Northland Regional Council

Kaeo River Catchment

Flood Model Upgrade Report

August 2013

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1. Introduction

Northland Regional Council (NRC) commissioned GHD Limited in May 2013 to prepare a model build report for the Kaeo River Catchment. This report summarises the modelling process, upgrade of the model at various stages, Verification of the model and preparation of floodplain mapping for various nominated design storms.

1.1 Background

Flooding of the lower Kaeo River including the Kaeo Township is a regular phenomenon. This flooding causes damage to property and presents a risk to the lives of residents who live in the floodplain. The 2007 floods prompted NRC to investigate mitigation options to alleviate flooding in the lower region of the Kaeo River. In January 2008, NRC engaged GHD Limited to undertake an assessment of the impacts of dredging the lower Kaeo River. The assessment considered the effects of dredging on flood levels, based on the use of an existing model of the river network developed by Environment and Business Group Ltd in 2001. The investigation concluded that the dredging of the lower Kaeo River will result in only a very modest reduction of flood level along the lower river reach, and that this benefit would not extend upstream to the Kaeo township. The cost of dredging was considered to be high relative to the magnitude of flood level reduction and degree of flood protection offered, therefore other options were subsequently investigated. A report on the dredging option prepared in February 2008 is included in Appendix A of this report.

NRC subsequently commissioned GHD Limited in February 2008 to develop a detailed hydrologic and hydraulic model using MIKE Flood model (MIKE11 and MIKE21 models) of the catchment incorporating major tributaries of the Kaeo River. The model was calibrated against the post flood water marks along the lower reach of the Kaeo River during the July 2007 storm event surveyed by NRC. This model calibrated against the available debris levels was used to prepare flood hazard mapping using various design storms. A summary report was prepared in April 2009 and is included in Appendix A of this report.

In February 2010, NRC engaged DHI to undertake a peer review of the MIKE Flood model. The reviewer recommended several adjustments to the model including checks on the hydrological response of the middle catchment, improved calibration of overflows, use of variable tides instead of constant tidal boundary, checking consistency of road and other berms with LiDAR data and other survey information. The peer reviewer also recommended installation of one additional rain gauge in or near the headwaters and installation of one additional level/flow gauge at Waiare Road. These latter recommendations were implemented by NRC. The peer review report (DHI May 2010) is included in Appendix B of this report.

Following the peer review of the model by DHI, GHD was engaged in May 2012 to upgrade the MIKE Flood model. This upgrade included further development and extension of the MIKE21 model incorporating full extent of available LiDAR coverage, extension of the MIKE11 model, generation of large number of cross-sections from LiDAR to improve the representation of channel hydraulics, and recalibration of the model based on the January 2011 storm event.

1.2 Study Objectives

The principal objectives of the Kaeo River Catchment Flood modelling study are:

- Calibration of the model using recorded storm event in the catchment.
- Determine the design flows and flood levels for the nominated design storm events for both existing land use for both existing and / future rainfall scenarios.
- Determine 10-year ED and 100-year ARI ED CC floodplain maps for the Kaeo River Catchment based on the most recent topography, network and rainfall data.

1.3 Activities and Scope

The activities and scope of the present modelling study are:

- Upgrading of the model with additional survey information.
- Development of a hydrological and hydraulic model.
- Hydraulic model development, coupling one and two dimensional approaches.
- Linkage between hydrological and hydraulic model.
- Appropriate boundary condition selection.
- Calibration/Verification of the developed model with available recorded flood information.
- Floodplain mapping for the 10-year using existing land use and existing rainfall scenario and for the 100-year ARI CC storm event under the existing land use with future rainfall scenario.

1.4 Datum and coordinate system

The vertical datum used for LIDAR, channel surveys, flood levels, sea level, and all other model elevations was the One Tree Point (OTP 1964) datum.

The locational coordinate system (x,y) used for this study, and referred to in this report, is New Zealand Transverse Mercator projection (NZTM / NZGD 2000).

2. General Model Description

2.1 Location

The Kaeo River Catchment covers a total land area of some 11,560 hectares (115 km^2) and has its headwaters located to the north of Sandy Road/Pungaere Road adjoining the Kerikeri catchment. The Kaeo River along with its large number of tributaries passes through the alluvial foothills and down to the lowlands ultimately discharging into Whangaroa Harbour. All stormwater discharges to the Whangaroa Harbour with no flow passing to adjacent catchments.

The major streams within the Kaeo Catchment are:

- Kaeo River discharging into the Whangaroa Harbour
- Temata Upokorau Streams discharging to the Kaeo River near Upokorau Road
- Oakihau Stream discharging to the Kaeo River near Upokorau Road
- Waihuka Waiare Streams discharging to the Kaeo River
- Tata Stream, Inumia Stream and Rimu Streams all discharging to the Waihuka Waiare streams
- Poka Stream and Waionepu Stream joining before discharging to the Kaeo River at the junction of SH10 and Waiare Road.
- Waikara Stream discharging to the Kaeo River at Kaeo Township
- Mangatiti Creek discharging to the Kaeo River near Hospital Road
- Tawatawa Stream discharging to the Kaeo River
- Pahuhu Creek discharging to the Kaeo River
- Waikoura Creek discharging to the Kaeo River downstream of the SH10 Bridge.

The catchment boundary along with its approximately 93 kilometres of river network is shown in Figure C-1 in Appendix C of this report.

2.2 Topography

The Kaeo Catchment generally maintains a northern aspect. It slopes steeply down from its eastern and southern boundaries along the ridgelines towards the receiving environment at the estuary alongside Whangaroa Road. The upper catchment drains to 2 large basin areas, from where the tributary streams, the Waiare and the Upokorau streams flow along gorges to their confluence at the Upokorau Road Bridge over the Waiare Stream. Downstream of the confluence the Kaeo River continues to flow along a gorge emerging into more open terrain near the Waiare Road Bridge over the river. From this point, the river passes through three distinct basins, each with its own floodplain, and linked by gorges, before arriving at the estuary and discharging to the Whangaroa Harbour near Whangaroa Road. The Kaeo Township is located in the 2nd of these basins, which extends from Green Lane to Dip Road. The 3rd basin comprises the Waikoura Flats, and the channel in this area is tidally influenced.

The catchment ground elevation ranges from 440 m RL along the southern ridgelines to mean sea level on the northern tidal boundary near Whangaroa Harbour.

Most of the catchment except the Kaeo Township and its surrounding area is generally covered by bush or plantation forestry with steep topography. The basin areas and valley bottoms are typically in pasture.

2.3 Geology

The New Zealand Geological Survey Map broadly maps the geology of the Kaeo Catchment. Geology of the Kaeo catchment is categorised as Opahi Group, concretionary micaceous sandstone, and undifferentiated terrace deposits and undifferentiated alluvium etc.

2.4 Existing and Future Landuse

The landuse within the Kaeo River Catchment consists of eleven categories as shown in Figure C-2 in Appendix C of this report. The majority of land within the Kaeo River Catchment is zoned rural production/general rural zone (86.88%) while the remaining area (13.12%) comprises other categories of land but primarily the conservation zone. The current landuse within the Kaeo River Catchment was determined using available aerial photographs of the catchment. For each sub-catchment used in this study, the landuse and impervious area were analysed for input into the hydrological module model under two categories of pervious and impervious area. Each category was then assigned different hydrological parameters as required to describe the actual run off processes. The existing imperviousness data was used to calibrate the model using the measured flood levels at various gauge locations in the catchment

Based on the FNDC District Plan permitted activity standards for impermeable surfaces, Maximum Probable Development (MPD) impervious area percentages can be applied for various urban landuse (zone) categories. The MPD settings have been applied to urban areas in other models which have extensive urban catchments and stormwater networks. Due to the very limited extent of urban areas in the Kaeo model (less than 0.5% of catchment area), NRC advised that future rainfall scenario simulation should use the existing imperviousness for all categories of landuse as shown in Table 1 below. It can be noted that stormwater pipe networks are of very limited extent in the urban area and most of them are in the form of road crossing culverts which have been modelled as culverts in MIKE11 model.

Table 1: Landuse Category

Landuse Type	Area (ha)	% of Total	MPD Imperv. (%)
Conservation Zone (C)	972.7	8.41	Same as ED
Coastal Marine Zone (CM)	58.9	0.51	Same as ED
Commercial Zone (CO)	8.0	0.07	Same as ED
General Coastal Zone (GC)	117.0	1.01	Same as ED
Rural Production/General Rural Zone (GR)	10,045.4	86.88	Same as ED
Industrial Zone (I)	1.7	0.02	Same as ED
Lakes and Rivers (LR)	71.9	0.62	Same as ED
Minerals Zone (MI)	13.8	0.12	Same as ED
Residential Zone(R)	23.1	0.20	Same as ED
Recreational Activities Zone (RA)	5.5	0.05	Same as ED
Road (RD)	244.5	2.11	Same as ED
Total	**11,562.5**	**100.00**	**-**

2.5 Stormwater Drainage System

The primary stormwater drainage system of the Kaeo River Catchment consists of the river system and the very limited reticulated pipe network systems mainly in the form of road crossing culverts within the urban areas of Kaeo Township and the newly developed urban area around Hospital Road and Cemetery Road which discharge directly to the River channel passing through the town.

