Wellington studies was in the order of 0.05 L/s/ha/hr. By assuming an upstream catchment above Radcliffe Road of say 1600 ha, this would equate to baseflow rise of 0.08 m^3/s per hour, which over 25 hrs would add an additional 2 m^3/s to the stream interflow. While 2 m^3/s is lower than required to achieve calibration for the Styx 2022 event at Radcliffe Road, the principle is considered valid and demonstrates that groundwater driven interflow can occur at rainfall event timescales.

Based on this analysis, we suspect the groundwater driven interflow rise rates are higher than the baseflow from the GNS study during the calibration event. The *time varying groundwater discharge* approach developed and applied through the calibration event contributes to fixing the low discharge from initial calibration runs. The baseflow has been set to 50 % of original GNS value and this increases, peaking at 400 % of GNS value, to represent the increase in interflow during the storm event. This is based on testing of different values to achieve a calibration.

For design events, we propose that the *time varying groundwater discharge* starting value of 50 % is retained for discharges before the storm, and that the interflow increases to between 100 % and 400 % of the GNS baseflow depending on the ARI (see Table 3-6). These scaling factors have been developed by aligning to the groundwater response curve shown in Figure 3-18.

It is difficult to estimate what this scaling should be for 50-, 200- and 500-year ARI's and we did not want to establish a value beyond the 400 % scaling value established in the calibration event. The result of this is that additional discharge from these large events will likely come from direct run off rather than interflow in this model.

A limited number of scaling factors (four) has been selected to ensure simple implementation within the TUFLOW model. It has also been proposed that the small ARI events have a minimum of 100 % scaling factor to align closer to the Schema rather than reduce too much the baseflows compared to the Schema. Recommend peak scaling factors as percentage of GNS baseflows are:

- 100 %
- 200 %
- 250 %
- 400 %

Testing of this proposed method for design events is described in *Section 3.7 December 2021 Validation* .

Table 3-6. Scaling factors for GNS baseflows for different ARI discharge events and estimated groundwater response at monitoring Grays Road (M35/3614) monitoring site.

HISTORICAL EVENT	DISCHARGE ARI	GROUNDWATER RESPONSE (LEVEL, m)	GNS SCALING FACTOR %
	1.43		30
	2		30
2021 validation	3	0.12	30
2014	4	0.00	30
2012	5	0.10	125
2013 validation	7	0.30	250
	7.14		250
	10		250
	20		450
2022 Calibration	22	0.50	450
	50		450
	100		450
	200		450
	300		450
	500		450

In terms of implementation in TUFLOW of this method, here are some specific details.

- An Excel based calculator scales GNS discharges per reach and allows timing of shape to be edited. The calculator is straightforward and allows copy / paste to TUFLOW csv source area discharge file to be called by the *bc_database* file. There is a csv file per time varying flow scenario. For example, if the flow starts at 0 % then increases to 250 %, there will be one file for this.
- The use of scenarios, events and variables call different the different database and source area file. This means when a historic event or design event is called, the appropriate files will be called automatically. This takes advantage of the logic processes within TUFLOW control files.

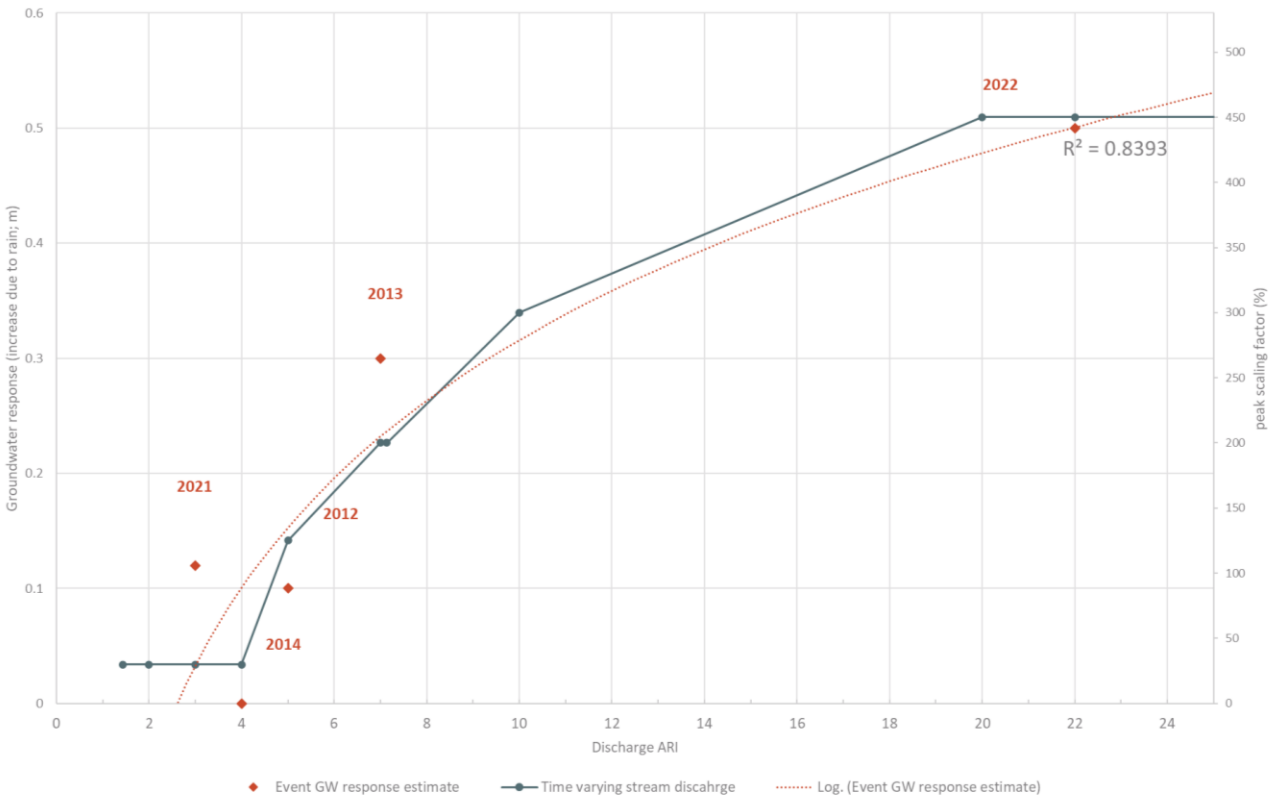


Figure 3-18. Peak scaling factor for GNS baseflows for different design event ARI's.

3.6. 2022 MODEL CALIBRATION RESULTS

The 2022 calibration event was run using a spatially varying rain dataset, Aqualinc initial groundwater level for the event, and Sumner head measured tide (with minor timing adjustment to the Waimakariri inlet). The weed growth is estimated to be low and the time varying baseflow scales between 0 % and 450 % of the GNS flows.

The following images depict the final calibration results for various locations within the catchment. The results are a good indication that the model is broadly representing measured levels and discharges. The varying configuration changes and testing completed and reported here have resulted in the underestimated initial results in *Section 3.2 July 2022 Initial Calibration Results* becoming much more in line with measured data. There is a slight underestimation of water level at Radcliffe Road, but total volume match is reasonable other than the faster post peak recession at about 66 hrs. There are slightly lower levels at Harbour Road also and the reasons could be more complex than just roughness and relate to groundwater levels and the impact of infiltration.

The integrated 1D / 2D model with groundwater has numerous settings and parameters that can be modified to change the shape, baseflow, interflow and peak of the discharge. However, there are also constraints on network quality, infiltration and soils that also mean that calibration at some point needs to be accepted. With this event being approximately 22-year ARI, smaller and large events will also behave differently.

Additionally, because of the validation runs (2021 in particular) overestimating the discharge, the calibration was revisited after interim peer review comments so that the time varying groundwater level initial scaling factor was reduced from 100 % of the GNS flow to 0 % of the flow. This resulted in a better fit between the different calibration and validation events.

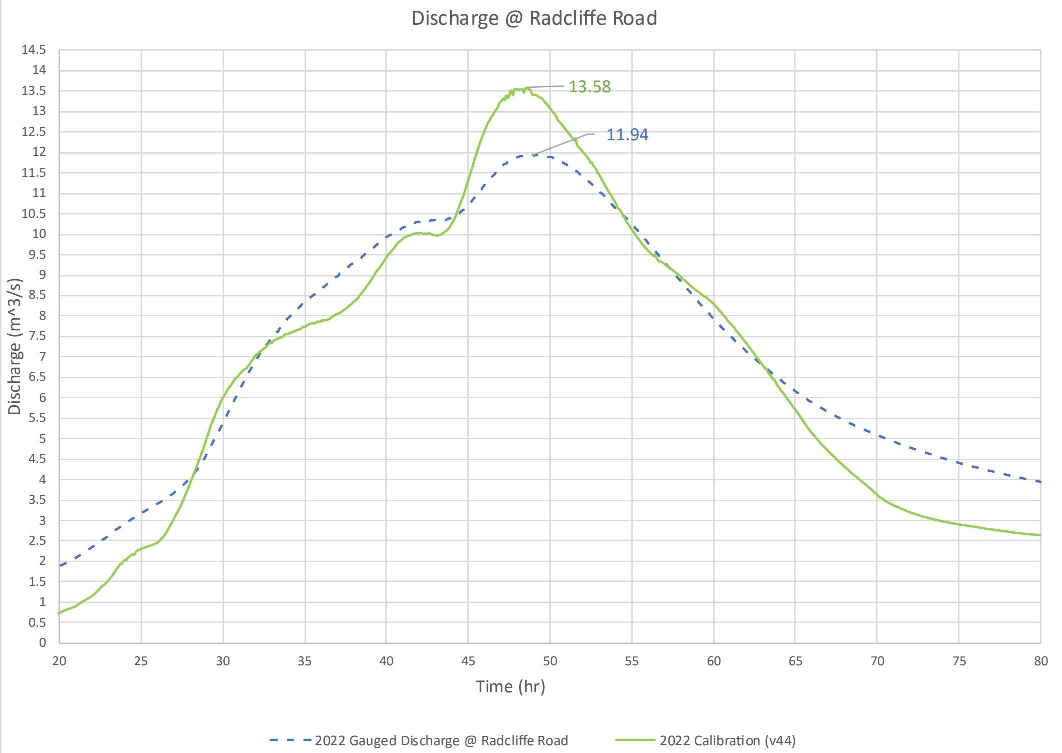


Figure 3-19. Comparison between observed flow and final calibrated flow at Radcliffe Road for 25-26 July 2022 event.

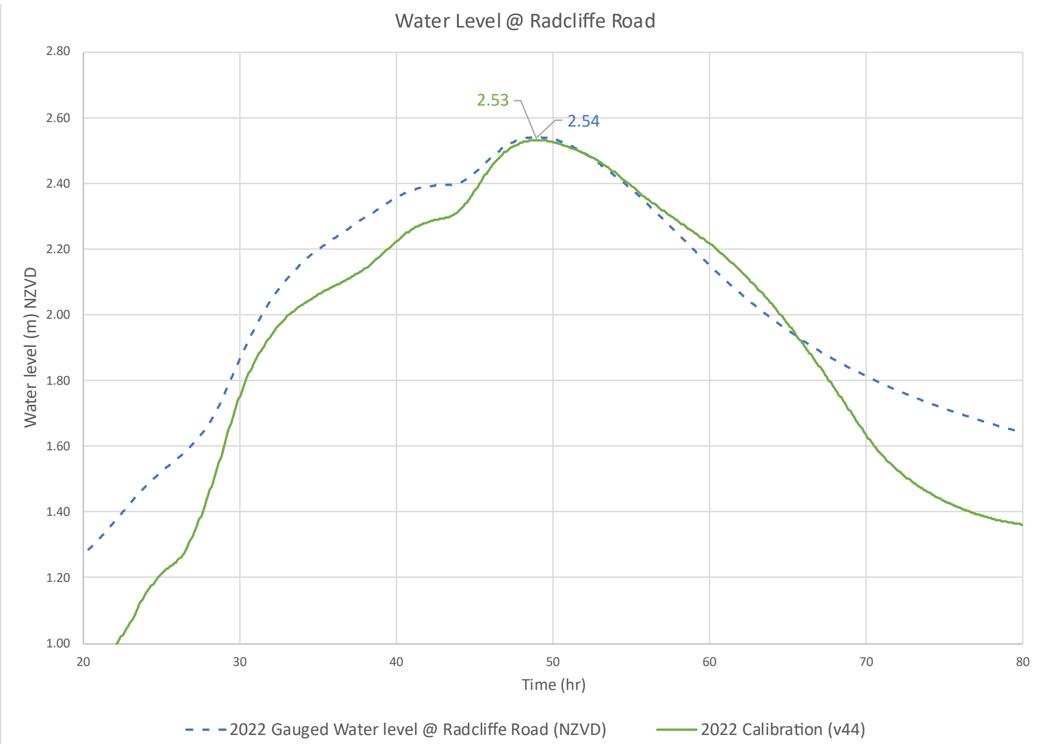


Figure 3-20. Comparison between observed water level and final calibrated level at Radcliffe Road for 25-26 July 2022 event.

