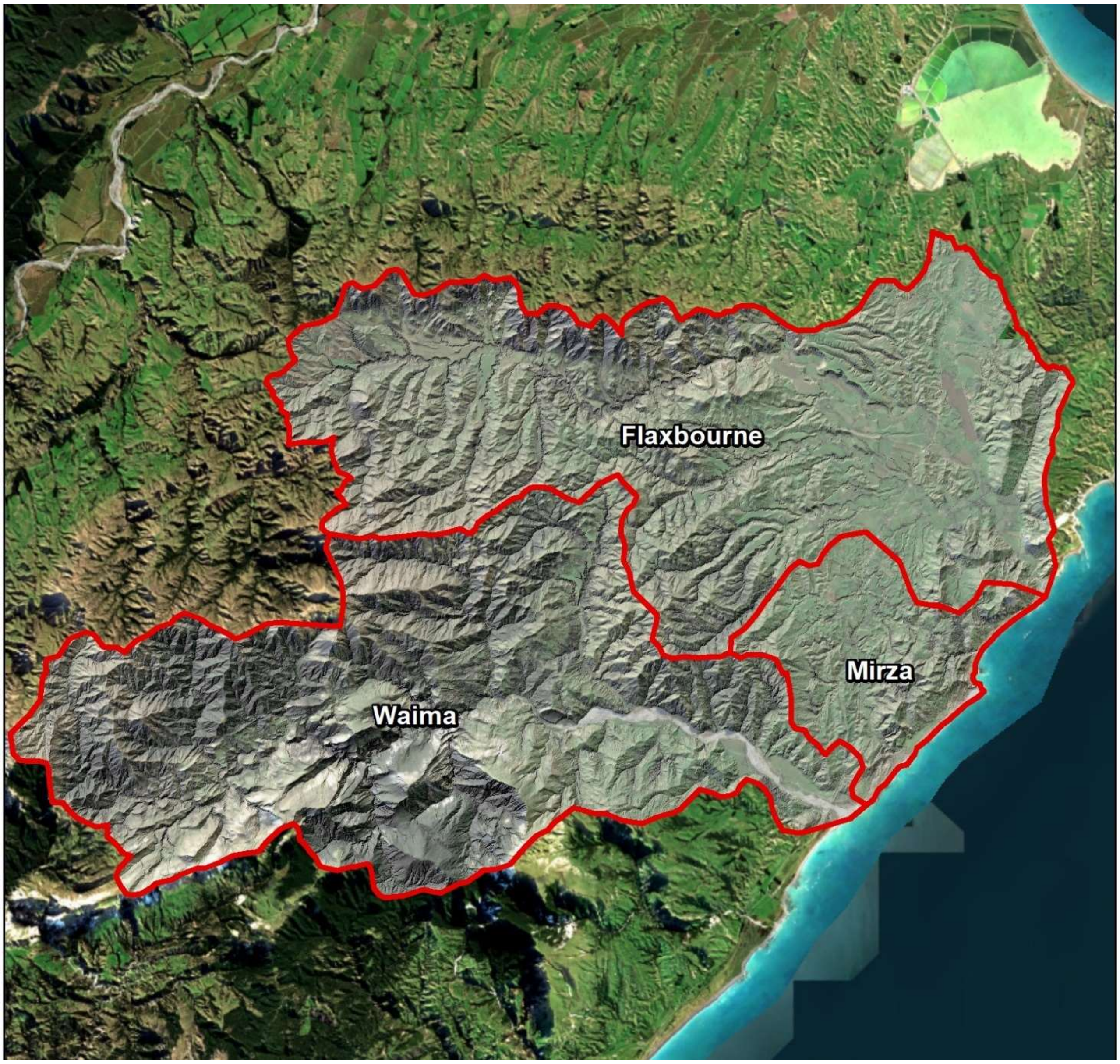
Flood Hazard Analysis

Summary Report



Contact Details

Name: Jack McConchie

L9, Majestic Centre, 100 Willis St
PO Box 12 003, Thorndon, Wellington 6144
New Zealand

Telephone: +64 4 471 7000

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Prepared by

Lizzie Fox & Kirsty Duff
Water Resource Scientists

Katie Elder & Louise Algeo
Hydraulic Modellers

Approved for release by

Jack McConchie
Technical Principal – Hydrology & Geomorphology

Executive Summary

The Kaikōura earthquake caused significant changes to both the landscape and hydrological environments in the Flaxbourne, Mirza and Waima/Ure catchments. These changes have affected both the surface and groundwater resources, the flood hazard, sediment transport processes, and water quality.

Differential uplift, including significant uplift at the coast, has altered the gradient of the rivers. This has affected the flood hazard, including the depth, extent and duration of inundation. It has also affected the amount of energy available to erode and transport sediment in the various rivers. As a result of the uplift, there is likely to have been significant changes to the flood hazard and sediment transport processes, particularly in the reaches of the various rivers downstream of the State Highway.

The focus of this report is to identify the flood hazard within the Flaxbourne, Waima/Ure and Mirza catchments following the Kaikōura Earthquake. This will allow proactive adaptions and management to mitigate the potential adverse effects both now and into the future.

Comprehensive hydrological and hydraulic modelling has been completed to identify and quantify the flood hazard within the Flaxbourne, Waima/Ure and Mirza catchments following the Kaikōura Earthquake for a 1% AEP event at 6, 12 and 24-hour design event durations. However, only the outputs for the critical duration are discussed. These critical durations produced the largest flood depths in each catchment.

Bed shear stress has also been extracted from the hydraulic model to give an indication of how the erosion and sedimentation processes may be acting within the catchments.

To carry out 2-dimensional computational hydrological modelling, first a detailed rainfall analysis was carried out. This has shown that:

- Thirteen hydrometric monitoring sites were identified across the three catchments. Ten of these provide empirical rainfall data. This data has been collated and reviewed for its applicability as input to a rain-on-grid model. The location of the available flow gauges, however, means that they are unlikely to be useful for model calibration;
- Analysis of the empirical data and the generalised Mean Annual Rainfall (MAR) identified spatial variation across the three catchments. Rainfall increased with elevation reflecting expected orographic enhancement. Therefore, specific design rainfalls are needed for each catchment. These should be obtained from the upper catchment to ensure they are conservative but still realistic;
- There is a lack of empirical data from the mid to upper Flaxbourne and Waima/Ure catchments. There are no high-resolution data from the Mirza catchment, although some are available adjacent to its headwaters. Therefore, design rainfalls from HIRDS were required to reflect rainfall likely to be experienced within the catchments;
- Design rainfalls from HIRDS are generally less than those using empirical data for mid duration storm events. However, for events longer than 24-hours, and infrequent, high magnitude events such as the 1% AEP, design rainfalls from HIRDS are slightly higher;
- To ensure conservative, but still representative, design rainfalls are derived, it is recommended that HIRDS design rainfalls from the highest location in the upper catchments be adopted

(Table 2.10, Table 2.11 & Table 2.12). When applied to the entire catchment, this will ensure a conservative approach, but still realistic outputs;

- To account for spatial variation within the larger catchments an areal reduction factor has been applied to the Flaxbourne and Waima catchment as per Table 2.14; and
- Empirical rainfall data for storms of 6, 12 and 24-hour duration approximates the PMP temporal distribution. It is therefore recommended that the PMP temporal distribution be adopted for modelling purposes.

The investigation was constrained by:

- Limited available LiDAR data prior to the earthquake which only covers a very small area near the mouth of the Waima/Ure River. As such, only the post-earthquake flood hazard has been assessed;
- Unknown details on road and railway culvert dimensions. It has therefore been assumed that during a 1% AEP event these will become blocked; and
- No calibration or validation information is available for the model at this stage. The results of the 2-d model should therefore be considered indicative rather than absolute

Although there are some limitations to the hydraulic modelling, particularly regarding calibration and validation, the results are valuable to understanding the flood hazard within the affected catchments.

A summary of the flood hazard analysis undertaken within the Flaxbourne, Waima/Ure and Mirza catchments is provided below.

Flaxbourne

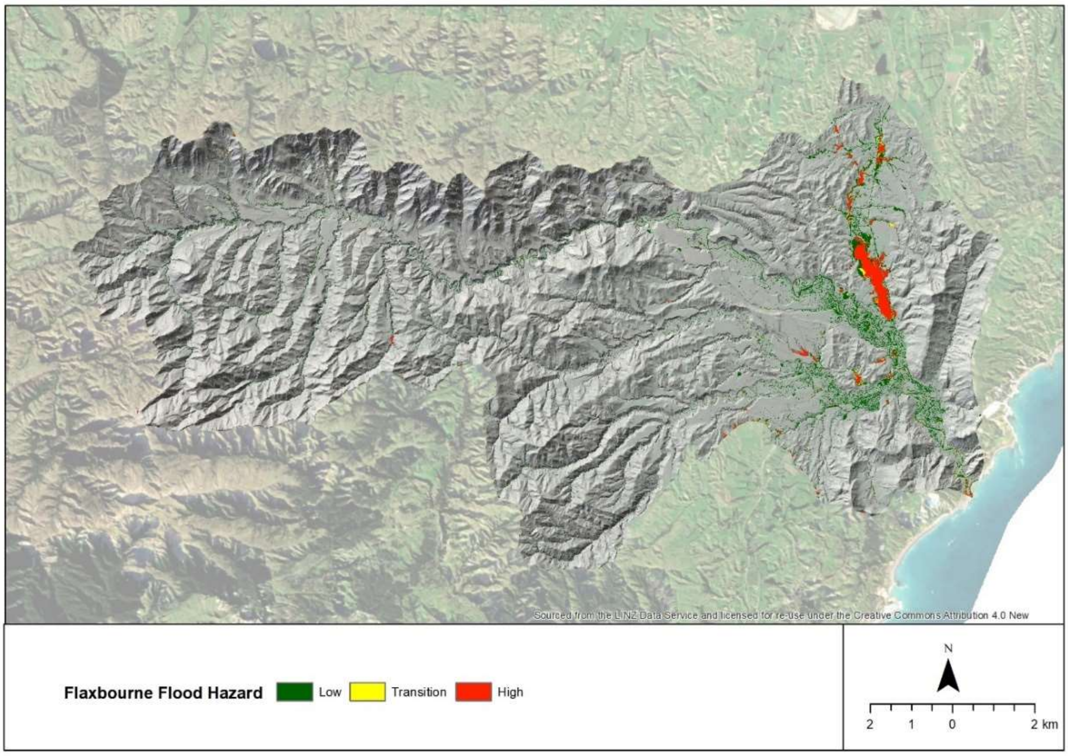

Figure 1: Flood hazard map for the 1 % AEP 24 hour flood event in the Flaxbourne catchment.

- Water depth is greatest in the main channel of the catchment, especially in the mid catchment where the valley is narrow, and the river is surrounded by steep topography. In the lowland areas, water depth increases around Lake Elterwater and on the floodplains towards the mouth of the river.
- Flow velocities are also greatest in the mid catchment although they also remain relatively high through the main channel over the lower catchment; particularly near the mouth of the river. Flow velocities slow as water moves across the floodplain and other surrounding land.
- Flood hazard in the Flaxbourne catchment is highest in the lowland areas, especially around Lake Elterwater. Further north around Taimate, the flood hazard is high as drainage culverts associated with road and rail infrastructure can become blocked allowing water to build up behind SH1 and railway line before eventually overtopping at multiple places.
- There are some areas of increased flood hazard in locations along the southern-most tributary not directly linked to this branch.
- Bed shear stress and, consequently erosion, is highest in the narrow deep channels of the upper catchment. It reduces as the river moves through the mid and lower catchment where the river widens and velocities slow. However, there are some areas of higher bed shear stress in the main channel, particularly near the river mouth. Lower shear stresses, where deposition of sediment is more likely, is seen around the floodplain where flood waters spread out.

Mirza

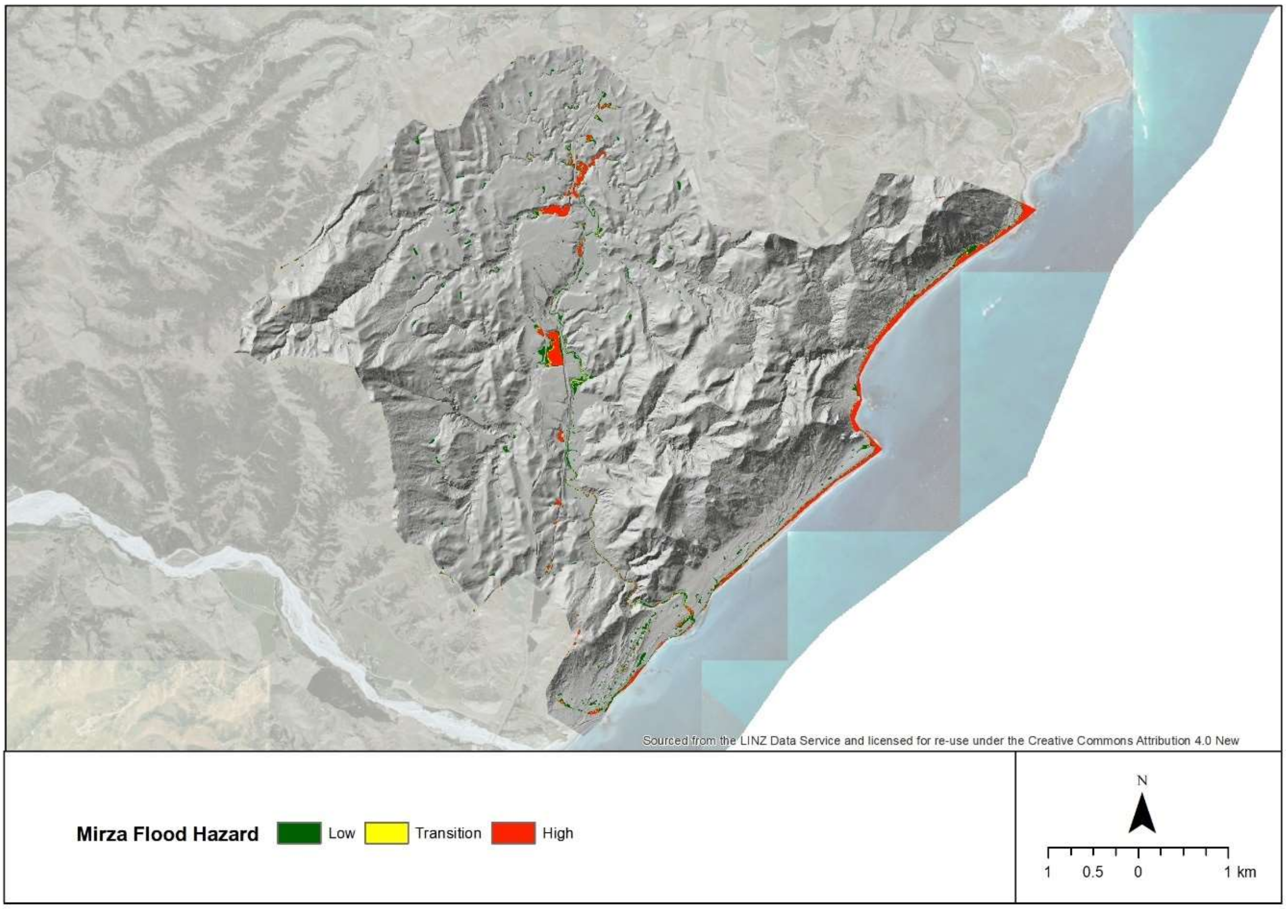

Figure 2: Flood hazard map for the 1 % AEP 6 hour flood event in the Mirza catchment.