The River system generally has a high degree of bush cover especially in the upper catchment, but the banks are less vegetated in the lower catchment, including the three basins referred to above. There are many footbridges, road crossing culverts and major road bridges within the catchment which have been incorporated in the flood model.. The stormwater discharges from the catchment drain via the Kaeo River into the Whangraroa Harbour. The downstream reaches of the Kaeo River are significantly wider as they enter the Whangaroa Harbour.

A summary of the main assets that have been modelled in MIKE11 module of the MIKE Flood model are listed in Table 2 below.

Table 2: Kaeo River Catchment Modelling Asset Information

Asset Type	Quantity	Model Module
River Network (km)	93.0	MIKE11
Cross-Section (nos.)	805	MIKE11
Bridge (nos.)	10	MIKE11
Culvert (nos.)	17	MIKE11
Weir (nos.)	88	MIKE11

It can be noted that weirs as shown in the Table 2 are the non-structural element used in the steep gradient section of the channel, primarily in the upper catchment, to overcome model instability.

3. Model Upgrade undertaken to address Issues raised in earlier Peer Review

3.1 Issues and Actions

The peer reviewer (DHI) made a number of recommendations which can be found in Section 6 of the peer reviewer report attached in Appendix B of this report. The previous version of the Kaeo flood model was reviewed in May 2010, prior to the model upgrade documented in this report. The reviewer concluded that the model was fit for running flood mitigation scenarios, but a number of recommendations were made to improve confidence in model results. The following paragraphs briefly describe recommendations and actions undertaken to meet the recommendations:

Hydrological Response of Headwater Catchments

Recommendation: Comparison of modelled hydrographs of the Kaeo River where it enters its floodplain be assessed against nearby gauged catchments.

Action: This recommendation was made by the peer reviewer because the earlier version of the model had not been fully calibrated using hydrograph data. The model has now been calibrated against the measured Kaeo River hydrographs for the January 2011 storm event from three newly installed river gauges. The calibration has achieved the required standard for high flow, and lag time. The comparison plots are provided in Appendix D of this report. It should be noted that a different design storm rainfall hyetograph has been adopted for the 2013 GHD model. The new storm profile was developed by MWH for the NRC's Priority Rivers Project.

The current MIKE11 model has been extended to include Poka Stream, Waionepu Stream and extension of Waikara Creek further upstream. The 2D model MIKE21 has also been extended to include the entire available LiDAR coverage.

Floodplain Hydraulics

Recommendation: Should there be a significant difference between the modelled design events and those established from comparison with other gauged catchments, the model parameters should be adjusted to regulate flow rate. Within the MIKE 21 model, and the MIKE FLOOD couplings, roads and other berms should be carefully examined for consistency with LIDAR to prevent spurious flows through berms.

Action: The further calibration of the Kaeo model against both site gauge data and a very extensive flood debris data set satisfies the peer reviewer's recommendation. Model parameters were adjusted through this process. The DTM along the major roads especially around road crossing structures such as bridges and culverts was compared against the actual elevation from LiDAR. The cell elevations at these locations has been set to the LiDAR cell elevation, if found different. This will ensure that overtopping across structures doesn't occur too early or too late.

Tidal Boundary Condition

Recommendation: Use time varying tides instead of constant sea level for the design storm simulations.

Action: Time varying tides with peak level from the model at the lower end of the catchment coinciding with the peak tides has been adopted for all design storm simulations. This was checked and confirmed by NRC for all design storm simulation. The sea level time series was developed by MWH for the NRC's Priority Rivers Project. This has been elaborated on in Section 7.3 of this report.

Future Improvements to the Model

Recommendation: Install new gauges so that the model can be improved by undertaking proper calibration in 5-10 years' time.

Action: The actions recommended by DHI were intended for NRC to implement. A summary of measures taken for each item as listed in Section 6.2 of the Peer Review report (attached in Appendix B of this report) is discussed below:

- **Continuation of present rain gauge and at least one new rain gauge in the headwaters:** NRC installed a new automatic rain gauge recorder on the Eastern side of the catchment at Touwai which has been used for model calibration.
- **Continuation of the Fire Station river gauging and installation of a new gauge at Waiare Road:** Since the previous calibration event (July 2007), NRC has established three river recording sites on the Kaeo River, at: Waiare Road Bridge, Kaeo Fire Station (Township), and downstream at Whangaroa Road (Estuary). These sites were all used for the re-calibration of this flood model. The flow rating is not well established at all these locations specifically for high flow, and therefore, exclusive calibration of the model against the flows was not undertaken. However a good correlation of model rating to site rating was achieved for the Waiare Road site to a level well above that covered by gaugings.

4. Model Upgrades Undertaken to Improve Calibration Results and Flood Mapping

4.1 Model Upgrade to Improve Calibration

Model upgrading was undertaken to improve the calibration results of the model. The upgrading of the model has been undertaken by inclusion of the following:

- Inclusion of two surveyed cross-sections along the river reach downstream of the Upokorau Road Bridge supplied by NRC.
- Realignment of the Waikara Stream along the deepest channel as indicated in LiDAR data and extension of the network up to the extent of available LiDAR.
- Inclusion of a 1.6 meters diameter culvert at School Gully Road in MIKE11 model along Waikara Stream upstream of SH10.
- Generation of 58 cross-sections along the Waikara Stream using LIDAR and modification of low flow channel using nearby surveyed cross-sections.
- Extension and re-alignment of the Waionepu Stream up to the available LiDAR extent and generation of five additional cross-sections with modification of low flow channel using near surveyed cross-sections.
- Re-alignment of the Kaeo River network along the deepest channel as indicated in LIDAR for the reach of the river mainly upstream of the Kaeo Township.
- Inclusion of approximately forty-three cross-sections Kaeo River mainly upstream of the Kaeo Township using LiDAR with the modification of the low flow channel using the nearby surveyed cross-sections.
- Extension of the Kaeo River network into the Whangaroa Harbour up to the Game Fish Club and inclusion of five cross-sections supplied by NRC, based on harbour bathymetry from navigation charts, for this reach of the MIKE11 network.
- Extension of 2D domain of the MIKE21 model covering the available entire LiDAR coverage supplied by NRC and linking of the 1D drainage network to the 2D domain.
- Adjustment of hydrological parameters of the model B parameters to achieve acceptable calibration fitness.
- Adjustment of channel roughness parameter to achieve the desired calibration fitness, based on surveyed flood debris levels.
- Inclusion of a suitable base flow to achieve calibration fitness along the beginning part of the hydrograph.
- Inclusion of a short section between two connecting branches to improve hydraulic connection.

4.2 Model Upgrade to Improve Flood Mapping

Upgrading of the model was undertaken to improve the flood mapping of the catchment. This includes incorporating wide channel cross-sections in MIKE along the estuary, which extend up to the Whangaroa Road on true right bank. This has been undertaken for the reach of the Kaeo River downstream of the location where Waikoura Creek enters into the Kaeo River. Previously part of the estuary was represented in MIKE 21, but modification was suggested by NRC to improve model calibration for the Whangaroa Road gauge.

5. Summary of Final Model Build and Methodology

5.1 Modelling Software

One dimensional (1D) and two dimensional (2D) models were run simultaneously in a single hydro-dynamically coupled simulation. This combines the advantages of both modelling approaches by modelling overland flows in 2D and pipe and stream flows in 1D. The choice between the two (2) modelling methods is generally done by matching specific components with the best available data in order to achieve the highest confidence in results for each model.

Two dimensional methods describe multidirectional flows over a Digital Terrain Model (DTM). They are, therefore, preferred where a DTM gives a better topographical representation and where the flow is not unidirectional (simple channel flow) but can diffuse in many directions over a surface. For these reasons, the two dimensional model has been chosen to represent the surface terrain.

Several limitations apply to the two dimensional method:

- Low resolution of the LIDAR (especially for channels, narrow, covered or vegetated areas). The model DTM comprises 5m x 5m cells which are assigned a level based on the average of LIDAR values within the cell area. Specific features, such as stopbanks, and many road causeways across the floodplain, have been assigned a specific crest value in the model DTM based on survey information provided by NRC.
- Long calculation time.
- Instabilities in model calculation on steep slopes.
- Lack of ability to represent underground pipes and for these reasons, the pipe system is usually represented in Mike Urban 1D model. It can be noted that Mike Urban model was not used for Kaeo Catchment modelling as there are very limited pipe asset available in the catchment.

The following DHI software as listed in Table 3 has been used to model the Kaeo River Catchment.

Table 3: Software Used

Software Name	Software Version
MIKE FLOOD	Version 2011, SP7
MIKE11	Version 2011, SP7
MIKE 21	Version 2011, SP7

MIKE FLOOD is a tool which integrates the one-dimensional models MIKE 11 and MIKE URBAN with the two-dimensional model MIKE 21 into a single, dynamically coupled modelling system. This realises the advantages of both modelling approaches by modelling overland flows in two dimensions and pipe/channel flow in one dimension.

MIKE 21 software describes multidirectional flow over a surface. The spatial domain is discretised into small cells to form a computational grid containing the elevation values used during the hydraulic simulation.

5.2 Hydrometric Data

Hydrometric data typically required are rainfall, flow and water level time series which are best obtained from long-term gauges for hydrological and hydraulic model calibration/validation. There are three permanent automatic rainfall gauges and two daily gauges (Data is available on daily basis) within the vicinity of the Kaeo River Catchment for the calibration of the model, based on the event of 28th January 2011. NRC provided a correlation coefficient for the two daily gauges to their nearest automatic gauge to generate time series data for input into the model. The details of the rain gauges are provided in Table 4 below.