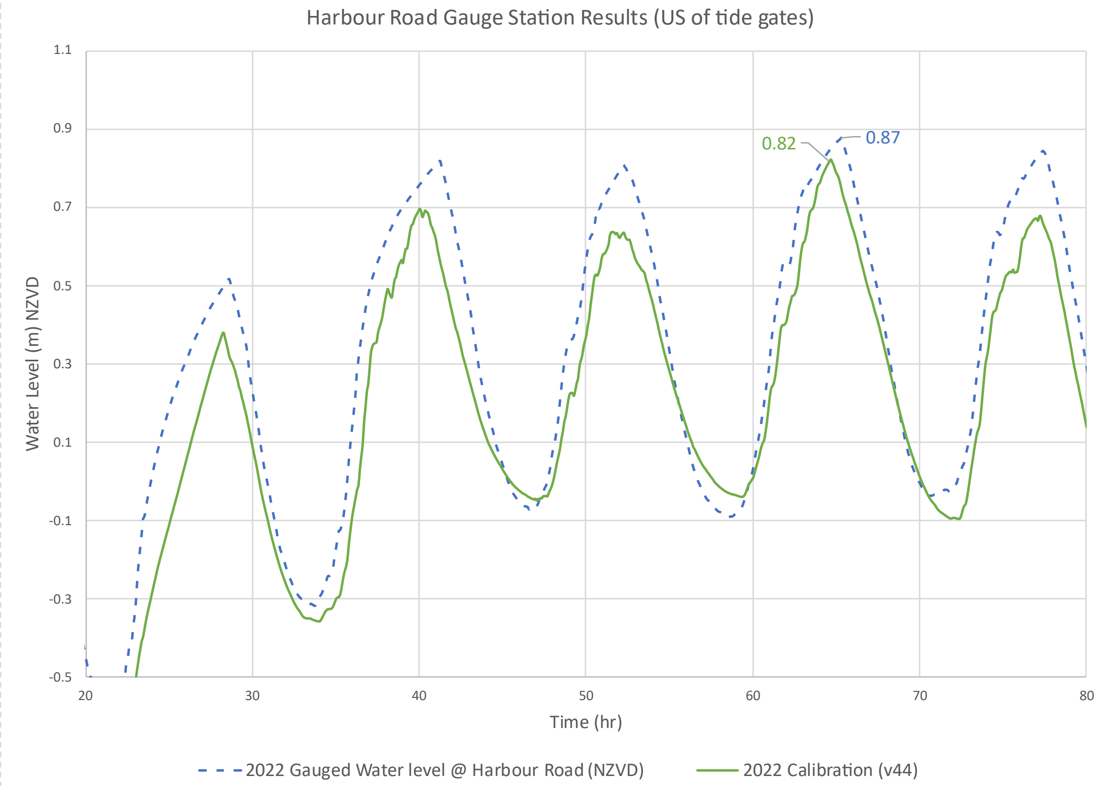


Figure 3-21. Comparison between observed water level and final calibrated level at Harbour Road for 25-26 July 2022 event.

3.7. DECEMBER 2021 VALIDATION EVENT

The 2021 validation event has been run using a spatially varying rain dataset, the Aqualinc groundwater level for the event, and the Sumner head measured tide with timing adjusted to the Waimakariri inlet. The time varying groundwater flows scale from 0 % to 30 % of the GNS flows as this is a small event where surface water overland flow is expected to dominate more than groundwater interflow.

The validation results are presented in the images below. With the weed growth estimated to be medium to high, a roughness value of 0.15 has been used for the model version submitted for peer review. We also performed a sensitivity test (roughness value of 0.1), which only produced a minor difference (0.2 m^3/s) in peak value. The roughness was revised to 0.08 after peer review model updates.

As can be noticed in Figure 3-22 and Figure 3-23, there is a gap between observed and modelled flows and water level at Radcliffe Road respectively. There is a general overestimation of both peak flow (1.56 m^3/s) and water level (0.19 m) at this location. However, there is no difference between peak water level observed and modelled at Harbour Road (Figure 3-24) which is located at the very downstream of the catchment.

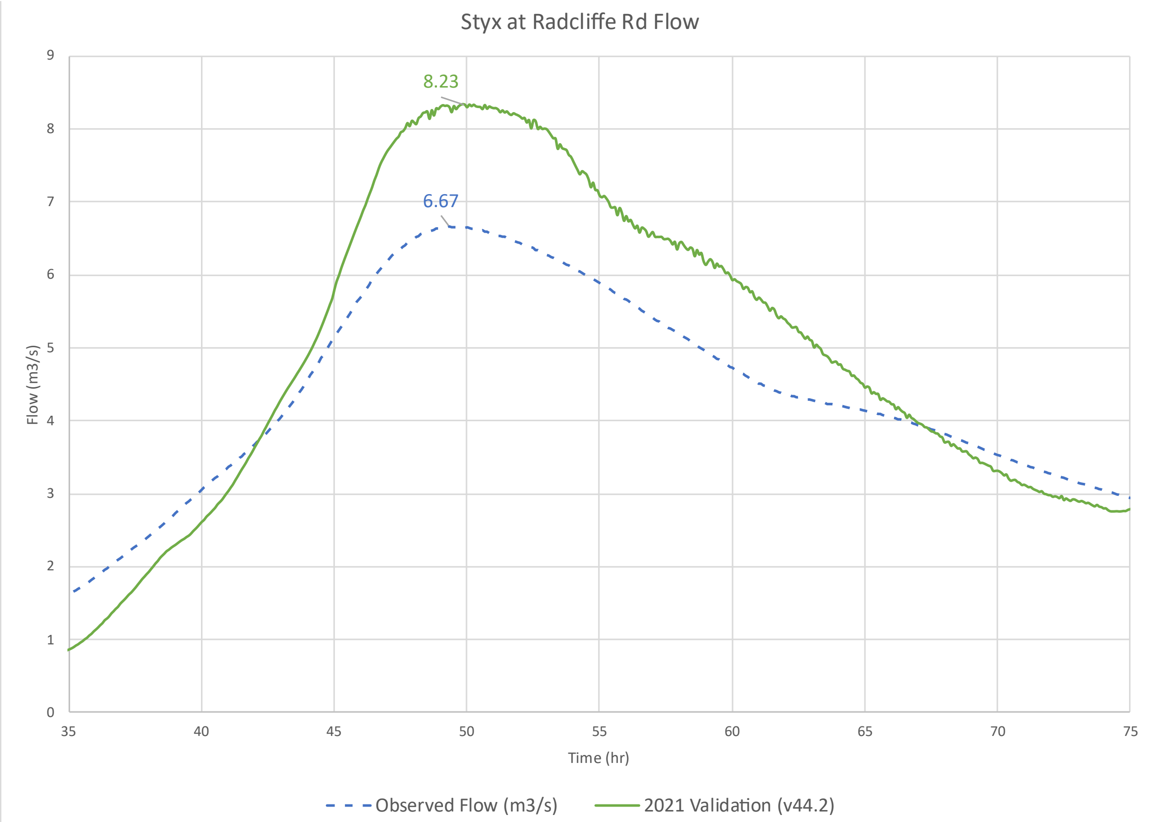


Figure 3-22. Comparison between observed flow and final modelled flow at Radcliffe Road for 15 December 2021 event.

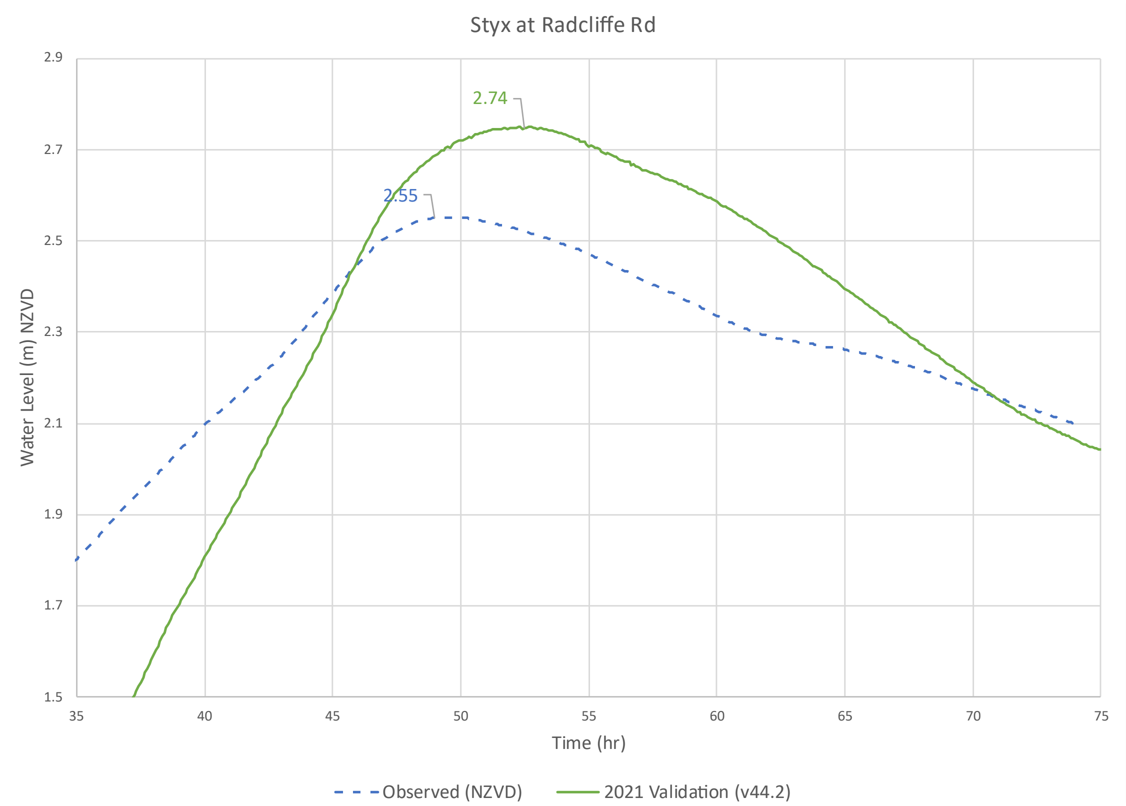


Figure 3-23. Comparison between observed water level and final modelled level at Radcliffe Road for 15 December 2021 event.

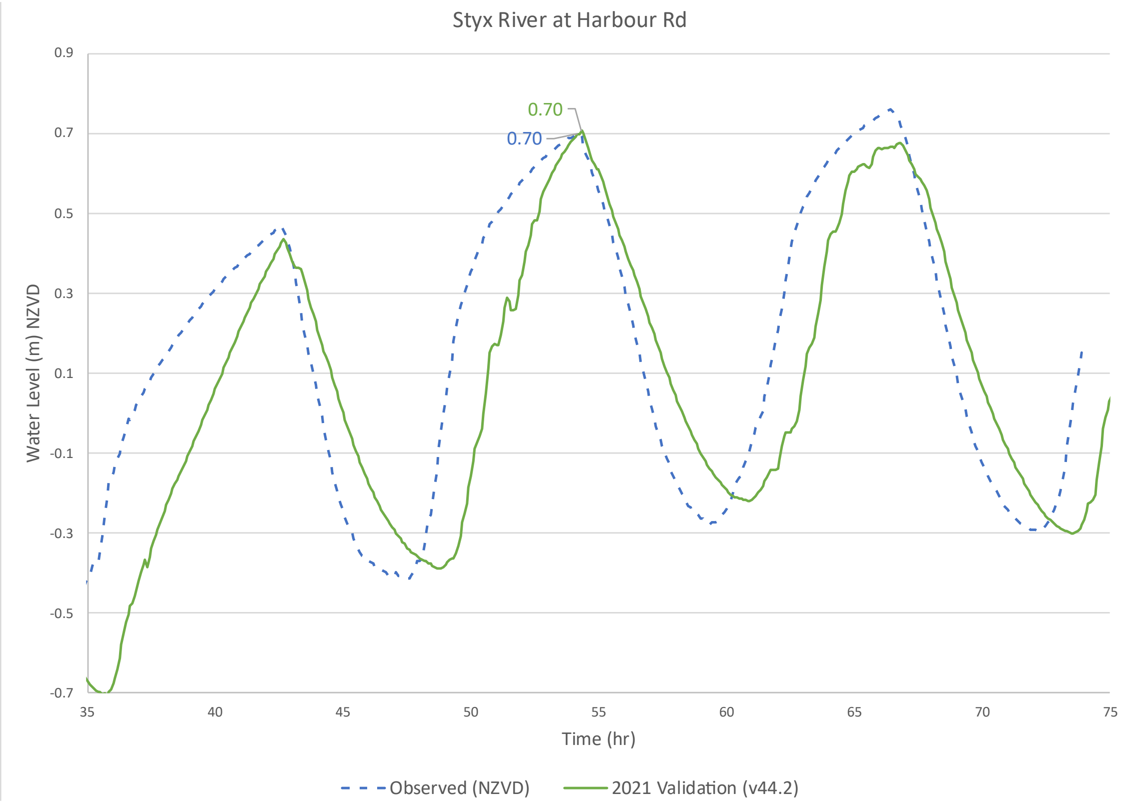


Figure 3-24. Comparison between observed water level and final modelled level at Harbour Road for 15 December 2021 event.

3.8. JUNE 2013 VALIDATION EVENT

Like the previous events, the 2013 validation event has been run using a spatially varying rain dataset, and the Aqualinc initial groundwater level for the event. However, due to unavailability of observed Sumner head measured tide, estimated NIWA tide was used for this event. This meant that the tide used here as a boundary condition at the downstream lacks the storm surge and atmospheric impacts accounted for with measured tides. This calls into question the validity of the results at Harbour Road.

For the June 2013 event, the weed growth is estimated to be medium to high based on ambient water levels at the time. The time varying groundwater flows scaling from 0 % to 250 % of the GNS flows to represent a moderate event where some additional interflow from groundwater is expected.