- Water depth in the Mirza catchment is greatest in the main channel towards the mouth and where water is held back by infrastructure or embankments.
- Flow velocities are fastest in the headwater tributaries, and particularly near the mouth of the river where flow is constrained within a narrow, deep channel.
- There are two notable areas of high flood hazard in the catchment. Towards the north, the flood hazard is increased where culverts near SH1 and the railway are blocked, and floodwaters spill over onto adjacent land.
- Floodwaters are enhanced in the middle of the catchment by several tributaries converging with the main branch. These floodwaters build up behind a 10m embankment which protects a vineyard from flooding but allows water to accumulate over the floodplain and beyond.
- Bed shear stress shows higher values in the narrower upper catchment tributaries. Lower shear stress occurs where the floodplain widens, and slower velocities are experienced, suggesting deposition would be likely in this area. Compared to the other two catchments, the Mirza has lower bed shear stress values and so will have less capacity to move larger grain sizes.

Waima/Ure

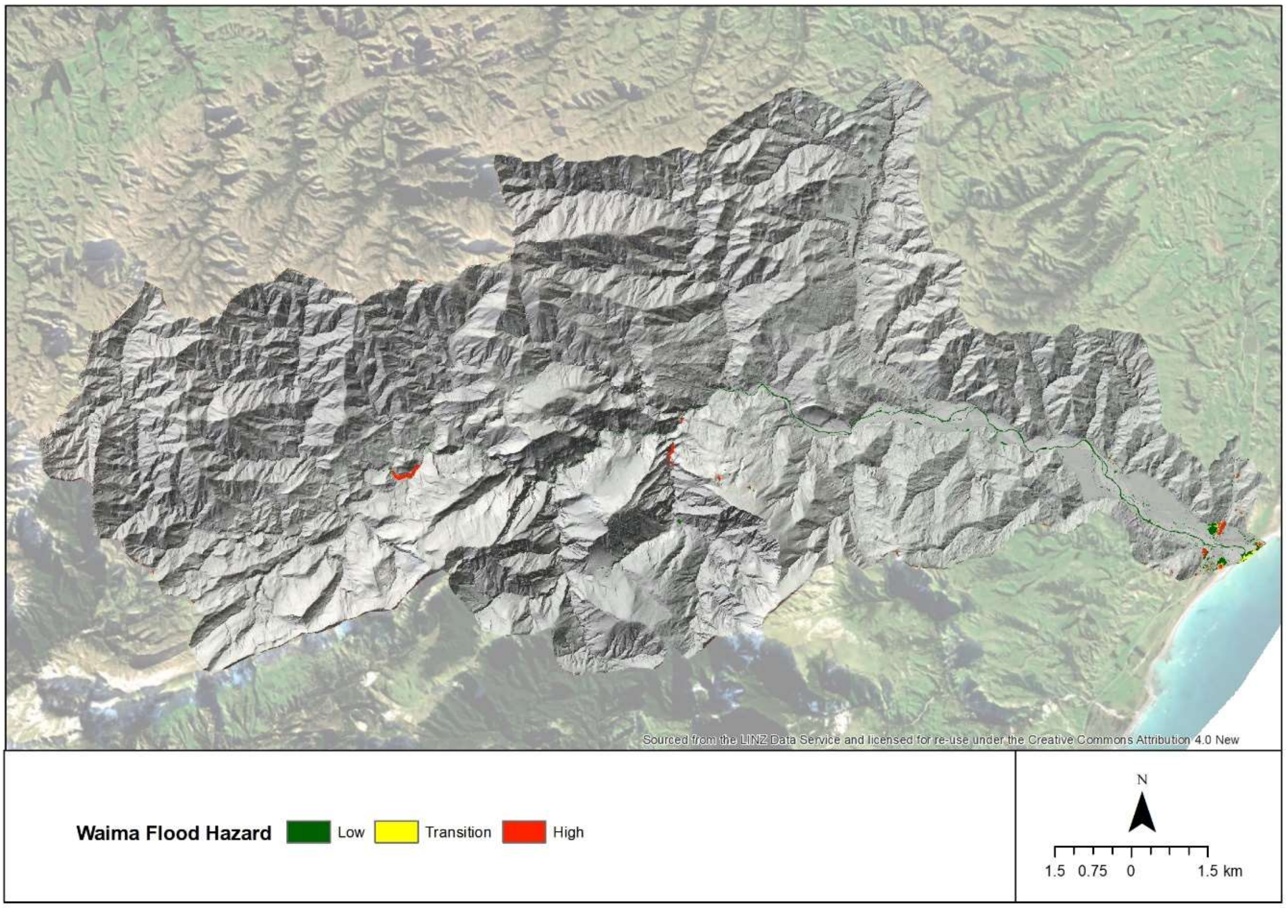

Figure 3: Flood hazard map for the 1 % AEP 24 hour flood event in the Waima catchment.

- In the Waima catchment, the steep narrow topography in the upper catchment constrains flow at various pinch-points allowing floodwaters to build up behind these topographic constraints. Further downstream, water depths are reduced as the floodplain widens and flow spreads out across the wider channel and floodplain.

- Flow velocities are highest where the river channel narrows or moves through topographic constraints. Velocities are highest through the main channel, slowing as floodwaters move across the floodplain and surrounding land.
- The flood hazard is generally low throughout this catchment. The main areas of high flood hazard are behind topographic pinch-points. In these areas, floodwaters build up and inundate the surrounding floodplain. However, the flooding is limited to a relatively small area given the surrounding topography.
- Near the river mouth, flood waters flow over surrounding land, but the flood hazard is low because of the lower velocities and depths. There are, however, smaller pockets of high flood hazard where water is constrained by roading infrastructure in this area.
- The Waima catchment has the highest erosive potential of the three catchments, with bed shear stress greatest in areas which are steep and narrow and within the main channel. As with the other catchments, areas of deposition could be expected on the outer floodplain where bed shear stress tends to be lower.

These results quantify the post-earthquake flood hazard and can be used to aid understanding and management of catchment processes within each of the three catchments.

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1 Introduction

WSP Opus is working with the Flaxbourne Settlers' Association, the Marlborough Research Centre, and Marlborough District Council (MDC) to identify the changes, and quantify the potential impacts, of the Kaikōura Earthquake on the water resources of the Flaxbourne, Mirza and Waima/Ure catchments.

The 14 November 2016 Kaikōura Earthquake impacted nationally significant infrastructure including roads, railway and township facilities, cutting off rural communities and access routes. Evidence collated and summarised following a community survey, and detailed terrain analysis, both by WSP Opus (2018a & 2018b) indicate dramatic changes to the landscape and waterways in the Flaxbourne, Waima/Ure and Mirza catchments. These include:

- Greater flow in the rivers;
- Changed groundwater levels;
- Changed channel alignments;
- Changes in channel gradient (with implications for erosion, channel stability, sediment transport, flood hazard etc.);
- Changes in the alignment of the thalweg (i.e. dominant channel);
- Changes to groundwater conditions, both in specific bores and at a catchment level;
- Changes to surface water – groundwater conditions;
- Changes to water quality through increased suspended sediment and bedload transport; and
- Changes to the flow regimes of rivers because of landslide-dammed lakes etc.

These changes will impact the potential flood hazard throughout the study area.

The focus of this project is to identify the flood hazard within the Flaxbourne, Waima/Ure and Mirza catchments following the Kaikōura Earthquake. This will allow proactive adaptions and management to mitigate the potential adverse effects both now and into the future.

To quantify the flood hazard, computational 2-dimensional hydrological models (2-d models) of the three catchments were developed, calibrated, and run under various design rainfalls to assess the impacts of the different events.

To give an indication on how erosion and sedimentation processes may be acting within each watercourse, the bed shear stress during these design flood flows has also been extracted from the 2-d models.

The three catchments, Flaxbourne, Waima/Ure and Mirza, are outlined in Figure 1-1.

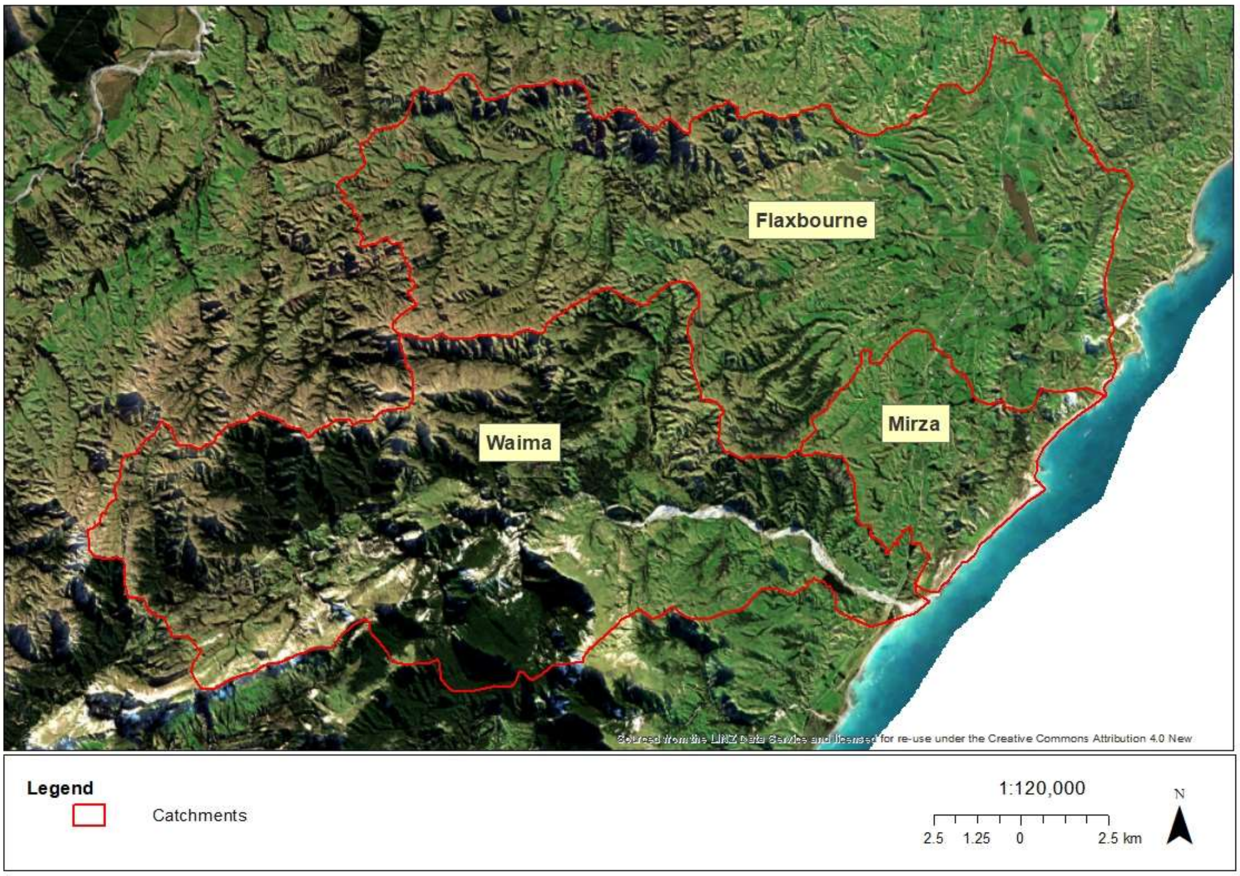

Figure 1-1: Flaxbourne, Mirza and Waima/Ure catchments.

2 Rainfall Analysis

This modelling requires detailed analysis of the available rainfall and flow data, and runoff characteristics, to derive the most representative inputs for model schematisation. The following steps were followed during this analysis:

- Collate and evaluate hydrometric data from the Flaxbourne, Waima/Ure and Mirza catchments, and the wider vicinity;
- Determine the spatial distribution of rainfall across the area;
- Derive a representative rainfall temporal distribution;
- Develop design rainfalls for each catchment, or if appropriate, rainfalls that are representative of all three;
- Generate a hyetograph in a format suitable for input to the 2-d model; and
- Run the 2-d model to quantify the flood hazard under a range of design events.

2.1 Available datasets

Analysing empirical data available across the catchments is important to accurately characterise the hydrological conditions, and to ensure the most representative data are used for modelling. The empirical data are used for model calibration, for deriving design rainfalls, and for determining the most realistic temporal storm rainfall distribution. Available hydrometric data from the Flaxbourne, Waima and Mirza catchments (Figure 2-1) were therefore collected and are summarised in Table 2.1.

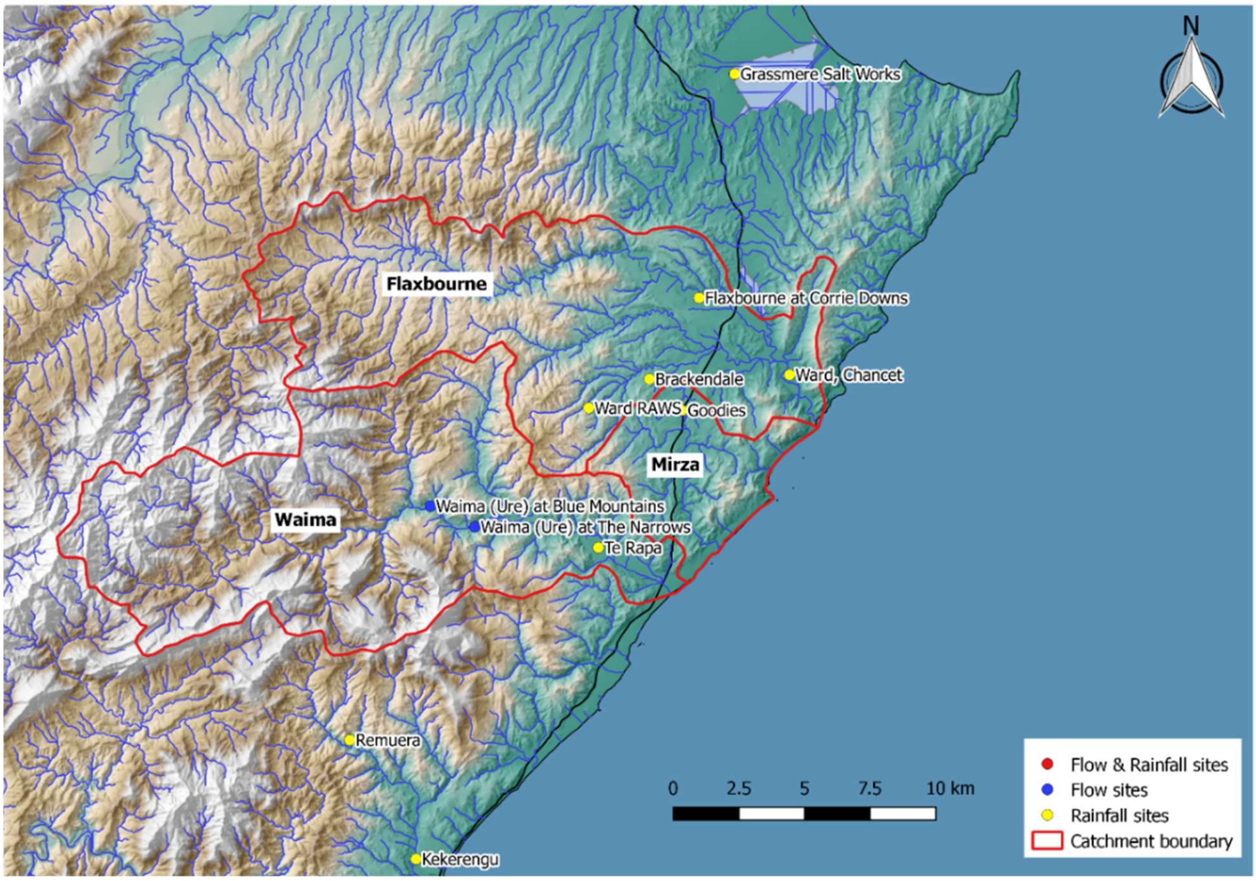

Figure 2-1: Hydrometric data sites in or near the Flaxbourne, Mirza and Waima/Ure catchments.

The ideal criteria that the empirical data need to meet include:

- Providing a high-resolution (i.e. <10 minutes) record for detailed analysis across a range of durations and storm magnitudes;
- Having few or no gaps (i.e. missing data), to ensure the full range of events are captured;
- Sufficiently long in length (i.e. >10 years) to reduce the uncertainty of derived design events; and
- Represent the spatial and temporal variability across the study area.