Table 4: Details of the Rain gauges used in the Model Calibration

Location of Rain Gauge	Easting	Northing	Type
Bramleys at Kaeo	1,672,077	6,108,873	Automatic
Touwai at Weta	1,676,231	6,119,873	Automatic
Kerikeri EWS	1,683,526	6,108,254	Automatic
Kaeo Northland Met Services	1,667,498	6,120,587	Daily
Paitu at Kaeo	1,672,631	6,113,540	Daily

There are three river water level gauges available in the Kaeo River Catchment for the calibration of the model.

Time series tides are available at the tidal gauges and were supplied by NRC. The recorded tides at Game Fish Club were used as the tidal boundary during the calibration event at the lower end of the model. The details of the flow/level gauges are provided in the following Table 5 below.

Table 5: Details of the Level/Flow gauges within Kaeo River Catchment

Flow/Level Gauge Location	Easting	Northing	Type
Waiare Road	1,672,717	6,113,705	Flow/Level
Kaeo Fire Station	1,670,905	6,115,587	Flow/Level
Whangaroa Road	1,667,951	6,118,878	Tidal
Game Fish Club	1,667,819	6,121,202	Tidal

5.3 Topographic Data

A Light Detection and Ranging (LiDAR) survey of the Kaeo River Catchment was available from NRC. The main LIDAR survey was carried out by New Zealand Aerial Mapping in March and July of 2008 with vertical datum of as One Tree Point (OTP). The LIDAR data produces a dense scattering of points with ground elevation (1m grid). LiDAR data was used to generate the 2D ground surface, referred to as Digital Elevation Model (DEM). The DEM was used as input topography into the two-dimensional MIKE 21 model for simulating variations in flows and water levels in overland flowpaths. The coverage of the LiDAR data is of limited width along the upper region of the Kaeo River and its tributaries while it has extensive coverage in the lower part of the catchment. The LiDAR coverage/2D model domain used in the model is shown in Figure C-3 in Appendix C of this report.

5.4 Hydrological Model

5.4.1 Method Used

The MIKE11 RR module has been used to determine runoff for all the sub-catchments related to both MIKE11 and MIKE21 (source point) models.

The Kinematic Wave equation (Model B) Module was used to represent the runoff surfaces. For further information regarding the runoff method and modules used, including details of runoff calculations visit: http://www.dhigroup.com/.

The Kaeo River Catchment hydrology is comprised of two separate hydrology methods:

Mike 11

The sub-catchments discharging directly into the river system were modelled in MIKE11 by connecting to the river networks. Model B was used for the assessment of the hydrology for these sub-catchments. The hydrology was assessed by using MIKE11 RR module. A brief description of the processes involved in Model B is described below:

- The Kinematic Wave equation (Model B) Module was used to represent the runoff surfaces.
- Runoff rate and volume calculated with the MIKE11 Model B Module parameters using catchment length, catchment slope, impervious and pervious areas, wetting loss, storage loss, start infiltration, end infiltration, Horton's exponent and Manning's number.
- A separate analysis of pervious and impervious components was adopted using separate area within the same sub-catchment analysis.
- Estimation of the areas of different land use categories as outlined in Section 2.4. Sub-catchment slope calculated using the Equal Area Method as outlined in ARC TP108 of Auckland Council.
- Recorded 5 to 10-minute time series rainfall data, obtained from the NRC for the gauges as stated in Section 5.2 were used for the calibration of the model.
- 12 hour temporal rainfall pattern as provided by NRC based on their Priority Rivers studies were used for the simulation of design storms.

Mike 21

The sub-catchments without any river network were modelled in MIKE21 as source points. These sub-catchments are located within Kaeo Township and were requiring for the detailed flooding and flow paths analysis. The sub-catchment runoff hydrographs were generated by MIKE11 RR model B and were applied directly to the 2D grid cell.

5.4.2 Sub-catchments

The catchment and sub-catchment boundaries were delineated in ArcGIS software based on the 1m grid raster dataset based on LiDAR data, 0.25m interval LiDAR contours, Topographic 20m contours, aerial photographs, overland flow paths (generated from the DEM based on LiDAR data), cadastral property boundaries, and the location of the stormwater collection system.

The Kaeo River Catchment was divided into 205 stormwater sub-catchments which were used for modelling purposes both for the design storm and calibration simulations. The locations of the sub-catchment boundaries for the stormwater system can be seen in Figure C-4 in Appendix C of this report.

Out of 205 sub-catchments, 187 sub-catchments are connected to MIKE11 networks and the remaining 18 sub-catchments are assigned as source points into the 2D model grids of the MIKE21 model.

5.4.3 Hydrological Parameters

Stormwater sub-catchment characteristics were defined using a combination of GIS data and data from field inspections. The slope for each of the stormwater sub-areas was determined using equal area method as specified in TP108, computed along the straight path from top of the sub-catchment to its exit at the bottom.

Each sub-catchment in the Kaeo River Catchment has a percentage area of roofs and other paved areas and pervious area. This percentage was calculated in GIS based on impervious surfaces as stated earlier.

The assessment of sub-catchment road surfaces imperviousness was undertaken as a GIS integration of the sub-catchment boundary and the road surface. The resultant impervious area was assigned as flat impervious area within the model. This was carried out by GIS integration of the road surface GIS shape file received from council. The paved and roof areas were combined and was represented in the MIKE11 RR model as flat while the pervious area was represented in the medium category. These contributing areas were calculated using the percentage of the total sub-catchment that was made up of roofs, paved and pervious area.

Model B Parameters

Within the MIKE Urban/MIKE11 software it is possible to define different hydrological parameter sets for various types of surfaces in Model B. A parameter set is identified by a string of up to 13 characteristics that describes Wetting, Storage, Infiltration and the Surface Roughness of the catchment

Flow gauge data located within the Kaeo River Catchment was collected for the calibration of the model. All pervious and impervious areas from a sub-catchment are simulated using the stormwater Model B. Initially, Model B Parameters were set based on geology of the area, physical characteristics of a sub-catchment and our modelling experience. Some parameters used are based on the physical characteristics of the sub–area such as average slope and flow path length. The start and end infiltrations for sub-catchments in Model B were estimated based on various geological soils in each sub-catchment. Finally, the Model B parameters were refined through the calibration process of the model.

A summary of various hydrological model parameters used in the model are given in Table 6 below:

Table 6: MIKE11 Model B Calibrated Hydrological Parameters

Parameters	**Parameter Values**
Wetting (mm)	5.0
Initial Loss (storage) (mm) – Flat Impervious Area	0.60
Initial Loss (storage) (mm) – Pervious Area	0.5
Start Infiltration (mm/hr) – Pervious Area	4.75-10.00
End Infiltration (mm/hr) – Pervious Area	3.15-9.50

Horton Exponent – Pervious Area	0.0085
Inverse Horton's Equation	3.00E-05
Manning's Number (M) – Flat Impervious Area	70
Manning's Number (M) – Bush Pervious Area	10.50–25.0

5.4.4 Hydrological Assumptions

During the modelling process, assumptions were made in order to appropriately represent the flow situation.

- The sub-catchment boundary is primarily based on the land contours and therefore, exclusive analysis of directly connected/unconnected imperviousness related to roof runoff and runoff from private driveways and roads has not been undertaken.
- The 10 year and 100 year Average Recurrence Interval (ARI) design storms as provided by NRC were used in the modelling. These were based on 12-hour rainfall depths in HIRDS v3, and the temporal distribution was according to a hyetograph developed for NRC by MWH. Storms of greater intensity and duration than those modelled, or with a more adverse rainfall profile, may occur and may give rise to greater flooding than modelled.
- The effects of climate change on the hydrology have been taken into account based on rainfall for the 10yr ARI CC design storm that was provided by NRC. The 12 hour rainfall depths were downloaded from NIWA's HIRDS v3 database, using an allowance of 2.1 degrees Centigrade for temperature increase which is an MfE mid-point projection for Northland. An allowance has also been made for the projected effects of climate change on sea level rise in those design storms reflecting MFE baseline guidance of 500mm to the 2090's (2008). A sea level time series developed by MWH was used for the coastal boundary condition in design storm model simulations, and this time series was adjusted upwards by 500mm for the climate change scenario.
- Under the Maximum Probable Development (MPD) scenario, the impervious percentages for urban areas were determined according to the permitted activity zone rules in the District Plan for impervious surfaces. The MPD scenario was just applied for urban zones in the model, and for only the futuristic climate change scenario design storms.
- Under the Existing Development (ED) scenario, the impervious area was derived from the aerial photographs. This was used for the 10yr ARI design storm run, reflecting existing development and existing climate.
- A total constant natural base flow of 1.43 m^3/s at a location upstream of Waiare Road along the Kaeo River network has been applied to the 1D networks derived during the calibration process. This base flow was retained during the design storm simulations. A very nominal low flow was assigned at the beginning of the all the MIKE11 networks and was required for modelling purpose.
- Horton losses have been applied to all pervious areas in the catchment. All other impervious areas are assumed to have no associated losses.

- The linkage between the hydrological model and the hydraulic model is done through individual source points. For each sub-catchment a runoff hydrograph is calculated in the hydrological model and applied as a source point in the hydraulic model.