Looking at the results for Radcliffe Road (Figure 3-25 and Figure 3-26) it can be noticed there is a slight under estimation of peak flow by 0.11 m^3/s but similar total volume. The peak water level difference is 0.22 m; the pre-peak level raises faster which could be due to the geometry effecting the rating in the model. The results at Harbour Road (Figure 3-27) clearly demonstrate that the lack of storm surge produces a gap of 0.24 m in the peak water level between the observation and model.

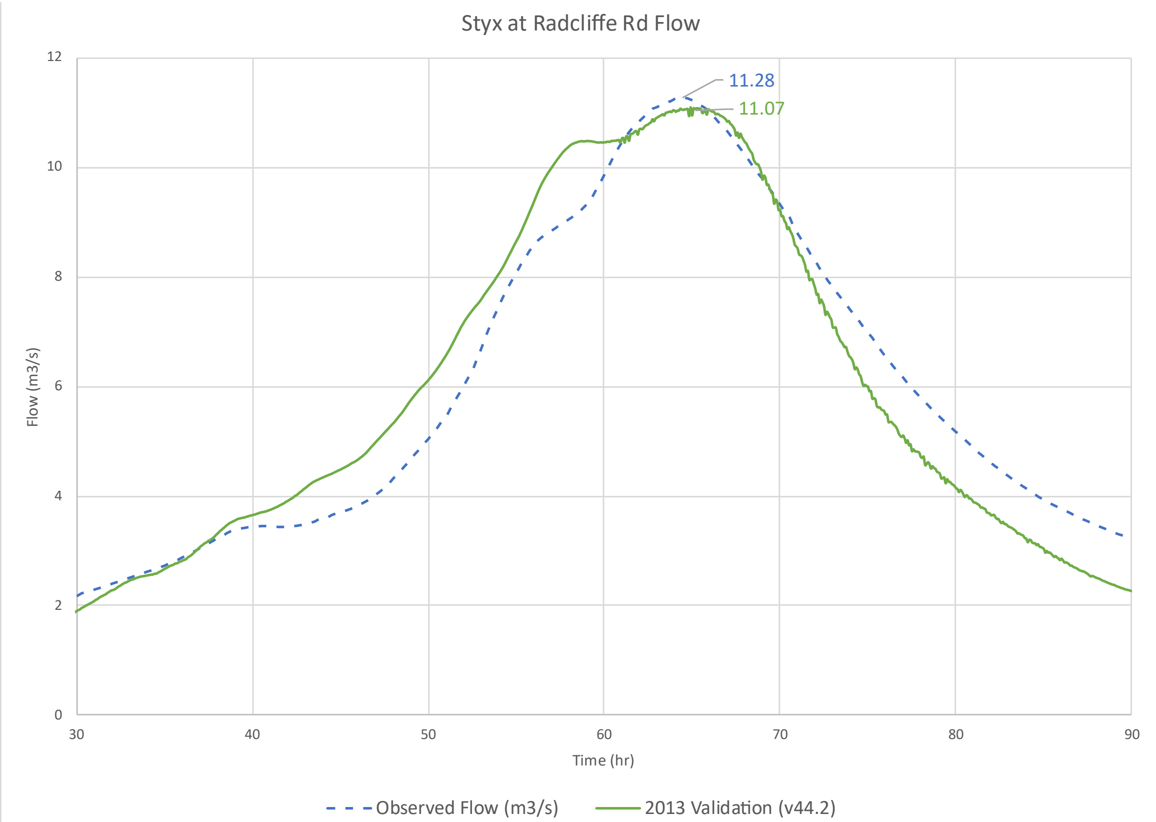


Figure 3-25. Comparison between observed flow and final modelled flow at Radcliffe Road for 17 June 2013 event.

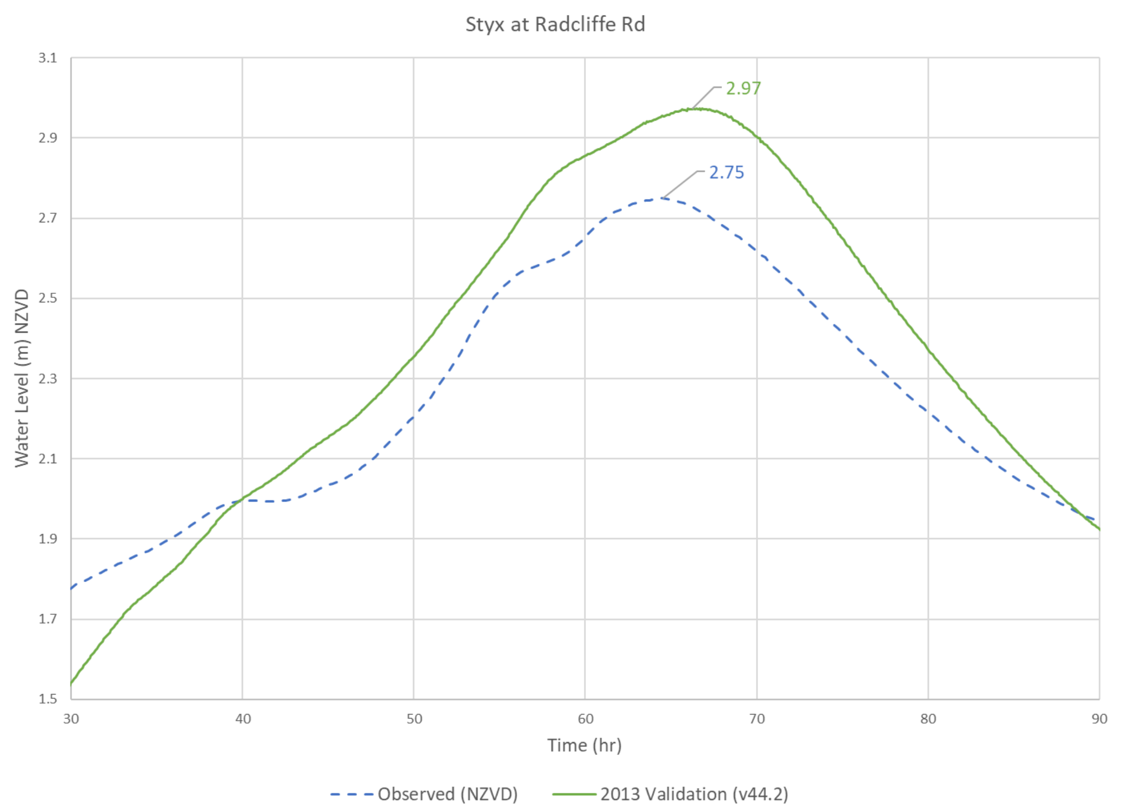


Figure 3-26. Comparison between observed water level and final modelled level at Radcliffe Road 17 June 2013 event.

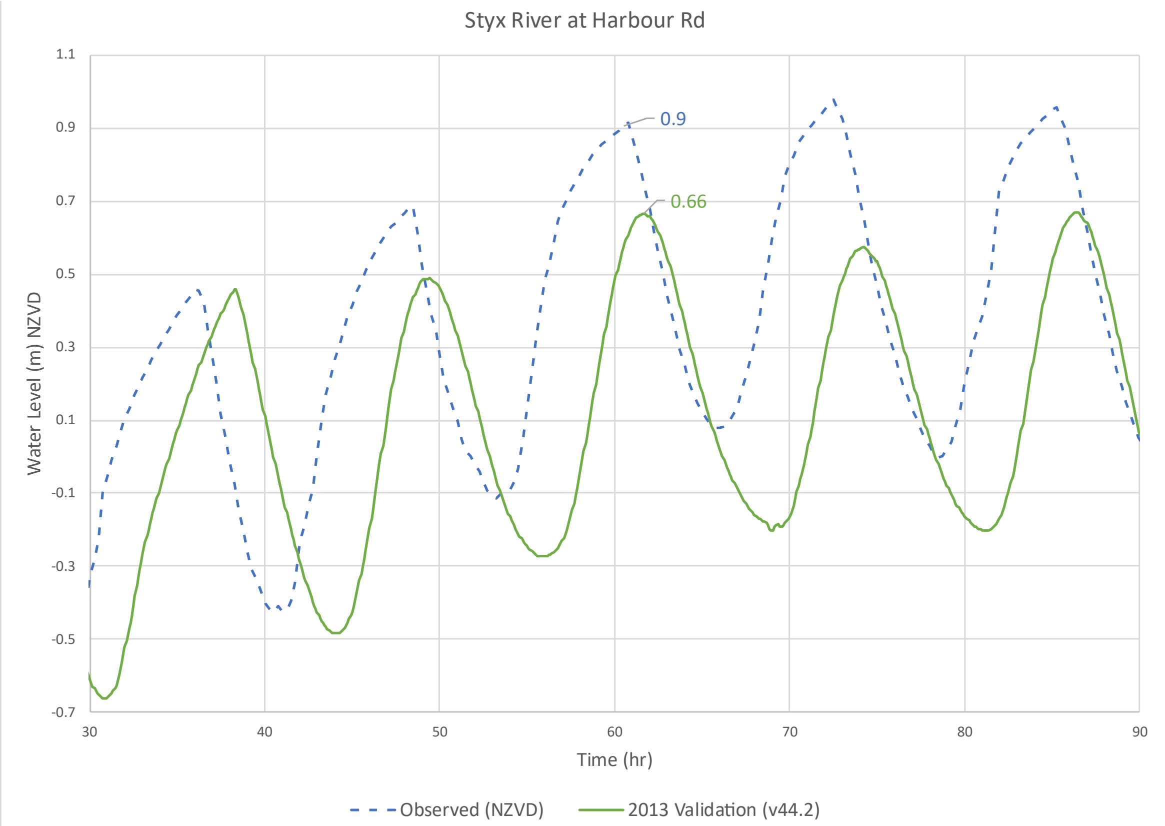


Figure 3-27. Comparison between observed water level and final modelled level at Harbour Road for 17 June 2013 event.

3.9. CALIBRATION/VALIDATION DISCUSSION

A summary of the calibration quality is provided here.

2022 Calibration

The 2022 calibration indicates that the model performs well for the largest available event, with simulated volumes showing a reasonable match to observed data. Discharge calibration at Radcliffe is satisfactory, and water-level calibration at Harbour Road demonstrates good agreement with measurements. Water levels at Radcliffe Road are acceptable; however, a survey of the gauge location is recommended due to known DEM inaccuracies that may influence the rating.

2021 Validation

The 2021 validation event is relatively small, and the model tends to over-predict both discharge and water level at Radcliffe Road. Despite this, water-level validation at Harbour Road remains robust and aligns well with observations.

2013 Validation

For the medium-sized 2013 event, validation at Radcliffe Road is generally reasonable. At Harbour Road, the model captures the overall shape and range of the water-level response; however, the absolute levels appear low. This discrepancy is likely due to the use of a NIWA tide constructed from tidal constituents in the absence of measured open-coast tide data. As a result, climatic and storm-related influences are not represented in the boundary condition.

Many large stormwater catchments such as the Styx have their own special complexities and characteristics when attempting to represent real world phenomena within numerical models. The Styx catchment is characterised by a number of these characteristics including:

- Being a well-draining catchment at the bottom of a major river system (Waimakariri) where the groundwater catchment that extends beyond the surface water catchment;
- Evidence of very fast groundwater responses to rainfall events above 5-year ARI, which rapidly discharge into the river (interflow component);
- 50-70 % of the catchment being a low-lying area where groundwater will accumulate;
- Two-way exchange of flow via channels with the Avon catchment in the order of 2-4 m^3/s;
- Evidence of surface infiltration magnitudes higher than Schema values; and
- Seasonal weed growth that is managed but with variations on timing due to operational considerations.

Peer review questions were raised about varying roughness spatially to align with measured data and Radcliffe Road gauge. Discussions resulted in agreement to proceed to design runs (Appendix B – Styx Recalibration Memo). It is noted that the roughness values used in this model are within CCC's accepted range and that the model also calibrates well at another important downstream location (Harbour Road). Overall, the mass balance error is well under 0.1% (within CCC's acceptable range of less than 1%). In context of the model drivers and changing methodologies, the roughness approach used for calibration is appropriate.

As flood modellers, there are choices and trade-offs to make in order to represent Styx catchment numerically. These decisions have real world impacts on growth, infrastructure, operations and properties within the catchment. While the findings of this model build and calibration process is that it has been largely successful, additional research and methodology development is required in the future on the approach to infiltration and groundwater. Pragmatically it is important to keep alignment to CCC methodologies via the Schema while only departing where absolutely required. We believe the approach reported here strikes the right balance.

In an ideal scenario, the many geological records from bores would be incorporated into a multi-layer subsoil groundwater model within TUFLOW HPC, surface infiltration would be measured, and the model calibrated to represent the actual exchanges between the rain, surface, groundwater and streams. This is a view of what is possible in the future but not required for this model build process.

Despite some of the technical complexity described, this is a detailed, stable and highly robust flood model in context of New Zealand good practice for such a tool. The network is well represented, and terrain and land cover have high resolution. The software with SGS and Quadtree approaches represents detail well to hydraulically conveyed overland flow through streams, overground and into the stormwater network. Detailed flood mapping can be produced across many parameters such as depth, velocity, level, bed shear stress, hazard and more.

3.10. IMPLICATIONS OF CALIBRATION FOR THE DESIGN MODEL

These are key configuration implications for the design model.