Table 2.1: Summary of available hydrometric datasets within or near the Flaxbourne, Waima/Ure and Mirza catchments.

SITE NAME	DATASOURCE	RECORDING AUTHORITY	START	END	LENGTH (YEARS)	RESOLUTION	GAPS	% MISSING
Grassmere Salt Works	Rainfall	CliFlo	2/08/1943	1/10/2018	75	Daily	0	-
Ward, Chancet	Rainfall	CliFlo	2/07/1913	1/10/2018	105	Daily	0	-
Blue Mountains	Rainfall	Local	1/03/1964	5/07/2008	44	Daily	0	-
Te Rapa	Rainfall	CliFlo & MDC	1/07/1990	28/11/2018	28	Daily, <10 mins from 20/10/2008	6	1.6%
Goodies	Rainfall	Local	31/01/1968	31/12/1993	25	Monthly	0	-
Kekerengu	Rainfall	CliFlo	2/08/1969	1/03/2000	31	Daily	2	0.8%
Remuera	Rainfall	CliFlo	1/09/1982	2/06/2008	26	Daily	1	30.4%
Brackendale	Rainfall	CliFlo	2/04/1959	1/08/1981	22	Daily	2	3.5%
Ward RAWS	Rainfall	FENZ	4/02/2014	5/12/2018	4	10 minutes	0	-
Flaxbourne at Corrie Downs	Rainfall	MDC	1/12/2006	28/11/2018	12	5 mins	1	0.1%
Flaxbourne River at Corrie Downs	Flow	MDC	4/06/2003	28/11/2018	15	15 min	26	3.5%
Waima (Ure) at Blue Mountains	Flow	MDC	22/12/2007	7/07/2008	1	5 - 15 min	0	-
Waima (Ure) at The Narrows	Flow	MDC	22/12/2007	7/07/2008	1	5 - 15 min	0	-

There are three rain gauges in the study area which meet most of these criteria: Te Rapa, Ward RAWS and Flaxbourne at Corrie Downs. Te Rapa has the longest record, 28 years, but only 10 of those are at high-resolution. This is the minimum recommended for detailed analysis. Ward RAWS is situated the furthest inland, and at higher altitude; although still at low elevation compared to the headwaters of the catchments. This record is more representative of the upper catchment and can be used to determine the temporal pattern. However, since the record is 4-years, it cannot be used to derive design rainfalls. Flaxbourne at Corrie Downs has the highest resolution, 5-minutes, and provides 12 years of data for analysis. The low elevation of the site means that it may under-represent rainfall in the upper catchment.

The three high-resolution rainfall sites can therefore be used to determine the temporal and spatial rainfall distribution of the catchments. However, only Flaxbourne at Corrie Downs and Te Rapa can be used for design rainfall analysis as the short record from Ward RAWS is insufficient for robust analysis.

All rainfall sites can be used to assess any pattern to the mean annual rainfall.

2.2 Spatial distribution

There is a lack of empirical data for the headwaters of the Waima/Ure and Flaxbourne catchments. In general, greater rainfalls are associated with higher topography because of orographic enhancement. The lack of empirical data in the upper catchments means that empirical data alone cannot be used to deduce the spatial distribution of rainfall across the entire catchments.

Mean Annual Rainfall (MAR) can be used to represent the spatial variability of rainfall across an area (Figure 2-2). These data have been derived from a thin-plate smoothing spline model, based on latitude and longitude combined with the annual mean rainfall from selected sites, to interpolate rainfall (Tait *et al.*, 2006).

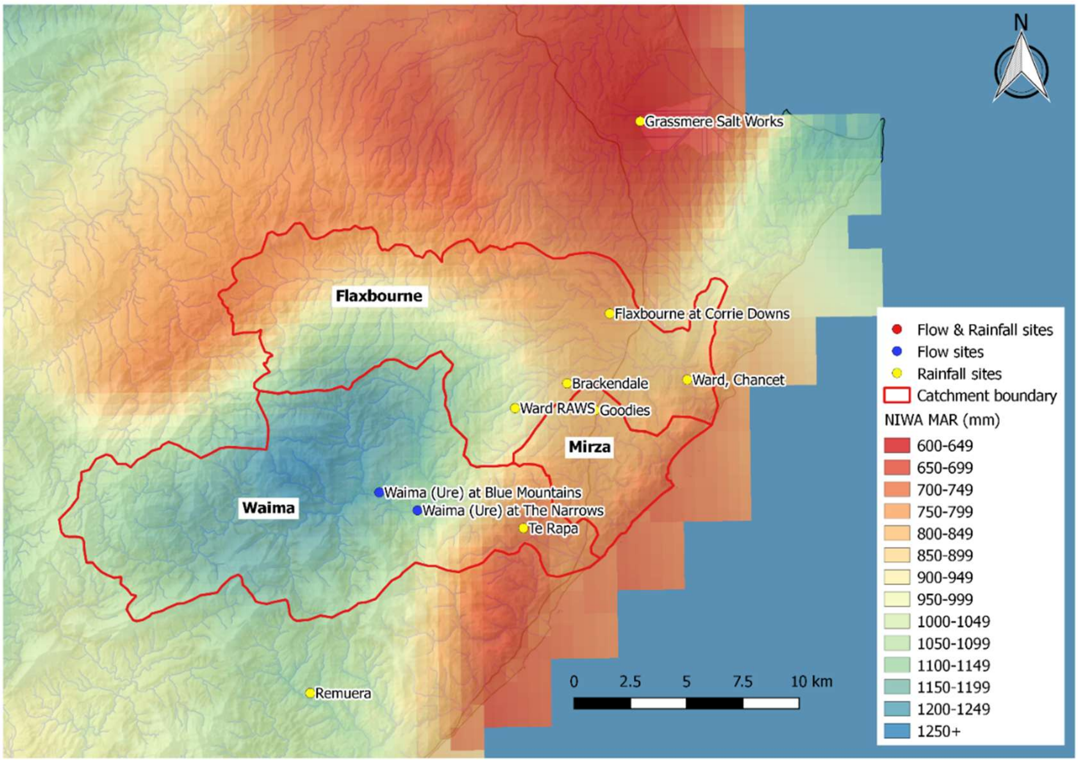

Figure 2-2: Mean Annual Rainfall (MAR) over the Flaxbourne, Waima/Ure and Mirza catchments.

To assess the appropriateness of the generalised MAR for representing the spatial variability of rainfall across the three catchments, these data were compared to the empirical data calculated from the 10 rain gauges available (Table 2.2). If there is minor difference, it would suggest that the MAR can be used to describe the spatial variability of rainfall across the catchment.

Table 2.2: Mean Annual Rainfall (MAR) of empirical data compared with Mean Annual Rainfall (NIWA MAR).

SITE NAME	ELEVATION (m)	EMPIRICAL MAR	GENERALISED MAR	DIFFERENCE (mm)	DIFFERENCE (%)
Grassmere Salt Works	2	576	597	21	4%
Ward, Chancet	20	759	772	13	2%
Blue Mountains	98	1026	1070	44	4%
Te Rapa	37	896	706	-190	-27%
Goodies	*44*	*3425*	*774*	*-2651*	*-342%*
Kekerengu	15	920	966	46	5%
Remuera	179	1035	1077	42	4%
Brackendale	104	755	814	59	7%
Ward RAWS	221	764	944	180	19%
Flaxbourne at Corrie Downs	38	689	747	58	8%

In general, there is good agreement between the empirical data and the generalised MAR, with the latter being generally higher. The exceptions are Goodies (which deviates significantly), Te Rapa and Ward RAWS. Goodies, however, is based on monthly data which ended in 1993. It is also very likely that the measured rainfall is over-represented, as it is inconsistent with that from adjacent gauges during the periods of overlap. These data have subsequently been excluded from analysis.

The Te Rapa empirical data is 27% greater than the generalised MAR. This site changed to recording high-resolution (i.e. <10-minute) data from 2008; from daily data previously. The generalised MAR, however, would not have had access to the more recent data. In comparison, the empirical MAR rom Ward RAWS is 19% less than the generalised MAR. However, this record is only 4 years duration, which is not sufficient to derive a robust mean annual statistic. The empirical MAR would be biased by recent weather phenomenon.

Therefore, the generalised MAR can be used to indicate the spatial distribution of rainfall across the three catchments. The MAR summary statistics for each catchment are displayed in Table 2.3.

Table 2.3: Summary statistics of the NIWA MAR demonstrating the spatial variability of rainfall across the catchments. Rainfall in mm.

SITE NAME	MINIMUM	MEAN	MEDIAN	MAXIMUM
Flaxbourne	706	868	817	1172
Waima/Ure	681	1079	1123	1223
Mirza	681	752	750	875

The Waima/Ure catchment has the greatest variation of rainfall; a difference of 542mm from the highest to the lowest total. This is expected since this catchment also has the greatest relative relief i.e. range of elevation. The Mirza has the least variation, a function of its smaller catchment area and generally low-lying elevation. Therefore, rainfall data from the lower lying areas in the Flaxbourne and Waima/Ure would most likely under represent the actual rainfall falling in the upper catchment, and subsequently under-estimate flows from the modelling.

In general, the greatest rainfall is associated with the highest topography within the catchments. Therefore, to ensure accurate modelling results, design rainfalls should be calculated using rainfall across the higher elevations. This also ensures a conservative approach, and reduces the chance of under-estimating of peak flows, and the extent and depth of inundation.

2.3 Design rainfalls

The spatial distribution of rainfall shows that there is a significant difference between rainfall in the upper and lower catchments, while empirical rainfall data are only available for the lower areas of the catchments. The use of an empirical rainfall data would under-represent the rainfall occurring in the upper catchment and is therefore not appropriate for use in the hydraulic models.

In the absence of measured data, more generalised design rainfalls can be obtained from HIRDS. HIRDS is an acronym for High Intensity Rainfall Design System. It is a generalised procedure to obtain spatially and temporally consistent depth-duration-frequency design rainfalls for New Zealand. The latest version of HIRDS, version 4, was released in August 2018 and incorporates empirical data up to the end of 2015.

To ensure that HIRDS data are applicable for the upper catchments of the Flaxbourne, Waima/Ure and Mirza, this data needs to be compared to empirically-derived design rainfalls. Although HIRDS has been shown to be appropriate in the absence of empirical data, actual site-specific measurements are more reliable than HIRDS. If design rainfalls from both HIRDS and empirical data are consistent, this would indicate that HIRDS may be an appropriate alternative in the absence of site-derived data for this project.

Design rainfalls derived from empirical data require high-resolution data, of a sufficient length, to derive accurately design rainfalls for events of 10-minute to over 24-hour durations. Of the available datasets, only the Flaxbourne at Corrie Downs and Te Rapa sites can be used; Ward RAWS rainfall record is too short to derive robust design rainfalls.

EMPIRICAL DESIGN RAINFALLS

Frequency analyses were undertaken on the annual rainfall maxima, over different rainstorm durations, derived from the entire length of the available records.

Three types of statistical distributions were assessed for how well they modelled the actual annual maxima series (i.e. Gumbel, Pearson 3 (PE3) and GEV). The distribution which provided the best fit to the annual maxima series was then used to estimate the magnitude of storm events of specific annual exceedance probabilities (i.e. AEPs) or average recurrence intervals (i.e. ARIs)).

As is standard practice, the frequency analyses were performed on a 12-month partition. That is, only the largest event in each year was plotted, and the most appropriate statistical distribution fitted to those annual values. It is sometimes difficult to find a single statistical distribution that provides an excellent model of the annual maxima series. In these situations, some subjectivity is required in selecting the most appropriate model. The criteria adopted in this study were:

- The distribution that provided the best-fit through all the data points;
- The distribution with the most realistic shape; and
- The distribution that provides the closest approximation to the extreme value.

While this process may appear subjective, in most cases the choice of a specific statistical distribution for the annual maxima series results in relatively minor differences in the estimated-frequency table.

The PE3 distribution fitted both sites well (Figure 2-3 & Figure 2-4). The resulting design rainfall depths are displayed in Table 2.4 and Table 2.5.

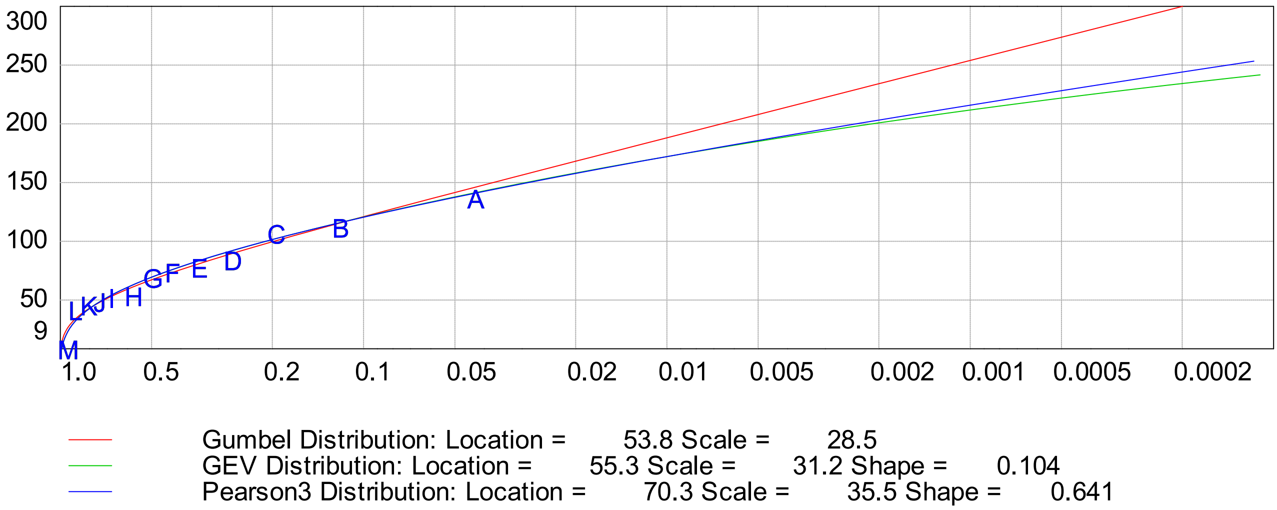

Figure 2-3: Frequency distribution of Flaxbourne at Corrie Downs.

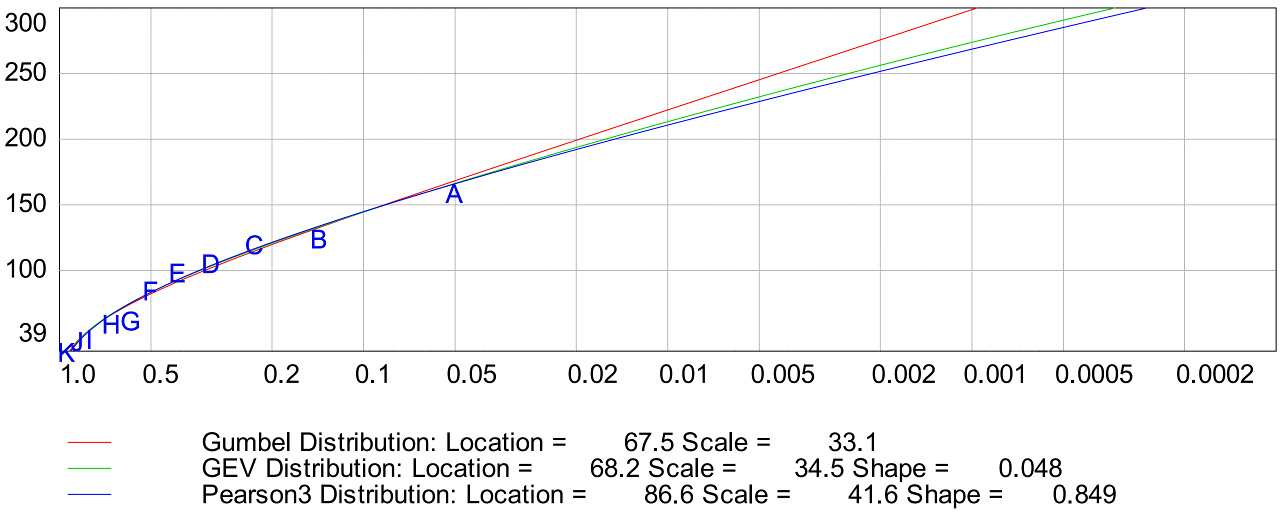

Figure 2-4: Frequency distribution of Te Rapa.