5.5 Hydraulic Model

5.5.1 Method Used

The hydraulic model of the Kaeo River Catchment was developed incorporating the existing limited stormwater pipe network (modelled in MIKE11 as culverts), open channels, culverts, bridges, overland flow paths and off-channel storage as captured in LiDAR. The rivers/open channels are modelled in MIKE11 1D model and overland flow paths are modelled using MIKE 21 two-dimensional model. The hydraulic computation in 1D model is based on an implicit, finite difference numerical solution of the basic 1-D free surface gradually varied unsteady flow equations (Saint Venant).

The hydrodynamic computation in MIKE 21 model is based on an Alternating Direction Implicit (ADI) finite difference numerical solution of the two-dimensional shallow water equations - the depth-integrated incompressible Reynolds averaged Navier-Stokes equations. The model consists of continuity and momentum equations. It simulates unsteady two-dimensional flows in one layer (vertically homogeneous) fluids.

5.5.2 Hydraulic Model Network

The hydraulic model networks are made up of culverts, bridges and rivers/channels and are modelled in MIKE11 while the overland flow paths are modelled using MIKE 21 two-dimensional model.

A summary of various hydraulic model components is given in Table 7 below and briefly described in the following paragraphs below.

Table 7: Summary of hydraulic model components

Hydraulic Model Components	Values
MIKE11 1D Model	
Total number of networks	50
Total length of networks (km)	92.9
Total number of cross-section	805
Total number of bridges	10
Total number of culverts	17
Total number of Weirs	88
MIKE 21 2D Model	
Total number of 2D model grid (8 m x 8 m cells)	1,409 x 1,613 = 2,272,717 cells

The locations of the 10 bridges used in MIKE11 model are presented in the Table 8 below:

Table 8: Locations of the Bridges used in the MIKE11 Model

Bridge Location	River/Channel Name	Chainage (m)
WhangaroaRoadBridge	Waikoura_Creek	2772.48
WaiareRoadBridge	Kaeo_River	11442.88

Bridge Location	River/Channel Name	Chainage (m)
LeighStreet Bridge	Waikara_Stream	2119.47
OmanuRoadBridge	Kaeo_River	16508
DipRoadBridge	Mangaiti_Creek	3205.95
SH10NearWhangaroa Road	Kaeo_River	19459.16
UpokorauRoadBridge	Waihuka_Waiare_Streams	8926.4
OmanuRoadBridgeNo1	Mangaiti_Creek	1664.96
MatawherohiaRoadBridge	MangaitiCreek_Branch1	1045.53
WairareRoadBridge	Waionepu_Stream	5055.15

There are seventeen culverts along various MIKE11 networks and their locations are shown in the Table 9 below:

Table 9: Locations of the Culverts Included in MIKE11 Model

Culvert Name	River/Channel Name	Chainage (m)	Type
Waokoura Road Culvert	Waikoura_Creek	1292.20	Rectangular
Hospital Road Culvert No. 1	Tributary_No5	40.92	Circular
Cemetary Road Culvert No. 1	Tributary_No7	63.52	Circular
KBr3 Culvert No. 1	KaeoRiver_Branch3	83.11	Circular
KBr3 Culvert No. 2	KaeoRiver_Branch3	171.28	Circular
Cemetary Road Culvert No. 2	Tributary_No4	27.99	Circular
Culvert No. 2	Tributary_No6	198.30	Circular
Culvert No. 1	Tributary_No6	42.25	Circular
Hospital Road Culvert No. 2	Tributary_No5	527.95	Circular
Field Culvert1	Tributary_No3	16.61	Circular
Field Culvert2	Tributary_No2	21.60	Circular
Field Culvert3	Tributary_No1	60.54	Circular
Field Culvert4	Pipe_In	28.98	Circular
Mangaiti Ford	Mangaiti_Creek	1502.30	Circular
Culvert1_New Across SH10	Kaeo_Diversion4	644.94	Circular
Culvert2_New Across SH10	Drain1	9.50	Circular r
Waikara Culvert	Waikara_Stream	1773.00	Circular

1D Model Weirs in MIKE11

There are eighty eight non-structural weirs used along various MIKE11 networks along the steep gradient reach of the MIKE11 networks to avoid instability in model due to significant drops between two subsequent cross-sections of the network.

1D MIKE11 Model Links

Lateral links allow exchange of flow between MIKE 11 and MIKE 21 along a MIKE 11 network. Lateral flow from the watercourse to the floodplain is calculated using a weir structure, linking the water level in the MIKE 11 channel with the water level in the adjacent MIKE 21 grid cells.

The software default cell-to-cell method has been used in Kaeo River Catchment modelling. During the simulation, the MIKE 11 watercourse starts to spill into the MIKE 21 model when the water level in MIKE 11 reaches the level of the adjacent MIKE 21 cells. Transfer between MIKE 11 and MIKE 21 is controlled by default link parameters. For a more detailed explanation of linkages, please refer to the DHI 2011 Software help in the MIKE FLOOD section – Options for standard and structure links (DHI Water & Environment, 2011).

2D Model Bathymetry

The bathymetry consists of the 2D ground surface (Digital Elevation Model) created from the LiDAR data. The dimension of the 2D ground surface (the grid size) is an important parameter as it sets the spatial resolution of the resultant floodplain. The 2D model grid used for Kaeo River Catchment is 7,045m by 8,065m in size with a grid cell size of 5m x 5m. The bathymetry was modified where necessary to include the crest elevation along major roads.

2D Model Flooding & Drying Depth

The flooding and drying depths used in the MIKE21 model were 0.1 m and 0.05 m respectively.

Eddy Viscosity

Energy losses were specified between each cell using a constant eddy formulation. To represent the eddy viscosity, the velocity-based formulation was chosen with an eddy coefficient of 0.1m^2/s.

5.5.3 Energy Losses

2D Model Surface Friction

The hydraulic roughness over the 2D model domain is expected to be variable based on various land uses. The catchment roughness in term of Manning's Number (M), which is the reciprocal of Manning's n, were assigned at each bathymetry grid cell based on aerial photographs, literature values and modelling experience. Road shape files in GIS format were received from FNDC and building footprints were generated using aerial photographs. Specific roughness values were assigned to these surfaces. Roughness values for other areas were assigned based on type of land covers. Table 10 presents the cell roughness values use in the two dimensional model for various land covers.

Table 10: MIKE21 - Bed Roughness Values for various Land Covers

Surface Type	Manning's Number (M)
Rural Bush Area	10.0
Urban Build-up Area	20.0
Rural with light grass cover	11.1 -12.5
Roads	50.0

Bridges and Culverts

All the bridge and culvert structures along the Rivers system were modelled in MIKE 11. Bridge sizes along with deck and soffit levels were captured from survey undertaken by NRC. The details of the culvert structures such as upstream and downstream invert levels, length and size were also provided by NRC. These structures were surveyed by NRC during various stages of the project. The vegetation of channel passing through the bridge and culvert structures was assessed from the available photographs taken during the survey and a Manning's "n" value was assigned. This roughness value was modified, as necessary, in order to achieve the calibration of surveyed flood levels in the vicinity of these structures. The Federal Highway Administration (FHWA) Water Surface Profile (WSPRO) method has been used to calculate flow characteristics through the bridges using the MIKE 11 model. This method is based on the solution of the energy equation. Contraction loss is taken into account through the calculation of an effective flow length. Expansion losses are determined through the use of numerous experimentally based tables. The method takes the effect of eccentricity, skewness, wingwalls, embankment slope etc. into account through the use of tables for these elements.

Water Courses

All the major rivers/streams namely Kaeo River, Waihuka Stream, Waiare Stream, Waikara Stream, Rimu Stream, Taita Stream, Poka Stream, Oakihau Stream, Inumia Stream, Whawha Stream, Waionepu Stream, Pahuhu Creek, Waikoura Stream, Mangatiti Creek and their tributaries were modelled in MIKE11. As stated earlier, cross-sections were surveyed for this project during various stages. Cross-sections were also generated using LiDAR information and the low flow channels were modified using surveyed cross-sections where possible. The friction factor along various reaches of the river system was initially assessed using available aerial photographs and photographs taken during survey of the cross-sections. Subsequently, where necessary the friction factor was modified to achieve the calibration fitness between the predicted results by the model and the available records. Generally, low flow channel which is usually relatively clean has been assigned a lower friction value than the high flow channel (including river banks which tend to be more vegetated). A large number of simulations were undertaken during the calibration process and NRC was well informed in setting the friction value especially along various river reaches to achieve the calibration fitness.

The summary of roughness used in the calibrated MIKE11 model is provided in the Table 11 below.

Table 11: Ranges of Manning's n-value used in MIKE11 Model

Structure Type	Manning's n-value
Bridges	0.030 – 0.075
Culvert	0.015 – 0.065
Open Channel (Ranges)	0.025 – 0.085
Kaeo River	0.030 – 0.085
Mangatiti Creek and its tributaries	0.040 – 0.075
Waikara Stream	0.065 – 0.075
Waikoura Creek and its tributary	0.055 – 0.075
Waionepu stream	0.065 – 0.075
Whawha Stream	0.050 – 0.075
Inumia Stream	0.075 – 0.075
Oakihau Stream	0.060 – 0.060
Rimu Stream	0.075 – 0.075
Tawatawa Stream	0.075 – 0.075
Taita Stream	0.075 – 0.075
Poka Stream and its tributary	0.065 – 0.065
Upokorau Stream and its tributary	0.075 – 0.075
Waihuka Stream and Waiare Stream	0.080 – 0.080
Whangaroa Harbour	0.035 – 0.035

5.5.4 Limitations

- The model represents the situation at the time of the study and survey. No account has been taken of the execution of any later construction, operations or maintenance work that may affect system performance.
- No blockage has been assumed in the modelled culverts, bridges and entry points into the stormwater system. Potential blockages should be allowed for when considering freeboard.
- The model represents the flood risk for the 10-year and 100-year ARI ED land use with future rainfall events with climate change allowances based on parameters derived from the calibration of January 2011 storm event. The model may not be applicable for representing lower return period events without modification.
- The model is valid for the prediction of flood hazards within the model extent at a catchment scale. Minor or localised flood risks (for example surface run off) may exist inside the model extent which is not represented in the flood mapping.
- The NRC flood mapping disclaimer for the Priority Rivers project should be referred to when consulting flood mapping generated by this flood model.

