REPORT

Tonkin+Taylor

# TUFLOW Model Build Report

## Manawatu Drainage Scheme

Prepared for

Horizons Regional Council

Prepared by

Tonkin & Taylor Ltd

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# 1 Introduction

Tonkin & Taylor Ltd (T+T) was engaged by Horizons Regional Council (Horizons) to undertake a flood hazard assessment for the area within the Manawatu Drainage Scheme (MDS). The purpose of this work was to provide a better understanding of the spatially varied flood hazard within this area. In addition, this hazard assessment work was aimed at being able to inform potential flood constraints relating to future development that is anticipated to occur.

Initial draft outputs were issued to Horizons in the absence of detailed survey information for stormwater infrastructure elements such as culverts and flap gates. Subsequently survey capture has been undertaken, and the outputs contained in this report now consider additional information from the survey conducted by Horizons in October 2020.

This report describes the model build and includes outputs for different rainfall durations and average recurrence intervals (ARI). The purpose of these outputs is to aid in developing a "trusted picture of the surface water flood patterns" as per Horizons' request.

The modelling and reporting have been prepared for Horizons in accordance with the conditions of engagement dated 23 December 2019.

# 2 Background

The MDS, located between the western edge of Palmerston North City and the Oroua River, consists of a network of drainage channels, culverts, flood gates and a pump station that drain into the Manawatū River to the south. The area is relatively flat and the drainage network was developed to facilitate agricultural development of the area. Due to the flat topography, and complex nature of the drainage network, a hydrodynamic model was seen to be required in development of an understanding of these complex flow patterns, especially under flood conditions.

The model covers an area of approximately 16,400 ha. Most of the catchment discharges into the Manawatū River at the Burkes Floodgates. When the floodgates are closed, drainage is facilitated by the Burkes Pump Station. It is understood that these gates are closed to prevent backwater inundation from the Manawatū River.

Land use is predominantly pastoral (sheep, cattle), horticultural or an increasing number of lifestyle blocks. The area is increasingly being looked to for lifestyle and residential development as Palmerston North grows. This project seeks to provide Horizons with a tool to inform flood management for future development in flood prone areas. The scheme consists of at least 146 floodgate culverts, 276 km of drainage channels, 1 pump station, 11 bridges and 32 km of stop banks, all of which have been represented in the model.

In 2004 this area experienced a significant flood event, and this precipitated an increased focus on drainage and flood management in subsequent years. Significantly, Burkes Pump station was constructed following the 2004 floods and enables flood gates to be closed, preventing backwater flooding from the Manawatū River while allowing pumped outflow from the MDS area.

A more recent large event occurred in June 2015 and was well documented by Horizons staff with aerial photos taken after the event.

# 3 Model purpose

The purpose of this work was to provide a better understanding of the spatial spread of flood hazard, mainly in areas subject to development and rezoning pressure where there is currently limited flood hazard information available. The purpose of the outputs generated from this modelling is to aid in developing a “trusted picture of the surface water flood patterns” as per Horizons’ request. While the model build methodology described in this document is appropriate for these purposes, caution should be taken when using model outputs for other means beyond the scope of this work.

In modelling of wide areas such as these reported on in this document, accuracy is limited, and field verification of flood predictions is advised when site-specific information is sought. The modelling approach adopted has been aimed at determination of flood hazard extent for the events considered and does not necessarily deliver design flood levels to meet statutory requirements. We recommend that if site specific flood levels are to be considered, that field verification be undertaken. This is particularly the case where a minor degree of flooding (both in depth and in extent) has been predicted on a parcel which, given accuracy limitations in the approach, may or may not be real. This approach (field verification) is also advised where the consequence associated with flooding is high.

It was agreed with Horizons that the Burkes Drain flood gates, located at the downstream boundary of the model, would remain closed in the model for the duration of the flood events simulated. This is the most conservative outcome for peak flood extents, which is the focus of this study. Although appropriate for this purpose, this may present an overly conservative outcome for other flood characteristics such as flood drawdown time following the peak of the flood event.

It was agreed with Horizons that the inclusion of any cross-catchment inflows, associated with spillways from rivers such as the Mangaone, Kopane and Rangiotu, was outside of the scope of this study. This presents a limitation to the model outputs derived from this model, in that flood extents and depths produced may mis-represent flooding in areas where these river spillways may overflow into the MDS catchment.

Therefore it can be considered that this investigation is aimed, as stated above, at developing a “trusted picture of surface water flood patterns” *in response to events during which such overflows are unlikely*. That is, the results are better suited to assessment of events that occur more frequently than for those extreme events when overflows contribute significantly to overall flood conditions.

Section 5.5 of this report describes how the model has been used to simulate rainfall events of Average Recurrence Interval of 2, 10, 100 and 200 years. Of these, significant overflows would not be expected in the 2 and 10-year events and therefore the “trusted picture” of flooding relates more to these than to the more extreme events. It is therefore advised that the potential for contribution of overland flow from these rivers is considered further when using these model outputs via field verification.

Further to above, listed below are a summary of general model build limitations, described further in the following sections, that Horizons will need to consider when interpreting and using these flood hazard outputs.

- Digital Elevation Model (DEM) derived from remotely sensed LiDAR survey data (refer Section 5.2). The limitations of accuracy of LiDAR data are well understood, and these limitations will apply to the model results obtained. In particular, LiDAR survey data and the resulting DEM will have lower accuracy in areas where point cloud density may be low, such as incised waterways, heavily vegetated areas, places where above-ground features have been removed (e.g., buildings) and water bodies. The LiDAR DEM data applied to this model has been generated from three different data sources, the most recent of which was captured in 2018.

The majority of the model domain is, however, contained within the 2005 capture. Where ground levels have been changed since the LiDAR survey was captured, the DEM and hence the model will not recognise these changes (and will be out of date).

- Direct rainfall methodology (refer Section 5.5.1) - A direct rainfall approach has been applied to this model, which can highlight accuracy deficiencies in input data by showing small "puddles" in predicted flooding. It is usual for flood depth results to be "cleaned" by removing puddles before publication or further analysis. T+T has presented raw model results in this report. Prior to any further analysis and/or presentation of model results it is advised that data cleaning be undertaken. This data cleaning involves removal of spurious flooding and field verification of model predictions.
- Hydrological losses and hydraulic roughness (refer Section 5.3 and Section 5.6) - The model has been built at a catchment-wide scale and as such several elements have been defined in the model at such scale. This is most obvious with regard to land use roughness zones that are based predominantly on the LCDBv5 national dataset, which is current as of December 2018. Where land use has changed since the latest update to this dataset, or where finer localised detail occurs, the model will not recognise these details (and will be out of date).

  The model has assumed no soil infiltration losses, which was required to achieve appropriate validation against the June 2015 rainfall event. This event was large with a low recurrence interval and occurred in winter, whereby soil saturation is more likely. Applying such assumptions to the design rainfall events request by Horizons is considered by T+T to be appropriately conservative, however under less severe rainfall events (which have not been modelled as part of this study), different assumptions of soil infiltration characteristics may be warranted.
- Model performance (refer Section 6) – model calibration to recorded flood events is advised to assess the performance of the model outputs to observed flood level data points. There is no known recently recorded flood level or flow recorded gauge data available in the catchment, which means that the confidence in model outputs is naturally lower than if model calibration data was available. In lieu of calibration data, and to gain confidence in model outputs, validation against a June 2015 recorded rainfall event, using indicative observed flood extent data was undertaken. In addition, sensitivity analysis of key model parameters was also undertaken.

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

# 4 Modelling approach

A 2-dimensional (2D) rain on grid model with 1-dimensional (1D) elements was built using TUFLOW software. Asset information for infrastructure such as bridges and culverts was provided by a survey of the area completed by Horizons in October 2020. Model build details are summarised in Table 4.1 and explained in detail in later sections.

Table 4.1: Model build summary

| Model element | Report Section | Description |
|---|---|---|
| Model software | - | 2020-10-AA TUFLOW HPC Quadtree solver. |
| Model overview | - | A 2D rain on grid model that includes 1D hydraulic structures. |
| Time step | - | The TUFLOW HPC model applies an adaptive time step, based on maintaining a Courant condition. |
| Eddy viscosity | - | Default WU viscosity coefficients for C3D and C2D (7.0, and 0.0 respectively). |
| Datums | - | Vertical: NZVD2016<br>Horizontal: NZTM (NZGD2000) |
| Model extent | Section 5.1 | The model domain covers an area of approximately 16,000 ha. |
| Model topography | Section 5.2 | A 1 m x 1 m (1 $m^2$) gridded DEM for ground level used in the model was provided by Horizons and is composed of data from LiDAR surveys flown in 2005, 2016 and 2018. |
| Model cell size | Section 5.2 | Quadtree testing of cell sizes using a 12 m x 12 m grid for floodplain areas, and a 4 m x 4 m grid for drainage channels.<br>Sub-grid-sampling of underlying 1 m DEM. |
| Land use roughness | Section 5.3 | Land use zones defined by Landcare Research's Land Cover Database version 5 (LCDBv5).<br>2D Manning's n roughness values, consistent with guidelines values from Australian Rainfall and Runoff (AR&R), have been applied to each grid cell based on land use. |
| Hydraulic structures | Section 5.4.1 | Hydraulic structure data were obtained from Horizons using three different sources:<br>· October 2020 Survey;<br>· Existing Mike11 hydraulic model; and<br>· Manawatu Drainage Scheme data |
| Hydrology | Section 5.5 | Design rainfall depths were obtained from the National Institute of Water and Atmospheric Research (NIWA) High Intensity Rainfall Design System (HIRDS) V4 values. |
| Upstream boundaries | Section 5.5 | Direct rainfall hydrology.<br>For the 2015 validation event only, derived spillway inflows were provided by Horizons. |

## 4.1 Software description

The model has been built and run using the latest 2020-10-AA TUFLOW HPC Quadtree solver and utilises recently released quadtree nesting and sub-grid-sampling technology.

Sub-grid sampling allows the underlying DEM volume and conveyance relationships to be represented within a more coarse grid, preserving overland flow and storage features while allowing a coarser base resolution, which can optionally be mapped back to a fine grid resolution.

Quad tree allows grid size nesting meaning that a fine resolution grid can be used where it is important to derive flow field patterns in more detail such as in open channels and other areas of interest. This allows model run times to be optimised so that multiple duration events can be simulated to identify critical storm duration relationships.

# 5 Model Inputs

## 5.1 Model extent

The hydraulic model extent, as shown in Figure 5.1, was provided by Horizons in the form of a shapefile in March 2020. The scheme covers an area of 16,000 Ha. T+T have made no adjustment to the model extent provided by Horizons. As described in Section 3, no cross-catchment boundary flows have been represented. Based on other modelling undertaken by T+T for Bunnythorpe and surrounding areas, we are aware that there is a potential for Mangaone Stream overflow to enter this model domain, particularly under severe flood event conditions. Inclusion of these would enhance the reliability of the model for extreme event and future climate scenarios but have not been considered in this model.

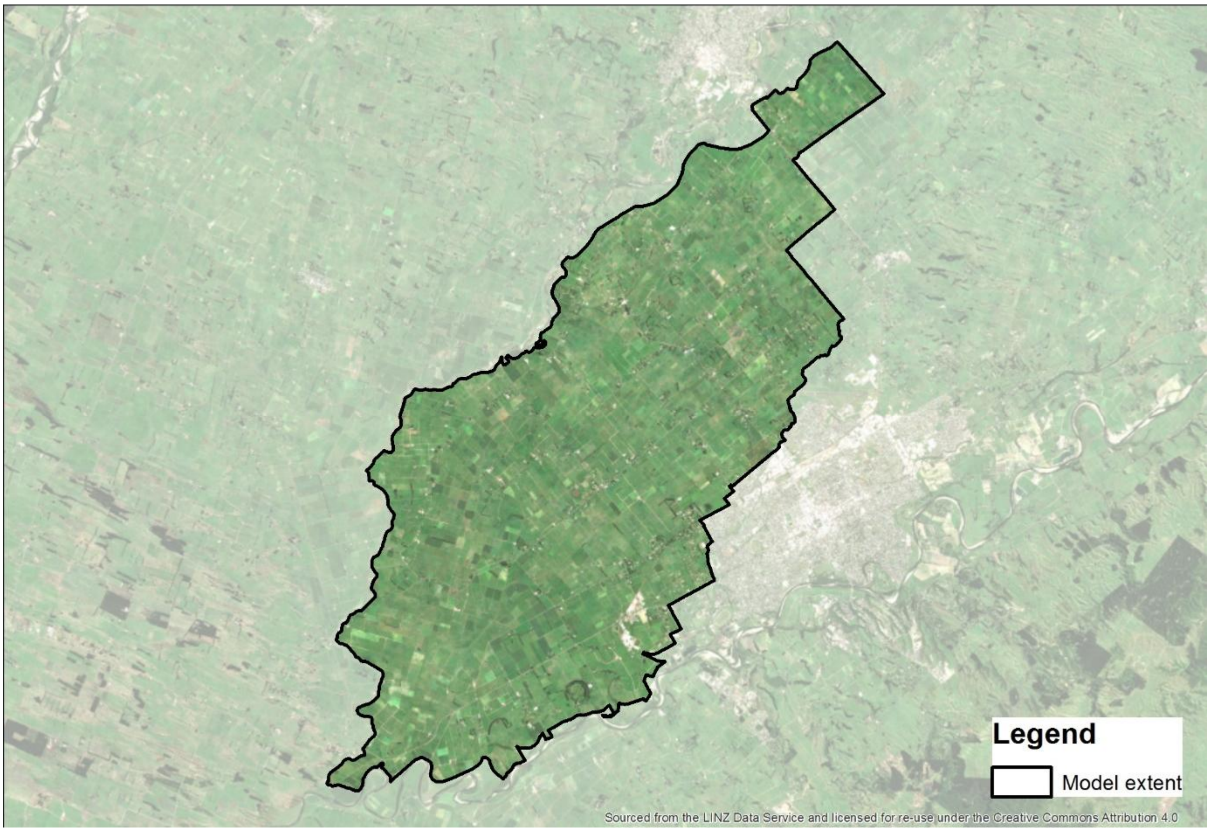


*Figure 5.1: Hydraulic model extent provided by Horizons*

## 5.2 Digital Elevation Model (DEM)

A 1 m x 1 m (1 $m^2$) gridded bare earth DEM for ground level used in the model was provided by Horizons. It is understood by T+T that the DEM is composed of data from LiDAR surveys flown in 2005, 2016 and 2018, as shown in Figure 5.2. Horizons provided T+T with a composite DEM made up from these surfaces. It is understood by T+T that Horizons undertook work to remove edge effects at the intersection of the surveyed datasets.

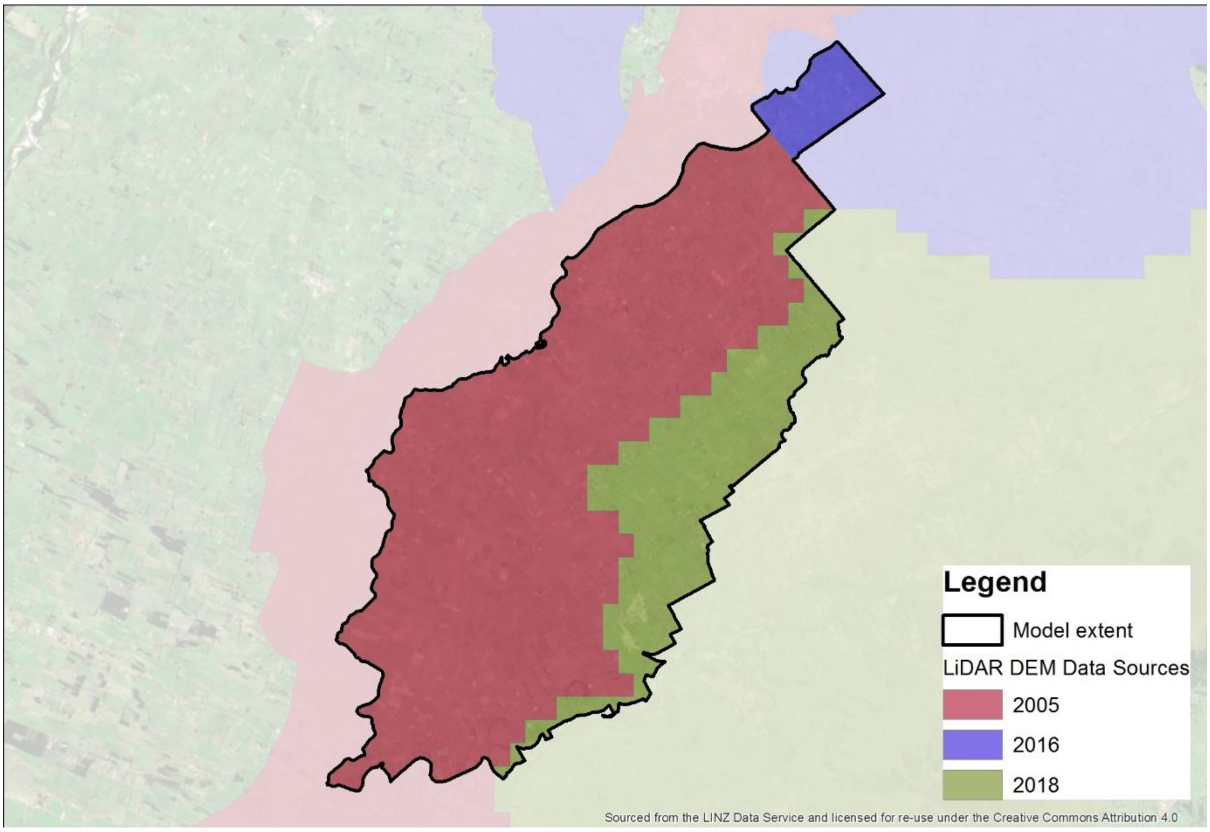


*Figure 5.2: LiDAR data sources that together make-up the composite DEM provided to T+T by Horizons*

It is also understood by T+T that data captured in 2005 and 2016 was projected to the Moturiki 1953 vertical datum (MVD-53) and for the purpose of this work has been converted to New Zealand Vertical Datum 2016 (NZVD2016) by Horizons to match the vertical datum of the most recent 2018 data. As a result, the composite DEM dataset used in the hydraulic model, and all results generated from the model, are projected to the NZVD2016 vertical datum.

T+T have assessed that the DEM provided by Horizons is of sufficient quality for achieving the objectives of this project, however note that the majority of data is up to 16 years out of date and may not capture landform changes since then.

The DEM represents a bare earth terrain with all buildings and above-ground features having been removed. Using this approach, it is sometimes possible that flooding is shown to occur through the area occupied by large buildings. This is because the model does not recognise these as buildings and works only off the DEM. Care should therefore be exercised in the interpretation of results, particularly in areas where there is a high percentage of ground area covered by above-ground features (trees, buildings, etc).

The DEM has been applied to the TUFLOW model using a range of computation grid sizes which is made possible with the latest TUFLOW quadtree nesting and sub-grid sampling technology. Quadtree nesting allows the user to refine the computation grid size in areas where detail is required and make the computation grid size more coarse in areas where detail is not required. Varying the grid size allows the user to optimise the overall run-time of the model without compromising on detailed grid resolution where it is needed. Table 5.1 shows the different Quadtree nesting levels applied to the model extent and Figure 5.3 shows how this has been spatially varied.

The finest nest level, which uses a 2 m x 2 m grid, has been applied to the inlet and outlet of all modelled hydraulic structures. Despite this, the model's "sub-grid sampling" capability allows for reading of the 1 m x 1 m grid at all nest levels and uses this for hydraulic calculation.