Table 2.4: Design rainfall depths using empirical data from the Flaxbourne at Corrie Downs gauge.

ARI (YEARS)	AEP (%)	DURATION									
		10m	20m	30m	1h	2h	6h	12h	24h	48h	72h
2	50	6	8	11	16	23	44	62	73	86	93
5	20	9	12	15	21	31	60	85	99	114	121
10	10	11	15	18	24	37	72	102	118	134	139
20	5	14	18	20	26	42	83	117	135	151	153
50	2	17	22	23	29	49	96	135	155	170	168
100	1	20	24	25	31	53	106	148	169	183	178

Table 2.5: Design rainfall depths using the empirical data from the Te Rapa gauge.

ARI (YEARS)	AEP (%)	DURATION									
		10m	20m	30m	1h	2h	6h	12h	24h	48h	72h
2	50	5	9	11	16	26	52	77	88	104	112
5	20	8	11	14	20	32	68	101	119	135	146
10	10	11	12	15	24	37	79	119	142	156	168
20	5	14	13	17	27	41	90	134	164	174	187
50	2	19	14	18	31	46	102	153	190	195	209
100	1	22	15	19	34	50	111	165	208	208	223

HIRDS DESIGN RAINFALLS

The HIRDS design rainfall depths for Flaxbourne at Corrie Downs and Te Rapa were also derived and are displayed in Table 2.6 and Table 2.7.

Table 2.6: HIRDS design rainfall depths at Flaxbourne at Corrie Downs at longitude: 174.1301, latitude 41.8028.

ARI (YEARS)	AEP (%)	DURATION									
		10m	20m	30m	1h	2h	6h	12h	24h	48h	72h
2	50	7	9	11	15	21	37	50	66	82	90
5	20	9	12	14	20	29	49	67	88	110	121
10	10	11	14	17	24	35	59	81	106	131	145
20	5	13	17	21	29	41	70	95	124	154	170
50	2	15	21	25	35	50	84	115	150	187	206
100	1	18	24	29	40	57	96	131	171	212	234

Table 2.7: HIRDS design rainfall depths at Te Rapa at longitude 174.081, latitude -41.8897.

ARI (YEARS)	AEP (%)	DURATION									
		10m	20m	30m	1h	2h	6h	12h	24h	48h	72h
2	50	5	8	10	16	24	44	62	84	106	118
5	20	7	11	14	21	32	60	85	114	144	159
10	10	9	13	17	25	39	72	102	137	173	191
20	5	10	16	20	30	46	85	120	161	203	225
50	2	13	19	24	37	56	103	146	196	247	273
100	1	15	22	28	42	64	118	167	224	282	311

The differences between the two sets of design rainfalls are displayed in Table 2.8 and Table 2.9. Negative values indicate that the HIRDS design rainfall depths are lower than the empirical data and *vice versa* for positive values.

Table 2.8: Difference in HIRDS and empirical data at Flaxbourne at Corrie Downs.

ARI (YEARS)	AEP (%)	DURATION									
		10m	20m	30m	1h	2h	6h	12h	24h	48h	72h
2	50	1	1	0	-1	-2	-7	-13	-7	-4	-3
5	20	0	0	0	-1	-3	-11	-18	-11	-4	0
10	10	-1	-1	0	1	-3	-13	-21	-12	-3	7
20	5	-1	-1	0	3	-2	-13	-22	-11	3	17
50	2	-2	-1	2	6	1	-12	-20	-5	17	38
100	1	-2	-1	3	9	4	-10	-17	2	29	56

Table 2.9: Difference in HIRDS and empirical data at Te Rapa.

ARI (YEARS)	AEP (%)	DURATION									
		10m	20m	30m	1h	2h	6h	12h	24h	48h	72h
2	50	0	-1	-1	0	-2	-8	-14	-4	2	6
5	20	-1	0	0	1	0	-8	-17	-5	9	14
10	10	-2	1	1	2	2	-7	-17	-5	17	23
20	5	-4	3	3	3	5	-5	-14	-3	29	38
50	2	-6	5	6	6	10	1	-7	7	52	64
100	1	-7	7	8	8	14	7	2	16	74	88

APPLICABILITY

There are differences between the design rainfalls derived from empirical and HIRDS data at each site. The empirical design rainfalls from Flaxbourne at Corrie Downs have greater depths for the mid-duration events across all magnitudes, but only minor differences for short (<30 minute) events. The longer duration, less frequent events have greater rainfall depths when derived using HIRDS. Te Rapa differences were large for short, 10-minute durations, but overall for the 1% AEP event the design rainfalls from HIRDS were more conservative. For more frequent events, the empirical data generated greater rainfall depths.

The comparative analysis suggests that generally for the 1% AEP event, HIRDS provides a conservative i.e. greater, design rainfall depths. For more frequent events, the empirical data are likely to be more representative. As this project is focused on the flood hazard, which is generally the result of extreme, less frequent events, the use of design rainfalls from HIRDS are considered appropriate.

The results also demonstrate that the empirical data can be greater than that interpolated from HIRDS across the catchment i.e. HIRDS may be under-estimating the design rainfall depths. Therefore, it is recommended using HIRDS rainfall depths obtained from the high point in each upper catchment. This contrasts with using an 'average' HIRDS design rainfall table across the catchment. The spatial distribution of rainfall shows significant variation within each catchment i.e. orographic affect with increasing topography.

The approach adopted ensures that the largest 'realistic' design rainfall depths for the catchment are used in the runoff modelling. The limitation of this approach is that it may result in over estimation of rainfall across the lower lying areas of each catchment. For flood modelling, it is important that the peak discharge is not under-estimated as this would have implications for flood risk management and mitigation strategies. Therefore, a conservative approach is considered appropriate in the absence of robust empirical data.

The recommended HIRDS design rainfall for each catchment are displayed in Table 2.10, Table 2.11 and Table 2.12.

Table 2.10: Flaxbourne catchment design rainfalls at longitude 173.9408 latitude -41.8349.

ARI (YEARS)	AEP (%)	DURATION									
		10m	20m	30m	1h	2h	6h	12h	24h	48h	72h
2	50	5	7	9	15	23	45	65	88	113	125
5	20	6	10	13	20	31	60	87	118	150	167
10	10	8	12	15	24	38	72	103	141	179	198
20	5	9	14	18	28	44	85	121	165	209	231
50	2	11	17	22	35	54	103	147	198	251	278
100	1	13	20	25	40	61	117	167	226	285	315

Table 2.11: Waima catchment design rainfalls at longitude 173.8353 latitude -41.8901.

ARI (YEARS)	AEP (%)	DURATION									
		10m	20m	30m	1h	2h	6h	12h	24h	48h	72h
2	50	5	7	10	15	23	45	66	90	116	130
5	20	6	10	13	20	32	61	88	120	154	172
10	10	8	12	16	24	38	73	105	143	183	205
20	5	9	14	18	29	44	85	123	167	214	238
50	2	11	17	22	35	54	103	148	201	256	285
100	1	13	20	25	40	61	117	168	228	290	323

Table 2.12: Mirza catchment design rainfalls at longitude 174.0787 latitude -41.8636.

ARI (YEARS)	AEP (%)	DURATION									
		10m	20m	30m	1h	2h	6h	12h	24h	48h	72h
2	50	5	7	9	14	21	37	52	69	87	96
5	20	7	10	13	19	28	51	70	94	117	129
10	10	8	12	15	23	34	61	85	112	140	155
20	5	10	15	18	27	40	72	100	132	165	182
50	2	12	18	22	33	49	87	121	161	201	221
100	1	14	20	25	38	56	100	139	184	229	252

2.4 Areal reduction factor

Applying the 1% AEP rainfall depths from HIRDS to every cell in a modelled catchment implies that the extreme event at a point occurs at every point within the catchment. This, however, is not the case. Rainfall patterns will vary across a catchment, and the average rainfall intensity will decrease as the catchment area increases.

Idealised relationships between mean depth, storm area, and maximum rainfall have been determined based on observed spatial patterns. They are usually called depth-area relations and can express a storm's potential for producing runoff.

Depth-area-duration analysis was devised to determine the greatest precipitation depths for a range of areas and durations (WMO, 1969). Errors in the depth-area-duration analysis can be quite large for very small areas because to the representativeness of rain gauge networks. Mean depths for small areas may be as much as 15% low.

Generalised depth-area relations have been developed for New Zealand from summaries of observed depth-area-duration data for many storms. These relations were developed with specific reference to defining the Probable Maximum Precipitation (i.e. PMP) event (Tomlinson & Thompson, 1992).

To estimate a catchment PMP from the 25km² index values, it is necessary to determine the depth-area relations for the maximised convergence component of precipitation. Depth-area curves of maximised convergence precipitation for a range of storms were derived and expressed as a percentage of the 25km² precipitation. This normalises the storm's depth-area curve and provides a basis for determining an appropriate smooth envelope of the rainfall quantity being analysed. Typical depth-area maximised convergent rainfall profiles for 24-hours were derived for three regions of New Zealand. These were based on storms producing the largest depths and having relatively uniform depth-area relations (Table 2.13).

Table 2.13: Depth-area PMP as a percentage of the 25km² index PMP (Tomlinson & Thompson, 1992).

Area (km²)	Region		
	Northern	South Island - Alpine	South Island - southeast
25	100.0	100.0	100.0
100	95.2	97.1	98.2
1000	80.3	82.0	87.1

2000	75.4	79.2	80.1
5000	63.1	72.1	65.5
10,000	55.6	63.5	55.5
15,000	49.3	58.5	49.7

Using the data provided in Table 2.13, the relationship between area and depth of rainfall during a PMP event relative to that experienced over 25km², was quantified for the South Island – Alpine data (Figure 2-5). The South Island – Alpine data were chosen given the steep topography in the upper reaches of the catchment. It is assumed that the 1% AEP 24-hour rainfall will follow the same depth-area relation as the PMP event. This assumption is reasonable given the PMP relation was derived from the analysis of many large rainfall events and is therefore not unique to the PMP.

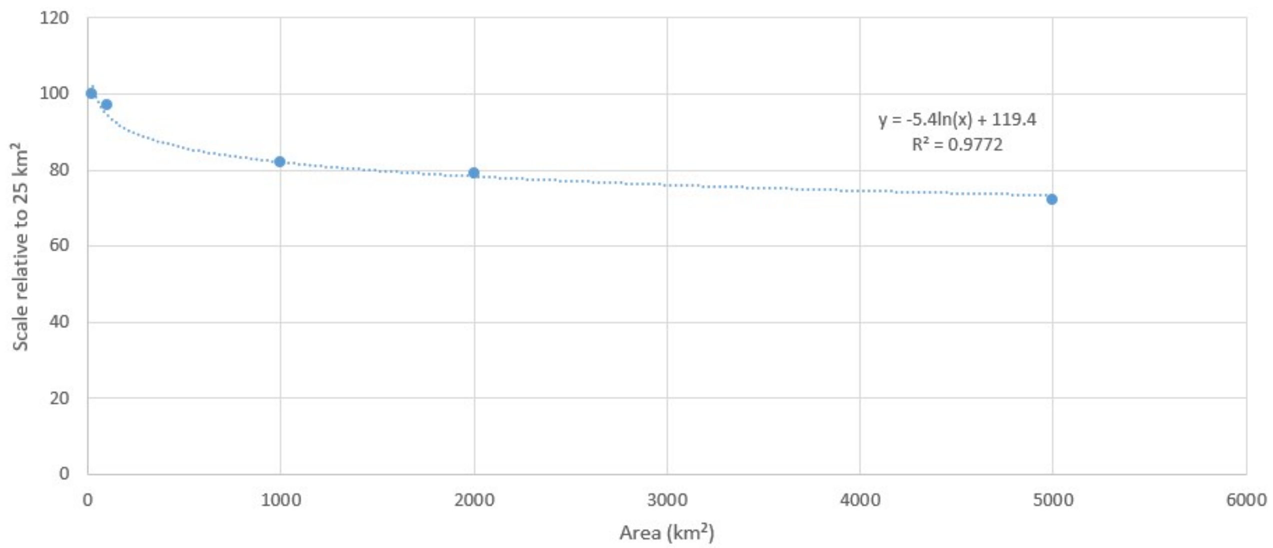

Figure 2-5: Relationship between rainfall depth and storm area for the South Island - Alpine of New Zealand (Tomlinson & Thompson, 1992).

The data available from HIRDS for the 24-hour, 1% AEP, event is provided on 2km grid. Consequently, the HIRDS design rainfalls represent rainfall over a 4km² area. Extrapolating the data from Tomlinson & Thompson (1992), it is possible to derive an areal scaling factor for the average 4km² HIRDS design rainfalls (Table 2.14 & Figure 2-6).

Table 2.14: Areal scaling factors for HIRDS 24-hour design rainfalls over an area of 4km².

Area (km²)	Flaxbourne catchments
4	100
25	91.5
100	85.0
1000	74.3
2000	71.0
5000	66.8

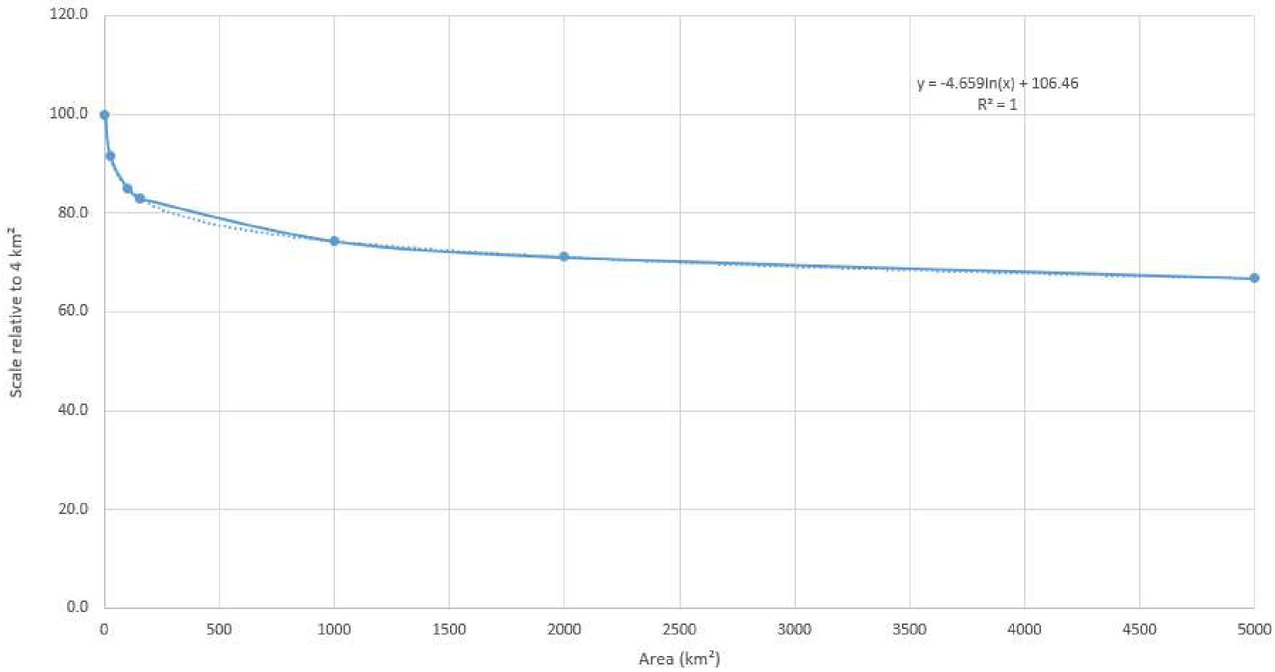

Figure 2-6: Relationship between HIRDS 24-hour design rainfalls and storm area.