- **Avon surface water exchange** –The eight boundary exchanges (two water level and six flows) are not related to the calibration methodology. The boundary conditions extracted from the Avon MIKE model are independent of the calibration.
- **Initial groundwater level** – The Aqualinc groundwater level layers used for initial groundwater conditions needed to be modified before including them in the design model. The modification was to set any groundwater water levels that are above the DEM to be set to the DEM level. The groundwater layer is primarily being used to limit infiltration rather than estimate surface water initiation conditions.
- **Time varying groundwater flows** – A methodology is in place that can be applied to design events and outlined in 3.5 Approach to Design Model. The model is configured so that an appropriate groundwater interflow can be selected for the size of the design event.
- **Development state and climate** – ED, MPD and climate will be able to be set for any given scenario via event file settings.
- **Roughness** – Different roughness values are used in the design model from the calibration and validation events.
- **Rain** – The calibration does not impact design rain.
- **Tide** – The calibration does not impact design tides.

Factors such as weed growth (dependent on seasonal variability and harvesting) are significant in the stream and need different channel roughness to be set up for different runs. Therefore, the roughness values used for the Styx during calibration are not used in design scenarios.

The model runs relatively fast considering the size and level of detail (e.g. 30 hrs real time for a 100-hr simulation using a Nvidia GeForce RTX 5090 GPU at time of writing). This is using single point precision, and it may be for some critical infrastructure design runs that double precision could be warranted.

4. CONCLUSION AND RECOMMENDATIONS

4.1. CONCLUSIONS

The existing model and significant new input data have been used to develop a new flood model for the Styx catchment. It is considered a detailed, robust and validated model in line with good practice for flood models in New Zealand at the time of development. The model is considered fit for purpose for the stated model purposes in Section 1.3. It has been through a number of rounds of peer review and internal CCC input on site specific considerations and methodologies options.

This is the second TUFLOW HPC model built for the CCC catchments, and lessons from the model build will support updates to the Schema in the future to support TUFLOW. Adaptations have been made to the MIKE based Schema approach to reflect the TUFLOW software. Some modifications to the schema approach have been made to reflect the nature of the Styx catchment and recommendation are made below about future investigations that, pending findings, could result in future modifications in approach for future model updates.

4.2. RECOMMENDATIONS

A number of recommendations are highlighted here for consideration in future model updates.

- **Survey Enhancements at Radcliffe Road Gauging Station**
  Conduct a detailed survey of the concrete walls, the area behind the walls, and the cross-sections encompassing the expected flood zone during peak storm events (e.g., the 2022 event). This will support improved confidence in the rating used for calibration.
- **Review of Infiltration Parameters**
  Investigate and validate the default infiltration values used in the model to ensure they accurately reflect local soil and ground conditions.
- **Integration of Updated LiDAR Data**
  Incorporate the most recent LiDAR data into the model as it becomes available to better capture recent developments and topographic changes since the original model build.
- **Refinement of Soil Representation**
  Reassess the assumption that the current schema soil layer appropriately represents horizontal conductivity. Update the model with more accurate and detailed sub soil information as it becomes available.
- **Update Model with Turners Road Pump Station Details**
  Add information on the culvert and flap-gate configuration for the Turners Road pump station once more detailed data is obtained.
- **Use of Gauged Inflow Data at Boundary Locations**
  Replace the constant inflow boundary conditions currently used at the Waimakariri River, Kaiapoi River, and Kairaki Creek with gauged inflow data when such data becomes available.
- **Stormwater Network Update Management**
  Maintain a model backlog to capture any alterations or additions to the stormwater network, ensuring regular updates to preserve the model's accuracy and currency.

- **Improvement of Kerb Line Representation**
  Enhance the accuracy of kerb line data to improve the model's surface flow representation and drainage behaviour simulation.
- **Enhancement of Open Channel Survey Data**
  Improve survey data for open channels by integrating recent bathymetric survey data with LiDAR information. This will enhance the representation of below-surface channel geometry and align the model with current surveyed conditions.
- **Assessment of Groundwater Interactions**
  Investigate the potential for groundwater flow across surface water catchment boundaries—particularly upstream (north toward the airport) and near the Avon model boundary (around Prestons Road)—to determine whether these interactions significantly influence flood events.
- **Dataset size**
  The model has good computational performance but results in file sizes. To minimise issues with large model such as this, specify in future schema what groundwater depth, level and velocity (GWh, GWd, GWv) data should be stored. Consider only storing NetCDF format (.nc files) to be compatible will ArcGIS Pro without producing the standard TUFLOW XMDF files when not required.

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APPENDIX A – ROUGHNESS VALUES MEMO

This memo is republished here as context for the report:

> *Martell, C., 2024. Roughness Values used for CCC catchment flood models. Unpublished internal memorandum to CCC, Awa Environmental, 21 August 2024.*

MEMO

TO:	Christchurch City Council	**DATE:**	21 August 2024
FROM:	Craig Martell		
SUBJECT:	Roughness Values used for CCC catchment flood models		

BACKGROUND

Awa has been tasked by CCC to build catchment flood models for the following catchments:

1. Styx
2. Sumner

One part of building and calibrating these new models is to define the roughness values both across the open channel and flood plains within these catchments. We have been provided by CCC with the "Christchurch City Council Citywide Flood Modelling (LDRP097) Model Schematisation 2020 Update - Avon/Estuary, Heathcote and Sumner - Rev 7, July 2022" referred from hereon as the ***Schema***. We have also been provided with the latest landcover (mapping impervious surfaces in Christchurch City) report by Lynker Analytics Ltd. (29 January 2024), which was prepared using the 0.075m imagery from 2023 LiDAR.

This memo summarizes the roughness values proposed by Awa for the model build process and the various references that we have considered to inform these values. In places we are suggesting additions to the schema and as such this memo is intended to provide a starting point for this technical discussion.

The National Stormwater Modelling Guide[1], does not provide specific parameters for either Floodplain or open channel roughness values but instead points to local guidance. *"2D hydraulics for the floodplain and small open channel using averaged parameters are informed by land cover estimates. Roughness parameters will be taken directly from literature or local authority guidance. Estimates of flood plain hydraulics will be verified against other sources even if validation event simulation results are not available."* Essentially, the guide suggests that while the roughness values are to be sourced from literature or local authority guidance, it will be a key parameter that needs to be adjusted at the model calibration stage.

MANNINGS ROUGNESS COEFFICIENT

Manning's n coefficient is a parameter in hydraulic engineering used to describe the roughness or friction of a channel or floodplain surface, influencing the velocity of water flow and as such it's depth. The n value is determined from the values of the factors that affect the roughness of channels and flood plains. In densely vegetated flood plains, the major roughness is caused by trees, vines, and brush. The n value for this type of flood plain can be determined by measuring the vegetation density of the flood plain.

[1] N. Woods et al, "National Stormwater Modelling Guide", Water New Zealand, 2024

It should be noted that roughness value varies based on the depth of flow. Figure 1 shows the variation of Manning's n against gauged discharge[2]. For flood modelling, manning's n is used as a calibration factor for larger storm events and then these are typically applied to storms of every return period. The potential inaccuracies associated with this approach are part of what is considered in post-model freeboard application, and some thought should be given to this if models are being used to understand higher frequency events.

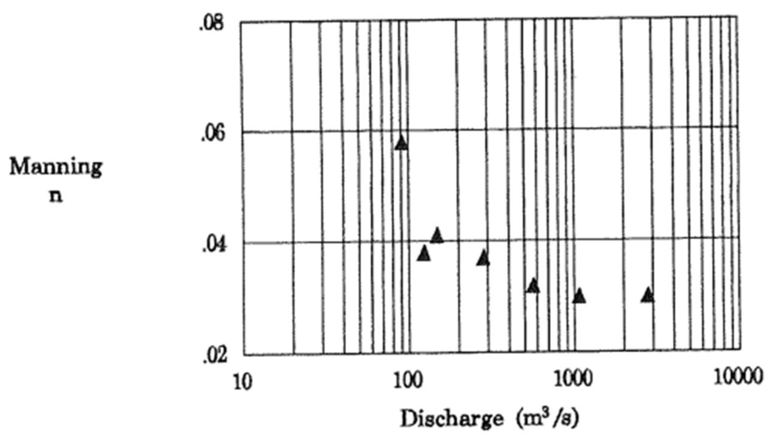


Figure 1: Variation of Manning's n across discharge measurements (Buller at Woolfs)

OPEN CHANNEL ROUGHNESS VALUES FROM CCC SCHEMA

The Schema also states that an initial global Manning's n value of 0.03 will be adopted for all unlined and natural channels. Branches listed below will have local roughness values based on guidance provided by NIWA (2004).

Location	CFM branch name	NIWA(2004) range in Manning's 'n'	Assumed Manning's n (city-wide model)
Cross Stream (Elmwood Park)	Avon.crosstr	0.052-0.124	0.087
Snellings Drain (Claire Park)	Avon.snellings	0.127-0.560	0.198
Cashmere Stream (Hoon Hay Valley Road)	Heth.hoonay	0.05-0.294	0.202
Avon River (Harakeke Street)	Avon.avon	0.027-0.059	0.036
Wairarapa Stream Wairarapa Terrace)	Avon.wairarapa	0.029-0.044	0.034

With regards to lined channel roughness the Schema provides the following values:

[2] D. Hicks and P. Mason, "Roughness Characteristics of New Zealand Rivers", New Zealand National Institute of Water and Atmospheric Research, Auckland, 1998

	Assumed Mannings n	Reference source
Concrete lined	0.013	
Rock lined	0.02	
Timber lined	0.03	From previous M11 models. Retained roughest of the original two timber lined types.
Earth / unlined	0.03	WWDG
Undefined lining	0.03	(Effectively timber by assumption)

This guidance has been used as the starting parameter for all our models. We will obviously consider these as part of the calibration process and may provide some additional clarity for the Styx and Sumner as part of that process.

FLOODPLAIN ROUGHNESS VALUES FROM CCC SCHEMA

The Schema report has the following manning's values for various categories in 2D domain:

Area classification	Roughness value (Mannings 'M')	Roughness value (Mannings 'n')
Building footprints (residential or commercial)	5	0.200
Commercial/Industrial property (outside of building footprints)	50	0.020
Residential property (outside of building footprints)	20	0.050
New commercial/industrial (where there are buildings but no building footprint data)	7	0.143
New residential (where there are buildings but no building footprint data)	8	0.125
Open space	20	0.050
Vegetation	8	0.125
Red zone	20	0.050

Area classification	Roughness value (Mannings 'M')	Roughness value (Mannings 'n')
Roads	71	0.014
Rail	10	0.100
Water	40	0.025
Estuary (water)	40-50	0.025 – 0.020
Steep hills[1]	5	0.200

[1] For steep hills and in particular using the direct rain on mesh approach, the roughness could be modified to help with the model stability. Recommended range n=0.20 to 0.40. Need to do sensitivity testing if using high ('n') values to check the peak flow and the timing of the resulting hydrograph has not been significantly affected by the changes to roughness.

There is a question with the floodplain schema values around open space and vegetation values. It may be beneficial to have some additional detail around the open space and vegetation categories to align with the additional detail associated with the Lynker land classification.

LANDCOVER CLASSIFCATION BY LYNKER

The landcover classification provided by Lynker is shown below:

Category Name		Description
Water		Water bodies including river, pond, lake, and ocean
Bare earth/gravel/sand		Tilled land, bare earth, loose gravels, and sand beaches
Grass		Open space without trees and shrubs
Rough Low Vegetation		Shrub species, rushes, low profile vegetation
Trees		Taller trees of all species
Other Impervious		Driveways, carparks, footpaths, other paved areas
Road		Sealed and unsealed
Building		Commercial and residential

As can be seen from the image above, there are only 8 broad classifications provided in this latest report. Now, the task at hand while we decide on the roughness values based on this new landcover data is to assign and match the various categories specified in the Schema report appropriately. For clarity, we have divided the manning's values between open channel and the extended flood plain.

The tables below, show the type of land use, their associated roughness values as per the Schema and values that we suggest are considered for use with references.

Table 1: Manning's n value for flood plains

ID	LAND USE	SCHEMA VALUES	PROPOSED STARTING VALUES	REFERENCES
1	Water	0.025	0.025	CCC Schema report
2	Bare Earth/ Sand/ Gravel/ Clay/Rock	N/A	0.03	Waterways, Wetlands and Drainage Guide - Part B: Design
3	Grass*	0.125	0.035	https://www.ccc.govt.nz/assets/Documents/Environment/Water/waterways-guide/22.-Hydraulics.pdf
4	Rough Low Vegetation*	0.125	0.125	CCC Schema report
5	Trees*	0.125	0.125	CCC Schema report
6	Other Impervious	0.05	0.02	Values that Awa has used in models built for KCDC
7	Roads	0.014	0.014	CCC Schema report
8	Buildings	0.2	0.2	CCC Schema report
9	Wooden Open Channels	0.03	0.03	CCC Schema report
10	Rail	0.1	0.1	CCC Schema report

Table 2: Manning's n value for open channels

ID	LAND USE	SCHEMA VALUES	PROPOSED STARTING VALUES	REFERENCES
1	Styx River	0.03	0.035	https://www.nzta.govt.nz/assets/resources/research/reports/088/088-Waterway-design-parameters.pdf
2	Light grass	0.03	0.03	CCC Schema report
3	Dense weeds* (depth of flow higher than weeds)	0.125	0.045	https://www.ccc.govt.nz/assets/Documents/Environment/Water/waterways-guide/22.-Hydraulics.pdf
4	Light shrubbery on banks*	0.125	0.05	https://www.ccc.govt.nz/assets/Documents/Environment/Water/waterways-guide/22.-Hydraulics.pdf
5	Heavy shrubbery on banks*	0.125	0.06	https://www.ccc.govt.nz/assets/Documents/Environment/Water/waterways-guide/22.-Hydraulics.pdf
6	Weeds dense willow on banks*	0.125	0.125	CCC Schema report
7	Trees – little under growth, flood stage below branches*	0.125	0.05	https://www.gw.govt.nz/assets/GWRC-Flood-Hazard-Modelling-Standard-R1-May-2021.pdf
8	Trees – little under growth, flood stage above branches*	0.125	0.125	CCC Schema report

One point to note is that the Schema has one land use classification named "vegetation" which has a Manning's n value of 0.125 assigned (indicated by * in the tables above) and this classification is quite broad to cover the various types of land use that we have listed in the tables. Also, this classification was made only for the 2D domain (as part of a 1D-2D model setup) in the Schema and those values need to be adopted in open channels (previously modelled as 1D channels) which is currently being modelled in 2D.