Table 5.1: Quadtree nesting grid size levels

| Type | Quadtree Nest Level | Grid Size (m) |
|---|---|---|
| Floodplain | 1 | 32 |
| Drainage channels and roads | 4 | 4 |
| Hydraulic structure inlet and outlet | 5 | 2 |

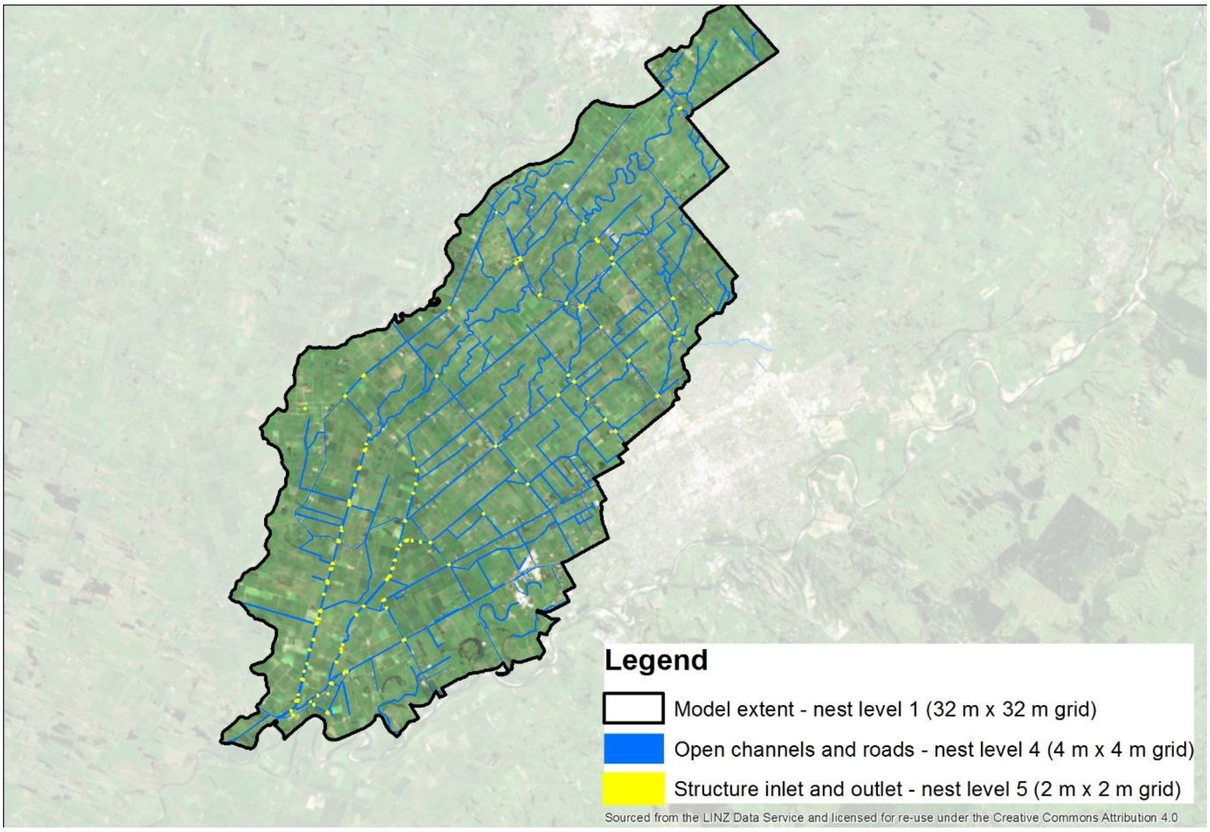


*Figure 5.3: Quadtree nest levels applied to the model domain*

## 5.3 Land Use (surface roughness)

Surface roughness and hydrological losses are best determined through model calibration. In the absence of suitable calibration data, we have adopted a sensitivity-based assessment using past experience to determine loss values, and validated results against indicative flood extents estimated for the June 2015 flood event.

Surface roughness values adopted in the model were based on land use as categorised in Landcare Research's Land Cover Database version 5 (LCDBv5). This database was the most up to date at the time of model build. It released in January 2020 and considers land use classification up until the end of 2018. The land use of each model domain, according to LCDBv5, is shown in Figure 5.4. In addition to LCDBv5, road polygons and building outlines were sourced from publicly available Land Information New Zealand (LINZ) data service. Details of specific roughness values applied to the different land uses are summarised in Table 5.2 and are consistent with 2D roughness values published by Australian Rainfall and Runoff (AR&R[1]).

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

It should be noted that land use types such as urban built-up areas, buildings, roads and rivers, would typically be allocated a fraction of imperviousness in a direct-rainfall model such as this, where soil infiltration losses are often applied directly to the 2D cells. However, as is detailed further in Section 5.6, soil types are characteristically very poorly drained across the model extent, and soil infiltration was not applied, effectively making all land use types 100% impervious. As is described further in Section 6, applying zero infiltration was done to appropriately validate the model against a past flood event. Further justification for this approach is that the model was aimed to be used for simulation of significant flood events, during which time saturation of surface soil is more likely.

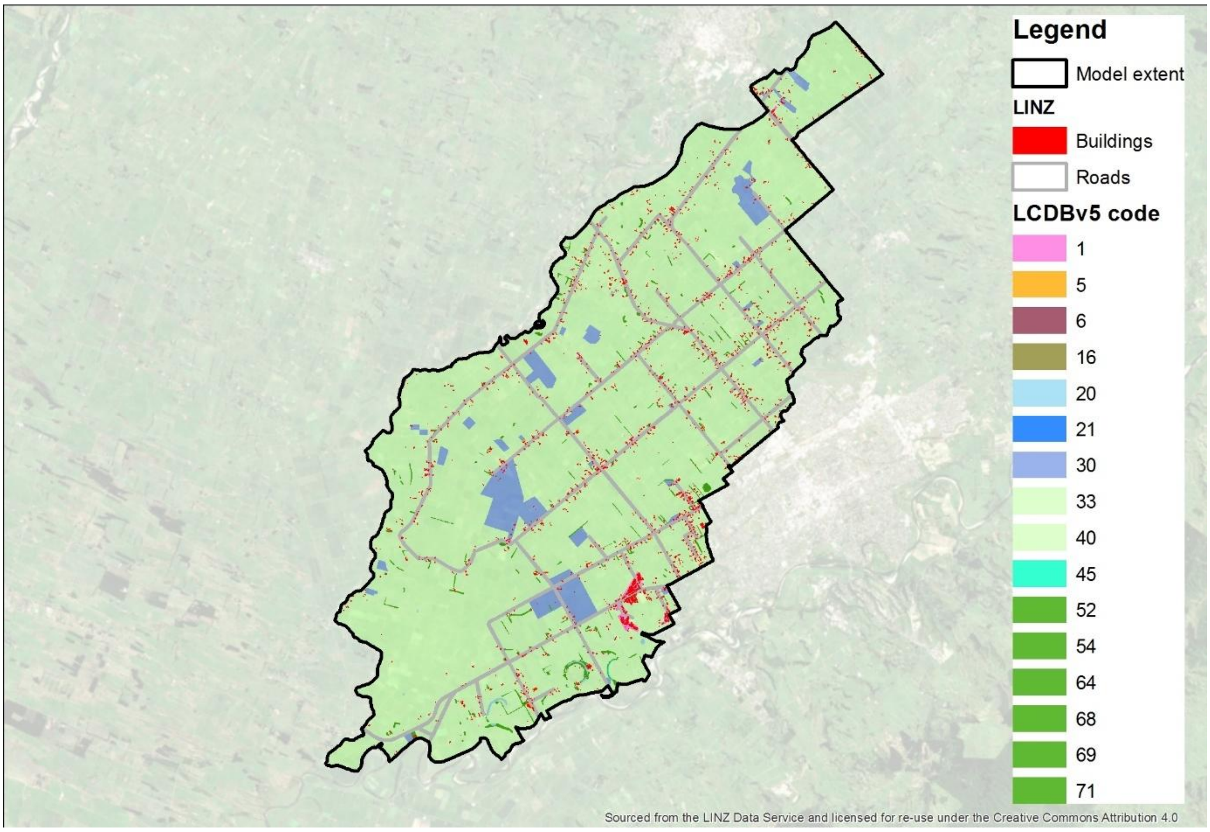


*Figure 5.4: Land use (sourced from LCDBv5) and LINZ Data Service*

Table 5.2: Land types and corresponding Manning's n coefficients

| Description | Code | Manning's n | Legend (refer Figure 5.4) |
|---|---|---|---|
| LCDBv5 | | | |
| Built-up Area | 1 | 0.1 | |
| Transport Infrastructure | 5 | 0.016 | |
| Surface Mine and Dump | 6 | 0.028 | |
| Gravel and Rock | 16 | 0.039 | |
| Lake and Pond | 20 | 0.02 | |
| River | 21 | 0.035 | |
| Short-rotation Cropland | 30 | 0.10 | |
| Orchard, Vineyard and Other Perennial Crops | 33 | 0.05 | |
| High Producing Exotic Grassland | 40 | 0.05 | |
| Herbaceous Freshwater Vegetation | 45 | 0.09 | |

| | | | |
|---|---|---|---|
| Manuka and or Kanuka | 52 | 0.10 | |
| Broadleaved Indigenous Hardwoods | 54 | 0.10 | |
| Forest Harvested | 64 | 0.16 | |
| Deciduous Hardwoods | 68 | 0.125 | |
| Indigenous Forest | 69 | 0.15 | |
| Exotic Forest | 71 | 0.15 | |
| LINZ Data Service | | | |
| Roads | 88 | 0.02 | |
| Buildings | 91 | 0.2 | |

## 5.4 Hydraulic Structures

### 5.4.1 1D elements

#### 5.4.1.1 Culverts and flap-gates

Several 1D elements have been included in the model from three different data sources, provided to T+T by Horizons, as below:

- October 2020 survey data;
- Oroua MIKE11 Flood model; and
- MDS data

The data provided to T+T included bridge, culvert and flap-gate locations with corresponding structure invert levels and diameters. An overview of all the 1D infrastructure model elements is shown in Figure 5.5.

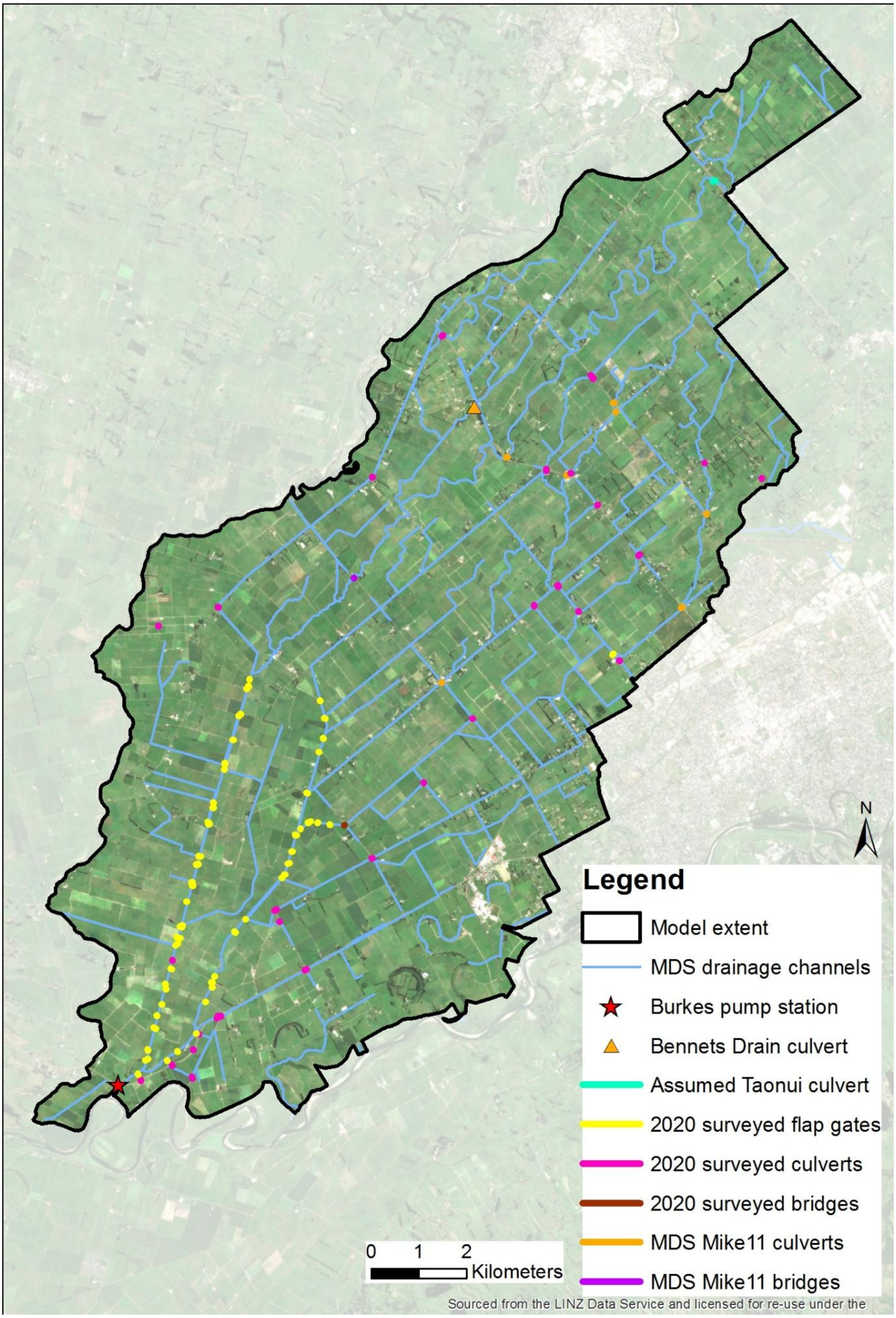


*Figure 5.5: 1D infrastructure elements included in the model*

All data surveyed in October 2020 were provided to T+T in NZVD2016 vertical datum.

According to DHI (2008), the data included in the Oroua Mike 11 flood model are referenced to the Wellington Vertical Datum 1953 (WVD-53), and therefore has subsequently been converted by T+T to NZVD2016 for consistency with the vertical datum of the model DEM. The difference between WVD-53 and NZVD2016 ranges from -0.396 m in the South-East to -0.425 m in the North-West. The average difference is -0.41 m. Given the inherent differences between levels from a LiDAR derived DEM and surveyed data, and the need to link surveyed 1D structures to the DEM, it was considered within comparable tolerances to assume a single correction of -0.41 m over the entire Scheme to bring WVD-53 levels into terms of NZVD2016.

Some known structures were not captured by any of the aforementioned data sources and in some instances, invert levels for structures, including the Taonui culvert, were not available. In such cases, inlet and outlet positions and their respective levels were assumed based on the LiDAR DEM (generally based on matching invert levels). Where known flap-gates were not captured by data sources, a nominal size of 600 mm diameter was assumed.

The model has assumed that the Burkes Flood Gates will be closed during the simulation due to high water levels in the Manawatū River. This is the most conservative assumption with respect to flood levels and was agreed with Horizons.

#### 5.4.1.2 Bridges

One bridge structure at Milson Line, shown in Figure 5.5, was included in the model as a 1D element, linked to the 2D model domain. Details of the structure dimensions were sourced from the existing Oroua MIKE11 model. Note that T+T did not independently undertake checking of the Oroua model and have assumed data contained within it is suitable for use.

TUFLOW 2D layered flow constriction was used to represent another ten bridge structures in the model, shown in Figure 5.6. Layered flow constriction allows blockages and form losses to be applied directly to the 2D model cells at different elevations to account for energy losses such as the bridge deck and handrails, while other losses, such as contraction and expansion through the bridge structure are solved implicitly through the 2D solution. As bridges in the MDS are relatively small and do not contain complex structural elements such as bridge piers, this was considered by T+T to be more appropriate than using 1D elements, as the additional energy losses associated with these bridge structures occur only once water levels reach the bridge deck.

In most cases the bridge opening width, bridge deck soffit and bridge deck thickness was inferred from data extracted from the Oroua MIKE11 model and/or survey data. Where insufficient data existing, dimensions such as bridge deck thickness was inferred from LiDAR surveyed road levels.

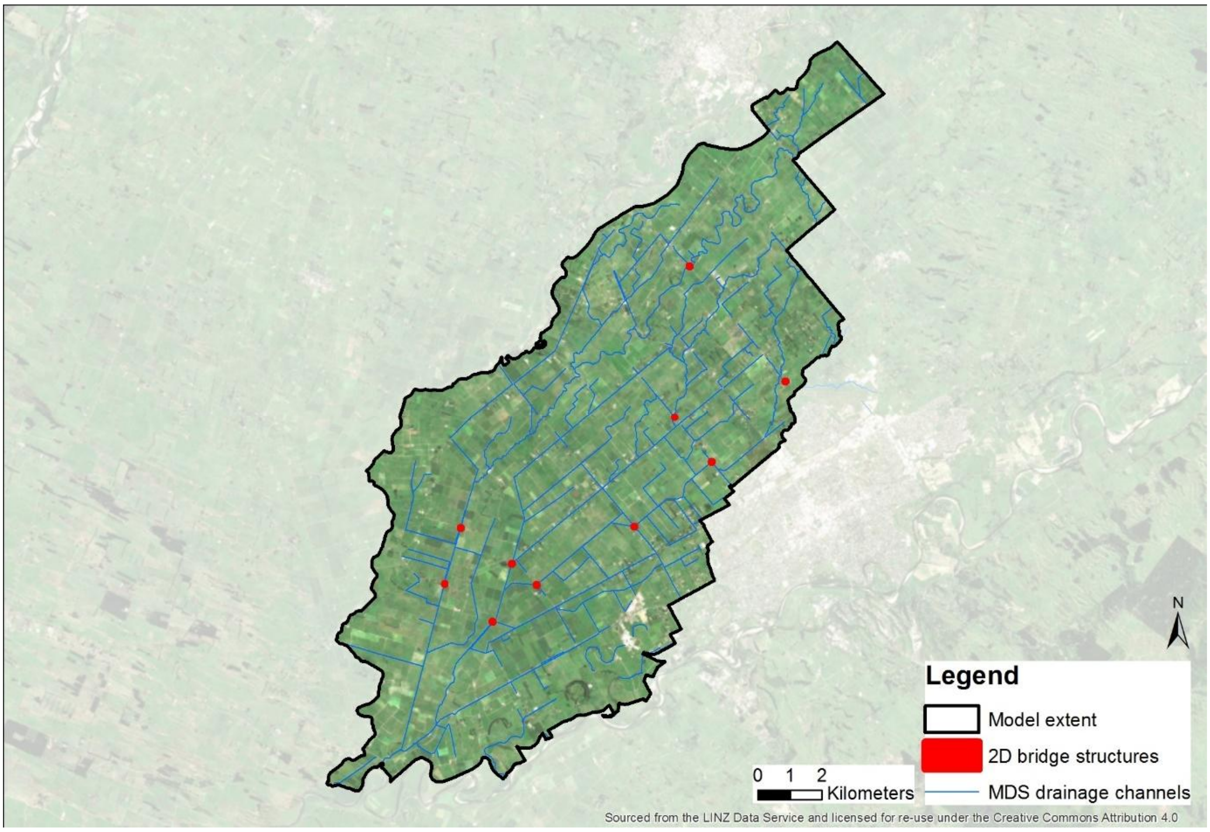


*Figure 5.6: 2D bridge structures applied to the model*

### 5.4.2 Stopbanks

There are two main stopbanks located along the Main Drain and Burkes Drain, shown in Figure 5.7. Data containing the crest elevations of the stopbanks was provided to T+T by Horizons in the October 2020 survey as well as additional survey data captured in February 2011. As this survey data has a higher degree of accuracy compared to the LiDAR DEM, the surveyed crest levels were used to modify the LiDAR DEM, using TUFLOW ZSH lines, to more accurately represent the stopbank crest.