The scaling of design rainfall data from HIRDS to account for catchment area, in the manner described above, has been shown to produce more realistic estimates of catchment runoff and design hydrographs when using rain-on-grid models. Without this scaling, both peak runoff and runoff volume were over-estimated for a range of calibration events.

Therefore, to account for the size of the Flaxbourne and Waima catchments, an areal adjustment factor was applied to the HIRDS data (Table 2.15).

Table 2.15: Empirically-derived areal adjustment factors for each catchment.

Catchment	Catchment Area (km^2)	Scale Factor
Flaxbourne	155	0.83
Mirza	30	1
Waima	157	0.83

2.5 Temporal distribution

The distribution of rainfall throughout a storm event can have a significant effect on the results of the rainfall-runoff models. While the total storm runoff volume is not affected by the temporal distribution of rainfall, both the peak discharge and its associate lag time can be affected dramatically. Therefore, it is imperative that the right temporal pattern is selected that is representative of the catchments to ensure reliable results.

Two of the most common generalised rainfall temporal distributions that are applied to storms in New Zealand are TP108 and Probable Maximum Precipitation (PM). TP108 uses a nested hyetograph where, for any specified duration, from 10-minutes through to 24-hours, the maximum intensity of rainfall for each duration has the same Annual Exceedance Probability (AEP). The Probable Maximum Precipitation (PMP) temporal distribution, in contrast to TP108, was derived from autographic rainfall charts from New Zealand storms, using a temporal pattern of average variability, as proposed by Pilgrim *et al.* (1969 & 1975).

The two methodologies each have their own strengths and weaknesses: For example, TP108 has only been validated against small catchments less than 12km² in area in Auckland but does allow catchment runoff analysis to operate on the relevant duration embedded within the nested storm, for efficient modelling. In contrast, the PMP was derived from measured rainfall data from across New Zealand, but the rainfall data has not been updated or re-evaluated since the early 1990s i.e. no recent data in the last ~25 years.

Therefore, to determine the most appropriate generalised distribution to apply to the three catchments, five of the largest rainfall events recorded at the three high-resolution rain gauges i.e. Flaxbourne at Corrie Downs, Te Rapa and Ward RAWS, where the resolution was at least 10 minutes, were analysed in detail over 6, 12 and 24-hour durations. These are displayed in Figure 2-7, Figure 2-8 and Figure 2-9.

These durations were selected based on the likely Time of Concentration (ToC) for each of the catchments because of their size, shape, relative relief and likely response time to rainfall events. All three gauges were compared to ensure that the temporal pattern does not significantly change across the catchments, although the lack of empirical data from the mid and upper Flaxbourne and Waima/Ure catchments acts as a significant constraint. However, it is assumed that while the total rainfall varies with elevation, the temporal distribution of the rainfall is more uniform.

Of the different durations analysed, the empirical data more closely aligns with the PMP than the TP108 temporal pattern. For the 6-hour event, the PMP distribution has slightly more rain over the middle third of the storm than shown in the empirical data. For 12-hour duration events, the PMP distribution has slightly less rainfall distributed across the third quartile. The 24-hour pattern aligns very well for two of the three sites, with the Flaxbourne gauge showing slightly higher rainfall over the middle third of a storm event. Therefore, it is recommended using the PMP temporal rainfall distribution for storms with durations of 6-24 hours.

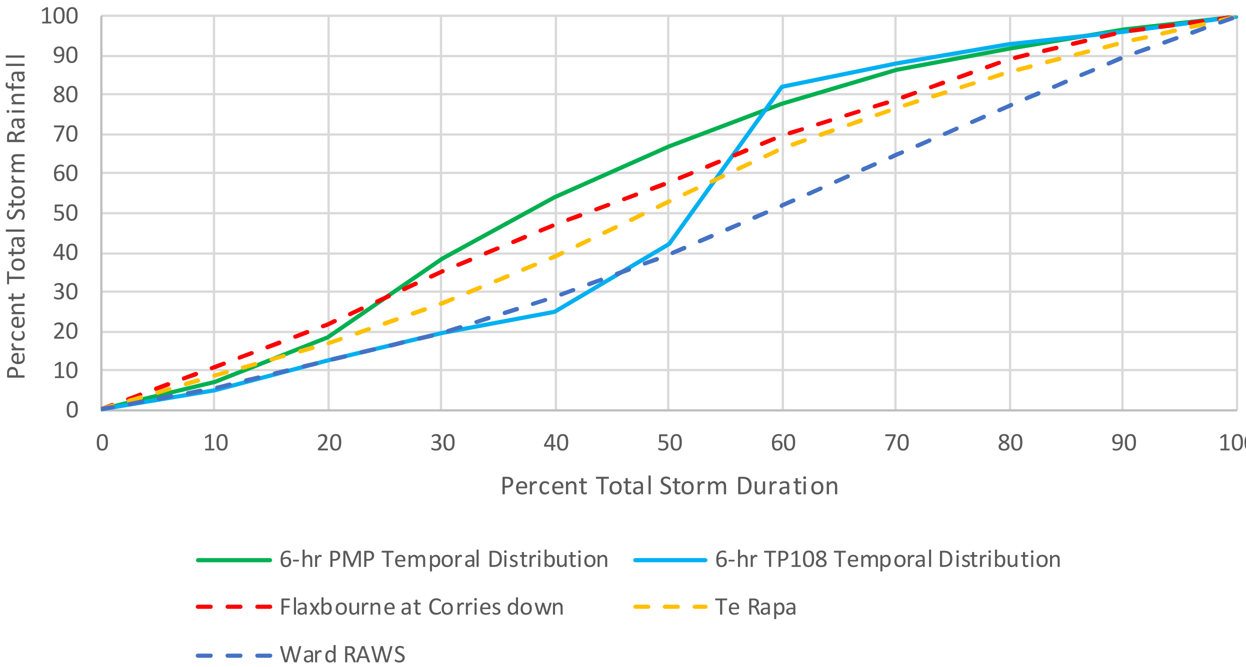

Figure 2-7: The 6-hour average temporal distribution pattern of the three high resolution rain gauges compared to the TP108 and PMP distribution patterns.

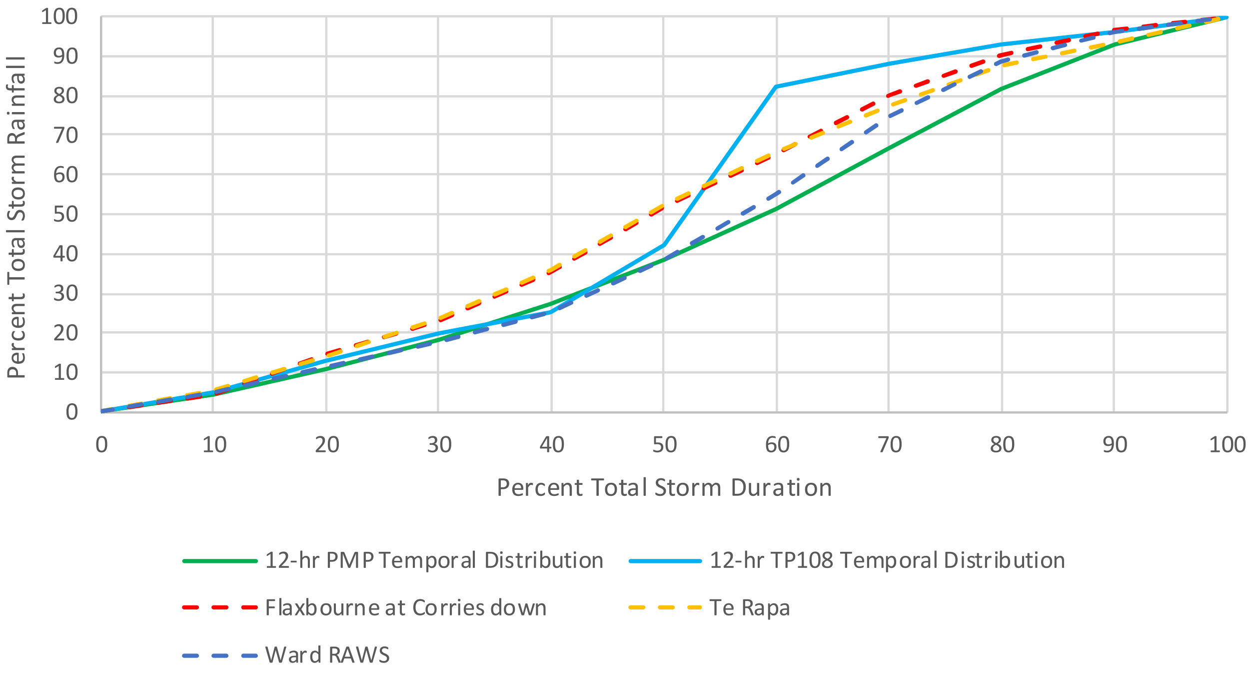

Figure 2-8: The 12-hour average temporal distribution pattern of the three high resolution rain gauges compared to the TP108 and PMP distribution patterns.

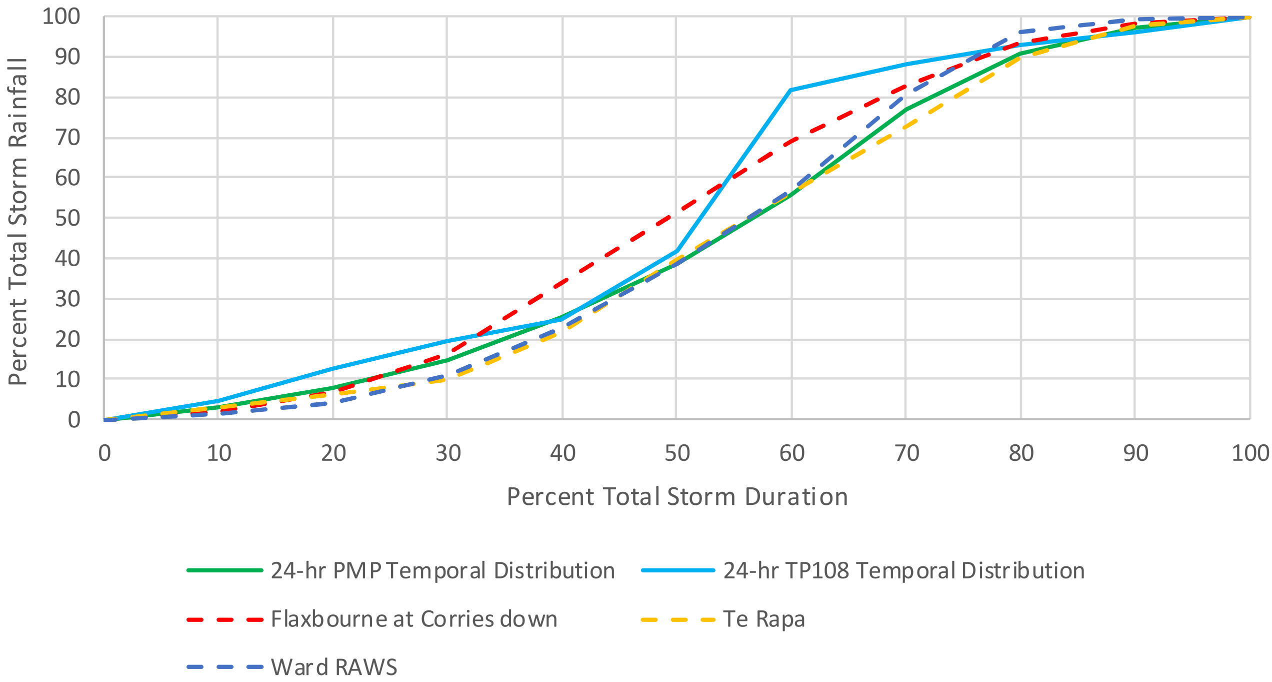

Figure 2-9: The 24-hour average temporal distribution pattern of the three high resolution rain gauges compared to the TP108 and PMP distribution patterns.

2.6 Rainfall analysis results

From the above analysis, the following data were provided as inputs to the rain-on-grid modelling to assess the flood hazard to the Flaxbourne, Waima/Ure and Mirza catchments under various scenarios:

- Design rainfalls for each of the three catchments: Flaxbourne, Waima/Ure and Mirza (Table 2.10, Table 2.11 and Table 2.12);

- The most appropriate temporal rainfall pattern that can be used to distribute the storm rainfall over the duration of the storm event i.e. Figure 2-7, Figure 2-8 and Figure 2-9; and
- Three high-resolution rainfall records, from Flaxbourne at Corrie Downs, Te Rapa and Ward RAWS, which can be used to derive empirical data for validation.

2.7 Hydrometric summary

The above analysis allows the following conclusions:

- Thirteen hydrometric monitoring sites were identified across the three catchments. Ten of these provide empirical rainfall data. This data has been collated and reviewed for its applicability as input to a rain-on-grid model. The location of the available flow gauges means they are unlikely to be useful for model calibration, but they may aid in validation of modelled events.
- Analysis of the empirical data and the generalised Mean Annual Rainfall (MAR) identified spatial variation across the three catchments. Rainfall increased with elevation reflecting expected orographic enhancement. Therefore, specific design rainfalls are needed for each catchment. These should be obtained from the upper catchment to ensure they are conservative but still realistic;
- There is a lack of empirical data from the mid to upper Flaxbourne and Waima/Ure catchments. There are no high-resolution data from the Mirza catchment, although some are available adjacent to its headwaters. Therefore, design rainfalls from HIRDS were required to reflect rainfall likely to be experienced within the catchments;
- Design rainfalls from HIRDS are generally less than those using empirical data for mid duration storm events. However, for events longer than 24-hours, and infrequent, high magnitude events such as the 1% AEP, design rainfalls from HIRDS are slightly higher;
- To ensure conservative, but still representative, design rainfalls are derived, it is recommended that HIRDS design rainfalls from the highest location in the upper catchments be adopted (Table 2.10, Table 2.11 & Table 2.12). When applied to the entire catchment, this will ensure a conservative approach, but still realistic outputs;
- An areal reduction factor (ARF) has been applied to the Flaxbourne and Waima catchments as per Table 2.14 to account for the variability across the larger catchments and prevent an over estimation in peak runoff and volume. The ARF was not applied to the Mirza catchment (30km^2) because of its small size. Rainfall in this catchment will not be attenuated to the same degree as in the larger Flaxbourne (155km^2) and Waima (157km^2) catchments; and
- Empirical rainfall data for storms of 6, 12 and 24-hour duration approximates the PMP temporal distribution. It is therefore recommended that the PMP temporal distribution be adopted for modelling purposes.

3 Model Development

The flood hazard within the Flaxbourne, Waima/Ure and Mirza catchments following the Kaikōura Earthquake has been investigated using a 2-dimensional computational hydraulic model (2-d model) developed using TUFLOW. Various design rainfall events were simulated to assess the potential impacts of the different events.

3.1 Data review

HYDROLOGY

Rainfall information from HIRDS v4 has been used for the flood hazard analysis. HIRDS design rainfalls were taken for each for the three catchments. Design rainfalls were derived from the highest location in the upper catchments to ensure conservative, but still representative, values. Design storm events of 6, 12 and 24-hour duration were selected, adopting the PMP temporal distribution.

An areal reduction factor has been applied to the Flaxbourne and Waima catchment to account for the larger catchment areas, which will typically experience a decrease in the average rainfall intensity as the catchment area increases. The analysis of this data, and the selection of the most appropriate rainfall is detailed in Section 2 of this report.