SUMMARY & NEXT STEPS

This memo is to start a conversation with the Council on the topic of assigning roughness values for a 2D only flood model, which is being built for the first time in the Council's catchments. Awa has prior experience in building similar 2D models for other councils throughout the country. At the same time, we acknowledge that this is our first endeavour in Christchurch, and we are putting a conscious effort to understand the specific characteristics of these catchments and recognise the prior work done on building past models.

The Schema provides good detail that is specific to Christchurch's environment. There may be benefit is providing some additional schema advice on more nuanced land cover information, and there are some areas where we would like clarification. In addition, as we consider 2D modelling options, there is a need to clarify some of the modelling recommendations and in particular the roughness values used, which this memo has focussed on. We welcome the Council's collaborative approach in working to an agreement on the methodology adopted.

REFERENCES

1. Christchurch City Council Citywide Flood Modelling (LDRP097) Model Schematisation 2020 Update - Avon/Estuary, Heathcote and Sumner - Rev 7, July 2022
2. Chow, V.T., 1959, Open-channel hydraulics: New York, McGraw-Hill, 680 p.
3. D. Hicks and P. Mason, "Roughness Characteristics of New Zealand Rivers", New Zealand National Institute of Water and Atmospheric Research, Auckland, 1998
4. Waterways, Wetlands and Drainage Guide - Part B: Design, Christchurch City Council, 2003
5. G.H. Macky, A.L. McKerchar, "Waterway Design parameters", Transfund New Zealand Research Report No.86, 1997
6. N. Woods et al, "National Stormwater Modelling Guide", Water New Zealand, 2024
7. Flood Hazard Modelling Standard, Greater Wellington Regional Council, May 2021

CRAIG MARTELL

MANAGING DIRECTOR

a: Level 1, 1 Ghuznee St, Wellington 6011

m: +64 21 356 039 e: craig.martell@awa.kiwi w: www.awa.kiwi

APPENDIX B – STYX RECALIBRATION MEMO

MEMO

TO:	Robert Kelly, Richard Brunton, Mark Pennington	**DATE:**	07 October 2025
FROM:	Avinash Chakravarthy	**PROJECT NO.:**	J000806
COPY:	CCC: Peter Christensen, Noelle Evans, Dave Ripley, Kate Dawkings, Graham Harrington Awa: Brad Scarfe, Hamish Horan, Ben Fountain		
SUBJECT:	Styx calibration updates post peer review findings on impervious zones and values		

BACKGROUND

During the ongoing Styx model peer review, the reviewers identified issues with the representation of impervious zones and their corresponding parameter values within the catchment. These issues, together with other findings and recommendations provided through the peer review, have been systematically addressed, and the model has been updated to reflect the required corrections. This memo documents the impact of these revisions on the model results, for the purposes of peer reviewer's sign-off on the calibration.

UPDATED MODEL RESULTS

Following these updates the model was re-run for the 2022 calibration event and results at key locations are plotted below (Figure 1 to Figure 3). The flow and water level at Radcliffe Road have increased in the latest results and this is primarily due to the change in the impervious zones and associated values within the catchment. However, there is a minor change in the water levels modelled at harbour Road which lies at the downstream of the catchment.

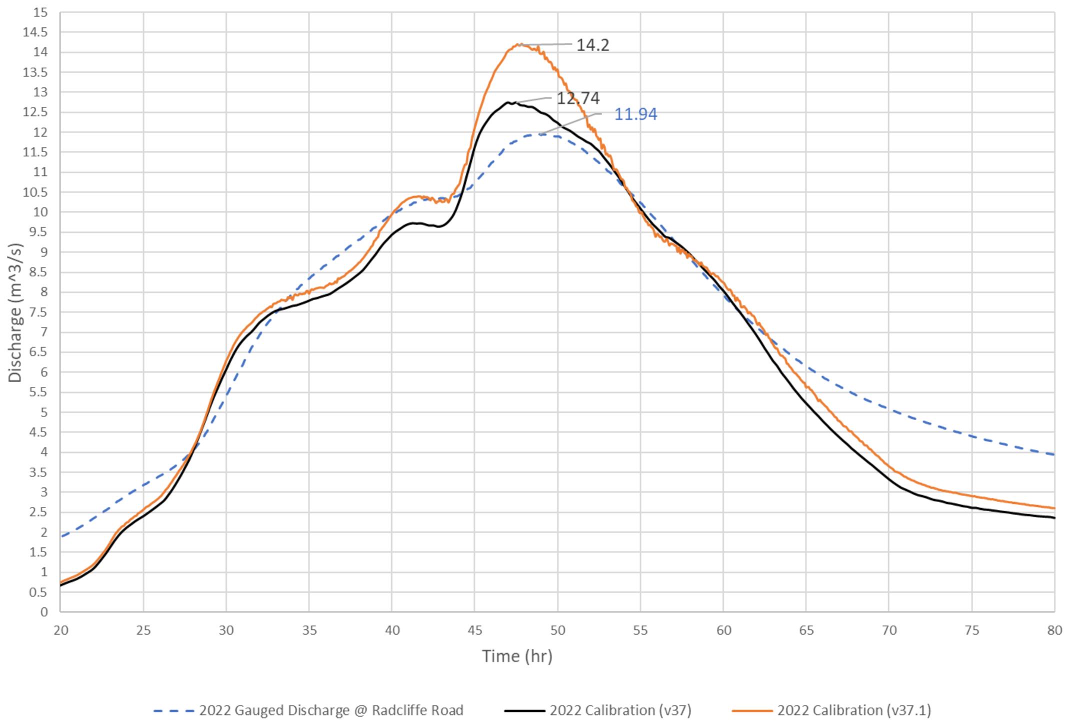


Figure 1. Comparison between observed flow, pre-peer review modelled flow (v37) and post-peer review modelled flow (v37.1) at Radcliffe Road for 25-26 July 2022 event.

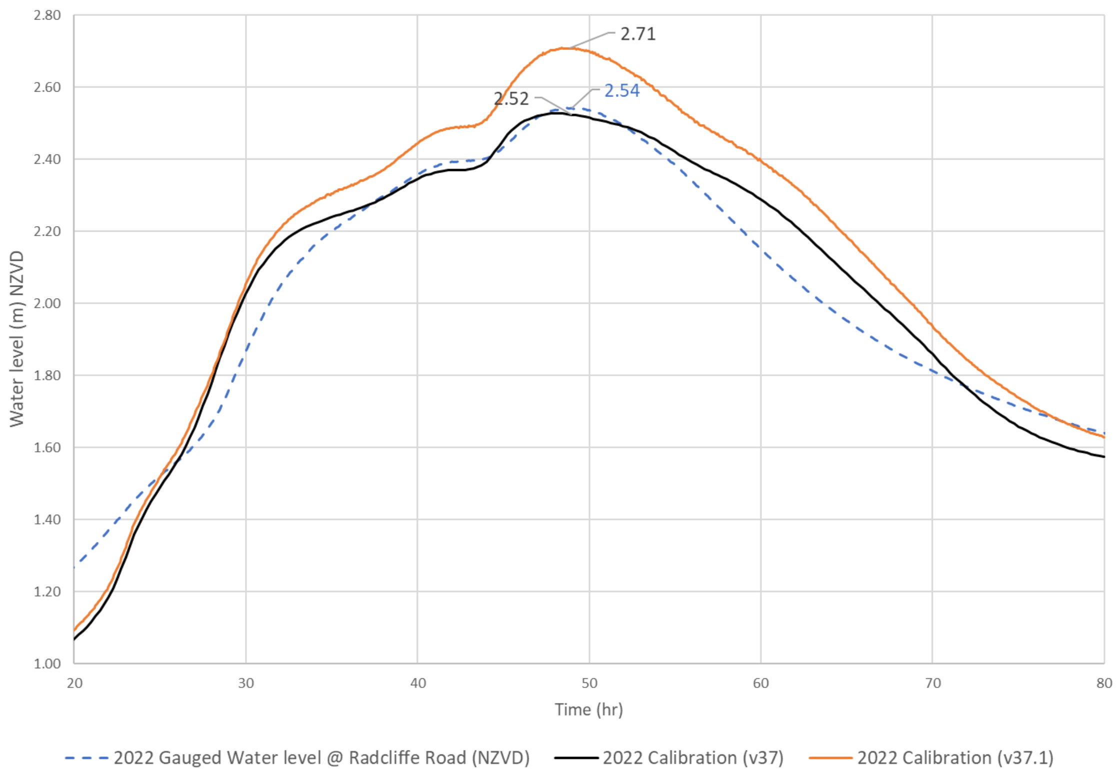


Figure 2. Comparison between observed water level, pre-peer review modelled level (v37) and post-peer review modelled level (v37.1) at Radcliffe Road for 25-26 July 2022 event.

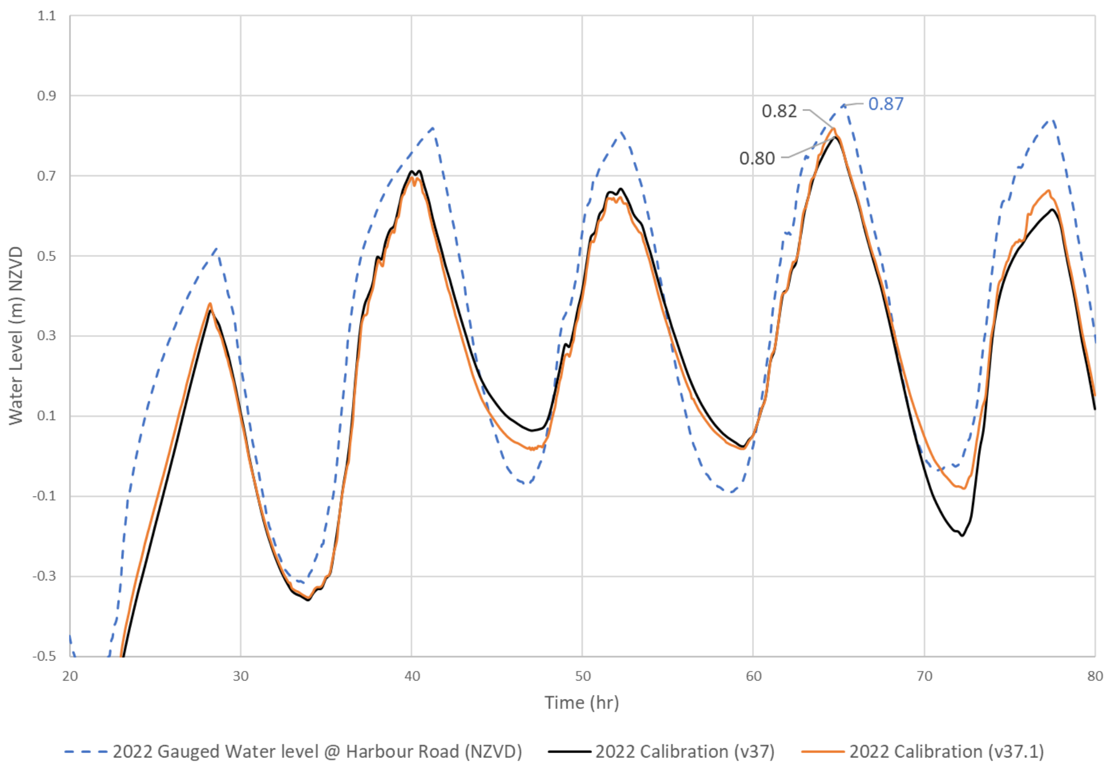


Figure 3. Comparison between observed water level, pre-peer review modelled level (v37) and post-peer review modelled level (v37.1) at Harbour Road for 25-26 July 2022 event.

Table 1. Comparison of peak modelled flow and water level at key locations between pre- and post-peer review results.

S.NO.	LOCATION	DATA	PRE-PEER REVIEW PEAK	POST-PEER REVIEW PEAK	DIFFERENCE (VALUE / %)
1	Radcliffe Road	Flow (m^3/s)	12.74	14.2	1.46 / 11%
2	Radcliffe Road	Water Level (m)	2.52	2.71	0.19 / 8%
3	Harbour Road	Water Level (m)	0.8	0.82	0.02 / 2%

RE-CALIBRATED MODEL RESULTS

Based on the results presented in the previous section, the update of the impervious zones has increased runoff, leading to higher modelled flows and water levels along the Styx River. To compensate for these changes the roughness—used as a key calibration parameter—have been adjusted. The adjustments are within the allowable calibration range, see Table 2 and Table 3 below.

Typically, the roughness's have been increased in the upper catchment to achieve a closer match of the timing of the peaks at the gauges. To achieve a closer match of water levels with the Radcliffe Road gauging station some of the lower reaches of the Styx have had the channel roughness lowered. These adjustments are within the range allowed in CCC Schema.