5.6 Boundary Conditions

5.6.1 Rainfall Data

Recorded 5 to 10-minute time series rainfall data, provided by NRC for the gauges as mentioned in Section 5.2 were used for the calibration event. Some of these gauges are operated by the NZ Met Service, and NIWA.

The 12-hour design rainfall depth was provided by NRC for use in the model for the simulations of both future and existing scenarios for various ARI design storm events for flood hazard mapping. Details of the design storm rainfall are discussed in Section 7.1.2 of this report.

5.6.2 Tidal Data

The model has a single outlet discharging into the Whangaroa Harbour. The measured 5-minute time series tide data recorded at Game Fish Club (Station No. 2703) was available from NRC for the period covering the calibration event. The time series tide data was input to the model as the lower boundary condition for calibration of the model.

Time series tides both for the existing scenario and future scenario with storm surge were provided by NRC to use for the design storm runs for various ARI storm events for flood hazard mapping and are discussed in Section 7.3 of this report.

5.6.3 Potential Evapotranspiration

Potential evapo-transpiration rates as provided by NRC have been applied. The potential evapo-transpiration was assumed to be constant over a month. The monthly average evapo-transpiration is shown in Table 12 below.

Table 12: Monthly Average Evapotranspiration

Month	Evapotranspiration (mm)
January	168.3
February	128.1

March	81.2
April	53.6
May	42.5
June	43.4
July	59.9
August	84.0
September	111.7
October	139.1
November	141.7
December	168.3

5.7 Quality Assurance and Quality Checks

This model has been internally quality assured and checked in accordance with the GHD Limited Modelling Team standard processes. GHD Project Delivery Framework, quality policy and procedures. This process includes:

- Check of the MIKE 21 grid and the accuracy of the interpolation process from the LIDAR elevation points.
- Check if the choice to represent the flow with MIKE 11 or MIKE 21 is correctly justified in each instance.
- Check of linkage types between MIKE 11 and MIKE 21.
- Check of critical points (bridges, overflows).
- Sub-area location and area.
- Parameter Sets for MIKE Flood, MIKE 21 and MIKE 11.
- Model stability.

6. Model Calibration Set-up and Results

The Kaeo River Catchment hydrological and hydraulic model was calibrated using recorded rainfall and stream gauging data. The calibration of the model was undertaken using the recorded January 2011 event. Relevant aspects of the calibration process are discussed in the following sections below:

6.1 Calibration Information

6.1.1 Rainfall

As stated in Section 5.2, time series rainfall data are available from three automatic rain gauges within the Kaeo River Catchment. NRC also provided daily total rainfall at two other locations within the catchment and their correlation with the neighbouring automatic gauges to generate time series data. The locations of these rain gauges are shown in Figure C-4 in Appendix C of this report. Long-term time series rainfall data was available from all the automatic rain gauges. The locational details are provided in Table 4 in Section 5.2 of this report for the rainfall gauges used in the modelling for the calibration event. The calibration event rainfall is detailed in Table 13 below:

Table 13: Details of the January 2011 Storm event at Rain Gauges

Location of Rain Gauge	Sub-catchment Area (ha)/(% of Total)	Type	24 hour Rainfall (mm)
Bramleys at Kaeo	4,629.3 (40.0%)	Automatic	219.50
Touwai at Weta	201.4 (1.8%)	Automatic	279.50
Kerikeri EWS	600.3 (5.2%)	Automatic	252.30
Kaeo Northland Met Services	1,045.0 (9.0%)	Daily	283.90
Paitu at Kaeo	5,086.5 (44.0%)	Daily	243.00

The rainfall for this 2011 event fell generally within one recording day 28th Jan 09:00:00 to 29th Jan 09:00:00. Rainfall recorded within the catchment was in the range 219.5mm – 283.9mm over 18-hours. The temporal distribution of rainfall at the various rain gauge sites was reasonably consistent, making this a very suitable event for calibration. The total rainfall depth for the calibration event was reasonably consistent with the 12-Hour HIRDS v3 100-Year ARI CC MPD rainfall depths (see Table 17), but the duration of rainfall in the calibration event was approximately 18 hours with a lower peak intensity of 37mm / hour occurring between 5:50pm on 28/01/2011 and 00:20am on 29/01/2011.

The Jan 2011 event is ranked 3rd largest event for the Kaeo catchment in recent times. Both the March 2007 and July 2007 floods were larger events.

6.1.2 River Flow and Level Data

Time series water level and flow data at four gauges as stated in Table 5 in Section 5.2 were available for the period of the calibration event. NRC has also established rating curve at Waiare Road and Kaeo Fire Station gauge locations in order to derive flow rates at these gauge locations while no rating curve is available at the Whagaroa Road gauge (tidal). However, the rating information is available only at low flow and therefore, model calibration against the rating for Waiare Road gauge was done for low to medium flows.

6.1.3 Calibration Event

Based on the recorded data from the two gauges located within the Kaeo River Catchment, the maximum level and flow at each gauge for the calibration/validation events are provided in Table 14 below.

There is no frequency analysis available for the Kaeo catchment, as the river gauges have only been installed recently, since 2008. Based on flood history and model results, it is likely the calibration event had a return period of approximately 10 years.

Table 14: Details of the January 2011 Storm event at River Gauges

Gauge Location	Catchment Area (km^2)	Maximum Level (m RL)	Maximum Flow (m^3/s)
Kaeo River at Waiare Road	70.1	11.15	213.2
Kaeo River at Fire Station	86.7	4.95	185.8

It should be noted that a high proportion of flood flow at the Fire Station site is out of bank flow.

A large number of flood debris levels were also available for calibration.

6.2 Boundary Conditions

6.2.1 Tidal Boundary

The measured 5-minute time series tide data recorded at Game Fish Club as stated in Section 5.6.2 was available from NRC. The time series tide data was input to the model as the lower boundary condition for the lower end of the river network near Game Fish Club for the calibration event of the model using the recorded event of January 2011.

6.2.2 Potential Evapotranspiration

The monthly average potential evapotranspiration value of 168.3 mm for the month of January was used for the calibration of the January 2011 event.

6.2.3 Initial Conditions

An initial nominal flow of 0.00001 m^3/s was used at all upstream open flow boundaries of the model for the purpose of running MIKE11 model. The initial water depth for the MIKE11 network was set to zero.

6.2.4 Stream Base Flow

Stream base flow was assessed through calibration process. As stated in Section 5.4.4 that a total base of 1.43 m^3/s was necessary to replicate the low flow at the gauges. This base flow was assigned along the Kaeo River at the upstream of the Waiare Road gauge.

6.3 Calibration Results

6.3.1 Results at River Gauge Locations

The model results were viewed using the DHI MikeView Module to assess the goodness of fit between the modelled results and the observed values. The result verification tool of MikeView provides a range of parameter values to quantify the differences between the modelled and measured data. The major parameters are:

- Peak observed and modelled flow over the calculation period.
- Peak observed and modelled flood level over the calculation period.

- Correlation coefficient for the flow and level which is a measure of the interdependence between the measured data and modelled data and is reported as R^2. A coefficient higher than 0.75 is an indication of better fitness.
- Observed and modelled volume for flow which is the accumulated volume under the flow hydrograph.
- Observed and modelled flow volume for level which is the accumulated volume under the water level hydrograph.
- Volume error between the observed and modelled volume under the flow hydrographs as percentage.
- Volume error between the observed and modelled volume under the water level hydrographs as percentage.

A comparison of the Peak level and flow at the two gauge location are shown in Table 15 below:

Table 15: Comparison of Peak flow and level at the gauge location for the January 2011 Event

Gauge	Peak Flood Level (mRL)			Peak Flow (m^3/s)		
	Observed	Modelled	Difference (mm)	Observed	Modelled	Error (%)
Waiare Road	11.15	11.31	-160	213.2	306.1	-43.5
Fire Station	4.95	5.01	-60	185.8	181.5	2.3

As per the calibration requirement standard as set out in Section 3.8 of NRC's "Modelling Policy Statement for the Priority Streams Flood Risk Reduction Project' it is required that the modelled flood level should be within 100 mm of the measured level at the gauge. It can be seen from the above tables that model predicted flood level is higher than 100 mm at Waiare Road while it within 60mm at the Kaeo Fire Station gauge. This difference was discussed and agreed by NRC. The requirement for the flow as per the aforesaid document is that the model predicted flow should be within ±15% of the recorded flow at the gauge and the above tables indicates that the peak flow difference at Fire Station gauge is well below ±15% while it is higher than the required at the Waiare Road gauge. As stated earlier that the ratings at both gauges were available only for low flow and therefore, the model was not exclusively calibrated against the flow and was agreed by NRC. A good fit has been achieved for the model rating against the gauge site rating for Waiare Road site, for low to medium flow (up to 140m3/s). The maximum gauged flow at this site is 57.6 m3/s.