TOPOGRAPHICAL

Available LiDAR data was used to derive Digital Elevation Models (DEM). There are two post-earthquake LiDAR surveys and one limited LiDAR data captured prior to the earthquake. The LiDAR data available from two surveys following the Kaikōura Earthquake are:

- LiDAR data captured within the weeks of the November 2016 earthquake. However, this data was of limited extent, and did not cover the whole of the Flaxbourne, Mirza and Waima/Ure catchments; and
- Further LiDAR data captured approximately 18-months after the Kaikōura Earthquake, between May and July of 2018. This LiDAR was 'captured' as part of this project to ensure full coverage of the study catchments.

Available LiDAR data prior to the earthquake is very limited. There is only a small area (i.e. 3.5km^2) of DEM available near the mouth of the Waima/Ure River. This DEM is based on LiDAR data 'captured' in 2008, however the process of its generation unknown. The DEM has a 0.5m cell size and is in the Lyttleton 1937 datum. Given the very limited availability of pre-earthquake DEM it has not been used in the analysis.

The DEM derived from the LiDAR post the Kaikōura Earthquake (2016-2018), which covers the full extent of the catchment areas, has been used for the development of the hydraulic model.

DRAINAGE AND HYDRAULIC STRUCTURES

No information on existing drainage or hydraulic structures has been provided and therefore this information has not been included in the 2-d model. The 2-d model can be adapted later to include this level of detail if required.

Larger hydraulic structures, such as bridges, have been removed from the DEM provided. Some smaller bridges have also been removed subsequently to ensure hydraulic connectivity of streams.

AERIAL PHOTOGRAPHS

Aerial photographs were obtained from LINZ of the Marlborough region in the summer of 2015-2016. The photographs have a resolution of 0.2m and have a spatial projection of New Zealand Transverse Mercator 2000. These photographs were used to provide information regarding the land use within the catchments, and subsequently the hydraulic roughness of the floodplain.

The photographs have also been used to identify areas where structures may impact the flood flow. These aerial photographs were taken prior to the LIDAR data and so some differences may exist.

HISTORICAL FLOODING INFORMATION

Historical gauged flood information is limited and is not sufficient to undertake a calibration of the 2-d model. There are no flow recorders on the rivers within the Mirza and Waima catchments.

Limited anecdotal flooding information or flood photographs in the catchments has meant that the results have not been validated. Therefore, while best practice has been used to develop this 2-d model, the results should be treated as indicative.

LIMITATIONS

There are some limitations associated with the methodology undertaken. These include:

- The rainfall data have been derived from HIRDS V4 (NIWA, 2018). This provides a reasonable estimation of the design rainfall in the catchments; however, there are uncertainties associated with using these data;
- Available LiDAR data prior to the earthquake is very limited and only covers a very small area near the mouth of the Waima/Ure River;
- Details of road and railway culvert dimensions are unknown. Large bridges have been adapted in the DEM and smaller bridges have been removed to ensure hydraulic conductivity. Small culverts have not been edited and it has been assumed that in a 1% AEP event these will become blocked and therefore the results of this study are conservative; and
- No calibration or validation information is available for the model at this stage. The results of the 2-d modelling simulations should therefore be considered indicative rather than absolute.

3.2 Hydraulic modelling

To determine the flood hazard within the Flaxbourne, Waima/Ure and Mirza catchments, 2-d hydrological models were developed for each catchment using a 'Rain on Grid' approach in Tuflow™. The model extents for each catchment are shown in Figure 1-1.

This type of modelling produces a gridded representation of the catchment terrain using the elevation data; applies rainfall directly to this grid; and simulates the flow of the water throughout the catchment.

Each hydrological model was run for the 6, 12 and 24-hour duration 1% AEP design rainfall events.

A summary of the 2-d model set-up and simulation parameters for each of the scenarios is detailed in Table 3.1.

Table 3.1: Summary of the inputs and parameters used in two versions of 2-d hydrological model.

SCENARIO	TERRAIN	LAND USE	DURATION DESIGN EVENTS FOR THE 1% AEP	DOWNSTREAM BOUNDARY
Flaxbourne.	Using post-earthquake (2016-2018) LiDAR and DEM to create a 1m grid.	Taken from the Land Cover Database version 4.1 Mainland New Zealand	6, 12 and 24-hour	Stage verses time tidal boundary set at a constant 2m. Initial water level (IWL) set at 2m.
Waima	Using post-earthquake (2016-2018) LiDAR and DEM to create a 1m grid.	Taken from the Land Cover Database version 4.1 Mainland New Zealand	6, 12 and 24-hour	Stage verses time tidal boundary set at a constant 2m. Initial water level (IWL) set at 2m.
Mirza	Using post-earthquake (2016-2018) LiDAR and DEM to create a 1m grid.	Taken from the Land Cover Database version 4.1 Mainland New Zealand	6, 12 and 24-hour	Stage verses time tidal boundary set at a constant 2m. Initial water level (IWL) set at 2m.

TERRAIN

The development of the hydraulic model uses post-earthquake LiDAR data. To represent the terrain of the three catchments, a Digital Elevation Model (DEM) was derived from the LiDAR data. All terrain data used was spatially projected in NZTM 2000. The terrain data were derived from the following sources:

- LiDAR data covering the lower ends of each catchment 'captured' during a survey of SH1, the rail line, and associated infrastructure immediately following the earthquake (i.e. 2016 DEM). The DEM derived from these data was then meshed with that derived from more recent LiDAR data 'captured' in 2018 (i.e. 2018 DEM).
- The 2018 DEM provided by MDC is based on LiDAR data 'captured' by AAM(NZ) Ltd from 26 May to 29 July 2018; approximately 18-months after the Kaikōura Earthquake. This data has a vertical accuracy of ±0.1m. This LiDAR was 'captured' as part of this project to ensure full coverage of the study catchments.

Both post-earthquake LiDAR surveys had the houses and vegetation removed from the topographic data, are in NZVD2016 datum, and the DEMs have a 1m cell size. Little manipulation was therefore needed when meshing the two DEMs. The 2016 LiDAR data was added to the 2018 LiDAR to complete the catchment areas.

The DEM base was manipulated at bridge locations to prevent the bridge acting as a hydraulic control. Where the LiDAR data records the height at the top of the bridge this has been lowered to reflect the level of the river, allowing water to flow through the bridge. Where water passes under a road or railway via a culvert, but where the culvert size is unknown although smaller and more constrictive than a bridge, it has been assumed that during a 1% AEP event the culvert will become blocked. Therefore, no adaptations have been made to the DEM to ease water flow. Consequently, water will back up behind the culvert before spilling over the embankment.

A 3m grid was used because of the need for relatively quick computational run-times. The grid can be refined if further detail is required; however, this is an appropriate resolution for understanding the catchment-scale flood hazard.

LAND USE AND ROUGHNESS

Land use throughout the catchments was determined using the Land Cover Database version 4.1 Mainland New Zealand (LCDB4) classifications. Land use classifications taken from LCDB4 were grouped, as per Table 3.2, and validated using aerial photographs taken in the summer period 2015-2016.

Table 3.2: Land use grouping.

LCDB4 LAND USE CLASSIFICATION	LAND USE GROUP
Manuka and/or Kanuka Broadleaved indigenous hardwoods Deciduous hardwoods Exotic forest Flaxland Gorse and/or broom Sub-alpine shrubland Matagouri or grey scrub	Forest
Low producing grassland Short-rotation cropland High producing exotic grassland	Grass
Gravel or rock Landslide Sand or gravel Surface mine or dump	Gravel
Tall tussock grassland Aerial photos show larger tree growth	Tussock
Orchard, vineyard or other perennial crops	Vineyard
Herbaceous freshwater vegetation Lake or Pond	Water

Grass and forest in the upper catchment, where the topography is notably steeper, were assigned as Alpine grass and Alpine forest.

Land use was used to estimate appropriate Manning's n values (i.e. the resistance to flow) for the 2-d models (Table 3.3).

Table 3.3: Hydraulic roughness used for different land uses.

LAND USE	HYDRAULIC ROUGHNESS (MANNING'S n VALUE)
Grass	0.045
Tussock	0.05
Vineyard	0.047
Water	0.03
Forest	0.08
Alpine grass	0.075
Alpine forest	0.08

BOUNDARY CONDITIONS

The catchment areas were defined using topography and the River Environment Classification version 2.0 (REC2) database.

The design rainfall scenarios for the 6-hour, 12-hour, and 24-hour for each catchment (detailed in Table 2.10, Table 2.11 and Table 2.12) were applied directly onto the grid for each 2-d model. No losses were included as only very limited information is available regarding the likely infiltration, storage and evaporation rates.

To consider catchment size, a scaling factor was applied to the design rainfall data to avoid over estimating the peak runoff and runoff volume. An areal reduction factor (ARF) was applied to the Flaxbourne (catchment size 155km^2) and Waima (catchment size 157km^2) but not to the Mirza (catchment size 30km^2). The ARI applied to the catchments are listed in Table 2.15.

The location of the downstream boundary of the 2-d models was dictated by topography and the river mouth at the coast. The downstream tidal boundary (2m) was set to the level of the Mean High Water Spring (MHWS) tide; the average of the highest tides at Kaikōura (LINZ New Zealand Nautical Almanac, 2018/9). A constant tidal boundary was chosen as a mean tide (MHWS) is being used and it is not known when the tidal peaks and troughs will occur during the design flood. It is possible to undertake a sensitivity analysis to assess the impact of the tidal boundary if necessary. The initial water level of the downstream boundary was set to 2m to match the tidal boundary for stability.

3.3 Validation

There are no flow recorders on the rivers within the Mirza and Waima catchments to compare any recorded events to the modelled results. The Flaxbourne catchment has a flow gauge at Corrie Downs which has 15 years of data; with 3.5% missing data and no recorded 1% AEP events. While this data is insufficient to validate the model, it can be used to sense-check the results and provide confidence in the modelled outputs.

Flood frequency analysis of the Flaxbourne River at Corrie Downs flow data was undertaken to estimate the magnitude of the 1% AEP flood which could then be compared against the modelled flow at the same location. The modelled flow at the location of the gauge was 310m^3/s and the estimated design flood was 253m^3/s. The modelled flow is therefore overestimating that assumed from the instrumental record by 18%. The reason for this difference may be a result of the following:

- Comparing a 1% AEP rainfall event with a 1% AEP flood which are not the same;

- The design rainfall has been applied across the whole catchment which will produce higher runoff volumes;
- The 1% AEP design flood estimated from the flow gauge may not be accurate given the length of record (only 15-years); and
- Using a conservative HIRDS value from the upper catchment. Even after applying an areal reduction factor (reducing the 24-hour rainfall to 188mm) the design rainfall is still higher than the HIRDS value at the flow recorder (24-hour at 169mm). However, while the use of a conservative HIRDS value from the upper catchment has resulted in a potential higher design flood, such an approach is still considered appropriate for a catchment-wide application.

Given the uncertainty in the magnitude of the design flood from the flow gauge, and the potential use of the flood results, a conservative (over-estimation) output is considered to be acceptable.

4 Analysis

4.1 Modelling results

Water levels, depths, velocities, and bed shear stress are direct outputs from the 2-d model simulations. The following events have been simulated:

- Flaxbourne post-earthquake 1% AEP design rainfall events of 6-hour, 12-hour and 24-hour durations;
- Mirza post-earthquake 1% AEP design rainfall events of 6-hour, 12-hour and 24-hour durations; and
- Waima post-earthquake 1% AEP design rainfall events of 6-hour, 12-hour and 24-hour durations.

Using Waterride Flood Manager, the flow profiles and flood peak can be determined at any location within the model. The model outputs can therefore be used to ascertain the flood hazard at any point resulting from 1% AEP rainfall events.

Water levels, depths, and velocities can be used to quantify the flood hazard. Whereas bed shear stress can be used to give an indication of how sedimentation processes may be acting within the river.

4.2 Flood hazard analysis

The results from the 2-d model simulations have been mapped to illustrate the flood extent throughout each catchment. The 6-hour, 12-hour and 24-hour storm durations have been simulated, however, only the critical duration, that which produced the greatest flood depths, has been shown in the results below. Maps of the other duration results can be produced if required.

For the larger catchments i.e. the Flaxbourne and Waima, the results from the 24-hour duration rainfall have been reported. For the Mirza, which is a small catchment, the results from the 6-hour duration rainfall have been reported. This approach allows the worst case scenario to be seen for each catchment.

FLAXBOURNE CATCHMENT

The flood hazard has been quantified for the Flaxbourne catchment during a 1% AEP 24-hour duration design rainfall using the maximum depth and velocity maps. The extent of flooding typically stays within the floodplain and Lake Elterwater, apart from some areas of spilling over the SH1 and the railway; most notably around Taimate. Here drainage culverts feeding low lying ephemeral field drains become blocked and flood water ponds behind the road before either spilling over or flowing along the line of the road or railway (Figure 4-1).

Water depth

The water depth is generally greatest in the centre of the river channel (Figure 4-2 & Figure 4-3). Within the mid-catchment, the valley narrows and is constricted by steep valley slopes. Here the flood waters are deeper as a result of the limited space for flow to spread out. In the lowland areas, water depth increases around Lake Elterwater and Taimate (Figure 4-3, left) as well as on the floodplain towards the mouth of the river (Figure 4-3, right).

Figure 4-1: Example of drainage culvert under the SH1 taken from Google maps near Taimate.

Velocity

The highest velocities are experienced within the narrowest sections of the steep upper catchment (Figure 4-5, left), where the southern branch joins the main channel (Figure 4-5, middle) and at the mouth of the river (Figure 4-5, right). Velocities slow as water moves across the floodplain and surrounding land.

Overall flood hazard

Flood hazard in the Flaxbourne catchment the most significant in the lowland areas (Figure 4-6). The largest area is surrounding Lake Elterwater. To the north, around Taimate, the flood hazard is high as drainage culverts associated with road and rail infrastructure can become blocked. This allows water to build up behind SH1 and railway line before eventually overtopping at multiple places (Figure 4-7). There are also areas of flooding on the surrounding land of the southern branch that are not directly connected with the main river channel.

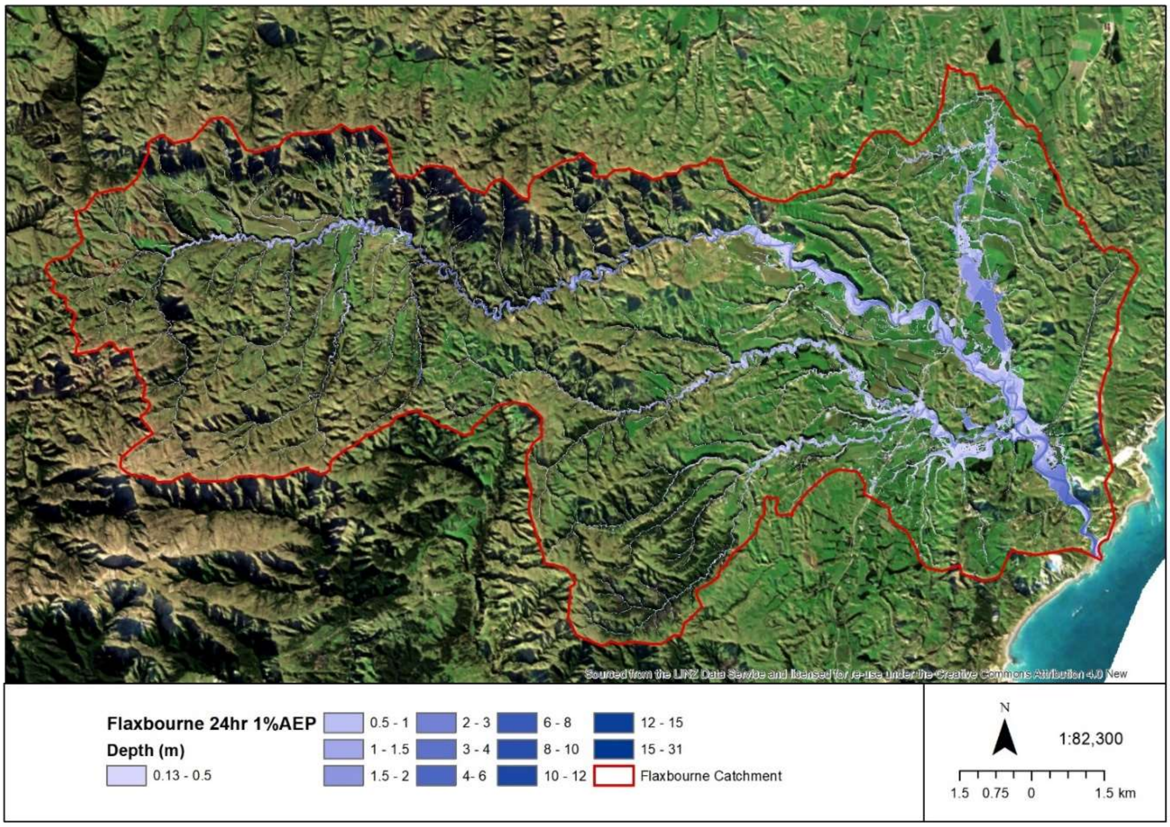

Figure 4-2: Maximum water depth during a 1% AEP 24-hour rainfall event in the Flaxbourne catchment.