Table 2. Manning's n value for flood plains.

ID	LAND USE	PRE-PEER REVIEW VALUES	MODIFIED VALUES
1	Grass	0.035	0.045

Table 3. Manning's n value for open channels in the upper catchment.

ID	LAND USE	PRE-PEER REVIEW VALUES	MODIFIED VALUES
1	Styx River	0.05	0.055[1]

With these changes, the updated model results over the duration of the storm event show improvements in both flow (Figure 4) and water level (Figure 5) at Radcliffe Road, as well as at Harbour Road (Figure 6). The model now provides a more reliable representation of water levels at both locations. At Harbour Road in particular, the modelled water level more closely replicates the observed rise and fall, indicating improved alignment with recorded data.

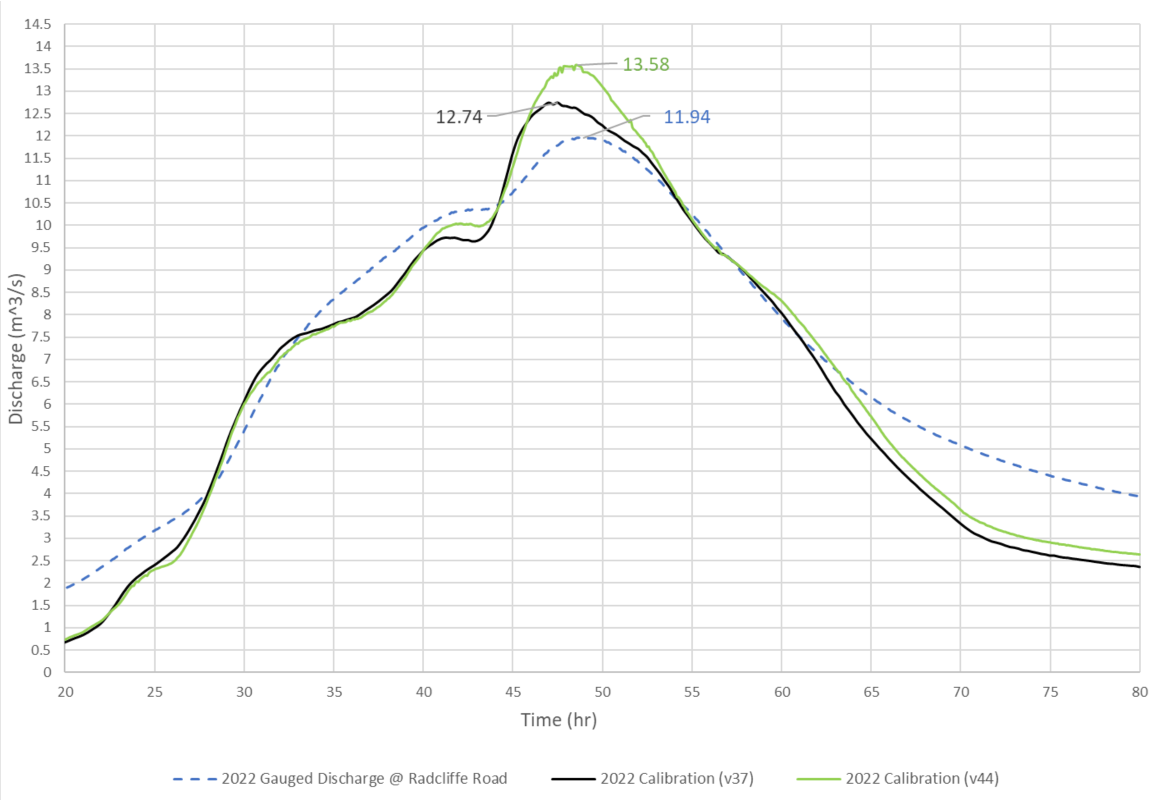


Figure 4. Comparison between observed flow, pre-peer review modelled flow (v37) and modified post-peer review modelled flow (v44) at Radcliffe Road for 25-26 July 2022 event.

[1] roughness values were locally reduced around the Radcliffe road gauge site

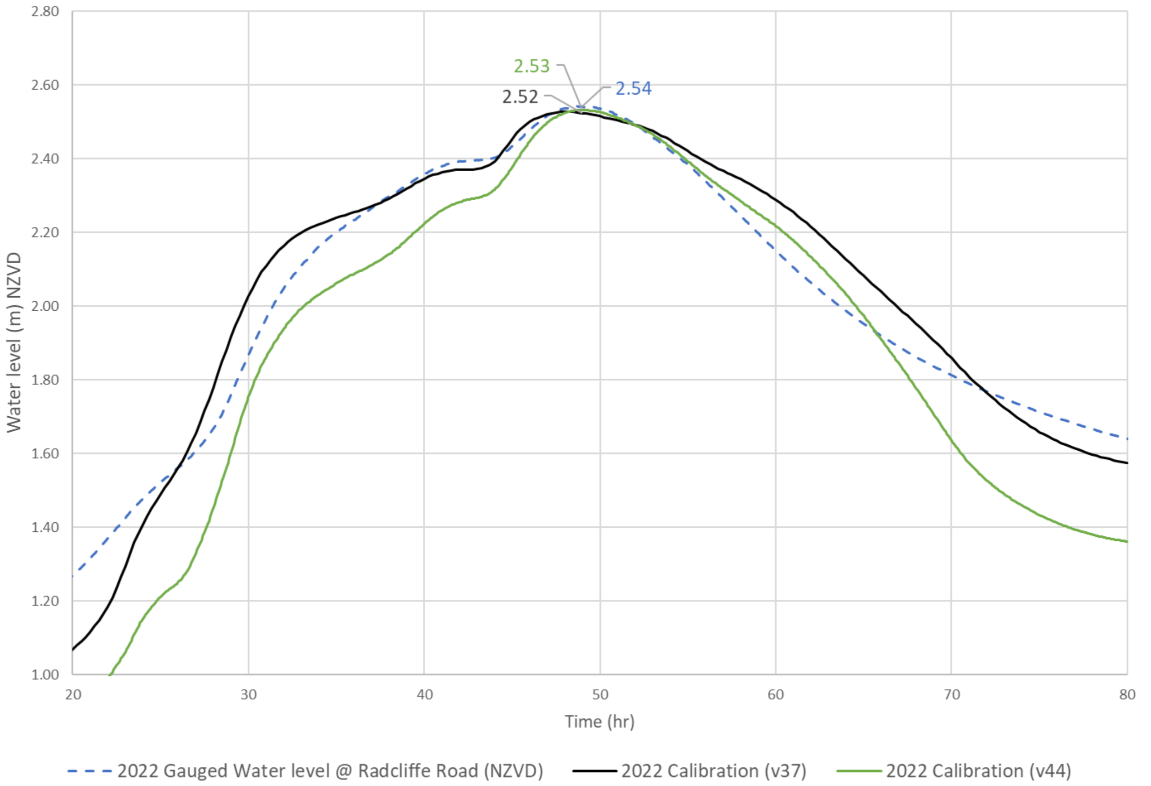


Figure 5. Comparison between observed water level, pre-peer review modelled level (v37) and modified post-peer review modelled level (v44) at Radcliffe Road for 25-26 July 2022 event.

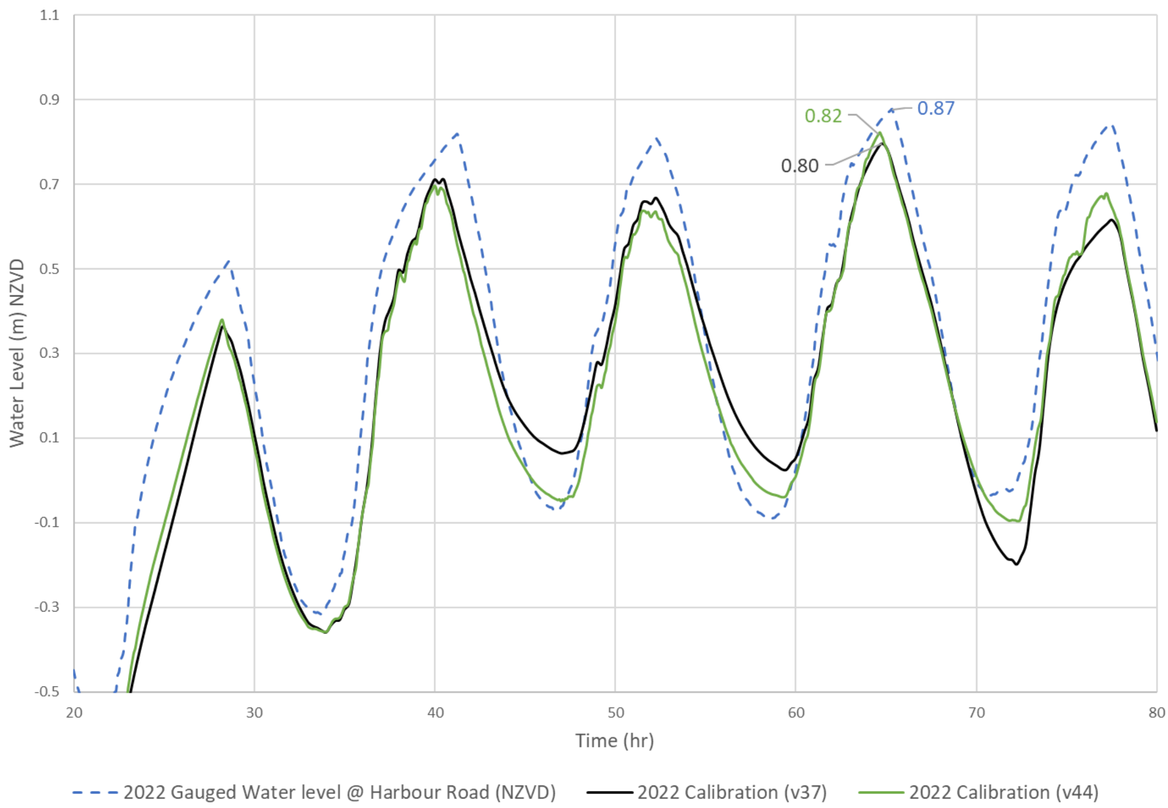


Figure 6. Comparison between observed water level, pre-peer review modelled level (v37) and modified post-peer review modelled level (v44) at Harbour Road for 25-26 July 2022 event.

Table 4. Comparison of peak modelled flow and water level at key locations between pre- and modified post-peer review results.

S.NO.	LOCATION	DATA	PRE-PEER REVIEW PEAK	MODIFIED POST-PEER REVIEW PEAK	DIFFERENCE (VALUE / %)
1	Radcliffe Road	Flow (m^3/s)	12.74	13.58	0.84 / 6.6%
2	Radcliffe Road	Water Level (m)	2.52	2.53	0.01 / 0.39%
3	Harbour Road	Water Level (m)	0.8	0.82	0.02 / 2%

CONCLUSION

The Styx model has undergone peer review, and the findings and recommendations from this process have been incorporated into the model. As a result of these updates, changes were observed in the results at key calibration locations. A targeted re-calibration was subsequently undertaken, primarily involving adjustments to roughness parameters for specific land uses (Table 2) and along the Styx River (Table 3). Overall, these results remain within acceptable calibration tolerances and are consistent with the expected system response. The updated results have been documented, and both the revised model and outputs are now provided to the peer reviewers for confirmation and sign-off on the calibration.

awa

AVINASH CHAKRAVARTHY

SENIOR HYDRAULIC MODELLER

a: Level 1, 1 Ghuznee St, Wellington 6011

m: +64 22 102 6521 e: avinash.chakravarthy@awa.kiwi w: www.awa.kiwi

APPENDIX C – STYX DESIGN SCENARIOS

A total of 44 design scenarios has been modelled and results provided. These are listed below.