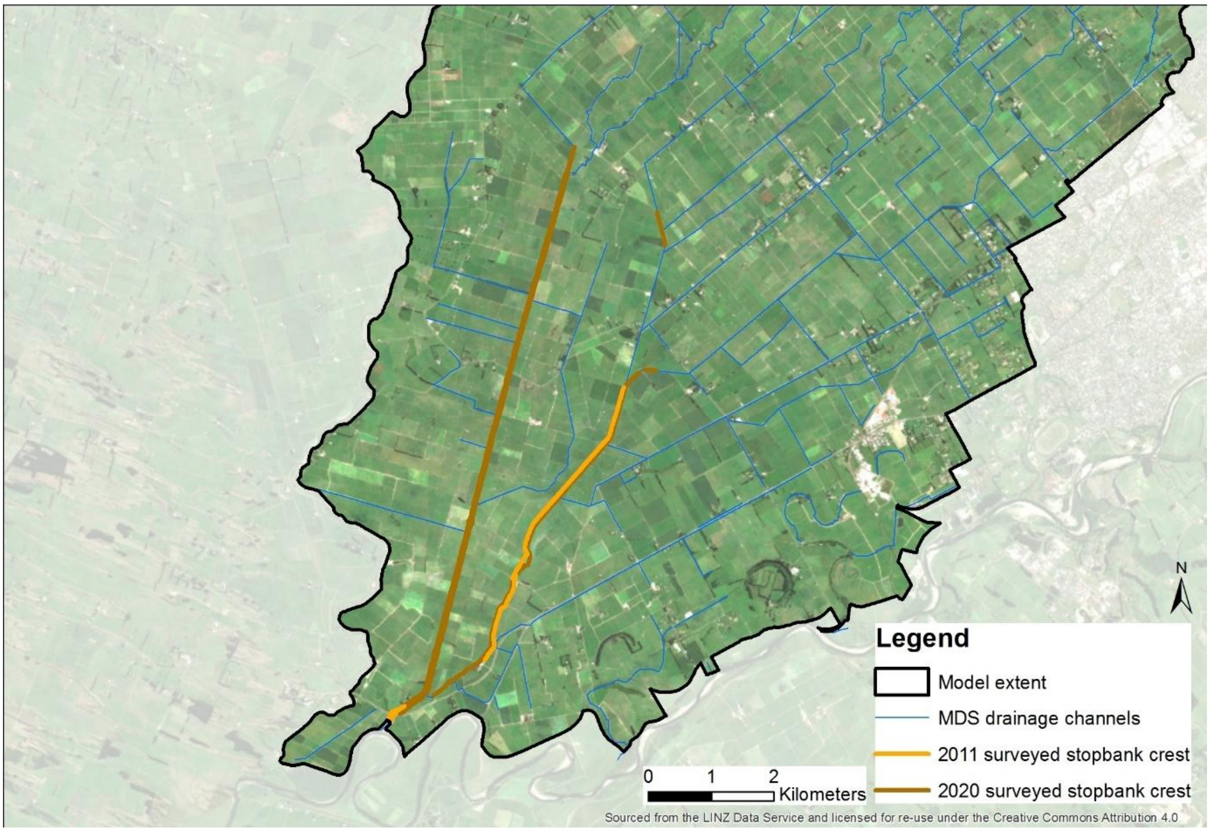


*Figure 5.7: Stopbanks defined in the hydraulic model*

### 5.4.3 Open drainage channels

As is mentioned in Section 3, there are limitations associated with LiDAR data, in particular the accuracy of the resulting DEM in areas such as incised waterways, heavily vegetated areas, places where above-ground features have been removed and water bodies. Open drainage channels are a significant feature of the MDS catchment, and in many cases appeared to be poorly represented by the LiDAR DEM, particularly in areas that were vegetated and/or obscured by standing water at the time of the survey.

To improve conveyance in these channels within the model, and to better represent the hydraulic performance of these channels, the DEM was artificially deepened by 0.5 m, using TUFLOW ZSH lines, to account for the likelihood of LiDAR data missing the true invert of the channel. The open drainage channels lowered are shown in Figure 5.8. Given the arbitrary nature of this channel invert lowering, we undertook sensitivity testing where model results with and without lowered inverts were compared. This sensitivity testing indicated that peak flood levels were not particularly sensitive to such an adjustment. In spite of this lack of sensitivity, the lowered inverts scenario was preferred as it improved model stability and reduced run-times.

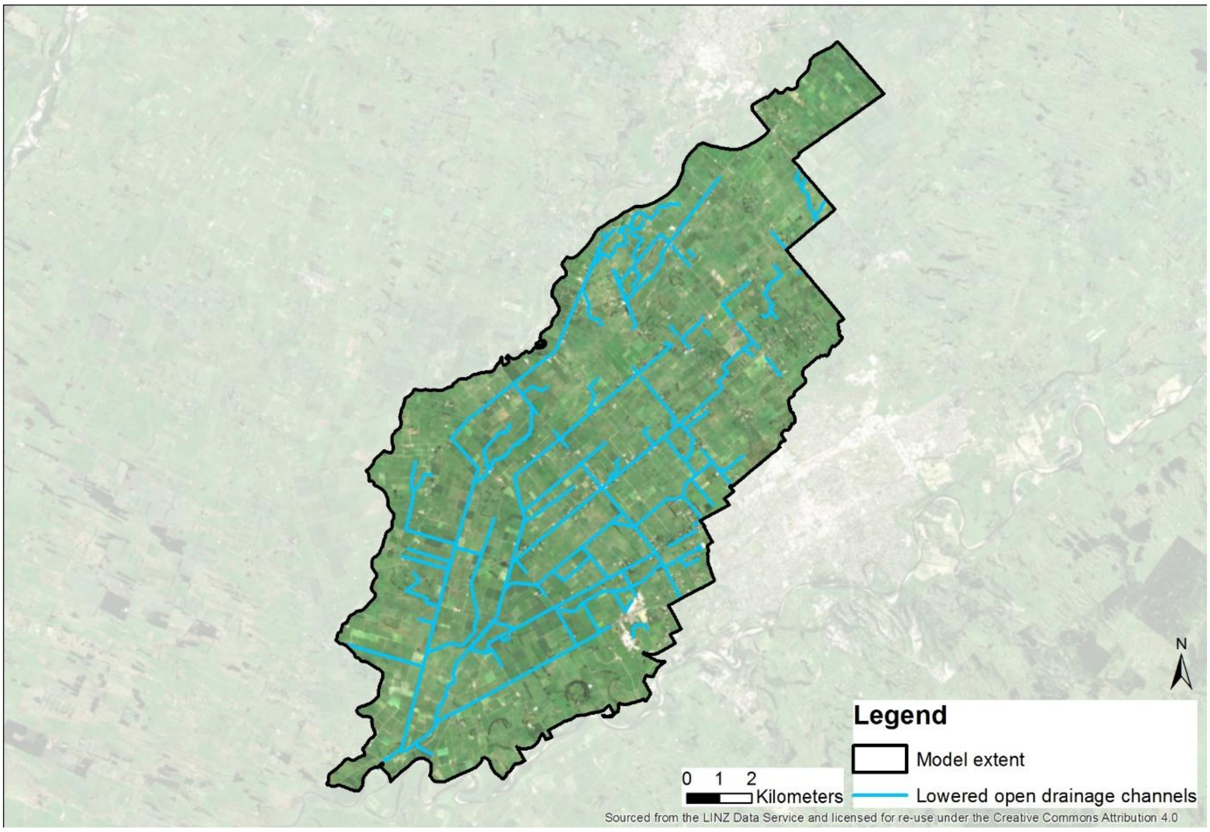


*Figure 5.8: Open drainage channels lowered by 0.5 m*

### 5.4.4 Burkes Pump Station

Burkes Pump Station forms the only modelled outflow from the MDS. It is understood by T+T that the pump station consists of four individual pumps, with a combined maximum pump capacity of 7 $m^3$/s. To simplify the representation of the pump station in the model, each of the four pumps was assumed to have a maximum pumping capacity of 1.75 $m^3$/s, which was achieved over a duration of 1 minute once the start level was reached.

The pump start and stop levels are shown below. It should be noted that these were provided to T+T in MVD-53 and have subsequently be converted to NZVD2016 by T+T, using an -0.26 m adjustment, as per recommendations detailed on LINZ data service. Note that the conversion between different local vertical datums (e.g. WVD-53 and MVD-53) and NZVD2016 are not always the same due to the reference locations.

Table 5.3: Pump start and stop levels

| Pump Station | Start level (m NZVD2016) | Stop level (m NZVD2016) |
|---|---|---|
| 1 | 6.03 m | 5.33 m |
| 2 | 6.23 m | 5.33 m |
| 3 | 6.53 m | 6.03 m |
| 4 | 6.83 m | 6.03 m |

## 5.5 Boundary data

### 5.5.1 Rainfall

A direct rainfall approach was adopted for the hydraulic model, with rainfall depths generated using NIWA's HIRDSV4. This data was used to create HIRDSV4 temporal rainfall profiles for 2-year, 10-year, 100-year and 200-year average recurrence interval (ARI) events. As HIRDSV4 doesn't provide rainfall depths for a 200-year ARI event, the values shown in Table 5.4 were interpolated from available values provided for 100-year and 250-year ARI events.

To ensure that the different response times of all catchments contributing to flooding in the model domain were captured, 1-hour, 6-hour, 12-hour, 24-hour, 48-hour and 72-hour rainfall hyetographs were simulated within the model for each ARI event, and enveloped maximum flood levels were derived to provide a "worst case" output for each ARI event. Critical duration outputs are described further in Section 8.2.

The six event durations selected were deemed representative of critical response times in the catchments modelled. It is acknowledged that the true critical duration could sit somewhere between, or either side, of each of the four durations selected, however for the purposes of this flood mapping, modelling more event durations was considered to be beyond the level of detail required. Certain sites may require site-specific consideration, especially if deemed to be of high importance.

Rainfall depths are summarised in Table 5.4, while Figure 5.9 shows an example hyetograph for a 100-year ARI rainfall event with a 24-hour duration.

A single rainfall hyetograph was applied across the full hydraulic model domain as there is little spatial variability in HIRDSV4 rainfall depths in this area. To ensure an appropriately conservative outcome, areal reduction factors were not applied to rainfall hyetographs.

It was agreed with Horizons that a present-day climate would be used for ARI events modelled.

Table 5.4: HIRDS V4 rainfall depths

| ARI | 1h | 6h | 12h | 24h | 48h | 72h |
|---|---|---|---|---|---|---|
| 2 | 14.5 | 30.4 | 39.3 | 49.6 | 61.2 | 68.2 |
| 10 | 23 | 46.6 | 59.5 | 74.3 | 90.4 | 100 |
| 100 | 37.2 | 72.4 | 91.1 | 112 | 134 | 147 |
| 200 | 41.01 | 80.21 | 100.73 | 123.6 | 147.76 | 161.79 |

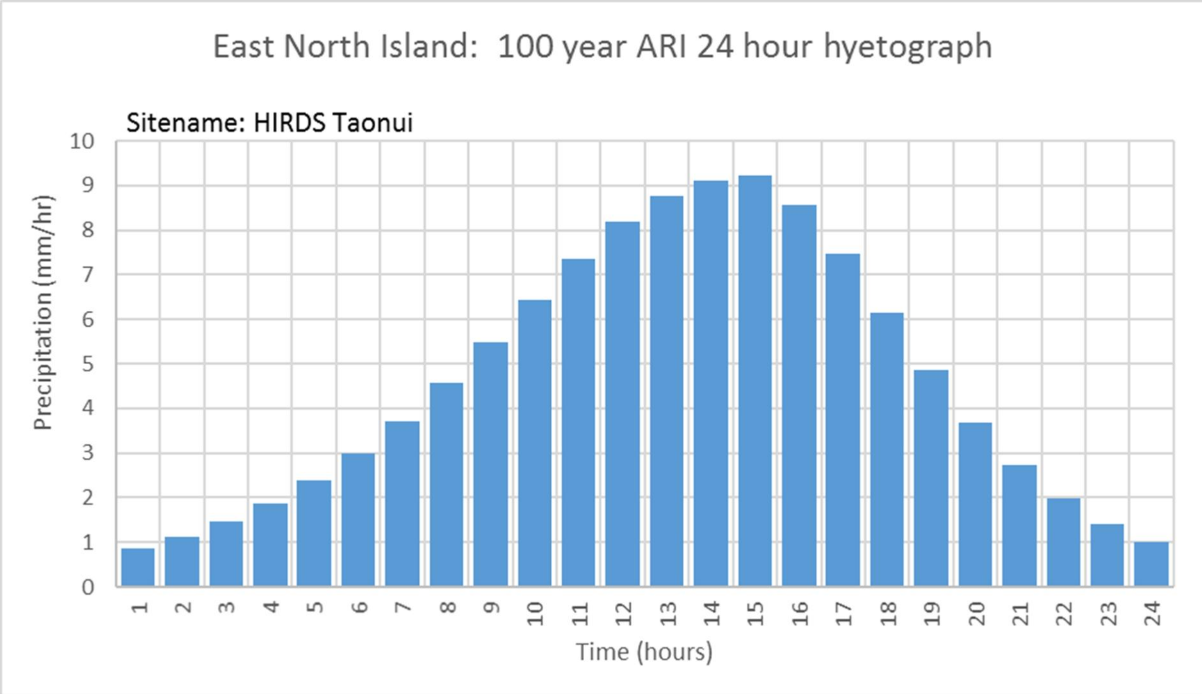


*Figure 5.9: 100 year ARI 24 hour duration rainfall hyetograph*

### 5.5.2 Inflows

The model does not consider inflows from the Oroua or Mangaone Rivers as this is outside the scope of this project. Any flows from these rivers to the model would be via overflow only.

### 5.5.3 Downstream boundary

There has been no downstream boundary applied to the model, which essentially operates like a "glass-wall" (i.e. water that abuts the boundary of the model cannot exit the model). The only outflow location, and means for water to existing the model, is the Burkes Drain pump station, as previously shown in Figure 5.5. The Burkes Drain flood gates, located adjacent to the pump station, are assumed to be closed. This approach is considered by T+T to be appropriate given the uncertainty around tailwater conditions in the Manawatū River during a flood event.

## 5.6 Infiltration losses

Similar to hydraulic roughness, hydrological losses are best determined through calibration. In the absence of suitable calibration data, we have adopted both a sensitivity-based assessment (refer Section 8), using past experience to determine suitable loss values, described below, and validation of model outputs using recorded rainfall and estimated flood extents from the June 2015 rainfall event, (refer Section 6).

Figure 5.10 shows the surface soil drainage types at the model extent, as classified by the fundamental soil (FS) drainage layer sourced from Landcare Research, while Table 5.5 shows suitable soil infiltration loss values that were applied to each soil drainage type. A Horton loss model was used to model the rainfall infiltration losses in the model. The Horton approach utilises the equation:

$$f = f_c + (f_0 - f_c)e^{-kt}$$

Where $f_0$ is the initial infiltration rate in mm/h, $f_c$ is the final (indefinite) infiltration rate, $t$ is time in hours and $k$ is the Horton decay rate. For the TUFLOW implementation, the time ($t$) is the period of time that the cell is wet.

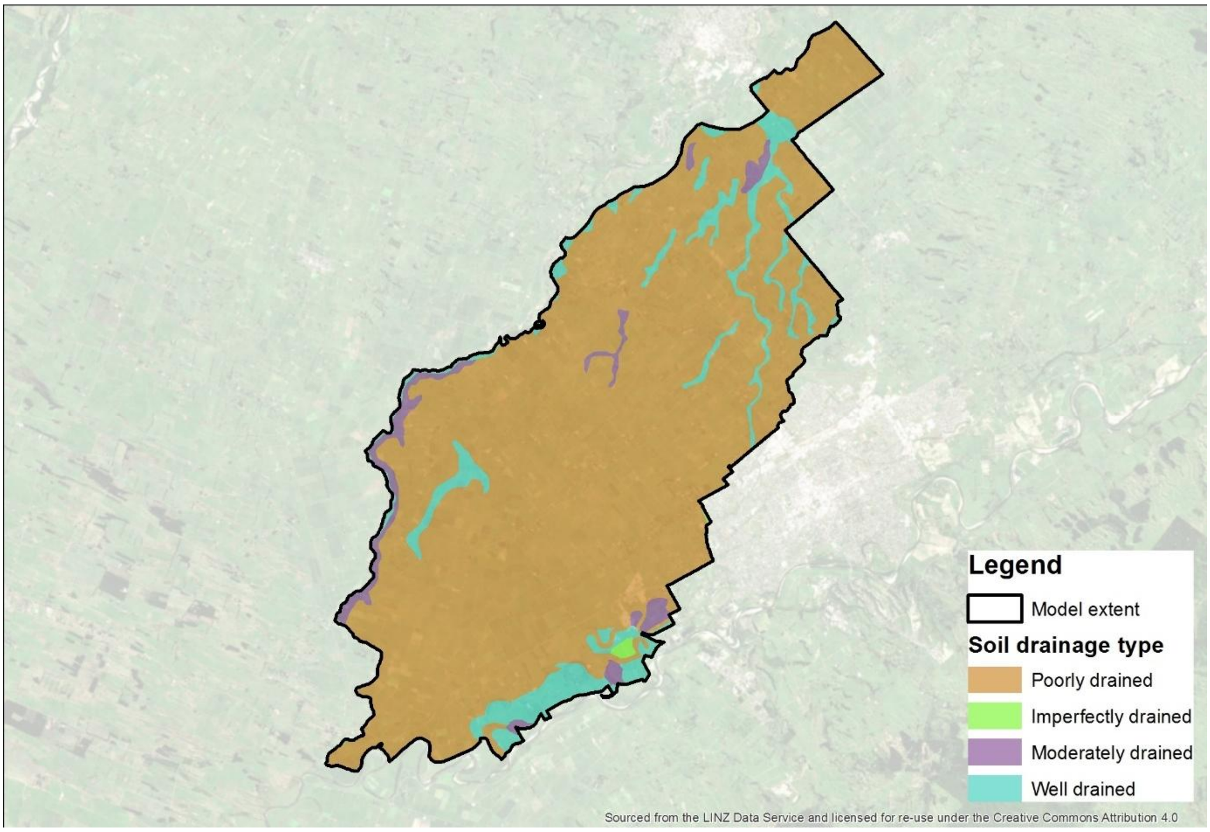


*Figure 5.10: Soil infiltration zones within the model extent, based on the FS drainage layer sourced from Landcare Research*

Sensitivity testing of soil infiltration values was undertaken by applying both the values shown in Table 5.5, forming a “with infiltration” scenario, as well as a “without infiltration” scenario where no losses were applied. The two scenarios were simulated using a June 2015 observed rainfall event and compared with estimates of flood extents and photographs of flooding provided by Horizons and described further in Section 6.

Results showed peak flood levels to be sensitive to “with and without infiltration” scenarios, most prominently in the lower areas of the Scheme where cumulative flow volume is important and where flood event observations were available. Results simulated using the “without infiltration” scenario generated flood extents most similar to estimated flood extents from the June 2015 rainfall event and so were selected for all subsequent design event simulations.

Table 5.5: Hortons soil infiltration values for “with infiltration” scenario

| Soil type | Initial loss (mm) | Initial loss rate (f0) (mm/hr) | Ultimate infiltration rate (fc) (mm/hr) | Horton decay rate (k) (1/hr) |
|---|---|---|---|---|
| Poorly drained | 0 | 2.0 | 1.50 | 0.29 |
| Imperfectly drained | 0 | 3.5 | 3.00 | 0.26 |
| Moderately drained | 0 | 8.0 | 7.20 | 0.23 |
| Well drained | 0 | 25.0 | 22.50 | 0.21 |

# 6 Model Validation using the June 2015 Rainfall Event

Validation of the model was undertaken using observations of flood level from an actual rainfall event that occurred on 20 June 2015. The June 2015 rainfall event was a 31-hour event with a total rainfall depth of 101.6 mm (refer Figure 6.1). The rainfall event was well documented by Horizons through aerial images and shapefiles with indicative flood extents.

The rainfall recorded at the Milson Line gauge (provided to T+T by Horizons), located close to the Palmerston North airport, immediately outside of the model domain, was applied globally over the entire model domain. This is an approximation to reality in that it is likely that landed rainfall would vary spatially over the scheme. However, in the absence of more detailed information on the spatial distribution of rainfall during the event we consider that this represents a reasonable approximation.