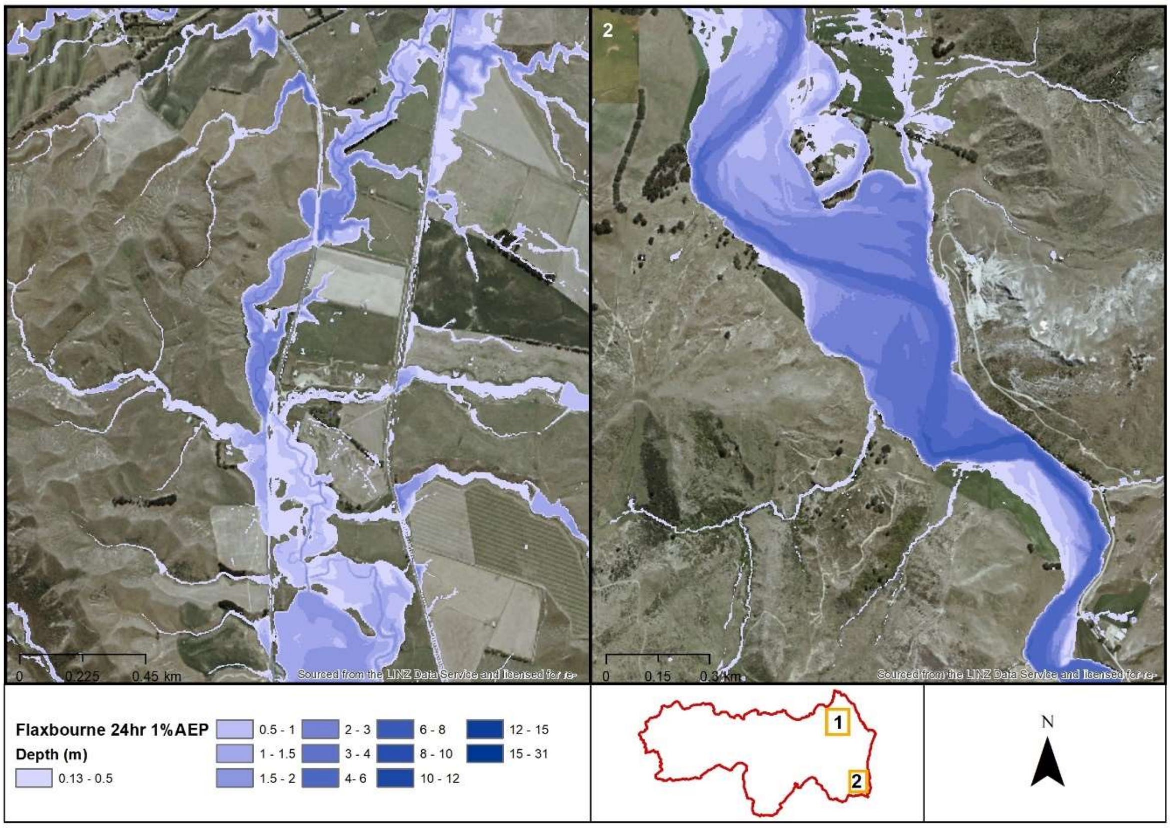

Figure 4-3: Maximum water depth during a 1% AEP 24-hour rainfall event in the north of the catchment around Taimate (left) and toward to the river mouth (right).

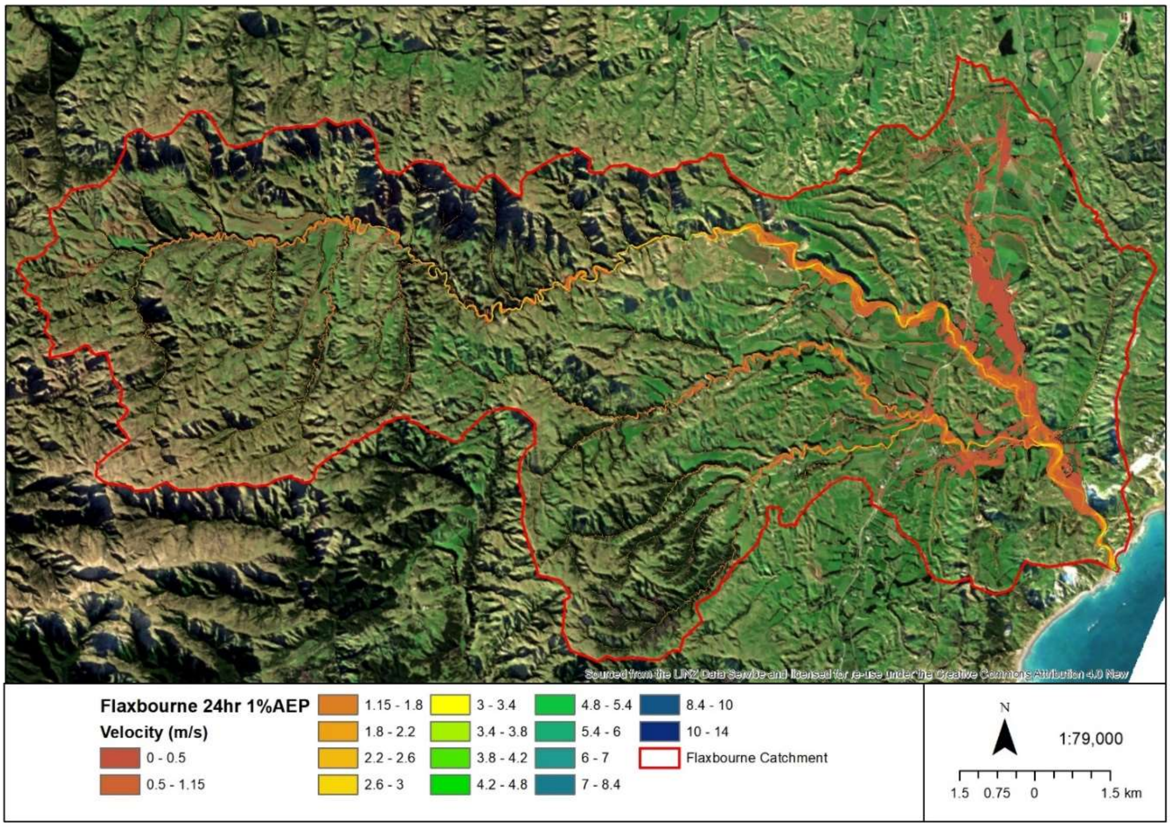

Figure 4-4: Maximum velocity during a 1% AEP 24-hour rainfall event in the Flaxbourne catchment.

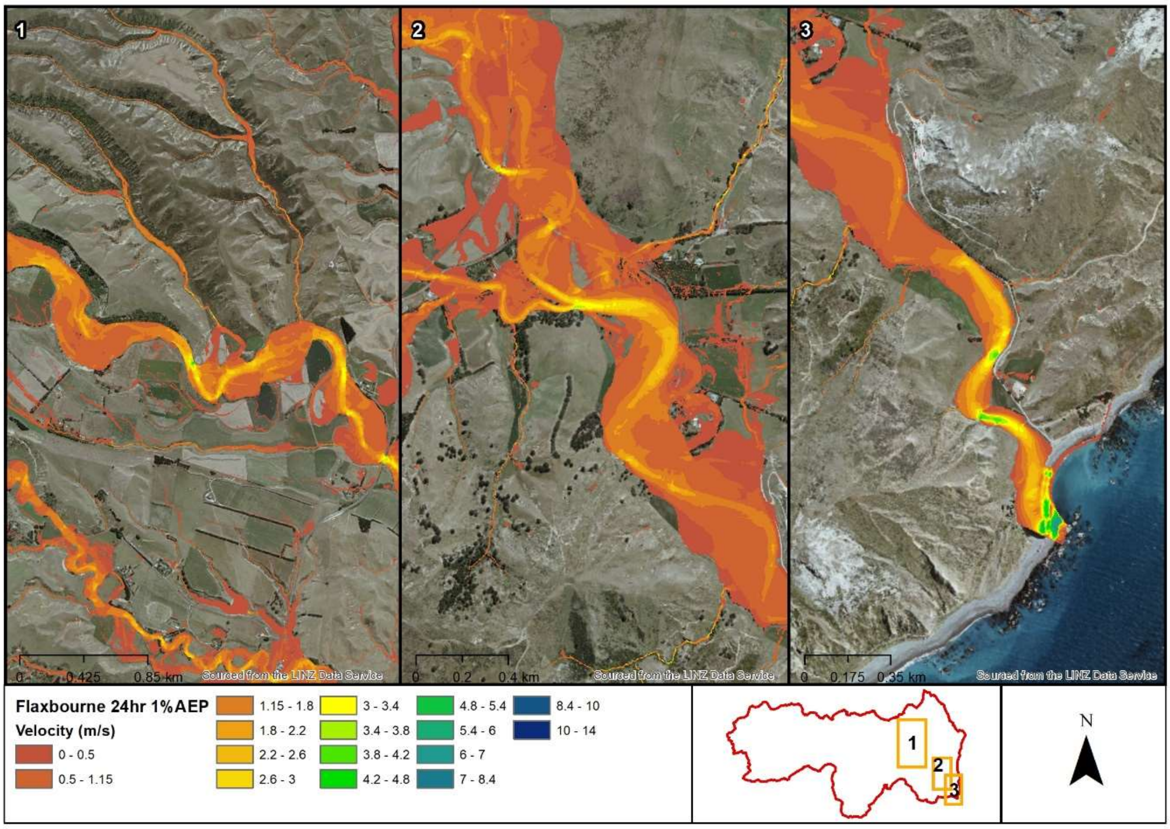

Figure 4-5: Maximum velocity during a 1% AEP 24-hour rainfall event in the steep upper catchment (left), where the southern branch joins the main channel (middle) and at the mouth of the river (right).

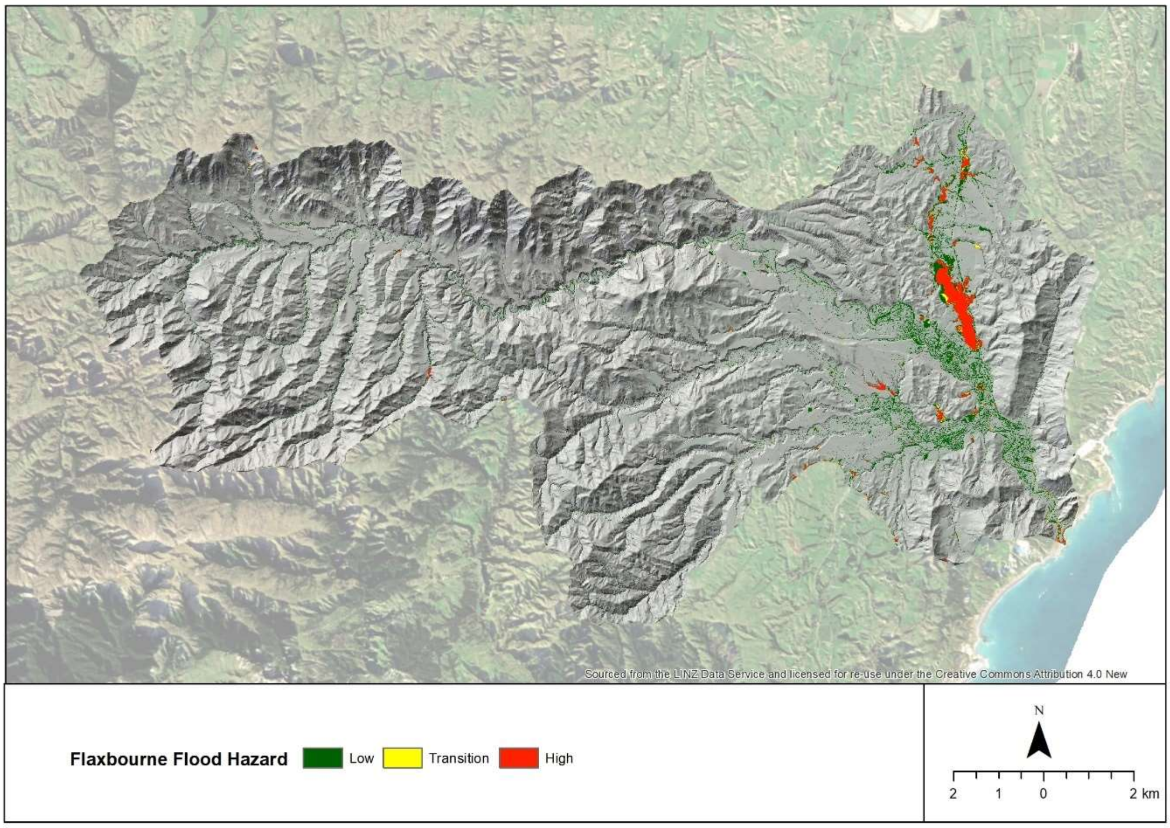

Figure 4-6: Flood hazard map during a 1% AEP 24-hour rainfall event in the Flaxbourne catchment.

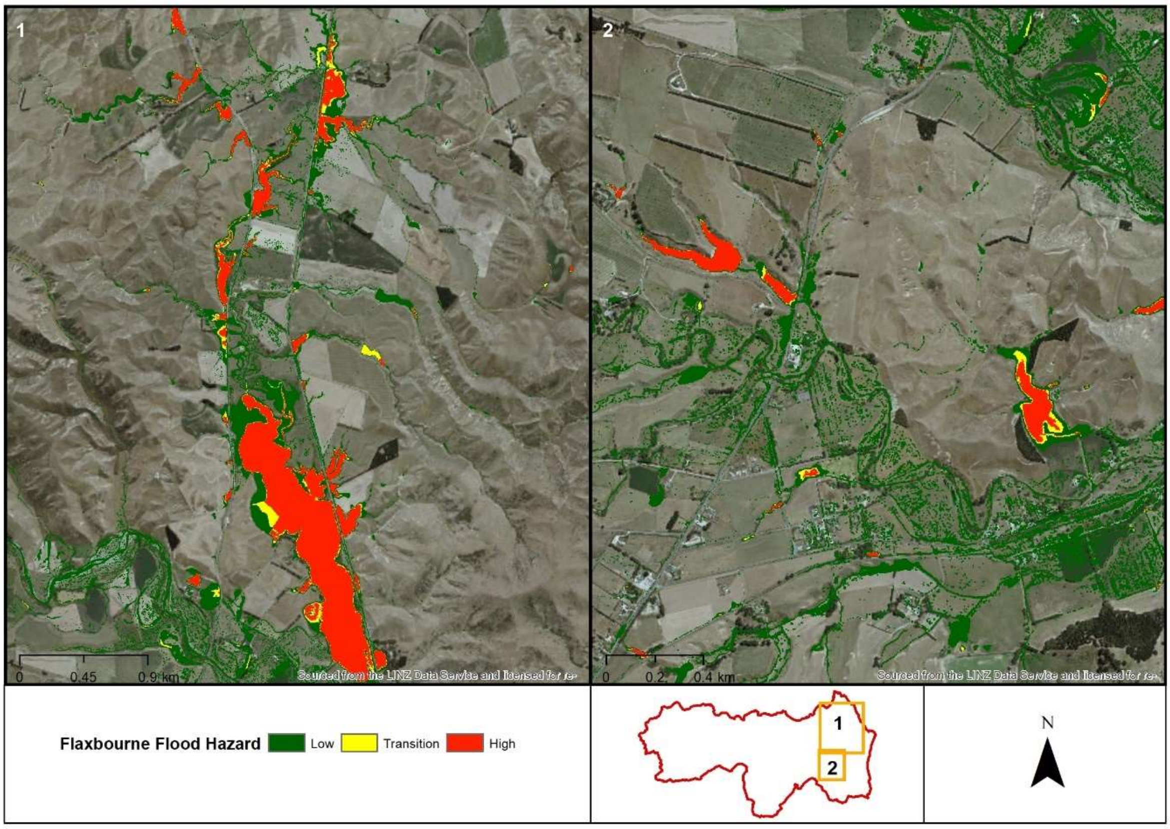

Figure 4-7: Flood hazard map during a 1% AEP 24-hour rainfall event around Lake Elterwater and Taimate (left) and areas around the southern branch near the confluence with the main river channel (right).