No.	Development Year	ARI Rain event (ARI)	Storm duration	ARI Tide event (ARI)	Sea level rise (m)	Rainfall climate scenario	TUFLOW result name
1	ED2024	0002	024HR	0010	0p00	R2024	V1_STYX_ED2024_R0002ARI_024HR_T0010ARI_SLR0p00_R2024
2	ED2024	0010	30MIN	0002	0p00	R2024	V1_STYX_ED2024_R0010ARI_30MIN_T0002ARI_SLR0p00_R2024
3	ED2024	0010	002HR	0002	0p00	R2024	V1_STYX_ED2024_R0010ARI_002HR_T0002ARI_SLR0p00_R2024
4	ED2024	0010	006HR	0002	0p00	R2024	V1_STYX_ED2024_R0010ARI_006HR_T0002ARI_SLR0p00_R2024
5	ED2024	0010	012HR	0002	0p00	R2024	V1_STYX_ED2024_R0010ARI_012HR_T0002ARI_SLR0p00_R2024
6	ED2024	0010	024HR	0002	0p00	R2024	V1_STYX_ED2024_R0010ARI_024HR_T0002ARI_SLR0p00_R2024
7	ED2024	0010	048HR	0002	0p00	R2024	V1_STYX_ED2024_R0010ARI_048HR_T0002ARI_SLR0p00_R2024
8	ED2024	0005	024HR	0050	0p00	R2024	V1_STYX_ED2024_R0005ARI_024HR_T0050ARI_SLR0p00_R2024
9	ED2024	0050	30MIN	0005	0p00	R2024	V1_STYX_ED2024_R0050ARI_30MIN_T0005ARI_SLR0p00_R2024
10	ED2024	0050	002HR	0005	0p00	R2024	V1_STYX_ED2024_R0050ARI_002HR_T0005ARI_SLR0p00_R2024
11	ED2024	0050	006HR	0005	0p00	R2024	V1_STYX_ED2024_R0050ARI_006HR_T0005ARI_SLR0p00_R2024
12	ED2024	0050	012HR	0005	0p00	R2024	V1_STYX_ED2024_R0050ARI_012HR_T0005ARI_SLR0p00_R2024
13	ED2024	0050	024HR	0005	0p00	R2024	V1_STYX_ED2024_R0050ARI_024HR_T0005ARI_SLR0p00_R2024
14	ED2024	0050	048HR	0005	0p00	R2024	V1_STYX_ED2024_R0050ARI_048HR_T0005ARI_SLR0p00_R2024
15	ED2024	0020	024HR	0200	0p00	R2024	V1_STYX_ED2024_R0020ARI_024HR_T0200ARI_SLR0p00_R2024
16	ED2024	0200	30MIN	0020	0p00	R2024	V1_STYX_ED2024_R0200ARI_30MIN_T0020ARI_SLR0p00_R2024
17	ED2024	0200	002HR	0020	0p00	R2024	V1_STYX_ED2024_R0200ARI_002HR_T0020ARI_SLR0p00_R2024
18	ED2024	0200	006HR	0020	0p00	R2024	V1_STYX_ED2024_R0200ARI_006HR_T0020ARI_SLR0p00_R2024
19	ED2024	0200	012HR	0020	0p00	R2024	V1_STYX_ED2024_R0200ARI_012HR_T0020ARI_SLR0p00_R2024
20	ED2024	0200	024HR	0020	0p00	R2024	V1_STYX_ED2024_R0200ARI_024HR_T0020ARI_SLR0p00_R2024
21	ED2024	0200	048HR	0020	0p00	R2024	V1_STYX_ED2024_R0200ARI_048HR_T0020ARI_SLR0p00_R2024
22	FD2074	0005	024HR	0050	0p45	R2074	V1_STYX_FD2074_R0005ARI_024HR_T0050ARI_SLR0p45_R2074

No.	Development Year	ARI Rain event (ARI)	Storm duration	ARI Tide event (ARI)	Sea level rise (m)	Rainfall climate scenario	TUFLOW result name
23	FD2074	0050	30MIN	0005	0p45	R2074	V1_STYX_FD2074_R0050ARI_30MIN_T0005ARI_SLR0p45_R2074
24	FD2074	0050	002HR	0005	0p45	R2074	V1_STYX_FD2074_R0050ARI_002HR_T0005ARI_SLR0p45_R2074
25	FD2074	0050	006HR	0005	0p45	R2074	V1_STYX_FD2074_R0050ARI_006HR_T0005ARI_SLR0p45_R2074
26	FD2074	0050	012HR	0005	0p45	R2074	V1_STYX_FD2074_R0050ARI_012HR_T0005ARI_SLR0p45_R2074
27	FD2074	0050	024HR	0005	0p45	R2074	V1_STYX_FD2074_R0050ARI_024HR_T0005ARI_SLR0p45_R2074
28	FD2074	0050	048HR	0005	0p45	R2074	V1_STYX_FD2074_R0050ARI_048HR_T0005ARI_SLR0p45_R2074
29	FD2074	0050	024HR	0500	0p45	R2074	V1_STYX_FD2074_R0050ARI_024HR_T0500ARI_SLR0p45_R2074
30	FD2124	0020	024HR	0200	1p00	R16pct	V1_STYX_FD2124_R0020ARI_024HR_T0200ARI_SLR1p00_R16pct
31	FD2124	0200	30MIN	0020	1p00	R16pct	V1_STYX_FD2124_R0200ARI_30MIN_T0020ARI_SLR1p00_R16pct
32	FD2124	0200	002HR	0020	1p00	R16pct	V1_STYX_FD2124_R0200ARI_002HR_T0020ARI_SLR1p00_R16pct
33	FD2124	0200	006HR	0020	1p00	R16pct	V1_STYX_FD2124_R0200ARI_006HR_T0020ARI_SLR1p00_R16pct
34	FD2124	0200	012HR	0020	1p00	R16pct	V1_STYX_FD2124_R0200ARI_012HR_T0020ARI_SLR1p00_R16pct
35	FD2124	0200	024HR	0020	1p00	R16pct	V1_STYX_FD2124_R0200ARI_024HR_T0020ARI_SLR1p00_R16pct
36	FD2124	0200	048HR	0020	1p00	R16pct	V1_STYX_FD2124_R0200ARI_048HR_T0020ARI_SLR1p00_R16pct
37	FD2124	0020	024HR	0200	1p20	R2124	V1_STYX_FD2124_R0020ARI_024HR_T0200ARI_SLR1p20_R2124
38	FD2124	0200	30MIN	0020	1p20	R2124	V1_STYX_FD2124_R0200ARI_30MIN_T0020ARI_SLR1p20_R2124
39	FD2124	0200	002HR	0020	1p20	R2124	V1_STYX_FD2124_R0200ARI_002HR_T0020ARI_SLR1p20_R2124
40	FD2124	0200	006HR	0020	1p20	R2124	V1_STYX_FD2124_R0200ARI_006HR_T0020ARI_SLR1p20_R2124
41	FD2124	0200	012HR	0020	1p20	R2124	V1_STYX_FD2124_R0200ARI_012HR_T0020ARI_SLR1p20_R2124
42	FD2124	0200	024HR	0020	1p20	R2124	V1_STYX_FD2124_R0200ARI_024HR_T0020ARI_SLR1p20_R2124
43	FD2124	0200	048HR	0020	1p20	R2124	V1_STYX_FD2124_R0200ARI_048HR_T0020ARI_SLR1p20_R2124
44	FD2124	0050	024HR	0500	1p00	R2124	V1_STYX_FD2124_R0050ARI_024HR_T0500ARI_SLR1p00_R2124

APPENDIX D – STYX DELIVERABLES

Date	28-11-25	
Revision:	2	Added in TUFLOW deliverables and separated out common deliverables

No.	Item	Common deliverable	TUFLOW Deliverable	Issue for CCC Handover *(Complete set of deliverables provided at completion of model build)*	Comment (28 Nov 2025)
1	Full raw Results		Time varying 1D results (csv files and shapefiles) can be obtained in 1D and 2D folders.	☑	Time varying results for 1d networks can be obtained; 1. shapefiles and csv files (*2d_Q.csv for flows , *2d_H.csv for water levels at nodes, *Open_Channel_H.csv for water level) in \03_Results\2D folder. 2. shapefiles and csv files in \03_Results\1D folder.
2	Full raw Results		Flow, water level and velocity in 1D network in csv format.Time series can be viewed in ArcPro using ArcPro v3 toolbar by TUFLOW. https://downloads.tuflow.com/ArcGISPro/TUFLOW_addin.0.3.0.zip	☑	Time varying results for 1d networks can be obtained; 1. shapefiles and csv files (*1d_Q.csv for flows in 1d network, *1d_H.csv for water levels in 1d network) in '\03_Results\2D\' folder. 2. shapefiles and csv files in \03_Results\1D folder.
3	Full raw Results		Time varying 2D results (water level, depth, velocity, flows, time step and etc) in netCDF format which can be viewed in ArcPro.	☑	Time varying results for 1d networks can be obtained; 1. shapefiles and csv files (*2d_Q.csv for flows, *2d_H.csv for water levels at nodes) in \03_Results\2D folder. 2. shapefiles and csv files in \03_Results\1D folder.
4	Full raw Results		Single value (including the end of the simulation) can be obtained from the time varying 2D results (water level, depth, velocity, flows, time step and etc) in netCDF format which can be viewed in ArcPro.	☑	netCDF files in \03_Results\2D folder.
5	Full raw Results		Single value (including the end of the simulation) can be obtained from the time varying 2D results (water level, depth, velocity, flows, time step and etc) in netCDF format which can be viewed in ArcPro.	☑	netCDF files in \03_Results\2D folder.
6	Full raw Results		Time varying 2D results (water level, depth, velocity, flows, time step and etc) in netCDF format which can be viewed in ArcPro.	☑	netCDF files in \03_Results\2D folder.

7	Model Log Files		Warning/error logs available with link to shapefiles showing locations of warning/error.	☑	tlf files and *_message_p.shp files in \03_Results\log folder.
8	Model Log Files		N/A Open channel will be modelled in 2D and thus there won't be any 1D-2D coupling	☐	Not applicable in TUFLOW.
9	Model Log Files		Warning/error logs available with link to shapefiles showing locations of warning/error. Lateral link information will not be provided as river/stream/open channel will be modelled by 2D in TUFLOW. Interaction between stream and floodplain can be obtained in 2D results.	☑	tlf files and *_message_p.shp files in \03_Results\log folder.
10	Model Log Files		Volume balance provided in TUFLOW model logs.	☑	tlf files in \03_Results\log folder.
11	Model Log Files		TUFLOW model logs.	☑	tlf files in \03_Results\log folder.
15	Processed Results	Metadata required for all supplied GIS data •When the runs were conducted •If runs are master-model runs, confirming the previous versions (and dates) which the new results supersede •Who carried out the runs (organisation, active staff and QA reviewer) •Consultant and Council project number references •Key features of the model setups including •summary of project scope •compliance or not with District Planning and Building Code specifications •elaboration of any project specific supplementary file naming conventions •known issues or areas of concern •Changes since the most recent previous comparable model runs •Summary of QA processes carried out and highlights of any QA findings •The above may be covered off by reference to supplementary reporting where that is available	Refer to the Model_runs_checklist_STYX DESIGN RUNS-28Nov25.xlsx	☑	
16	Processed Results	2D results Raster Formats - GeoTIFF, 2m grid, xy to nearest 100m, NZTM, NZVD 2016 datum	Provided in tif format.	☑	tif files in \03_Results\2D folder.
17	Processed Results	Raster, Max 2D level and depth	Provided in tif format.	☑	tif files in \03_Results\2D folder.
18	Processed Results	Raster, Final Timestep 2D level	Water level raster file can be extracted from TUFLOW results using 'TUFLOW to GIS' utility.	☑	
19	Processed Results	Raster, Max of Max, level and depth (filtered to 5mm)		☑	tif files (*_max_max.tif) in \04_Processed_Results\2D folder.
20	Processed Results	Raster, Critical Duration for each batch		☑	tif files (*_Tmax_h.tif) in \03_Results\2D folder.

21	Processed Results		Maximum water level in raster format for integrated 1D and 2D components is provided in tif format.	☑	tif files in \03_Results\2D folder.
22	Processed Results		Maximum water levels can be obtained in csv files and shape files.	☑	csv files (*2d_Q.csv for flows, *2d_H.csv for water levels at nodes, *Open_Channel_H.csv for water level) and shape files in \03_Results\2D folder.
24	Processed Results		Maximum and minimum discharges can be obtained in csv files and shape files.	☑	2d_Po files in \03_Results\2D folder.
25	Processed Results		Maximum and minimum discharge can be obtained from 1D results.	☑	(*1d_Q.csv for flows in 1d network, *1d_H.csv for water levels in 1d network) in '\03_Results\2D\' folder.
26	Stability	2D: Stability oscillation results Arc polygon gdb format, with one dataset per batch of results and both individual run results attributed in one field per result and aggregated field 'max of batch' and 'average of batch' and 'product of max-avg' Similar alternative using ArcGDB point format is also acceptable	Information on errors and warnings can be provided in model log folders are in texts and shapefile format. Stability issue is expected to be minimal in the 1D-2D coupling TUFLOW model.	☑	tlf files and shape files in \03_Results\log folder.
27	Stability	2D: Stability xls format oscillation frequency summary data, with one xls (or tab) per batch	Information on errors and warnings can be provided in model log folders are in texts and shapefile format. Stability issue is expected to be minimal in the 1D-2D coupling TUFLOW model.	☑	tlf files and shape files in \03_Results\log folder.
28	Stability	2D: Stability xls tabulated frequencies in each of the 8 bin amplitude ranges, for each of the results in the batch	Information on errors and warnings can be provided in model log folders are in texts and shapefile format. Stability issue is expected to be minimal in the 1D-2D coupling TUFLOW model.	☑	tlf files and shape files in \03_Results\log folder.
33	Stability		As per MIKE but for 1D storm network nodes only	☐	
34	Stability		As per MIKE but for 1D storm network nodes only	☐	

36	QA	Simplified polygon of extents for all flooding on the model boundary, for each batch of a given rain event size (ARI or AEP) Methodology per 20240608 hybrid GHD/DHI is; For each group (batch) start with the max of max depth raster (i.e. 2m grid) Convert raster to polygon – where depth is greater than 0.050m Generate smoothed polygons by sequential buffering; out by 5m, in by -20m, out by 15m - creates a smoothed and simplified version approx. the same of the flood extents Create 'boundary points' by buffering boundary inwards by 3m then converting this line to points at 2m intervals Transfer the values from the max of max depth results to the boundary point shapefile. Apply a filter to the point shapefile to show only points with a depth value greater than 0.200m Select the polygons that contain at least one filtered point (delete the rest) Clip these polygons where the extent is over 500m from the boundary, (or where there is an obvious high point which would restrict flow). This is to ensure the polygon does not just cover the entire flood extent in places. (As per Antoinette's email "User requirements and boundary ponding" 20240614 but further developed from discussion since)	To be reviewed for TUFLOW	☑	Provided
37	QA		N/A	☐	Not required for TUFLOW models
38	QA	Generate max of run minus end of run raster, level and depth for each run result (to demonstrate and vertically measure 'past the peak' condition at the end of the model run)	N/A	☐	Not required for TUFLOW models
44	QA	Polygon shape showing the areas of effect of instabilities identified in the stability standards work, and to a lesser extent the full set of model results. Key attributes to include in the stability polygons will be: · What model does the instability occur in · What events have instability including how many times it crops up · Max amplitude of the oscillation, among the points making up the polygon. · A categorisation of severity, e.g. 0-3 · Definition of if the oscillation is impacting the peak water level, and the max of max (linked to severity) Comment field, potentially with recommendation on what action to take (e.g. use 2D level instead), and explain possible impact of stability when interpreting the results.	Information on errors and warnings are in shapefile format (inside the model log folder) and can be viewed in GIS software. Stability issue is expected to be minimal in the 1D-2D coupling TUFLOW model.	☐	Not applicable in TUFLOW.