The comparison plots (figure D.1 through D.3) for the time series modelled results against the gauge levels and flows are provided in Appendix D of this report. The plots also provide a comparison of the parameters as stated in Section 6.3.1. It can be seen from these plots that the volume errors for the level are within ±15% of that at the gauge. Mass balance checks were undertaken during the calibration process and were found reasonable for the calibration event.

6.3.2 Debris Levels

The model was also calibrated using the debris levels. The debris levels are the post flood measurement of the water marks surveyed after the flood event. The model results were also compared with debris levels measured during the January 2011 event. The comparison of the model predicted level against the debris level for January 2011 event is shown in Table 16 below:

Table 16: Comparison of levels at Debris Locations for January 2011 Event

River Name	Chainage (m)	Debris Level (mRL)	Modelled Level (mRL)	Difference (m)
WAIHUKA_WAIARE_STREAMS	8900.13	19.76	20.01	-0.25
WAIHUKA_WAIARE_STREAMS	8913.20	19.92	20.00	-0.08
KAEO_RIVER	6471.73	19.71	19.30	0.41
KAEO_RIVER	6838.19	18.86	18.93	-0.07
KAEO_RIVER	8067.77	16.61	16.66	-0.05
KAEO_RIVER	8677.37	15.72	15.51	0.21
KAEO_RIVER	8712.54	15.53	15.50	0.03
KAEO_RIVER	8939.67	15.32	15.05	0.27
KAEO_RIVER	9029.20	15.16	14.92	0.25
KAEO_RIVER	9568.26	13.97	13.85	0.13
KAEO_RIVER	9647.46	13.98	13.62	0.36
KAEO_RIVER	11529.09	10.87	10.85	0.02
KAEO_RIVER	11757.82	10.73	10.69	0.04
KAEO_RIVER	11794.15	10.68	10.61	0.07
KAEO_RIVER	11866.82	10.30	10.36	-0.06
KAEO_RIVER	11905.34	10.25	10.35	-0.10
KAEO_RIVER	12326.42	10.16	10.21	-0.05
KAEO_RIVER	12665.94	10.03	10.09	-0.06
KAEO_RIVER	13163.88	9.45	9.30	0.15
KAEO_RIVER	13191.04	9.24	9.31	-0.07
KAEO_RIVER	13191.04	9.36	9.31	0.05
KAEO_RIVER	13243.77	9.68	9.29	0.39
KAEO_RIVER	13279.97	9.51	9.20	0.31
KAEO_RIVER	13316.17	9.27	9.10	0.17
KAEO_RIVER	13352.37	9.23	9.05	0.18
KAEO_RIVER	13724.35	8.53	8.29	0.24
KAEO_RIVER	13792.32	8.04	8.15	-0.11
KAEO_RIVER	13932.25	7.83	7.89	-0.06
KAEO_RIVER	14228.82	7.56	7.58	-0.02
KAEO_RIVER	14255.79	7.81	7.55	0.26
KAEO_RIVER	14304.91	7.54	7.45	0.09
KAEO_RIVER	14351.50	7.27	7.26	0.01
KAEO_RIVER	14404.59	7.27	7.04	0.23
KAEO_RIVER	14487.50	7.07	6.77	0.30
KAEO_RIVER	14561.94	6.72	6.66	0.06
KAEO_RIVER	14599.16	6.58	6.61	-0.03
KAEO_RIVER	14638.29	6.50	6.47	0.03
KAEO_RIVER	16070.26	4.76	4.99	-0.23
KAEO_RIVER	16291.38	4.77	4.86	-0.09

River Name	Chainage (m)	Debris Level (mRL)	Modelled Level (mRL)	Difference (m)
KAEO_RIVER	16526.60	4.56	4.31	0.25
KAEO_RIVER	16859.69	4.25	4.19	0.06
KAEO_RIVER	17318.67	4.07	4.07	0.00
KAEO_RIVER	17694.05	3.75	3.97	-0.22
KAEO_RIVER	17870.14	4.00	3.95	0.05
KAEO_RIVER	19479.81	2.41	2.16	0.25
KAEO_RIVER	21323.69	1.08	1.63	-0.55
MANGAITI_CREEK	2881.15	4.28	4.46	-0.18
MANGAITI_CREEK	2729.57	4.68	4.60	0.08
KAEORIVER_BRANCH4	234.71	3.69	4.03	-0.34
MANGAITI_CREEK	1830.88	10.85	10.80	0.05
MANGAITI_CREEK	1803.97	11.25	10.93	0.32
MANGAITI_CREEK	1765.46	11.38	11.10	0.28
MANGAITI_CREEK	1699.26	11.86	11.67	0.19
TRIBUTARY_NO6	137.62	4.52	4.65	-0.13
KAEORIVER_BRANCH3	220.19	4.49	5.25	-0.76
KAEORIVER_BRANCH2	287.44	4.70	4.91	-0.21
WAIKARA_STREAM	2255.26	5.13	5.23	-0.10
WAIKARA_STREAM	2203.19	5.18	5.28	-0.10
WAIKARA_STREAM	2193.06	5.61	5.24	0.37
WAIKARA_STREAM	2170.12	5.50	5.37	0.13
WAIKARA_STREAM	1800.22	5.54	5.61	-0.07
WAIKARA_STREAM	1778.97	6.02	5.61	0.41
WAIKARA_STREAM	1771.43	5.56	5.96	-0.40
KAEO_DIVERSION4	420.98	5.62	5.56	0.06

It can be seen from the above table that the difference between the debris level and the model predicted level well below the tolerable limit of ±500 mm except for very few locations.

6.3.3 Longitudinal Profiles and Bank Spilling

Bank spilling across the banks of major rivers during January 2011 calibration event was investigated by drawing longitudinal profiles. These profiles were drawn along the Kaeo River, Waionepu stream, Waikara Stream, Mangatiti Creek, Tawatawa Stream, Pahuhu Creek and Waikoura Creek. These longitudinal profiles are shown in Figure D-4 to D-11 in Appendix D of this report.

It can be seen Figures D-4 and D-5 that the spilling across the banks of the Kaeo River downstream of Upokorau Road crossing (Ch. 7,173) occurs on both sides of the river This is the upstream extent of the 2D model (MIKE 21), and also the upstream extent of LIDAR coverage. Significant spilling of both banks downstream of the Kaeo Township (Ch. 14,500) can be noticed from Figure D-5. Downstream of the SH10 bridge, the floodplain on the right bank side is fairly flat and acts as basin before discharging into the Whangaroa Harbour. The flooding along this reach of the Kaeo River is largely controlled by the tides from the Whangaroa Harbour.

Figure D-6 indicates that there is spilling from Waikara Stream across both banks occurs occasionally downstream of Ch. 1,076, and more significant spilling from both banks occurs downstream ofCh.1,800 (approximately 130 m upstream of Leigh Street).

Figure D-7 indicates that there is very little spilling on the banks of the Mangaiti Creek between Omaunu Road (Ch. 1,540) and Ch. 2,543. Both banks are under flood once the creek enters into the floodplain from Ch. 2,543 onward.

Figure D-8 shows the longitudinal water surface profile along the Waionepu Stream. This figure indicates that there is some spilling between Ch. 2010 (upstream of Mcgee Road) and Ch. 4,109 (upstream of SH10 near its outfall). Significant spilling across both banks can be noticed from this figure along the reach downstream of the SH10 crossing.

Figure D-9 indicates the longitudinal water surface profile along the Tawatawa Stream. This figure indicates that there is spilling across both banks from Ch. 2,410 approximately 300 m upstream of SH10.

Figure D-10 indicates the longitudinal water surface profile along the Pahuhu Creek. This figure indicates that there is no spilling across both banks except along approximately 270 m of the lower reach of the creek.

Figure D-11 indicates the longitudinal water surface profile along the Waikoura Creek. This figure indicates that there is spilling across both banks of the creek from Ch. 475 to its outfall to the Kaeo River. Significant spilling across both banks can be noticed from Ch. 1,561 up to its outfall to the Kaeo River, which is the area of the Waikoura Flats.

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7. Summary of Design Storms Set-up and Results

7.1 Design Storm Rainfall Depth and Aerial Reduction Factor

The design storm rainfall depths for various ARI storm events were derived from HIRDS v3 of the NIWA Rainfall data base. Considering the size (115.6 km^2) of the Kaeo River Catchment and significant variation of elevations over the catchment forty (40) locations were selected to derive the 12-hour rainfall depths. The rainfall depths along with their locational coordinates in a grid formation were provided by NRC for input into the model. NRC also provided the rainfall depths considering the aerial reduction factor for the catchment. The following sections briefly describe the rainfall depths and aerial reduction factor.

7.1.1 Aerial Reduction Factor

The rationale for the use of an Aerial Reduction Factor (ARF) is well established. ARF applied to probabilistic rainfall data should account for the lower probability that a predicted point rainfall depth, of a given ARI, will occur across an entire catchment. ARFs decrease both with increasing catchment area, and with shorter duration reflecting that a greater reduction should be made to the predicted point rainfall to generate probabilistic areal rainfall for larger catchments as well as over shorter duration storms.