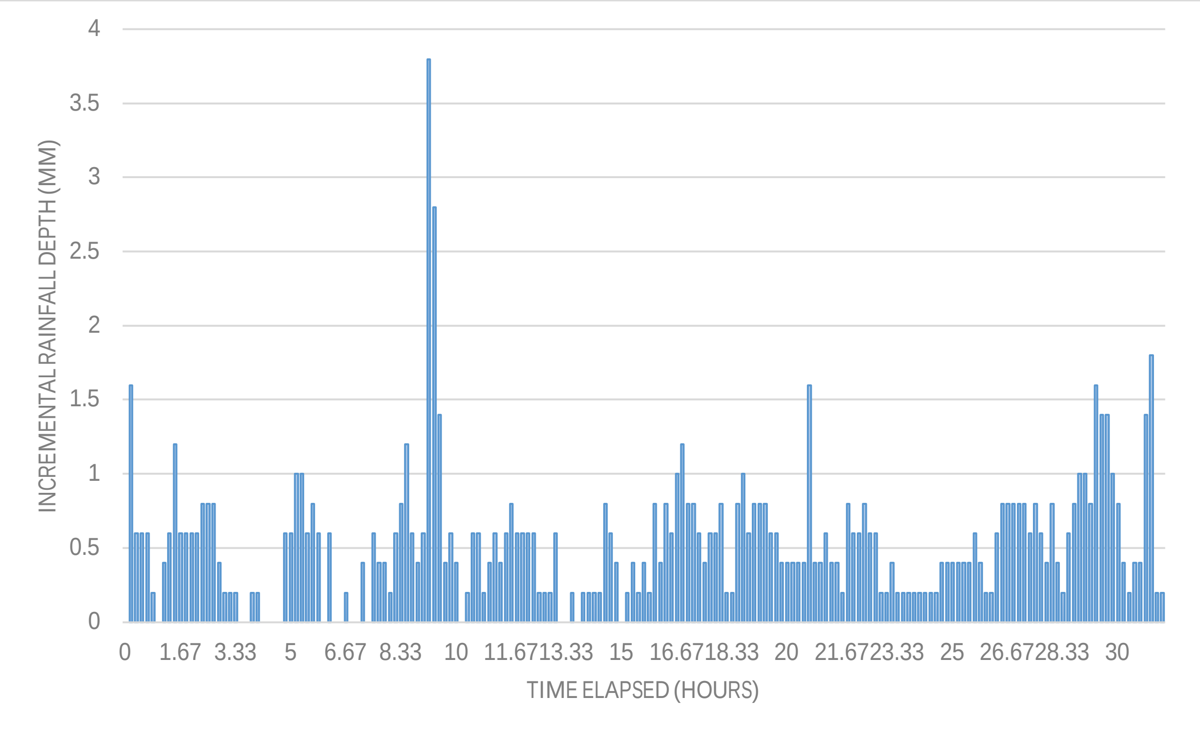


*Figure 6.1: Rainfall at 'Mangaone on Milsons Line' gauge (June 2015), sourced from Horizons*

In addition to rainfall data, spillway hydrographs were provided by Horizons for use in the June 2015 validation event, as shown in Figure 6.2. Flow data from the Mangaone, Kopane, and Rangiotu rivers were recorded during the event, and spill estimates compiled as inputs for the model at various locations around the model extent, as shown in Figure 6.3. Spillway information provided a more accurate validation event. It should be noted that spillway inflows were not incorporated into any subsequent design flood event model runs.

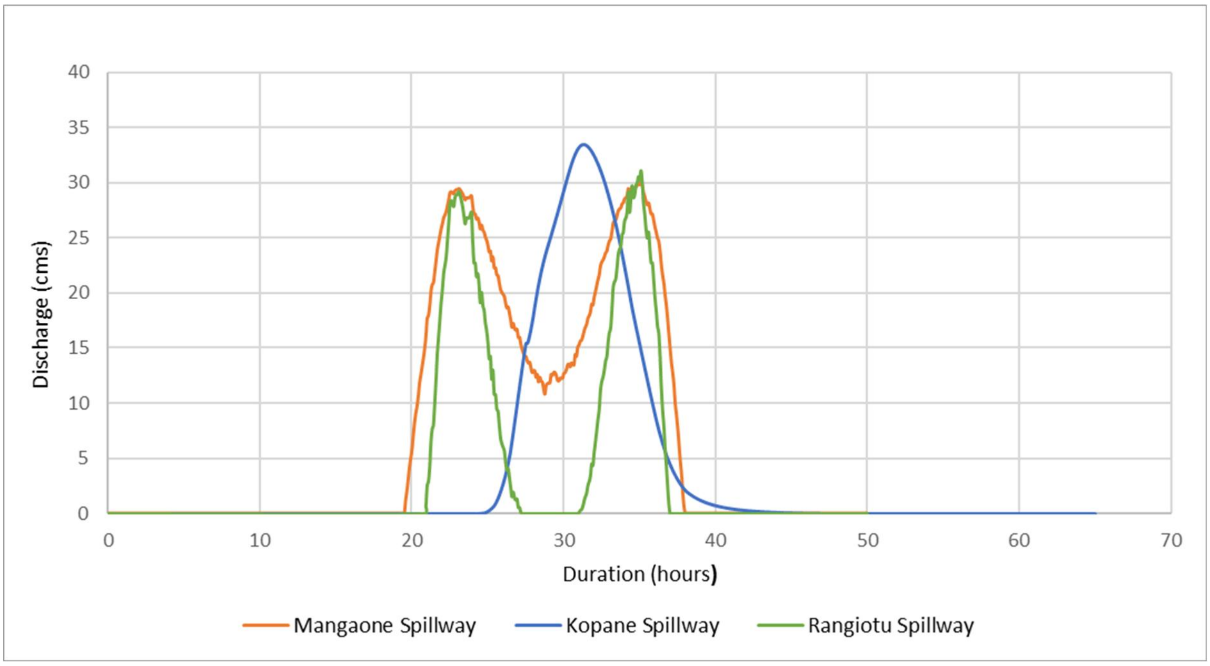


*Figure 6.2: Spillway hydrographs applied to the model extent for the June 2015 flood event, sourced from Horizons*

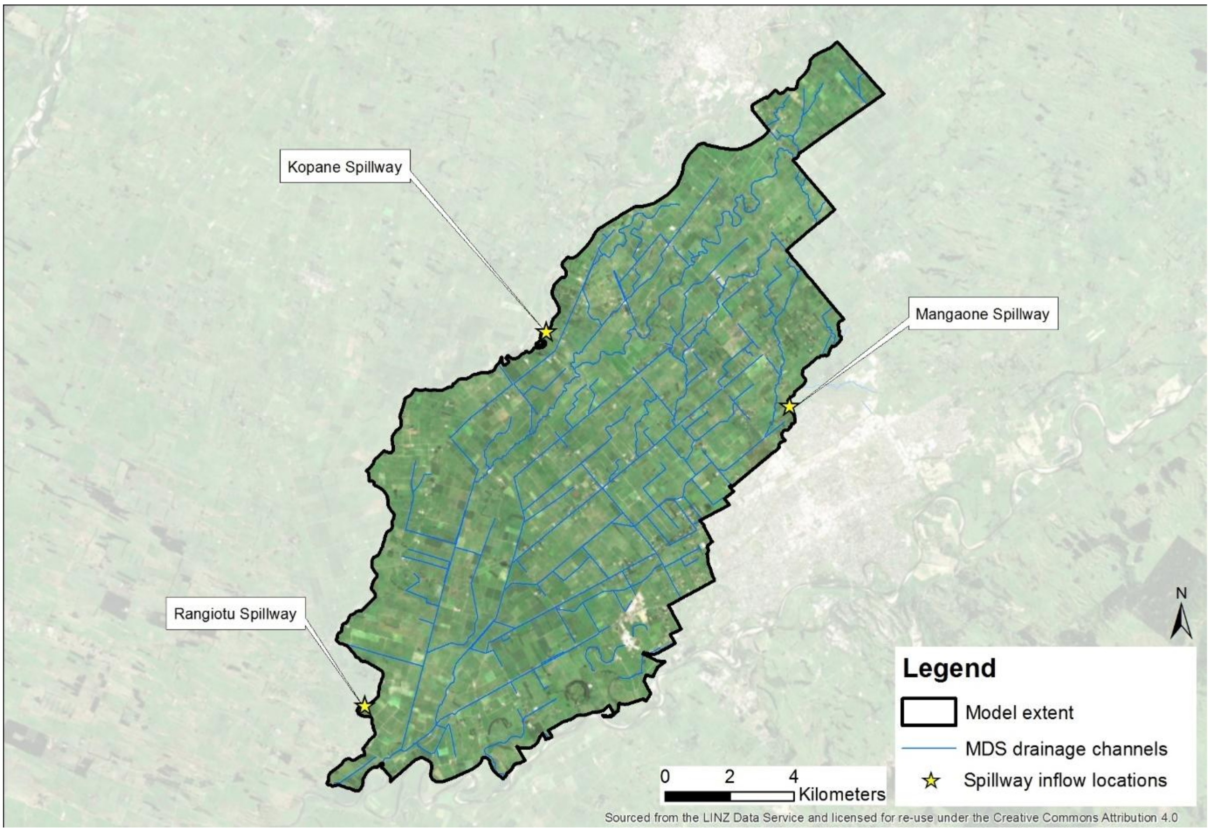


*Figure 6.3: Locations of spillway hydrographs applied to the model extent for the June 2015 flood event, sourced from Horizons*

To validate the model against observed flooding of the June 2015 rainfall event, several baseline model parameters including soil infiltration, Manning's n roughness, and rainfall depths, were adjusted in an attempt to produce flood extents similar to those observed. Appendix A and Figure 6.4 and Figure 6.5 show flood maps comparing observed flood extents and modelled flood extents.

*Figure 6.4: June 2015 modelled flood extents and observed flood extents in red (sourced from Horizons)*

*Figure 6.5: June 2015 modelled flood extents and observed oblique aerial photograph of flooding (sourced from Horizons) looking north along Burkes Drain. Note the photograph shows flooding in the Oroua River, which was not included in this model.*

As is described in Section 5.6, it was found that applying no infiltration helped produced flood outputs that were more representative of the observations made of the June 2015 flood event. While this approximation may appear to be conservative, this behaviour is not unexpected. As pervious areas become saturated during wet weather, infiltration generally declines and, in many soils, approaches zero. Use of the zero infiltration approximation implies that pre-saturation of the soil has taken place (precedent rainfall). Furthermore, given the poor drainage quality of soils, as shown in Figure 5.10, pre-saturation, particularly during winter conditions, is likely.

While removing soil infiltration resulted in modelled flood extents closely matching observed flood extents in most areas, the model appeared to underestimate observed flooding towards the southeast of the model domain, and conversely overestimate flooding in the southwest of the model domain. In an attempt to further match observed flooding, sensitivity testing of Manning's n roughness was undertaken whereby baseline values, detailed in Table 5.2, were altered by ± 50%. Reducing Manning's n resulted in a slight increase in flood extents in the southwest, as it caused time of concentration for catchment flows to decrease to the downstream boundary of the model where flood waters accumulate. While increasing Manning's n had little effect. Such Manning's n values are outside of the range typically used for these land uses, and given the relative ineffectiveness at better matching observed flood extents, were not considered to be an appropriate solution to better validate the model.

Other sensitivity testing, such as structure blockages and structure failures were considered unlikely to influence model validation to the flood event. There are several other factors, that were not modelled, that could influence the differences in modelled and observed flood extents, as below:

- As is mentioned above, the rainfall applied to the model for the flood event was recorded at Milson Line gauge, which is located immediately outside of the model domain close to Palmerston North airport. There is a possibility that rainfall intensity and volume varied spatially across the model domain during the rainfall event, and that the Milson Line gauge may have missed this spatial variation.
- The LiDAR DEM being used across the majority of the model domain, and in particular at the areas of discrepancies in modelled and observed flood extents, was captured in 2005, 10-years prior to the flood event. Any changes in terrain during this time will not be represented in the model, and could influence the volume distribution of flooding.

The difference in modelled and observed flooding was considered by T+T to be minor, and given the above possible discrepancies in input data, and inherent uncertainties in indicative flood extents being compared to, no further validation testing was undertaken.

Following model validation, no soil infiltration was chosen as the base case for all subsequent design flood event model runs.

# 7 Model run matrix

All model runs completed are summarised in Table 7.1 with reference given to the location of their respective outputs, as described further in Section 8.

Table 7.1: Model runs simulated

| Model Run | ARI rainfall (Present day) | Duration | Infiltration | Roughness | Figure Reference |
|---|---|---|---|---|---|
| *Model validation* | | | | | |
| 1 | June 2015 | | Without infiltration | Base Case | Appendix A |
| *Model design event sensitivity* | | | | | |
| 2 | 100 | 24 | Without infiltration | Base Case Manning's n +20 | Appendix B "fuzzy map" and depth difference maps |
| 3 | 100 | 24 | Without infiltration | Base Case Manning's n -20 | |
| 4 | 100 | 24 | Without infiltration | Base Case | |
| 5 | 100 | 24 | With infiltration | Base Case | |
| *Final design events* | | | | | |
| 6 | 2 | 1 | Without infiltration | Base Case | Appendix C C1 - critical duration map<br><br>Appendix D D1 and D5 - peak flood depth and velocity maps |
| 7 | | 6 | Without infiltration | Base Case | |
| 8 | | 12 | Without infiltration | Base Case | |
| 9 | | 24 | Without infiltration | Base Case | |
| 10 | | 48 | Without infiltration | Base Case | |
| 11 | | 72 | Without infiltration | Base Case | |
| 12 | 10 | 1 | Without infiltration | Base Case | Appendix C C2 - critical duration map<br><br>Appendix D D2 and D6 - peak flood depth and velocity maps |
| 13 | | 6 | Without infiltration | Base Case | |
| 14 | | 12 | Without infiltration | Base Case | |
| 15 | | 24 | Without infiltration | Base Case | |
| 16 | | 48 | Without infiltration | Base Case | |
| 17 | | 72 | Without infiltration | Base Case | |
| 18 | 100 | 1 | Without infiltration | Base Case | Appendix C C3 - critical duration map<br><br>Appendix D D3 and D7 - peak flood depth and velocity maps |
| 19 | | 6 | Without infiltration | Base Case | |
| 20 | | 12 | Without infiltration | Base Case | |
| 21 | | 24 | Without infiltration | Base Case | |
| 22 | | 48 | Without infiltration | Base Case | |
| 23 | | 72 | Without infiltration | Base Case | |
| 24 | 200 | 1 | Without infiltration | Base Case | Appendix C C4 - critical duration map<br><br>Appendix D D4 and D8 - peak flood depth and velocity maps |
| 25 | | 6 | Without infiltration | Base Case | |
| 26 | | 12 | Without infiltration | Base Case | |
| 27 | | 24 | Without infiltration | Base Case | |
| 28 | | 48 | Without infiltration | Base Case | |
| 29 | | 72 | Without infiltration | Base Case | |

# 8 Model results

## 8.1 Model Sensitivity

Four sensitivity tests were undertaken where model parameters were varied to determine the confidence in baseline flood outputs for the 100-year ARI design event with a 24-hour duration. Model sensitivity is likely to vary with ARI event and event duration, so for practicality purposes only the 24-hour duration was tested. The sensitivity tests included the following scenarios:

- Manning's n roughness + 20%;
- Manning's n roughness – 20%;
- With infiltration (refer Section 5.6); and
- No drainage channel lowering (refer Section 5.4.3).

Where Manning's n roughness values have been adjusted by ± 20%, this adjustment has been made to baseline values described in Section 5.3.

Appendix B shows a "fuzzy" map of the baseline and sensitivity model runs which gives an indication of results confidence in areas that are flood prone. The figure was produced by firstly removing any flood depths less than 0.1 m, as this is the threshold depth above which flooding has been considered to be "real" and not potentially an artefact of inaccuracies in the DEM. For each input grid (four sensitivity scenarios detailed above and the one corresponding baseline scenario (five in total)) the grid is classed as either 1, if the results grid is wet or 0, if dry. The total score for each grid cell is summed and then divided by the total number of input grids. A value of 1 indicates that the cell was wet in all simulations while a value of 0.20 indicates the cell was wet only once across all five simulations. Where the map is pink there is a low confidence of flooding, yellow and green indicate that the area may flood and the blue areas show areas that have greater than 0.1 m flood depth in all of the sensitivity runs. The blue areas show a high confidence that the area will flood for the event modelled.

Further analysis of the effects of adjustment of the individual parameters is also found in Appendix C, showing the change in peak flood depth caused by changing the individual parameters. The greatest change in flood outputs is caused by turning infiltration on, as this significant reduces the flood extent, as shown by the areas coloured blue in the "fuzzy" map, and reduction in peak flood depths by up to 1 m compared to using no infiltration. Model sensitivity to infiltration was also recognised in validation of model results to the June 2015 flood event, described further in Section 6, where turning infiltration off provided a better bit with estimated flood extents. Other sensitivity testing was shown to have a very minor effect on peak flood depths.

## 8.2 Critical Duration

Critical duration maps, based on maximum flood depth, for each ARI event are shown in Appendix C. These maps are intended to be read in conjunction with maximum flood depth maps to determine both the critical duration and the corresponding flood depth for specific areas of interest.

Critical duration across the model domain has been assessed as the event duration that generates the greatest flood depth at a given model cell. Critical duration varies for each ARI event modelled. That is, the same rainfall duration will not always yield the highest peak water level at a specific location for every ARI event. As expected, the 1-hour, 6-hour and 12-hour durations generally produce the greatest flood depths in upper catchment areas, while the 48-hour and 72-hour durations are most critical in lower catchment areas.

The six event durations selected were deemed representative of critical response times in the catchments modelled. It is acknowledged that the true critical duration could sit somewhere between, or either side of each of the four durations selected, however for the purposes of this flood mapping, modelling more event durations was considered to be beyond the level of detail required. Certain sites may require site-specific consideration, especially if deemed to be of high importance.

## 8.3 Model outputs

Model outputs, represented as "peak of peak" maximum outputs for each of the simulated ARI events have been derived. "Peak of peak" outputs are the enveloped maximum value for a given parameter (e.g. flood depth or velocity) reached at any one cell in the model domain across the six event durations simulated and provide a "worst-case" estimate. The "peak of peak" overlays do not come from any single event simulation, but are compiled from all event simulations. Table 8.1 shows an example of the process of enveloping model outputs to determine one result file.

Table 8.1: Process for deriving peak of peak model outputs

| Model run | Design event (ARI) | Rainfall event duration (hours) | Process | Result |
|---|---|---|---|---|
| 20 | 100 | 1 | Envelope to find maxima across all durations | "Peak of peak" 100-year ARI event data |
| 21 | | 6 | | |
| 22 | | 12 | | |
| 23 | | 24 | | |
| 24 | | 48 | | |
| 25 | | 72 | | |

Peak of peak flood depths and velocities are shown in Appendix D. Flood depths less than 0.1 m, and the corresponding velocity outputs at such depths, have been removed from flood maps as this is the threshold depth above which flooding has been considered with confidence as "real" and not potentially an artefact of inaccuracies in the DEM. Furthermore, peak of peak flood depths shown in Appendix D have been post-processed into high resolution grid outputs using the 1 m LiDAR DEM provided to T+T by Horizons. This was done by subtracting the LiDAR DEM from the peak of peak flood level grid outputs.

It is worth reiterating that the modelling undertaken has been based on remotely sensed ground levels (LiDAR survey) and on design future rainfall events, both of which have accuracy limitations. The model results have generally been presented only to show flooding where maximum depth in excess of 50 mm has been estimated, as per Horizons standard flood mapping guidelines. Furthermore, a direct rainfall approach has been applied, which can highlight accuracy deficiencies in input data by showing small "puddles" in predicted flooding. It is usual with flood depth results from this kind of modelling approach that the results be "cleaned" by removing puddles before publication. T+T has presented raw model results in this report, in anticipation of Horizons undertaking "cleaning" of model result before any form of publication or further use.

# 9 Advised model improvements

The following points are advised for improving the performance of the model, that Horizons may wish to consider moving forward with future development of the model.