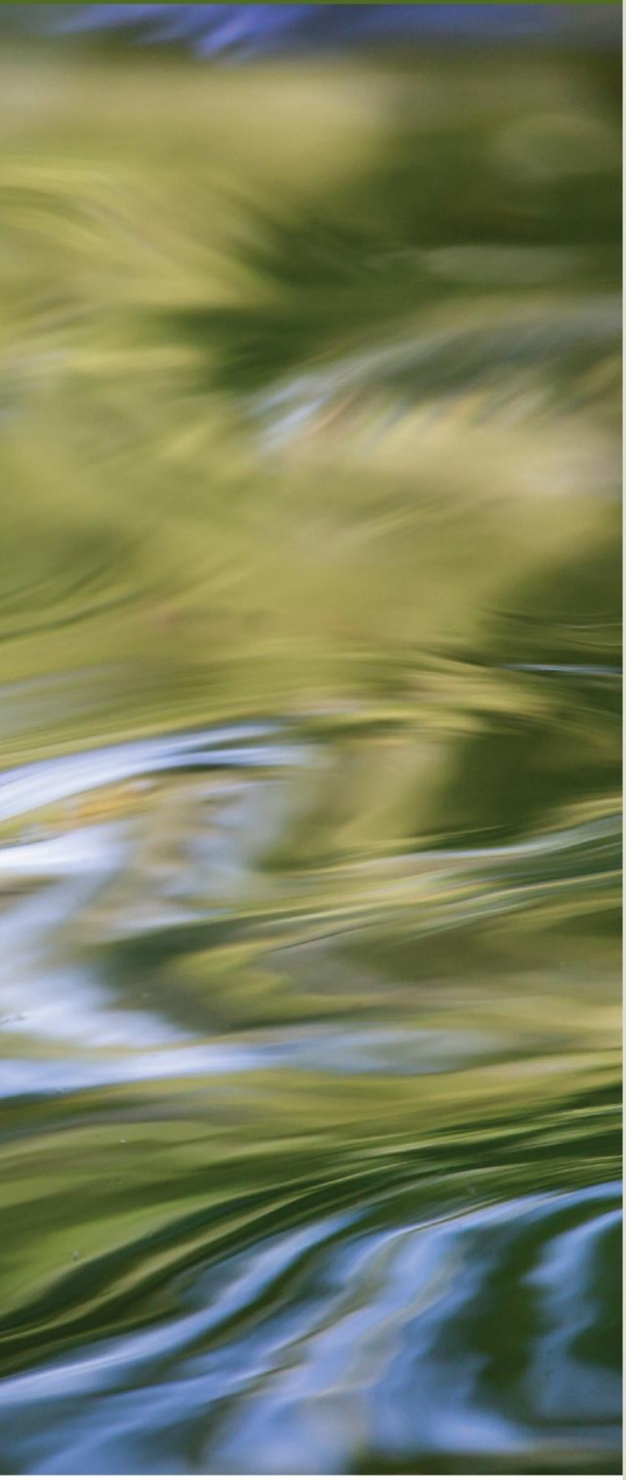
45	QA	Polygon shapefile with anomalies identified developed at end of project through workshop with Council. A rating system will be applied to the anomalies based on the system developed for Avon.	Information on errors and warnings are in shapefile format (inside the model log folder) and can be viewed in GIS software. Stability issue is expected to be minimal in the 1D-2D coupling TUFLOW model.	☐	Not applicable in TUFLOW.
47	Model Geometries	GIS files (to be confirmed with CCC) showing all model geometry files with useful symbology	TUFLOW geometries are provided using csv and shp files.	☑	Shape files of geometry files can be obtained in tgc file, including all GIS layers for geometry.
	Model Geometries	All model elements TBC but from Antoinettes email "User requirements deliverables review" the method for all model data looks like it should be this; Convert model to Mike+ (as a temporary thing) Within Mike+ use "ArcGIS integration" function (to GDB and ArcPro) Within ArcPro, save APRX (the Pro equiv of MXD), with relative paths etc to preserve formatting Transfer the GDB and APRX as deliverable to cover off all of MU M11 M21 MF items in one step **Or TUFLOW equivalent**	TUFLOW geometries are provided using csv and shp files.	☑	Shape files of geometry files can be obtained in tgc file, including all GIS layers for geometry.
48	Model Geometries	MU (pipes, channels, pumps, weirs, flap gates) •MU all data exported to GIS format (with only default format) •Layer formatting for nodes and links showing components of the network that are modelled as circular/rectangular pipes or open cross-sections and identifies non-return valves and whether nodes are open channel (no-crs) or normal manhole headloss •Model setup files – *.MUP, *.MDB **Or TUFLOW equivalent**	TUFLOW geometries are provided using csv and shp files.	☑	Shape files of geometry files can be obtained in tgc file, including all GIS layers for geometry.

49	Model Geometries	M11 (pipes, culverts, pumps, channels, weirs, flap gates) •H and Q-points and branch network •Model setup files – *.XNS11, *.NWK, *.SIM11 •Cross section bank marker points (1,2,3,4,5) with associated branch, chainage and number and ground levels •Cross section lines olines drawn between markers 1+3 oattribute with cross section type – open / closed oattribute with data source classification •Structures (culverts) as line segments with length, diameter (or height / width) and invert levels •Survey cross section points and lines in GIS format attributed with unique cross section ID, point sequencing and date of survey •Bridges as line segments •Linear spatial extent of closed cross sections •Other features and formatting as described in the 2018 Memo •M11 calibrated route network (polyline file from which any branch/chainage location can readily be looked up spatially) •M11 branch connectivity lines •M11 roughness lines mapped from the HD11 file •LiDAR cross section lines and points •M11 graphical points (underlying point sequences that define the branch network) •Weirs •Control structures •Energy losses •Regulated structures **Or TUFLOW equivalent**	TUFLOW geometries are provided using csv and shp files. Model Setup files are text files that can be read through notepad++	☑	All model set up (geometry, 1d network and 1d-2d coupling) can be viewed in ArcPro.
50	Model Geometries	M21 (mesh triangles, ground levels, basins, stopbanks) •River catchment boundaries (as polygons with name attributes) •Mesh blockouts (for M11 model) •Model ground level polygon (bathymetry) •Model ground level raster (bathymetry) •Dike lines and points (basins and stopbanks in M21) •Model ground level data source (polygon) •Model Z5 points (point locations where the general mesh build levels are artificially controlled – this is most commonly to meet model requirements for coupling to 1D elements such as pipe inverts where incompatible with mesh ground levels) **Or TUFLOW equivalent**		☑	All model set up (geometry, 1d network and 1d-2d coupling) can be viewed in ArcPro.

51	Model Geometries	Mike Flood couples (M21-MU, M21-M11, MU-M11) •M21-MU couples as lines in Arc gdb format othis includes curb inlets (sumps), MU open channel couples, pipe ends such as headwalls (including MU outlets) and MU pumps to M21 oGIS line direction shall be defined consistent with the normal water flow direction for each couple type oattributed with required fields MUID, MaxQ, M21_XCoor, M21_YCoor, M21_LocMod and Type Type – MF couple type (e.g. M21 to inlet, M21 to outlet and pump to M21) odata shall be exported from the latest couple file oLines for standard linking (to M11) •M21-MU Lines for standard linking (as defined in the couple file) •M21-M11 Lateral links oLateral links (spider lines – converted from MFLateral.txt) •M21-M11 Lines for standard linking (as defined in the couple file) •MU-M11 River links oMU outlets to M11 oM11 water level boundaries to MU **Or TUFLOW equivalent**		☑	All model set up (geometry, 1d network and 1d-2d coupling) can be viewed in ArcPro.
53	Model Reports	Model build log		☑	Refer to TUFLOW control files (tcf).
54	Model Reports	Model run list		☑	Refer to Model_runs_checklist_STYX DESIGN RUNS-28Nov25.xlsx
55	Model Reports	Model Build report		☑	Provided v4.1
56	Model Reports	Calibration Report		☑	
57	Model Reports	Anomalies/Future improvement Register in both xls and shapefile format Note: GDB shows shapes on the map where anomalies exist in space, and xlsx can have more detail about this, and how to improve in future runs. Xlsx may also have overall model improvement ideas for the next run.		☐	Limiations, assumptions and recommendations are provided in the report.
59	Model Geometries		Model geometry with all inputs in 2D and 1D components (GIS format) and the connections can be viewed by GIS software. Data query and symbology editing can be done by GIS software for mapping and data interpretation purpose.	☑	All model set up (geometry, 1d network and 1d-2d coupling) can be viewed in ArcPro.
New items added 20 Feb 2025					
60	QA	Check differencing of max-max of 200 yr to 50 yr and 50 yr to 10 yr water levels to confirm that the smaller event is smaller than the larger event in both level and extent. A minor amount of 'noise' is acceptable.		☐	This was done as part of internal QA but not as a delivreable
61	Full raw Results		DxV	☑	NetCDF and timeseries format

62	Flood Extents package	In addition to the deliverables above, the following are to be provided as a zipped package for handover for Flood Extents processing: - Unfiltered raster result files (maxmax) for Water Level, Depth, Velocity (velocity non-directional - the strict meaning is speed). -> Files should have no filtering (except depth which may have up to 5mm depth cutoff filtering) -> Levels are required as 1D2D integrated results, with 2D-only results also preferred if readily available -> Depth and velocity should be 2D-only results, with null/no-data in 1D areas (filling 1D depth data with a large fictional depth, -eg: 99m-, is acceptable) -> Scenarios needed are 10 year (ED202x), 50 year (MPD2074, 0.45m SLR), and 200 year (MPD2060 + CC16%, 1m SLR) - Model topography (raster) - 1D blockout file (polygon/vector) if available – please note if model is purely 2d - Any areas where anomalous results have been identified (polygon/vector)		☐	Not required in the user requirements deliverables spreadsheet for Styx.
Item updated 12 Mar 2025					
63	Floor Levels Package	In addition to the deliverables above, the following are to be provided as a zipped package for handover for Floor Level processing: - Integrated depth and level max of max rasters (TIF or GBD) per CCC ex. specs - 1D max of max points – water levels (RES11 only) -> A key new spec point here would be flagging or removal of any 'dummy' M11 points – there were several of these in the Heathcote model - Mesh as polygons/triangles - Anomalies polygons - Boundary ponding areas polygons		☐	Not required in the user requirements deliverables spreadsheet for Styx.
Item updated 14 Mar 2025					
64	Result File Type Descriptions	Descriptions of file types used in result file names		☑	
Item updated 14 Apr 2025					
64	QA	Differencing of max-max 10,50,200 ARI to previous model results. Selection of models/scenarios to be agreed with Council. The purpose of this is to identify areas where there are significant differences in results that cannot be explained by infrastructure, topography and other changes		☐	Not required in the user requirements deliverables spreadsheet for Styx.
Deliverable Nice to Haves *The following deliverables are further to above requirements. Provision of these items to be agreed with CCC at the start of project*					
37a	QA			☐	
37b	QA			☐	

50a	Model Geometries	*Further to the core deliverables under Item 50:* •Model roughness raster •Infiltration rasters •Model bare soil design infiltration rate (by soil type) •Model impervious •Model actual infiltration rate (soil infiltration x pervious percentage) •Model initial ground water level and depth below ground	Information can be viewed in geometry (tgc file) explaining all layers.	☑	All model set up (geometry, 1d network and 1d-2d coupling) can be viewed in ArcPro.
51a	Model Geometries	*Further to the core deliverables under Item 51:* •An 'all sumps' layer should show -All sumps in GIS (that were considered prior to model build) -GIS input point layer and ID -Original xy and nudging -Date when built into model -Whether sumps are modelled and if not why not •M21-MU standard links (as defined at runtime) •Bank lines for lateral linking (including attribution of HGH, M21 link type) -HGH link type shows where the Avon stopbanks are defined in M11 •M21-M11 standard links (as defined at runtime) •M21-MU couples as lines in Arc gdb format -attributed with required fields MUID, MaxQ, M21_XCoor, M21_YCoor, M21_LocMod and Type -M21_LocMod – Flag "Yes" if M21_XCoor (location) has been modified as per the point below (else "No" or "Null"). •Type – MF couple type (e.g. M21 to inlet, M21 to outlet and pump to M21) -where line length would otherwise be zero, add 0.0025m to M21_XCoor and flag this using M21_LocMod field **Or TUFLOW equivalent where applicable**	Sump information can be provided. All geometries and linkage between 1D-2D can be obtained using ArcPro.	☑	All model set up (geometry, 1d network and 1d-2d coupling) can be viewed in ArcPro.



awa environmental limited
a: Level 1, 1 Ghuznee, Wellington
w: www.awa.kiwi

Prepared by Awa Environmental Limited

For Christchurch City Council