In New Zealand, the primary source of probabilistic rainfall data is the HIRDS package produced by NIWA on the basis of a statistical analysis of point rainfall data across the country. New releases of this data are made approximately every ten years, with the most recent version HIRDS v3, released in early 2010. Applying an appropriate ARF to point rainfall of a given ARI, based on catchment size and critical duration is promoted in TP108 of former Auckland Regional Council (ARC) publication. This Auckland Technical paper includes both a storm hyetograph, and a set of ARFs to use for catchment assessments.

The NRC has adopted a different storm hyetograph, developed by MWH for the Northland Priority Rivers Project. The ARFs adopted by NRC were derived by Auckland University based on a pilot study of Auckland Rainfall records during a recent review of the TP108[1]. The ARFs derived from that study are higher than the ARFs stated in TP108, resulting in higher design storm rainfall depths. For the Kaeo catchment, an ARF of 0.93 has been adopted, which is the Auckland Uni Services factor for a 12-hour storm in a 100 km^2 catchment. . This is the same as the UK NERC factor (0.93) for the same area and duration, but it is higher than the equivalent TP108 ARF of 0.89.

7.1.2 Design Storm Rainfall Depth

The future 12-hour design rainfall depth due to future climate change was provided by NRC at 40 locations spreading all over the catchment for use in the model for simulation of the 100yr ARI future climate scenario. NRC also provided 12-hour design rainfall depth for the 10yr ARI existing climate scenario at the same 40 locations as for the future climate 12-hour rainfall. The future rainfall depths (reflecting climate change)

[1] Dr A Y Shamseldin, Auckland Uni Services Ltd (2008) 'TP108 Rainfall: Updating for new Data with Provision for Climate Change'

were downloaded from HIRDS v3 database, using a temperature warming factor of 2.1 degrees celcius, which is an MFE (2008) mid-point projection for Northland to the year 2100.

The 12-hour rainfall depth for the various design storms undertaken for simulation is provided in the following Table 17 below and their locations are shown in Figure E-1 in Appendix E of this report.

Table 17: 12-hour Design Storm Rainfall for various ARI Events

Easting	Northing	10-Year ARI ED (mm)	100-Year MPD CC (mm)
1,668,062.0	6,106,950.0	140.7	266.0
1,668,062.0	6,108,950.0	132.2	250.3
1,668,062.0	6,110,950.0	133.3	252.2
1,668,062.0	6,112,950.0	133.6	252.9
1,668,062.0	6,114,950.0	130.8	248.1
1,668,062.0	6,116,950.0	126.8	241.8
1,668,062.0	6,118,950.0	126.6	242.6
1,670,062.0	6,106,950.0	139.1	262.7
1,670,062.0	6,108,950.0	131.4	248.4
1,670,062.0	6,110,950.0	129.7	245.1
1,670,062.0	6,112,950.0	134.6	253.6
1,670,062.0	6,114,950.0	129.2	243.8
1,670,062.0	6,116,950.0	127.7	242.0
1,670,062.0	6,118,950.0	129.2	245.9
1,672,062.0	6,104,950.0	138.7	261.9
1,672,062.0	6,106,950.0	137.8	259.9
1,672,062.0	6,108,950.0	131.6	248.4
1,672,062.0	6,110,950.0	127.8	241.2
1,672,062.0	6,112,950.0	130.9	246.4
1,672,062.0	6,114,950.0	128.9	242.5
1,672,062.0	6,116,950.0	132.8	249.8
1,672,062.0	6,118,950.0	136.4	257.2
1,674,062.0	6,104,950.0	143.7	270.4
1,674,062.0	6,106,950.0	139.0	261.7
1,674,062.0	6,108,950.0	133.5	251.3
1,674,062.0	6,110,950.0	129.0	242.7
1,674,062.0	6,112,950.0	130.0	244.0
1,674,062.0	6,114,950.0	129.9	243.8
1,674,062.0	6,116,950.0	138.5	259.1
1,676,062.0	6,106,950.0	140.7	264.2
1,676,062.0	6,108,950.0	136.5	256.0
1,676,062.0	6,110,950.0	131.2	246.3
1,676,062.0	6,112,950.0	133.5	250.2
1,676,062.0	6,114,950.0	135.6	253.3
1,678,062.0	6,108,950.0	136.6	256.1
1,678,062.0	6,110,950.0	133.8	250.8
1,678,062.0	6,112,950.0	135.5	253.4
1,680,062.0	6,108,950.0	136.2	255.2

Easting	Northing	10-Year ARI ED (mm)	100-Year MPD CC (mm)
1,680,062.0	6,110,950.0	135.7	254.1
1,680,062.0	6,112,950.0	136.2	254.4

7.2 Design Storm Temporal Profiles

Temporal rainfall profile was provided by NRC based on their “Priority Rivers Storm profile” for the simulation of the design storms. The temporal profile used for the Kaeo Catchment was the one developed by MWH for the priority Rivers project, and this was applied to all areas within the catchment, comprising 100% of rainfall points. The plot of the temporal pattern for Kaeo Catchment is shown in Figure 1.

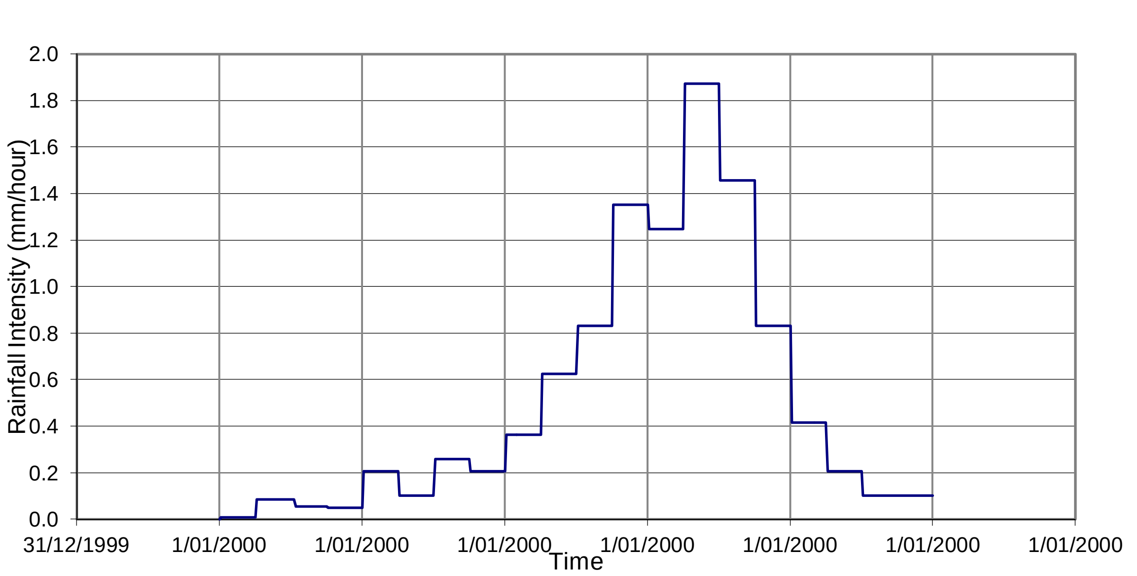

Figure 1: 12-hour Rainfall Intensity Priority Rivers (PR) Profiles 100-year CC event

7.3 Tidal Boundary Conditions

Time series tides both for the existing scenario and future scenario with storm surge were provided by NRC to use for the design storm runs for various ARI storm events for flood hazard mapping. The tides were developed by MWH for the NRC Priority Rivers Project, and the time series used for the Kaeo model was derived from the Opua sea level gauge site. The present day tidal peak within the time series is equivalent to a 2-year ARI sea level condition. This 2-year ARI sea level is above MHWS, and incorporates a modest storm surge allowance. The future climate tide series is the same dataset adjusted upwards by 500 mm for projected climate change induced sea level rise. This is an MfE (2008) baseline projection for sea level rise to the year 2100.

The time axis of this data was adjusted in such a way that the model predicted peak flood level at the downstream end of the river system coincided with the peak tide level. A plot of the tides for the design storm runs are shown in Figure 2 below.