- Model calibration – calibration of the model to known recorded data points is advised where possible to provide greater confidence in model outputs. There is no known monitoring data available in the MDS catchment. It is therefore advised that Horizons consider the installation of water level and rainfall monitoring devises in the MDS catchment to capture future rainfall events for use in model calibration. Rain-radar capture during flood events may also provide spatially varied rainfall that could be applied to future calibration/validation of the model. We advise that Horizons investigate means by which rainfall radar data can be captured (e.g. from Metservice) and processed.
- Terrain survey – as specific areas of the model become the focus of further investigation, it is advised that Horizons consider the quality of terrain data applied to the model, both in terms of the date it was captured and whether it is out-of-date, and the quality of the data to represent key hydraulic features (e.g., whether the LiDAR survey DEM accurately captures ground conditions, especially in areas of dense vegetation and water surfaces).

  Furthermore, LiDAR data covering the majority of the model domain was captured in 2004 and as such any changes to landform since the capture of this data will not be represented in the model. It is therefore advised that updated LiDAR is captured to improve the accuracy of outputs generated from the model.
- Land use characteristics – as above, where specific areas of the model become the focus of further investigation, it is advised that land use characteristics, such as Manning's n roughness zones and impervious surfaces, are updated, where necessary, to capture out-of-date information and refine the catchment-wide estimates made in this model build.
- Hydrology – it is advised that further consideration is given to the inclusion of design flood inflow hydrographs at the three spillway location (Mangaone, Kopane and Rangiotu) entering the model domain.

# 10 Summary

A TUFLOW Quadtree 1D/2D coupled hydraulic model has been built for a catchment encompassing the Manawatu Drainage Scheme. The purpose of this work was to provide a better understanding of the flood hazard within rural zoned areas subject to development and rezoning pressure where there is currently limited flood hazard information available.

The model included several hydraulic structures such as culverts, flap-gates, bridges and pumps, that are represented in the model as 1D elements linked to the 2D model domain and 2D elements using TUFLOW layered flow constriction. Data for hydraulic structures was sourced from Horizons and was composed of survey undertaken in 2020, GIS data from the MDS asset database, and data extracted from the existing Oroua MIKE11 hydraulic model.

The model utilised direct rainfall hydrology across the full hydraulic model domain, derived from rainfall depths sourced from HIRDSV4. Hydrological losses have been considered using soil infiltration parameters and land use roughness coefficients.

Model outputs were verified against the June 2015 flood event using recorded rainfall data, inflow hydrographs at three spillway locations, and observed flood extents provided by Horizons. To achieved comparable flood extents using the model, soil infiltration losses were turned off, which is considered appropriate by T+T given the poor soil drainage characteristics, resulting in a reasonable fit with observed data.

The model was run for 2-year, 10-year, 100-year and 200-year ARI design flood events using a present-day climate. 1-hour, 6-hour, 12-hour, 24-hour, 48-hour and 72-hour durations were run through the model for each ARI event, which revealed that some areas of the model domain responded differently to different rainfall intensities. As such, maximum flood outputs, such as depths and velocities, have been derived collectively based on maximum flood depth at critical durations across the model.

Maximum flood depth and velocity maps have been derived from model results, along with maps showing maximum flood depth critical duration. WaterRIDE files and maximum output grids have been developed and provided to Horizons under separate cover for more detailed interrogation.

# 11 References

DHI (2008). Oroua and Manawatū Rivers Flood Hazard Assessment, Hydraulic Modelling and Mapping. Report issued to Horizons Regional Council 03/04/2008. Project Number NZ50084

NIWA, 2015. The Climate and Weather of Manawatu-Wanganui - 2nd Edition. Niwa science and technology series number 66. ISSN 1173-0382

# 12 Applicability

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

Tonkin & Taylor Ltd

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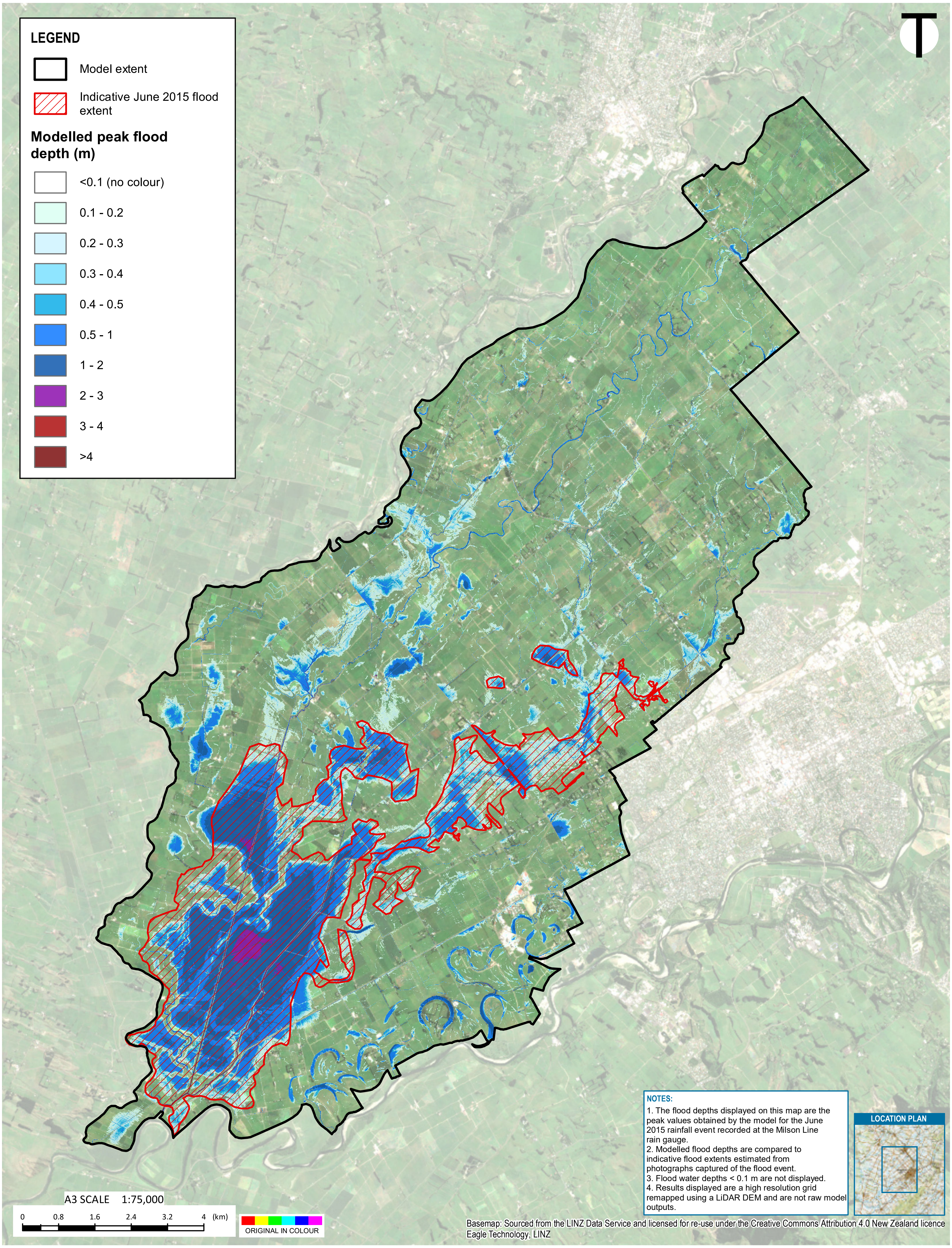
# Appendix A: June 2015 Event



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NOTES:
To be read in conjunction with the Manawatu Drainage Scheme TUFLOW Model Build Report. The information presented on these figures is based on a numerical representation of the physical reality and is reliant upon input data and therefore bears uncertainty.

| REV | DESCRIPTION | GIS | CHK | DATE | APPROVED | DATE |
|---|---|---|---|---|---|---|
| 0 | Final | MICF | MSP | 21/04/21 | KCG | APR.21 |

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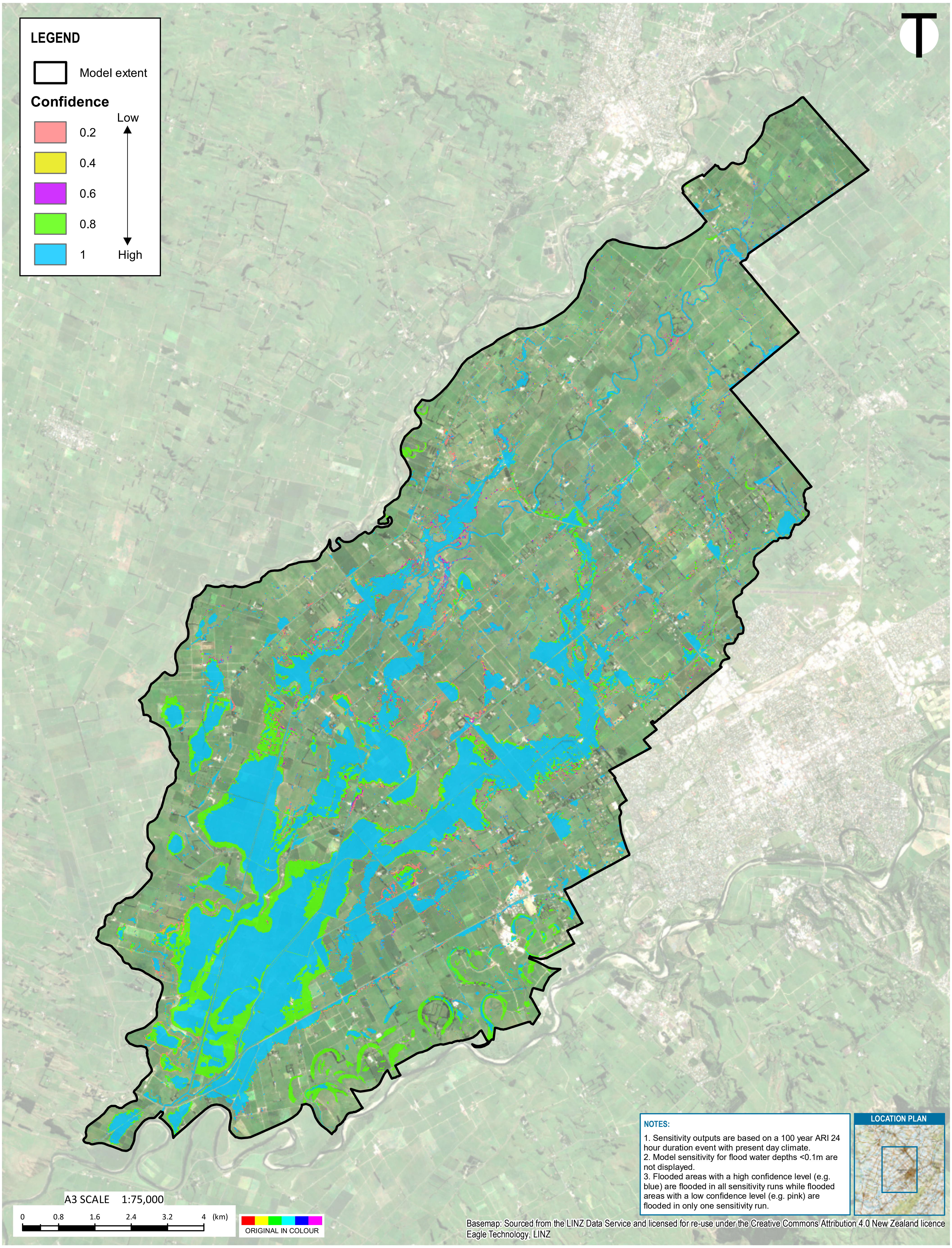
|---|---|---|
| PROJECT No. | 1011962.01 | |
| DESIGNED | HSMI | APR.21 |
| DRAWN | MICF | APR.21 |
| CHECKED | MSP | APR.21 |

CLIENT **HORIZONS REGIONAL COUNCIL**
PROJECT **MANAWATU DRAINAGE SCHEME FLOOD MODELLING**
TITLE PEAK FLOOD DEPTH
JUNE 2015 GAUGED RAINFALL EVENT
SCALE (A3) 1:75,000 FIG No. FIGURE A1. REV 0

# Appendix B: Model sensitivity testing

- Figure B1. 100-year ARI 24-hour duration fuzzy map
- Figure B2. 100-year ARI 24-hour duration high roughness difference map
- Figure B3. 100-year ARI 24-hour duration low roughness difference map
- Figure B4. 100-year ARI 24-hour duration infiltration difference map
- Figure B4. 100-year ARI 24-hour duration channel lowering difference map



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| PROJECT No. | 1011962.01 | |
| DESIGNED | HSMI | APR.21 |
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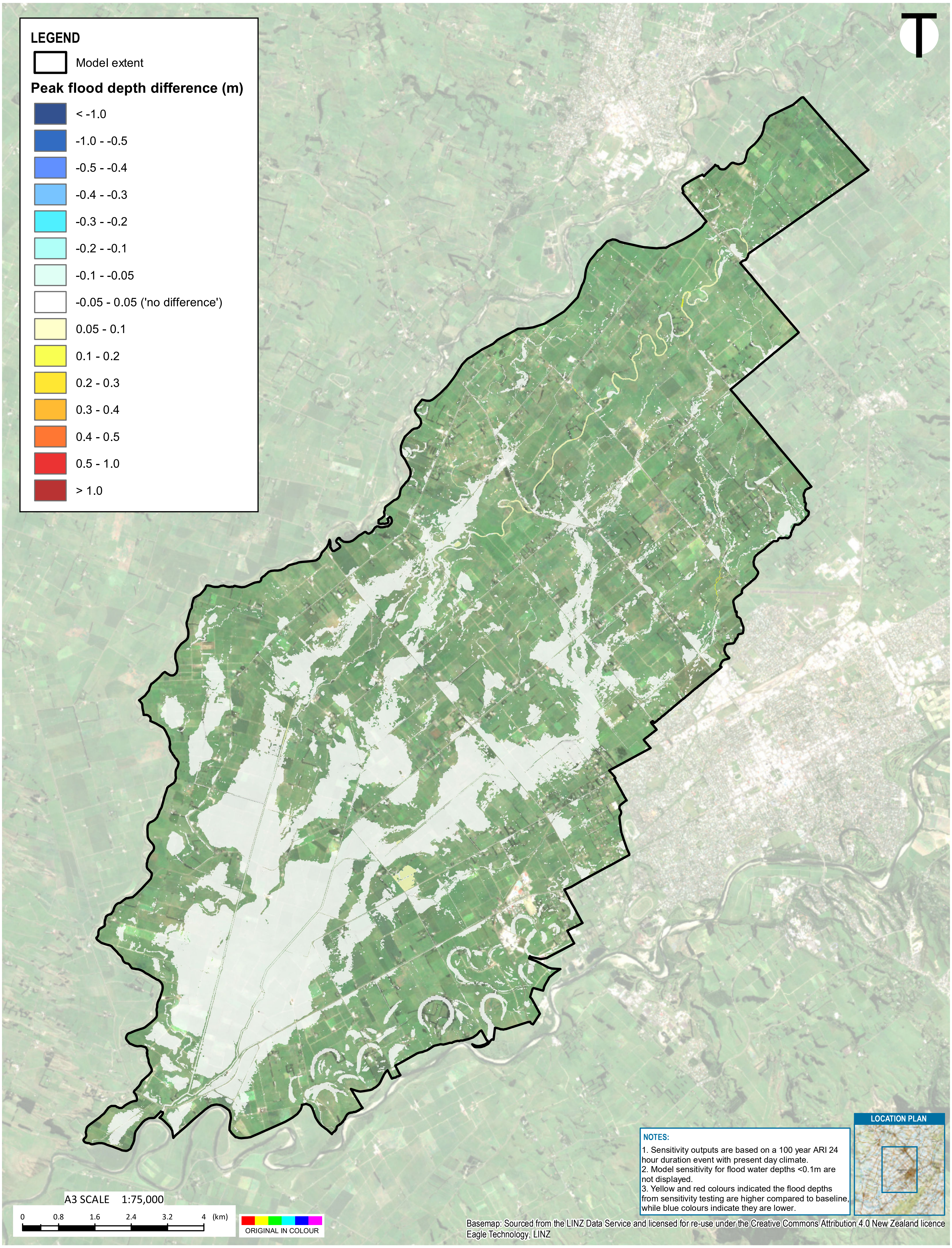
| CHECKED | MSP | APR.21 |
| APPROVED | KCG | APR.21 |

CLIENT HORIZONS REGIONAL COUNCIL
PROJECT MANAWATU DRAINAGE SCHEME FLOOD MODELLING
TITLE PEAK FLOOD DEPTH SENSITIVITY "FUZZY" MAP
100 YEAR ARI 24 HOUR DURATION PRESENT-DAY DESIGN EVENT
SCALE (A3) 1:75,000 FIG No. FIGURE B1. REV 0

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| REV | DESCRIPTION | GIS | CHK | DATE |
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| PROJECT No. | 1011962.01 | |
| DESIGNED | HSMI | APR.21 |
| DRAWN | MICF | APR.21 |
| CHECKED | MSP | APR.21 |
| APPROVED | KCG | APR.21 |

CLIENT HORIZONS REGIONAL COUNCIL
PROJECT MANAWATU DRAINAGE SCHEME FLOOD MODELLING
TITLE HIGH ROUGHNESS SENSITIVITY PEAK FLOOD DEPTH DIFFERENCE
100 YEAR ARI 24 HOUR DURATION PRESENT-DAY DESIGN EVENT
SCALE (A3) 1:75,000 FIG No. FIGURE B2. REV 0


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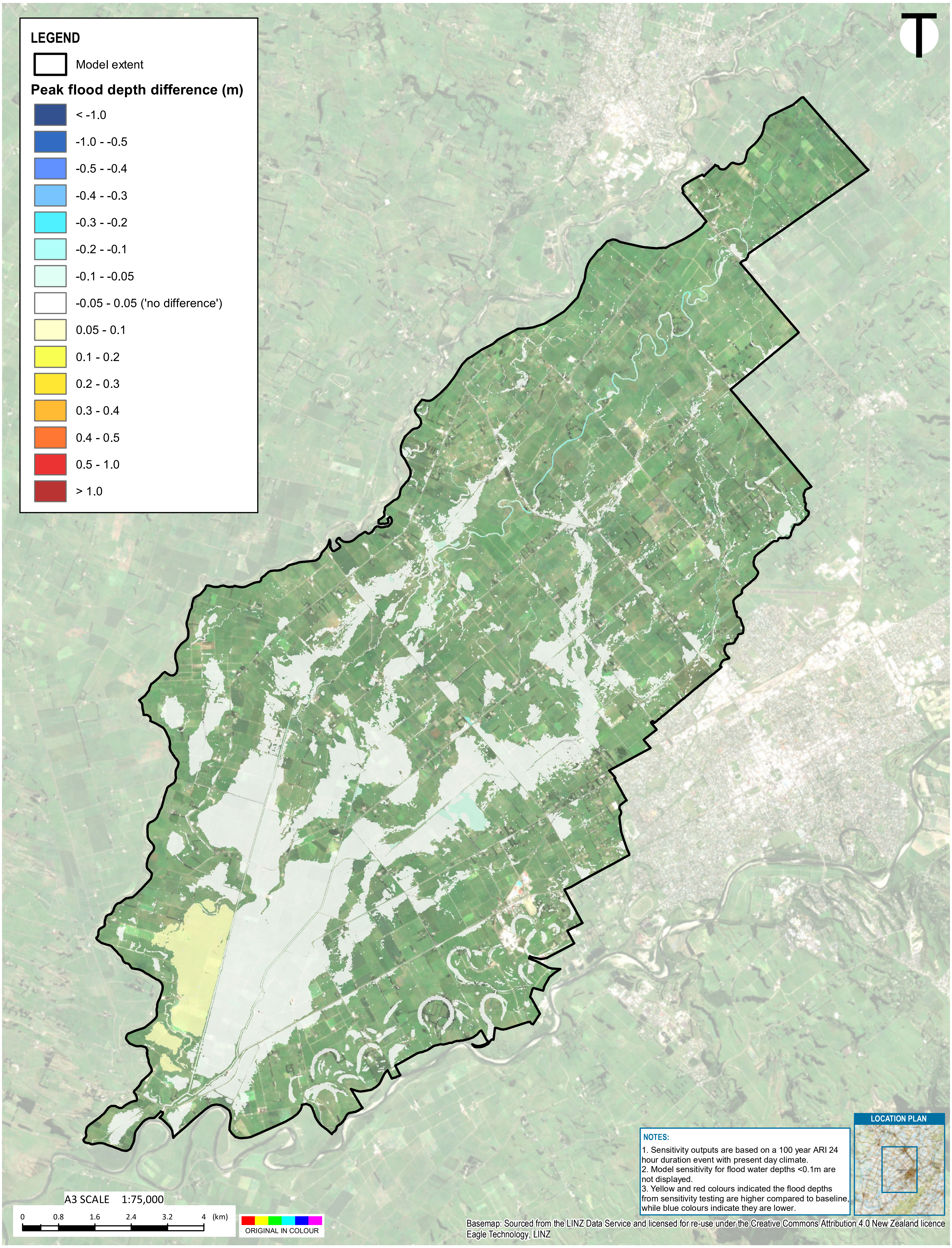




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| DESIGNED | HSMI | APR.21 |
| DRAWN | MICF | APR.21 |
| CHECKED | MSP | APR.21 |
| APPROVED | KCG | APR.21 |

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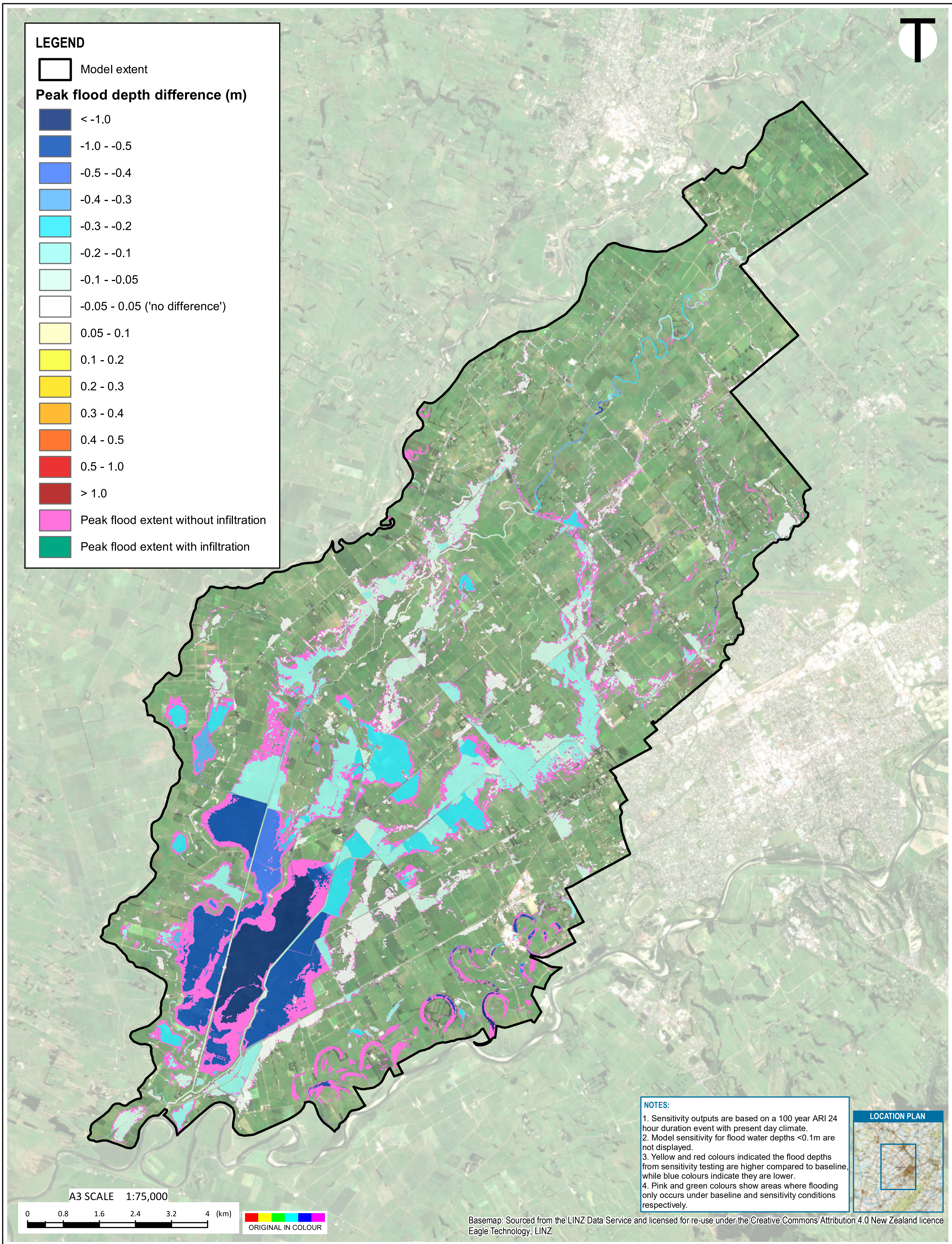
PROJECT **MANAWATU DRAINAGE SCHEME FLOOD MODELLING**
TITLE LOW ROUGHNESS SENSITIVITY PEAK FLOOD DEPTH DIFFERENCE
100 YEAR ARI 24 HOUR DURATION PRESENT-DAY DESIGN EVENT
SCALE (A3) 1:75,000 FIG No. FIGURE B3. REV 0



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| REV | DESCRIPTION | GIS | CHK | DATE |
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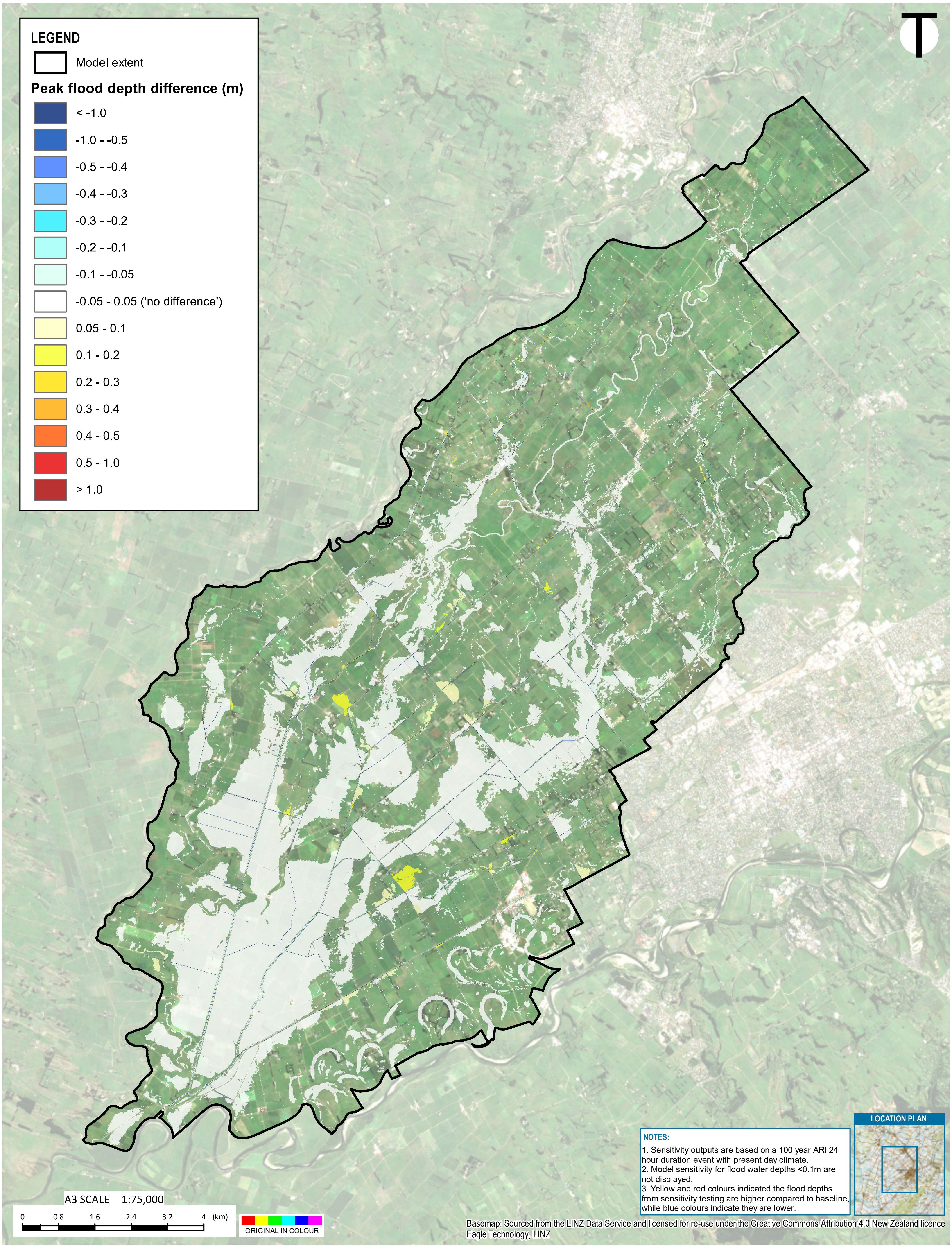
| DESIGNED | HSMI | APR.21 |
| DRAWN | MICF | APR.21 |
| CHECKED | MSP | APR.21 |
| APPROVED | KCG | APR.21 |

CLIENT: HORIZONS REGIONAL COUNCIL
PROJECT: MANAWATU DRAINAGE SCHEME FLOOD MODELLING
TITLE: INFILTRATION SENSITIVITY PEAK FLOOD DEPTH DIFFERENCE
100 YEAR ARI 24 HOUR DURATION PRESENT-DAY DESIGN EVENT
SCALE (A3) 1:75,000 FIG No. FIGURE B4. REV 0



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NOTES:
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| REV | DESCRIPTION | GIS | CHK | DATE |
|---|---|---|---|---|
| 0 | Final | MICF | MSP | 23/04/21 |

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| PROJECT No. | 1011962.01 | |
| DESIGNED | HSMI | APR.21 |
| DRAWN | MICF | APR.21 |
| CHECKED | MSP | APR.21 |
| APPROVED | KCG | APR.21 |

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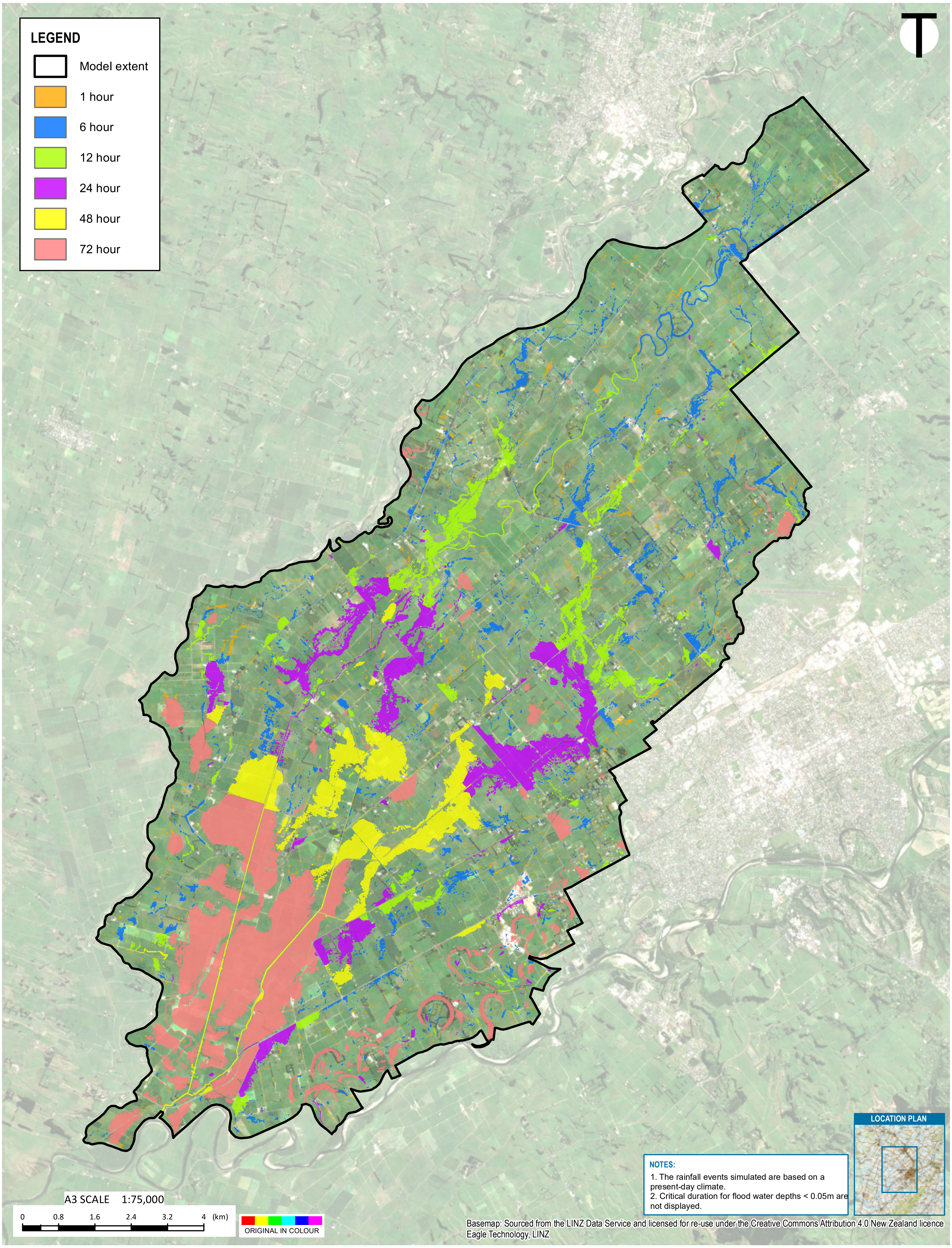
PROJECT MANAWATU DRAINAGE SCHEME FLOOD MODELLING

TITLE CHANNEL LOWERING SENSITIVITY PEAK FLOOD DEPTH DIFFERENCE 100 YEAR ARI 24 HOUR DURATION PRESENT-DAY DESIGN EVENT

SCALE (A3) 1:75,000 FIG No. FIGURE B5. REV 0

# Appendix C: Maximum flood depth critical durations

- Figure C1. 2-year ARI present-day maximum depth critical durations
- Figure C2. 10-year ARI present-day maximum depth critical durations
- Figure C3. 100-year ARI present-day maximum depth critical durations
- Figure C4. 200-year ARI present-day maximum depth critical durations



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| 0 | Final | MICF | MSP | 21/10/21 |

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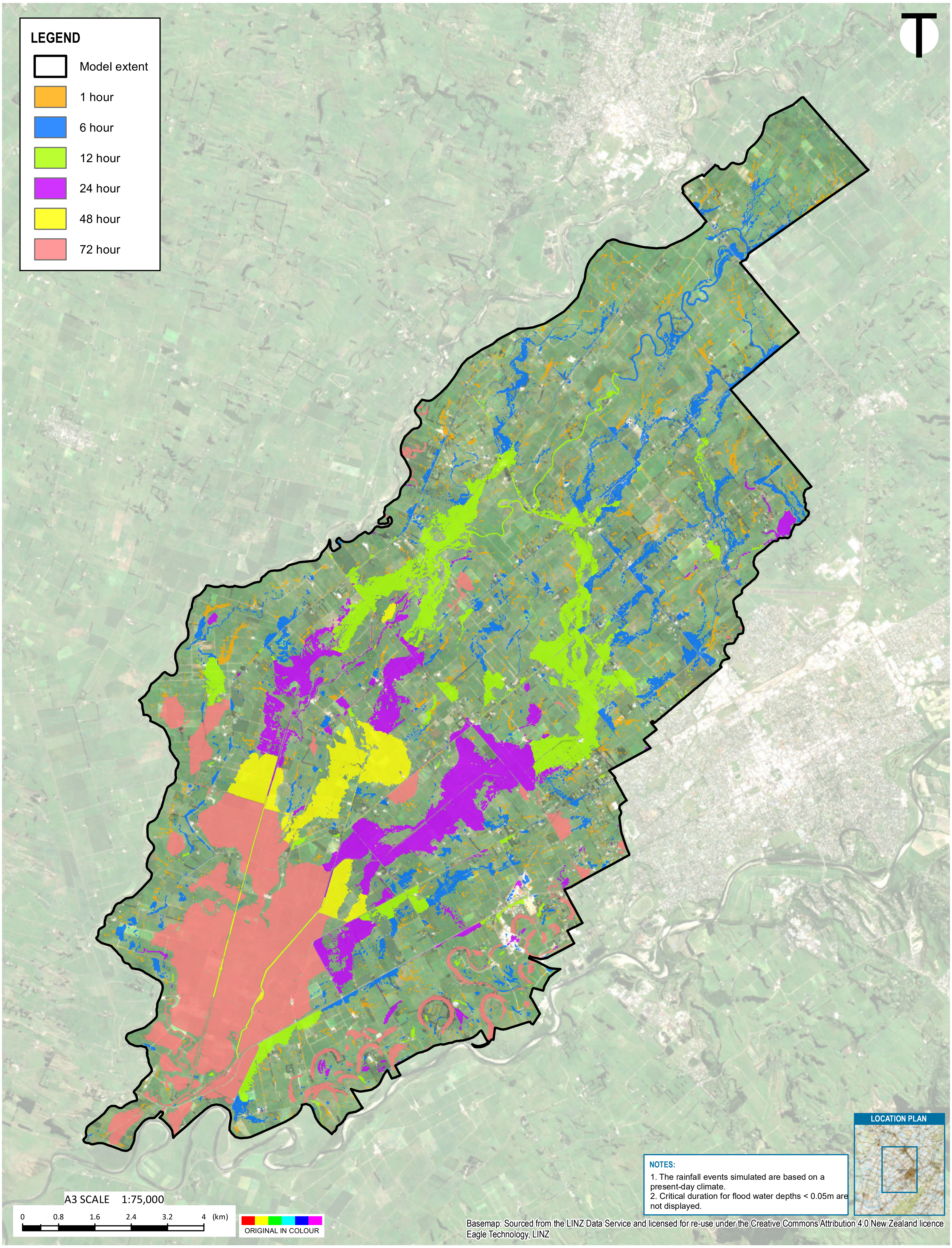
TITLE PEAK FLOOD DEPTH CRITICAL DURATION
2 YEAR ARI PRESENT-DAY DESIGN EVENT
SCALE (A3) 1:75,000 FIG No. FIGURE C1. REV 0




NOTES:
1. The rainfall events simulated are based on a present-day climate.
2. Critical duration for flood water depths < 0.05m are not displayed.