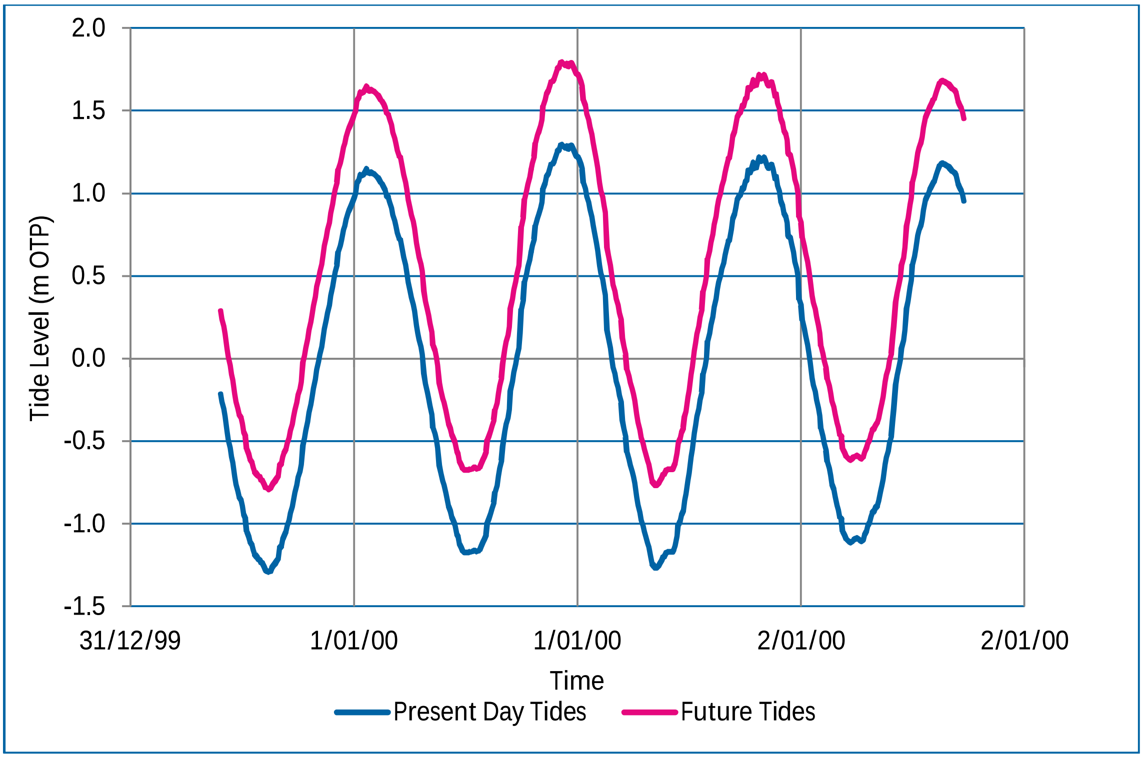

Figure 2: Time Series Tides used for the Simulation of Design Storms

7.4 Design Storm Results

The design storm simulations were carried out for flood hazard mapping for the following scenarios:

- 10-year ARI with existing land use and existing climate.
- 100-year ARI with existing land use and with climate change allowances for rainfall and sea level.

The peak flood level, peak flood depth and peak speed were extracted from the 2D model MIKE21 for plotting. The WaterRIDE software was used to generate the flood level and flood depth along the river/channel system in MIKE11 model. The two results were combined using WaterRIDE. The combined data for the two scenarios has been provided to NRC. The model predicted peak flood levels and flows at the gauge locations and at other major road crossing for the two design storm simulations are provided in the following Table 18 through Table 19 below:

Table 18: Peak flood Levels and Flows at various locations during 10-year ED Scenario

River/Stream	Location	Peak Flood Level (mRL)	Peak Flood Flow (m^3/s)
Kaeo_River	Waiare Road Bridge (Gauge)	11.02	315.6
Kaeo_River	Fire Station (Gauge)	4.64	150.1
Kaeo_River	Whangaroa Road (Gauge)	1.40	255.5
Waihuka_Waiare_Streams	Upokorau Road Bridge	20.37	273.3
Waikara_Stream	Leigh Street Bridge	5.09	6.4
Kaeo_River	Omanu Road Bridge	4.32	123.5
Kaeo_River	SH10 (Near DipRoad) Bride	2.10	163.4

Mangaiti_Creek	Dip Road Bridge	3.92	19.8
Waikoura_Creek	Whangaroa Road Bridge	1.22	13.5
Waionepu_Stream	Wairare Road Bridge	9.68	23.3

Table 19: Peak Levels and Flows at various locations Gauges during 100-year MPDCC Scenario

Gauge location	Location	Peak Flood Level (mRL)	Peak Flood Flow (m^3/s)
Kaeo_River	Waiare Road Bridge (Gauge)	13.44	460.1
Kaeo_River	Fire Station (Gauge)	6.16	325.8
Kaeo_River	Whangaroa Road (Gauge)	2.15	777.8
Waihuka_Waiare_Streams	Upokorau Road Bridge	23.64	679.2
Waikara_Stream	Leigh Street Bridge	6.63	12.5
Kaeo_River	Omanu Road Bridge	6.17	207.3
Kaeo_River	SH10 (Near DipRoad) Bride	3.10	417.1
Mangaiti_Creek	Dip Road Bridge	5.80	46.5
Waikoura_Creek	Whangaroa Road Bridge	2.59	54.0
Waionepu_Stream	Wairare Road Bridge	13.80	118.9

It can be noticed from the above tables that there is a significant increase in flood level and flood flow at all the gauge locations during the 100-year ARI ED climate change (CC) scenario compared to the 10-year ED scenario. This is because of significant increase in rainfall for the 100-year ED CC scenario compared to the other scenario. It was found that on average the rainfall at each location during the 100-year ED CC has increased by about 88.4% compared to the 10-year ED rainfall. The maximum predicted flood depth maps for the two design storm simulations are provided in Figure E-2 and E-3 in Appendix E of this report.

The flood flows and levels generated by the model for the January 2011 calibration event, as reported in section 6.1.3, is slightly higher than 10-year ED event. The 24-hour rainfall depths recorded at Paitu, located near the Waiare gauge, during the January 2011 calibration event is about 1.85 times of HIRDS v3 10-year ARI ED rainfall depths for the 12 hour duration.

In the tables above peak flows are given for the 1D network only. In some locations, such as the Waikara Stream at the Leigh Street (SH10) Bridge, a significant proportion of the overall flow will be conveyed in the 2D network (MIKE 21). The peak flows in the above tables should not be relied upon without further investigation into the proportion of flow routed through the 2D model.

8. Discussion and Conclusions

- A hydrological and hydraulic model of the stormwater drainage network system in the Kaeo River Catchment has been developed using MIKE FLOOD modelling software based on Model B rainfall-runoff modelling methods and 1-D and 2-D free surface gradually varied unsteady flow equations.
- The effect of predicted Climate Change has been included in the total rainfall depth for one of the design storms simulated (100yr ARI event). The allowances for climate change were assessed by NRC based on MfE guidelines, and the total rainfall depth with climate change allowance was provided to GHD for input into the model.
- A significant amount of data was collected during various phases of the project for upgrading the model. These include survey of river cross-sections, river crossing structures such as bridges and culverts, and improvement of DTM along major roads which has significantly improved the calibration of the model.
- Historical rainfall and water levels/flow data was utilised to calibrate the model. The data included rainfall from five rain gauges, two stream gauging sites and two tidal gauges. The calibration process involved adjusting model parameters (within reasonable bounds) until an acceptable fit between recorded flood levels and modelled flood levels were achieved.
- Exclusive calibration of the model against the flows at gauges were not undertaken due to lack of high flow ratings and was agreed by NRC. However, the model predicted flow at Kaeo Fire Station gauge was very close to the gauge flow. The model rating for the Waiare Road gauge site correlates closely with site rating up to a flow of 140m3/s, which is substantially higher than the maximum measured flow at this site.
- The model has achieved a high level of calibration correlation at all level gauge locations.
- The model has achieved a high level of confidence at almost all the debris level locations.
- The resulting ‘calibrated’ model was then used with HIRDS v3 design rainfall events to predict the 10-year ED and 100-year ED CC return period flows (or the ARI - Average Recurrence Interval) and flood levels using existing networks. The modelling approach generally provided a high level of confidence for predicted stream flood levels and flood extents within the confines of the main stream channels and their tributaries.
- The design rainfall on average for the 100-year ED CC was found about 88.4% higher than the 10-year ED rainfall.
- The flows associated with the Kaeo 10yr ED design flood are slightly less than for the model January 2011 calibration event. This is consistent with the findings for the Kerikeri catchment, to the South, which experienced similar rainfall depth and intensity for the January 2011 event. Anecdotally, over a period of 40 years, there are 3 other events in the Kaeo catchment which are known to have exceeded the Jan 2011 event, including the February 1974 event, the March 2007 event and the July 2007 event.

- Flooding along the Kaeo Township was predicted during the 10-year ED design storm event and this flooding is substantially increased during 100-year ED CC design storm simulation.
- There is scope for further work on assessment of flood flows in the Kaeo catchment. Running a 50-year ED and / or 100-year ED design storm event for existing rainfall would allow for further direct comparison of the flooding with surveyed data from previous events, including the 2007 flood events. Further comparisons of run off and flow could also be made with other nearby catchments.
- Further work is required to install few more gauges (rainfall and flow) along the upper Kaeo River and its major tributary the Waihuka/Waiare Streams discharging into the Kaeo River near Upokorau Road Bridge. Data from these gauges in future will enable further calibration of the model to provide higher confidence. The current version of the model has however been calibrated against a large number of debris levels for the calibration event.
- The current model has not been calibrated against peak flow because of lack of high flow gaugings. Further work is required to obtain high flow gaugings at all gauges, so the flow rating can be used with confidence for peak flow. Better site ratings in future will enable the model to be calibrated against both levels and flows using larger storm events and this will provide higher confidence.

9. Limitations

9.1 Purpose of this report

This is a model build report. The purpose of this report is to describe the model build, model calibration and flood hazard mapping process for the Kaeo River Catchment flood modelling study.

9.2 Limitations

This report has been prepared by GHD for Northland Regional Council and may only be used and relied on by Northland Regional Council for the purpose agreed between GHD and the Northland Regional Council.

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Appendices

Appendix A – GHD Dredging Report 2008 & GHD Summary Report 2009

Appendix B – DHI Peer Review Report 2010

Appendix C – Catchment Boundary, landuse, DTM and Sub-catchments and Gauge Locations

Appendix D – Model Calibration Results and Longitudinal Profiles

Appendix E – Locations of Design Storm Point Rainfall and Predicted Flood Depth Maps for various ARI Storm Events

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