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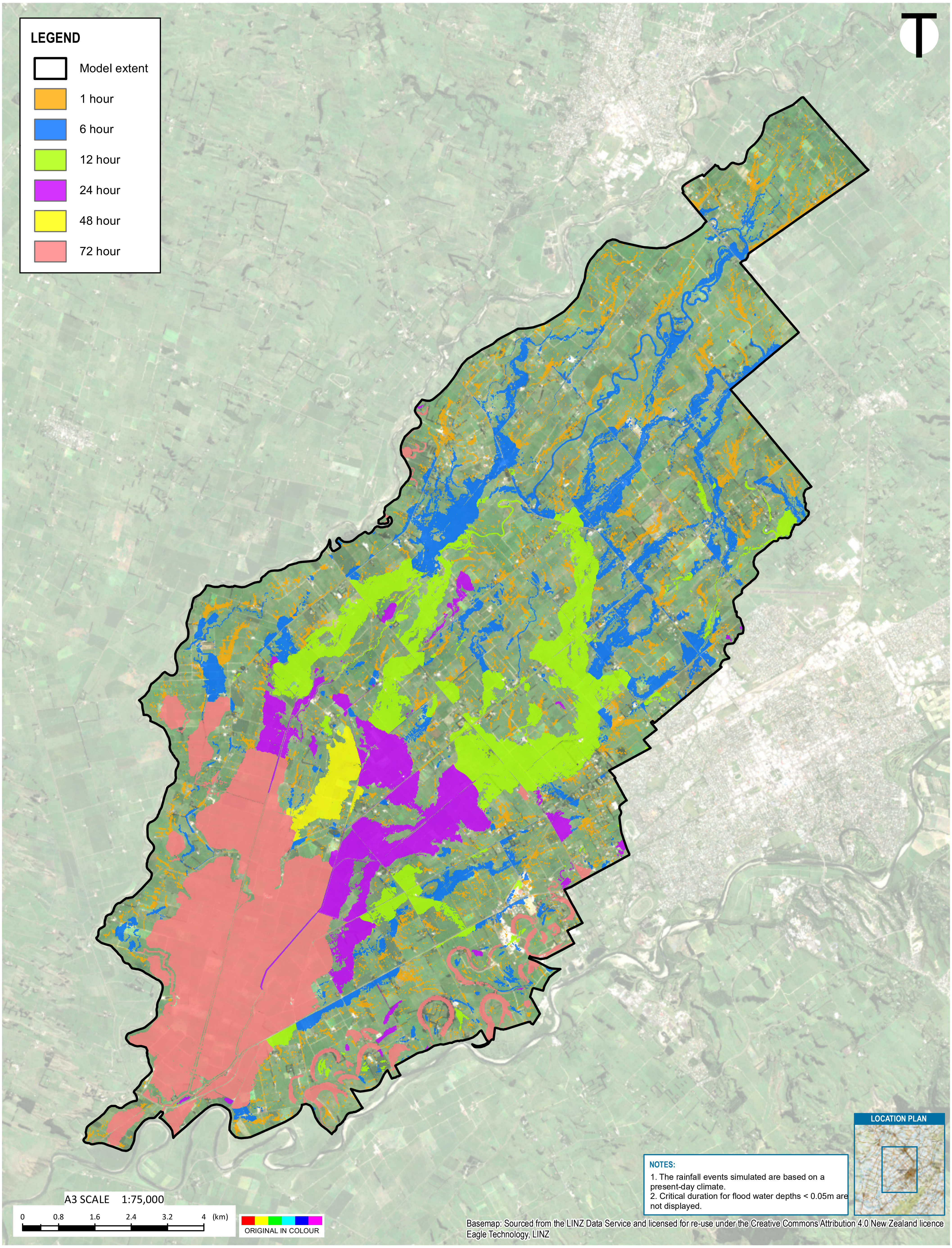
TITLE PEAK FLOOD DEPTH CRITICAL DURATION
10 YEAR ARI PRESENT-DAY DESIGN EVENT
SCALE (A3) 1:75,000 FIG No. FIGURE C2. REV 0



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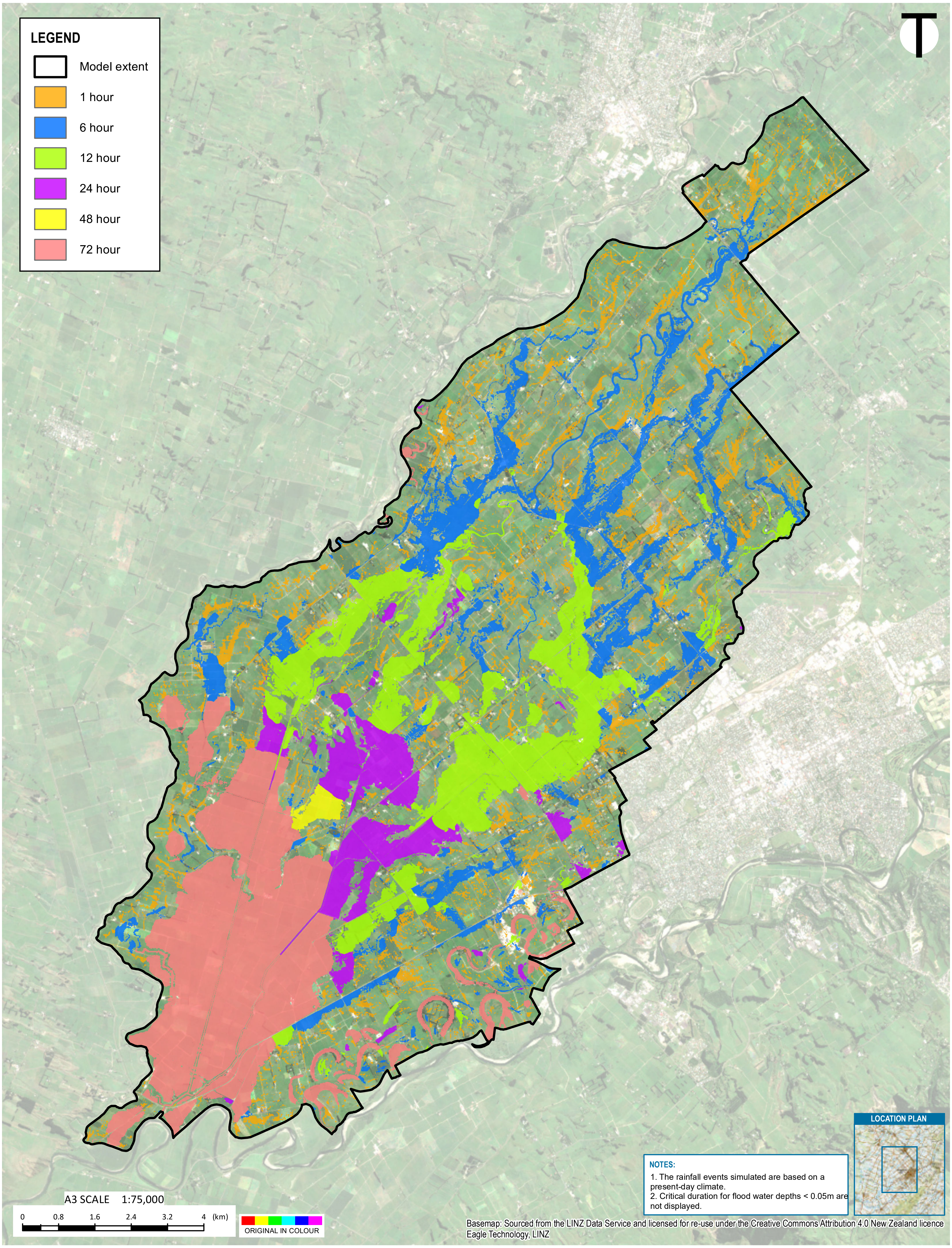
**TITLE** PEAK FLOOD DEPTH CRITICAL DURATION
100 YEAR ARI PRESENT-DAY DESIGN EVENT
**SCALE (A3)** 1:75,000 **FIG No.** FIGURE C3. **REV** 0



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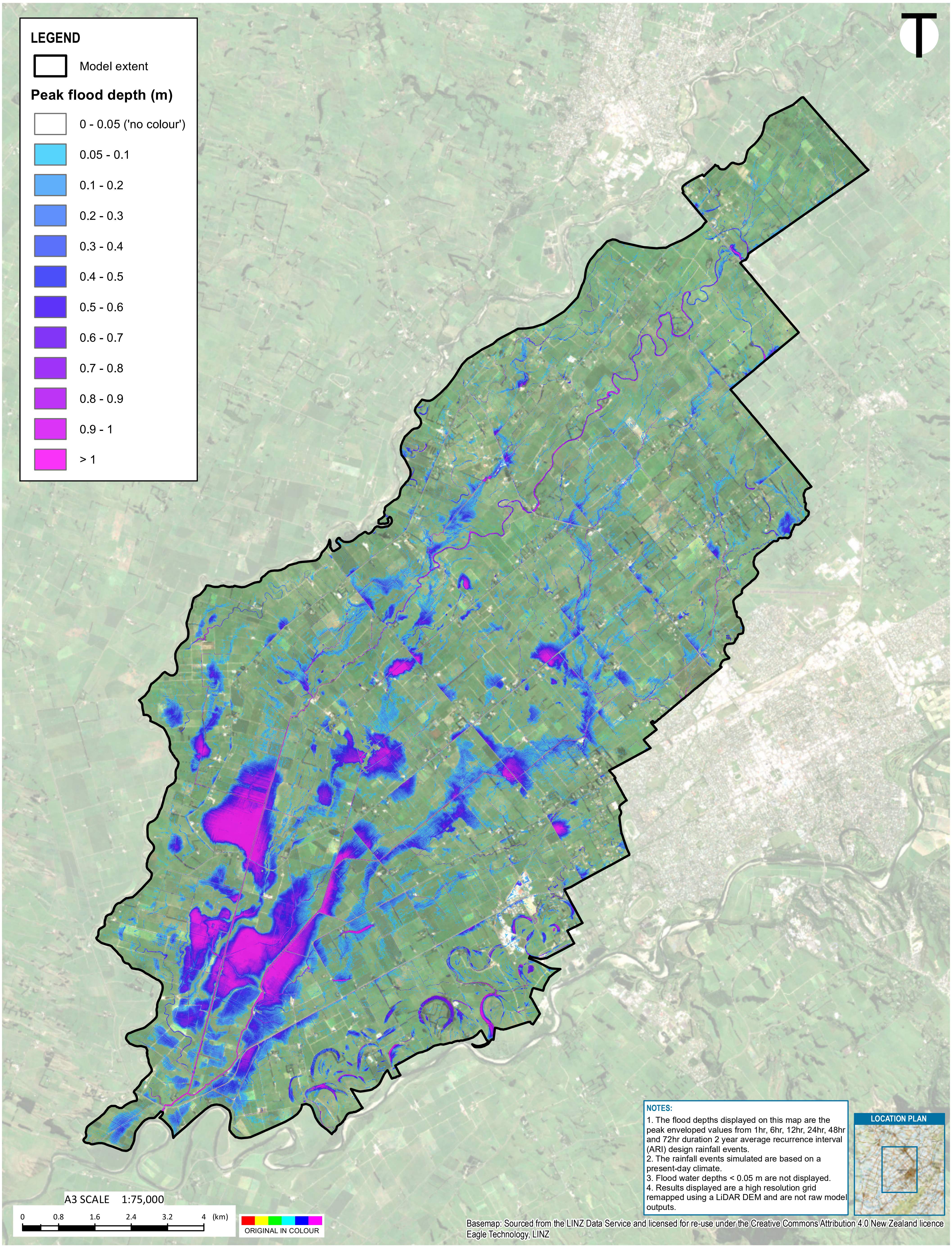
| TITLE | PEAK FLOOD DEPTH CRITICAL DURATION<br>200 YEAR ARI PRESENT-DAY DESIGN EVENT |
| SCALE (A3) | 1:75,000 |
| FIG No. | FIGURE C4. |
| REV | 0 |

# Appendix D: Peak of peak flood maps

- Figure D1. 2-year ARI present-day maximum flood depth
- Figure D2. 10-year ARI present-day maximum flood depth
- Figure D3. 100-year ARI present-day maximum flood depth
- Figure D4. 200-year ARI present-day maximum flood depth
- Figure D5. 2-year ARI present-day maximum flood velocity
- Figure D6. 10-year ARI present-day maximum flood velocity
- Figure D7. 100-year ARI present-day maximum flood velocity
- Figure D8. 200-year ARI present-day maximum flood velocity




**NOTES:**

1. The flood depths displayed on this map are the peak enveloped values from 1hr, 6hr, 12hr, 24hr, 48hr and 72hr duration 2 year average recurrence interval (ARI) design rainfall events.
2. The rainfall events simulated are based on a present-day climate.
3. Flood water depths < 0.05 m are not displayed.
4. Results displayed are a high resolution grid remapped using a LiDAR DEM and are not raw model outputs.



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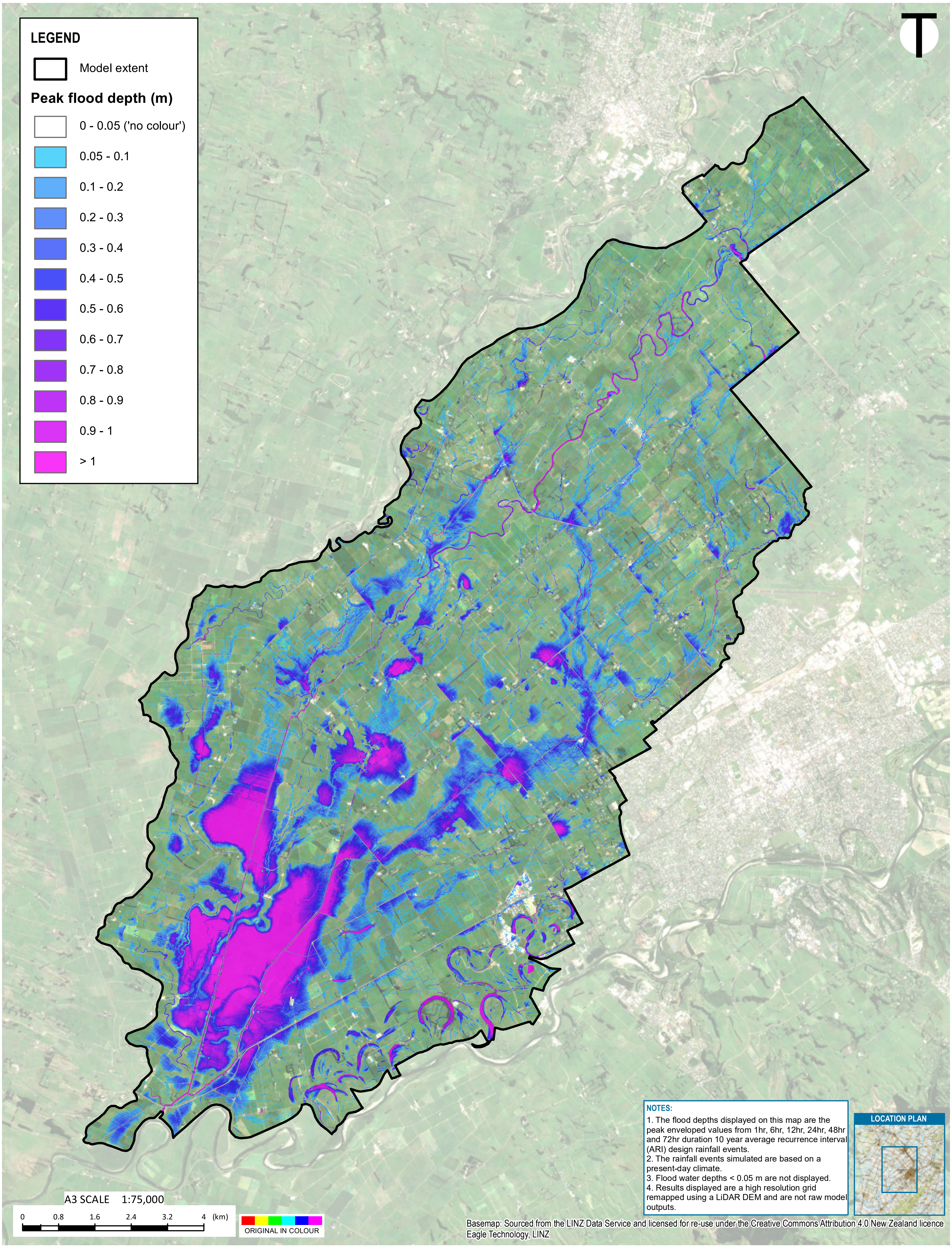
**TITLE** PEAK FLOOD DEPTH
2 YEAR ARI PRESENT-DAY DESIGN EVENT

SCALE (A3) 1:75,000 FIG No. FIGURE D1. REV 0




NOTES:
1. The flood depths displayed on this map are the peak enveloped values from 1hr, 6hr, 12hr, 24hr, 48hr and 72hr duration 10 year average recurrence interval (ARI) design rainfall events.
2. The rainfall events simulated are based on a present-day climate.
3. Flood water depths < 0.05 m are not displayed.
4. Results displayed are a high resolution grid remapped using a LiDAR DEM and are not raw model outputs.



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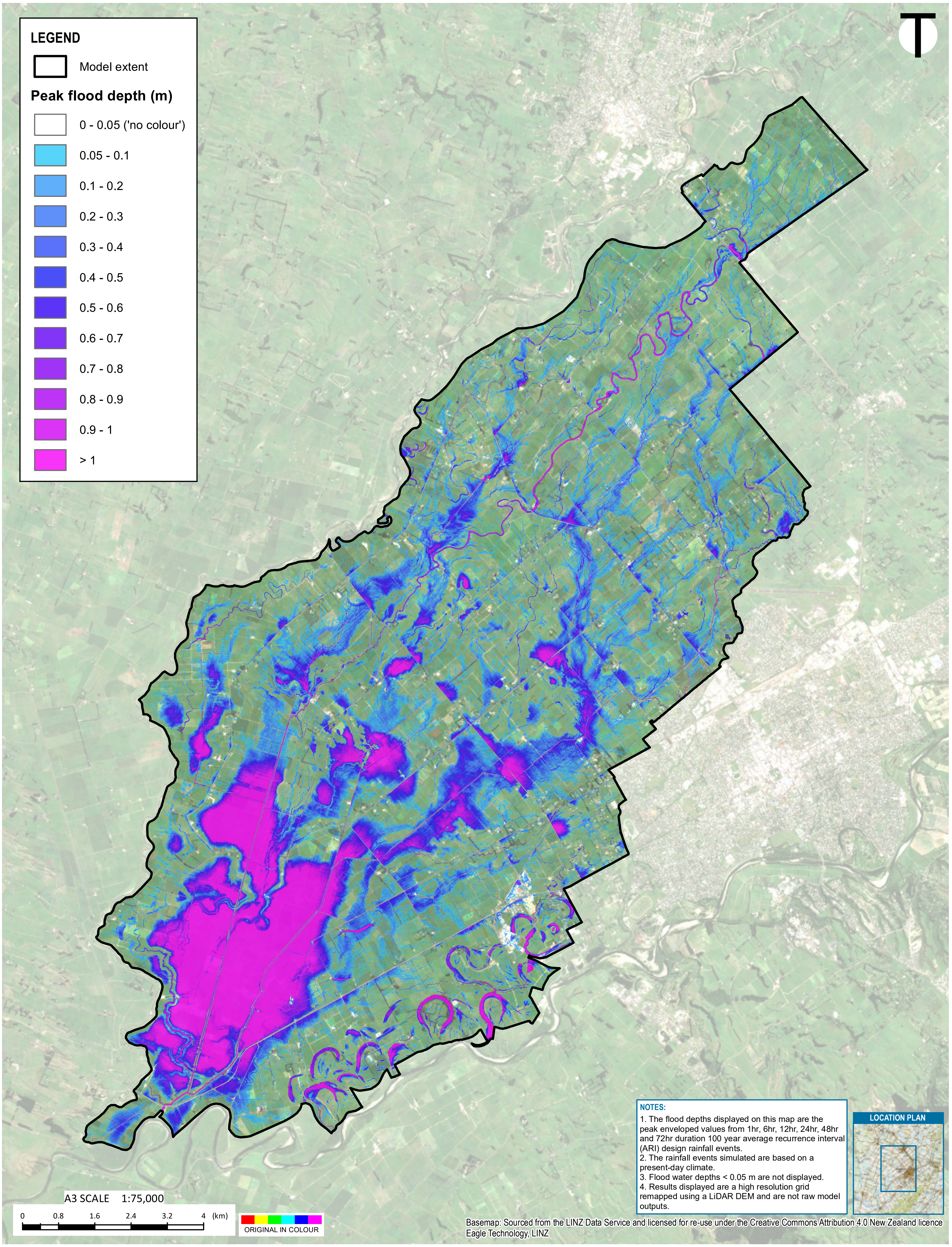
TITLE PEAK FLOOD DEPTH
10 YEAR ARI PRESENT-DAY DESIGN EVENT
SCALE (A3) 1:75,000 FIG No. FIGURE D2. REV 0



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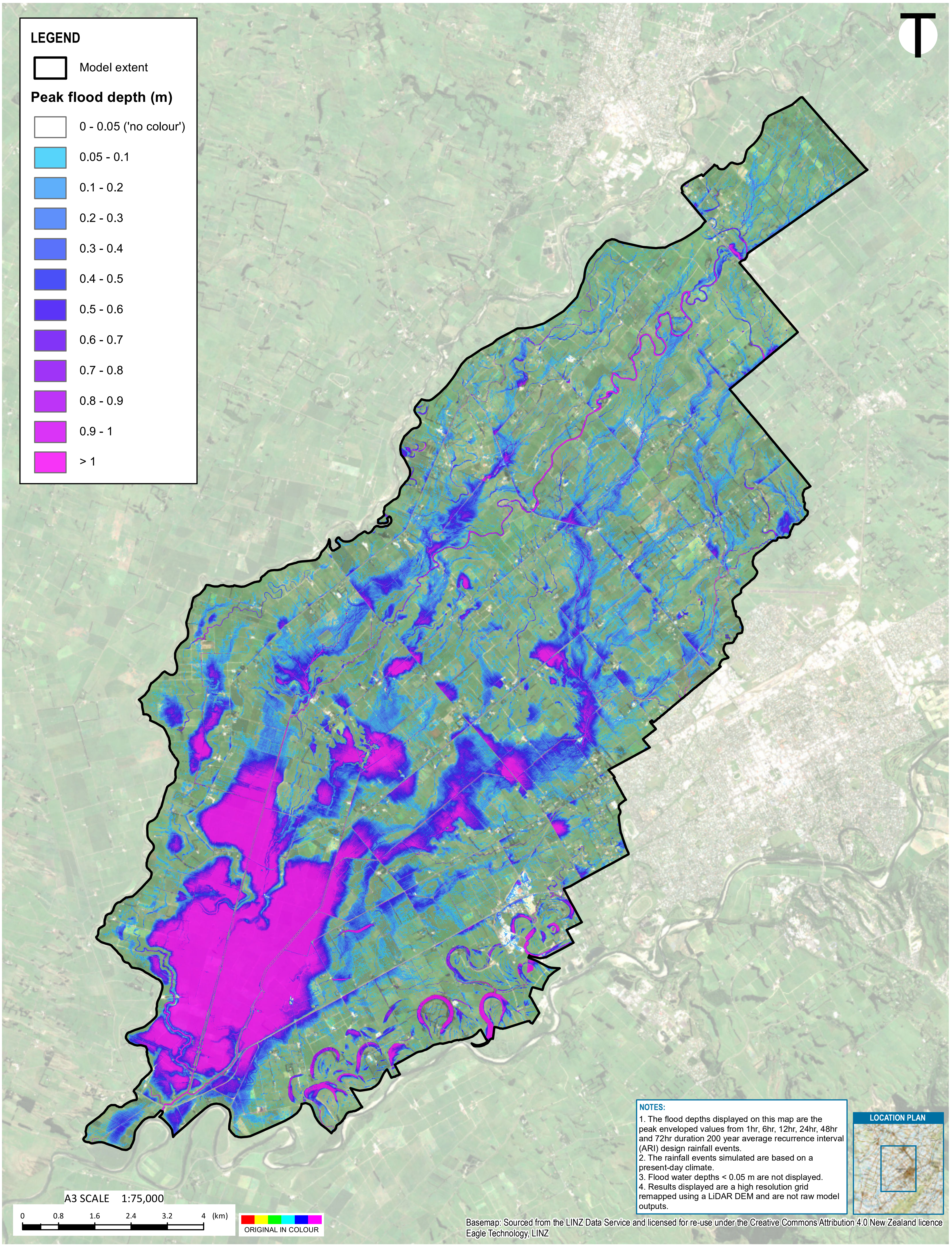
TITLE PEAK FLOOD DEPTH
100 YEAR ARI PRESENT-DAY DESIGN EVENT
SCALE (A3) 1:75,000 FIG No. FIGURE D3. REV 0



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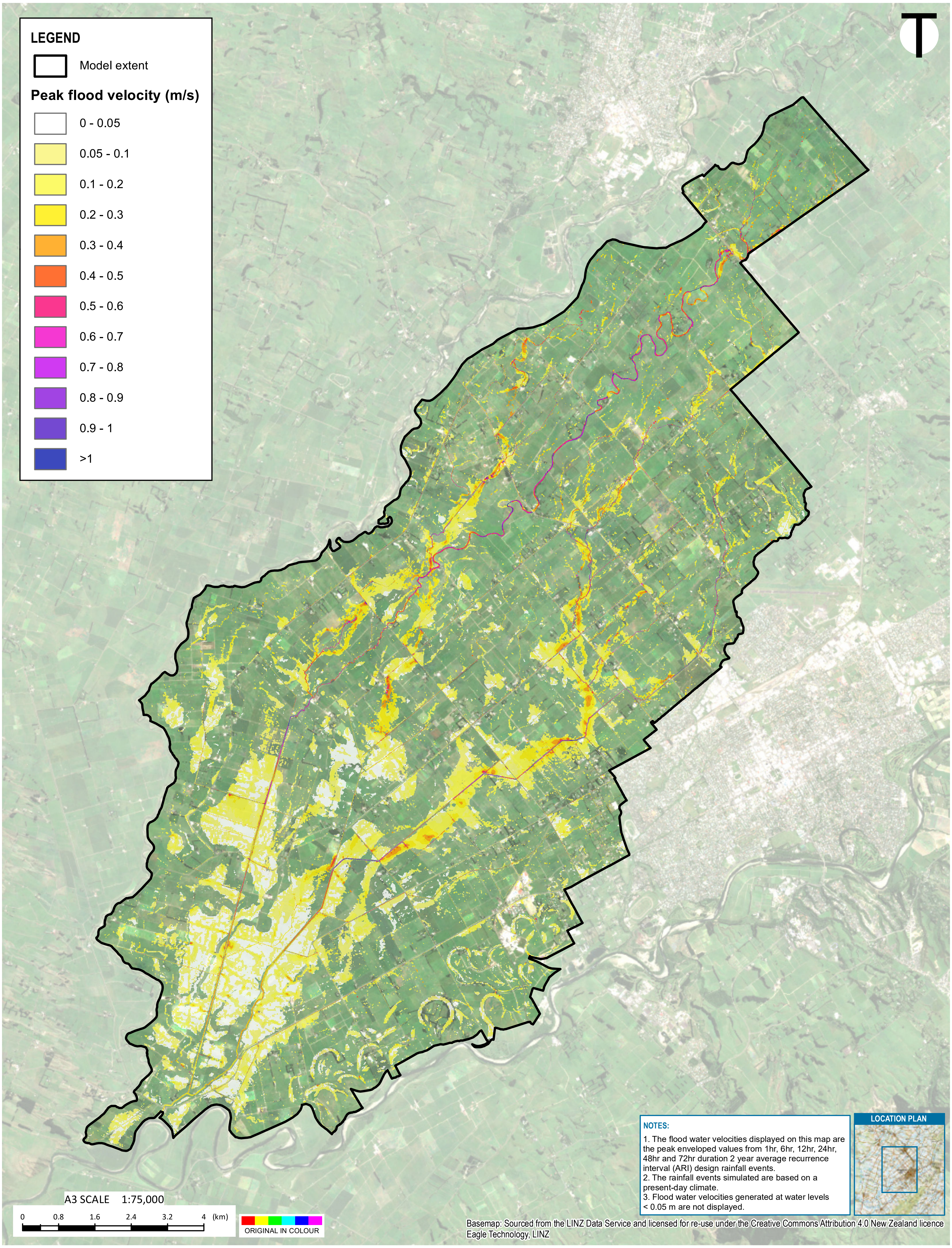
TITLE PEAK FLOOD DEPTH
200 YEAR ARI PRESENT-DAY DESIGN EVENT
SCALE (A3) 1:75,000 FIG No. FIGURE D4. REV 0



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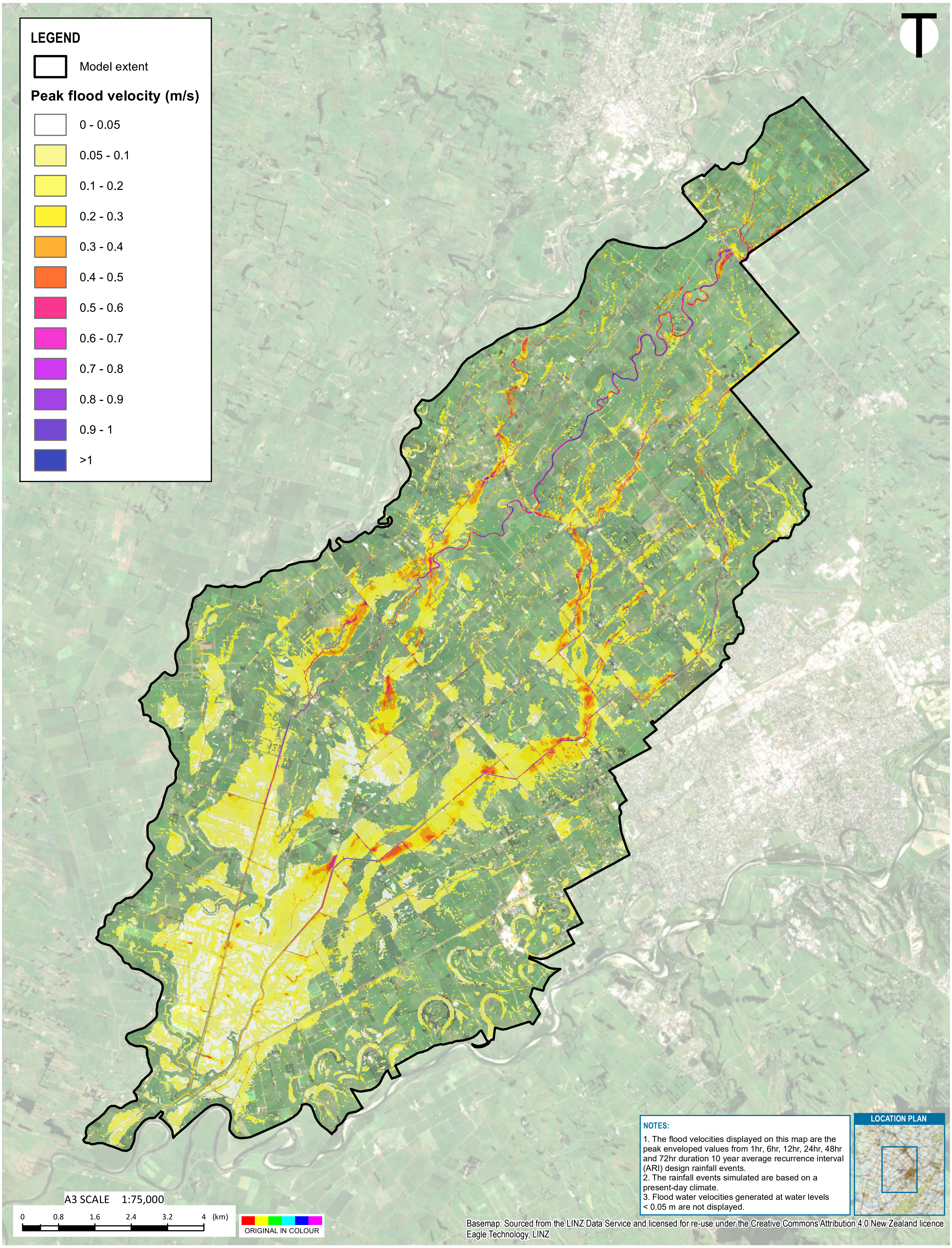
TITLE PEAK FLOOD VELOCITY
2 YEAR ARI PRESENT-DAY DESIGN EVENT
SCALE (A3) 1:75,000 FIG No. FIGURE D5. REV 0



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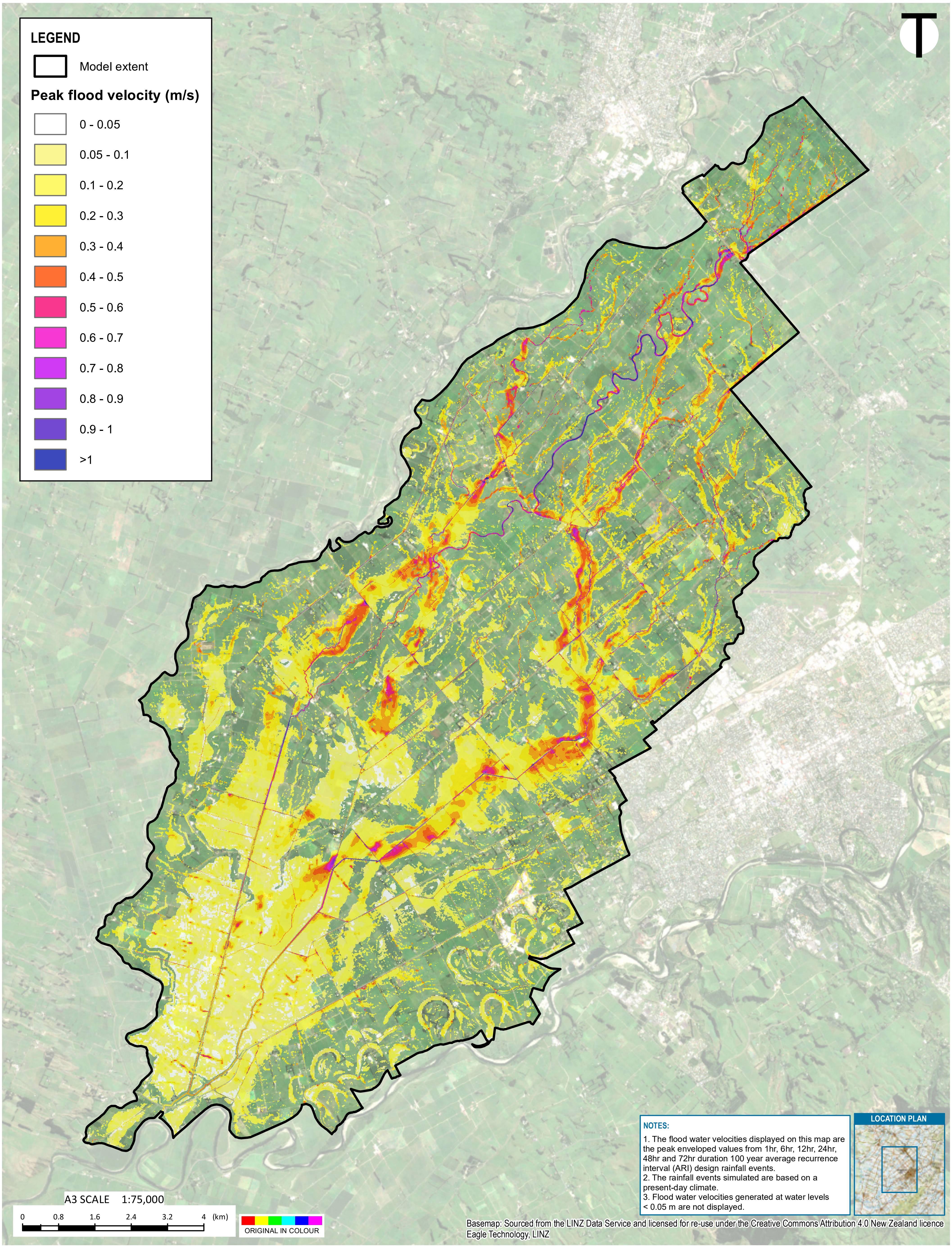
TITLE PEAK FLOOD VELOCITY
10 YEAR ARI PRESENT-DAY DESIGN EVENT
SCALE (A3) 1:75,000 FIG No. FIGURE D6. REV 0



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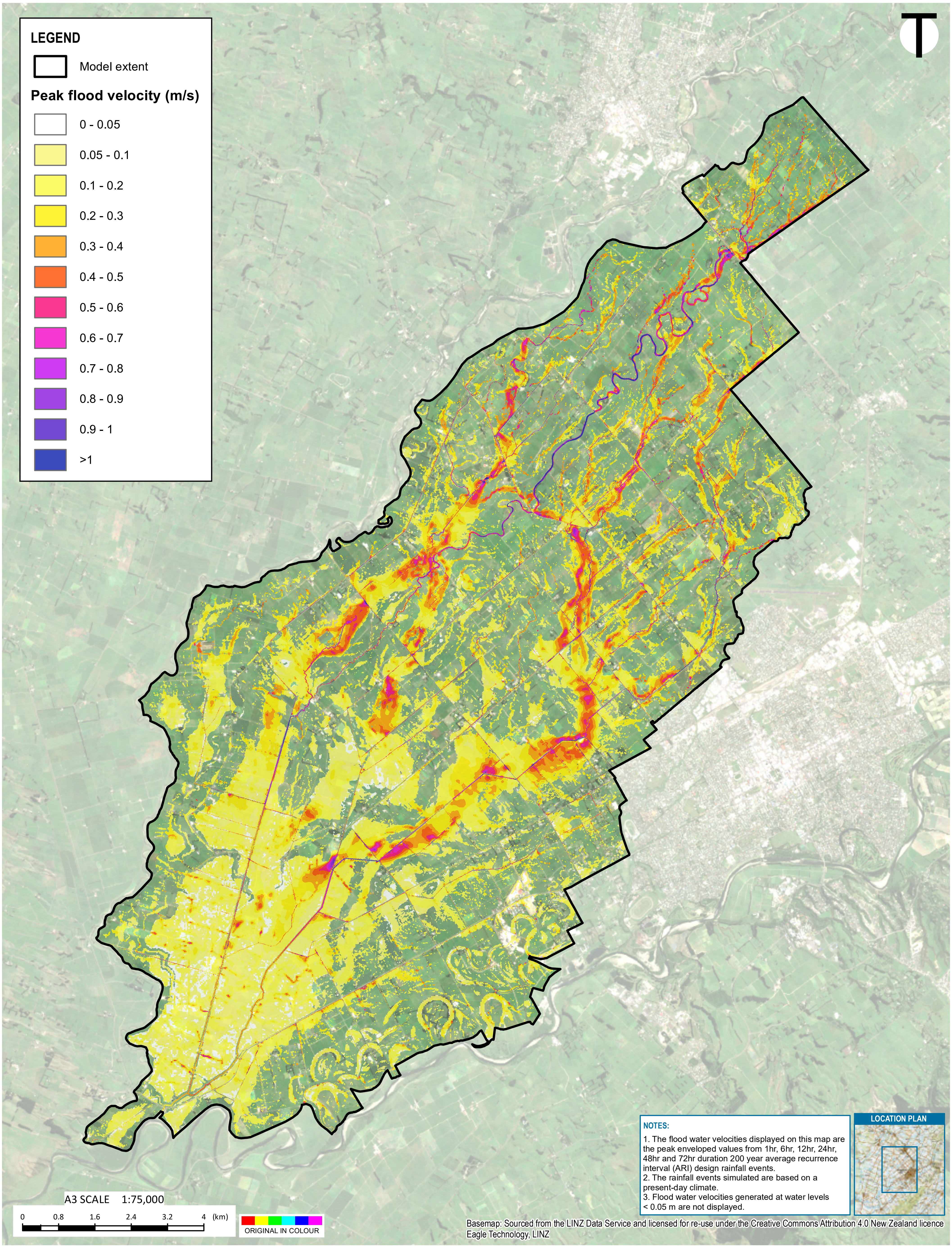
TITLE PEAK FLOOD VELOCITY
100 YEAR ARI PRESENT-DAY DESIGN EVENT
SCALE (A3) 1:75,000 FIG No. FIGURE D7. REV 0




NOTES:
1. The flood water velocities displayed on this map are the peak enveloped values from 1hr, 6hr, 12hr, 24hr, 48hr and 72hr duration 200 year average recurrence interval (ARI) design rainfall events.
2. The rainfall events simulated are based on a present-day climate.
3. Flood water velocities generated at water levels < 0.05 m are not displayed.





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200 YEAR ARI PRESENT-DAY DESIGN EVENT
SCALE (A3) 1:75,000 FIG No. FIGURE D8. REV 0

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