MIRZA CATCHMENT

The flood hazard has been quantified for the Mirza catchment during a 1% AEP 6-hour duration design rainfall using the maximum depth and velocity maps.

The flood extent generally stays within the floodplain, apart from where flow has been constricted by drainage culverts. Flooding of SH1 and railway occurs at a number of locations were these drainage culverts have become blocked (Figure 4-8). One of the larger areas of flooding occurs where tributaries flowing from different orientations join the main channel. In this area, a 10m high embankment allows floodwaters to build up, protecting the vineyard from flooding. In the lower catchment, unlike in the Flaxbourne and Waima catchments which become wider, flow in the Mirza is constrained within a narrower, deeper channel towards the mouth.

Water depth

Water depth for the Mirza catchment is shown in Figure 4-9. The deepest flooding occurs within the deeper channel in the lower catchment, and where the flood waters back up behind SH1 in the upper catchment (Figure 4-10, right). Water depth is also high where an embankment holds back water from flooding a vineyard (Figure 4-10, left). The flood depths experienced in the Mirza catchment are lower than those in the larger Flaxbourne and Waima catchments.

Velocity

Mirza experiences overall lower velocities than the other two catchments (Figure 4-11). The higher velocities, as expected, occur within the steeper upper catchment tributaries and towards the mouth of the river (Figure 4-12). In the northern part of the catchment, there are certain points in the landscape that velocities increase as water moves quickly as it overtops roads and railway lines.

Overall Flood Hazard

There are two notable areas of high flood hazard in the catchment. Towards the north, the flood hazard is increased where culverts near SH1 and the railway are blocked, and floodwaters spill over onto adjacent land (Figure 4-14, left). Floodwaters are enhanced in the middle of the catchment by several tributaries converging with the main stem. These floodwaters build up behind a 10m embankment which protects a vineyard from flooding, but which allows water to accumulate over the floodplain and beyond (Figure 4-14, right).

Figure 4-8: Area behind SH1 that experiences deeper flooding within the Mirza catchment.

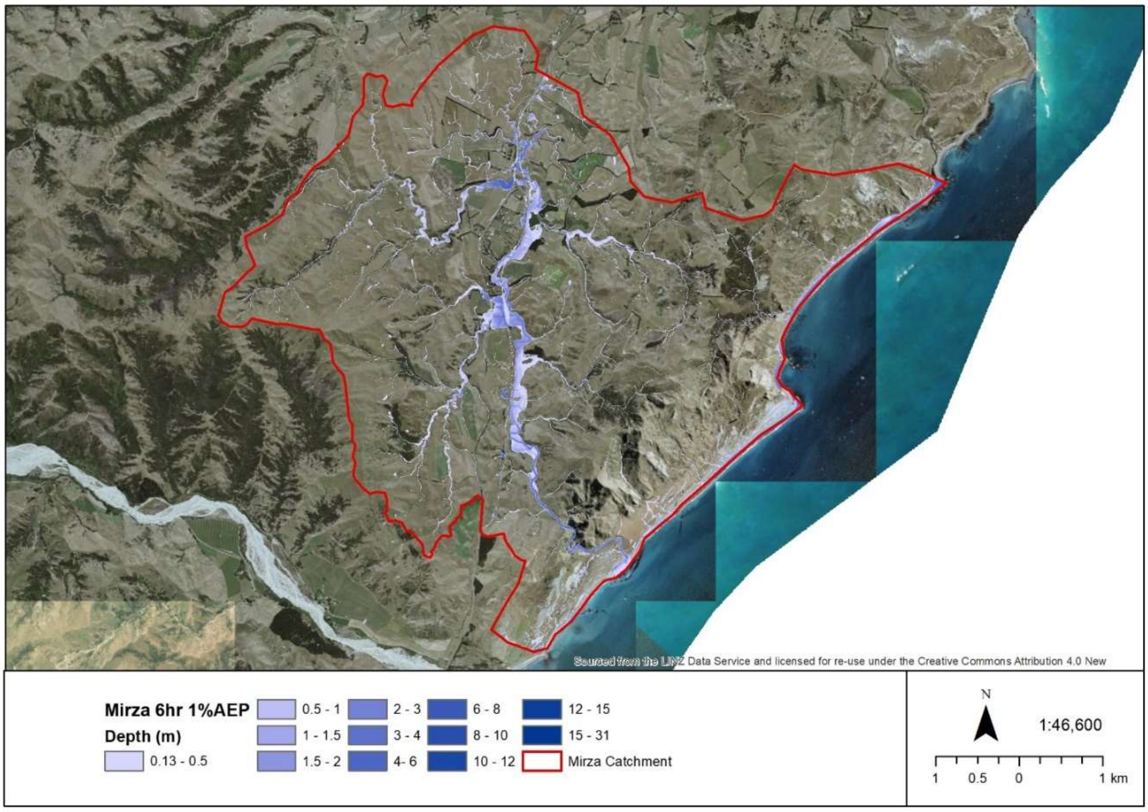

Figure 4-9: *Maximum water depth during a 1% AEP 6-hour rainfall event in the Mirza catchment.*

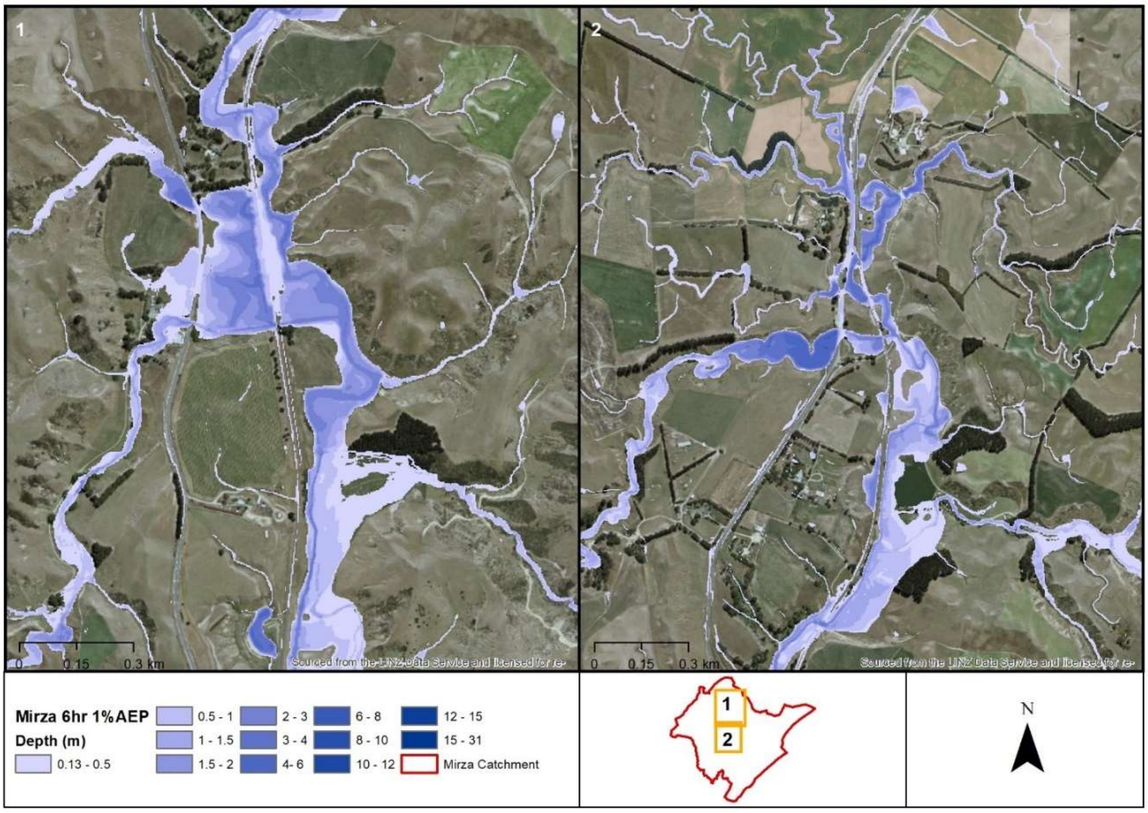

Figure 4-10: *Maximum water depth during a 1% AEP 6-hour rainfall event in the middle of the catchment where a 10m embankment protects a vineyard from flooding (left), and towards the north where culverts associated with rail and road infrastructure can become blocked (right).*

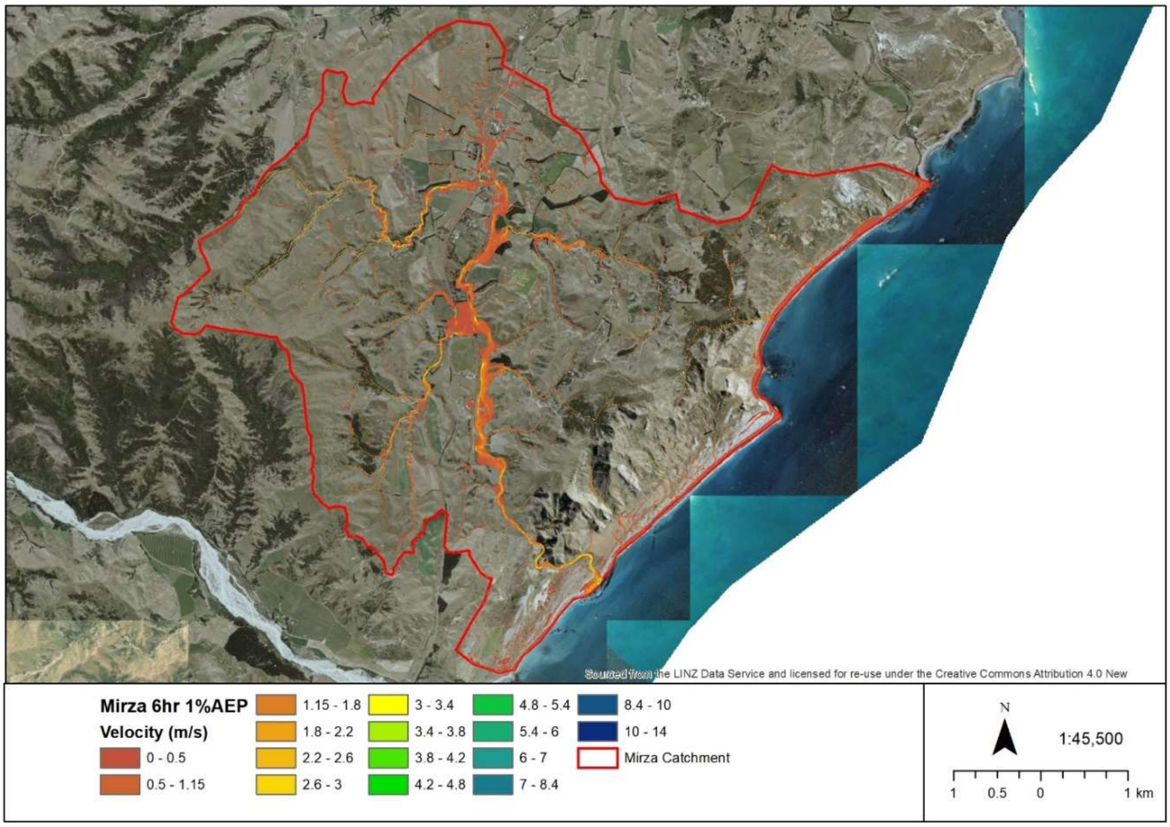

Figure 4-11: Maximum velocity during a 1% AEP 6-hour rainfall event in the Mirza catchment.

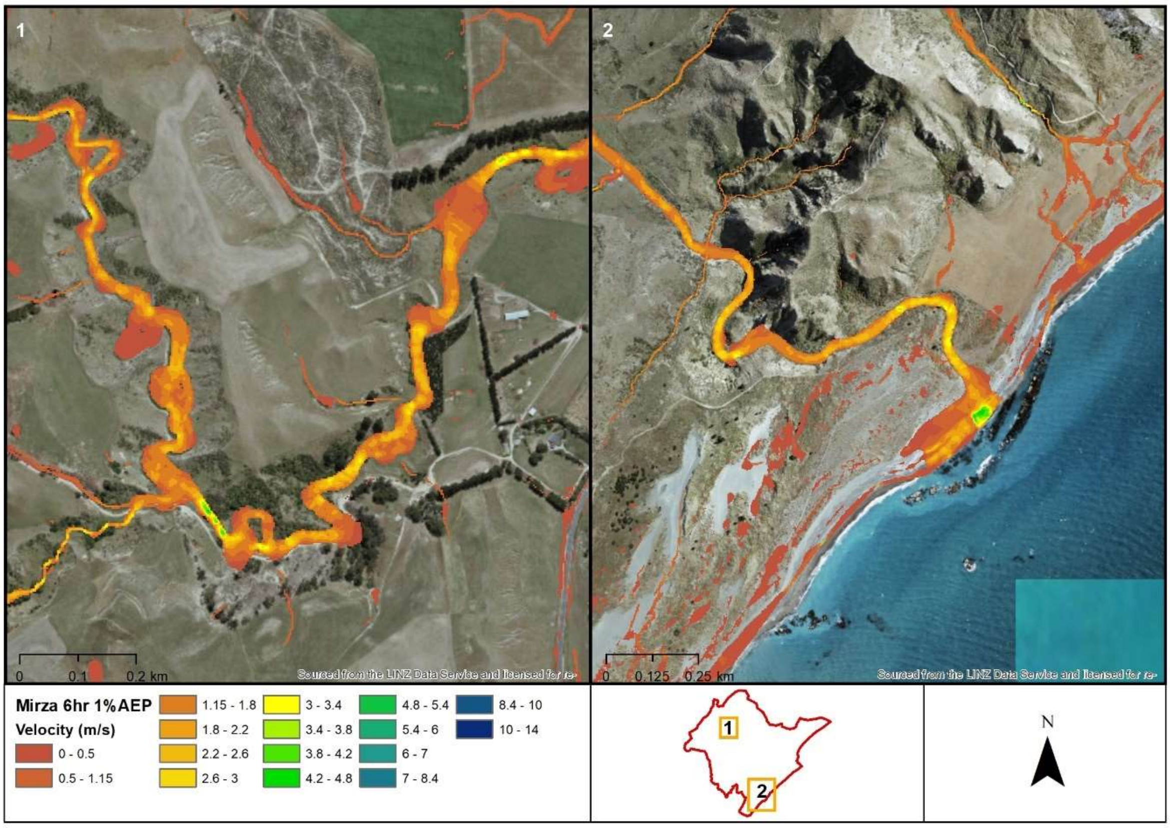

Figure 4-12: Maximum velocity during a 1% AEP 6-hour rainfall event in headwater tributaries of the catchment (left) and near the mouth of the river (right).

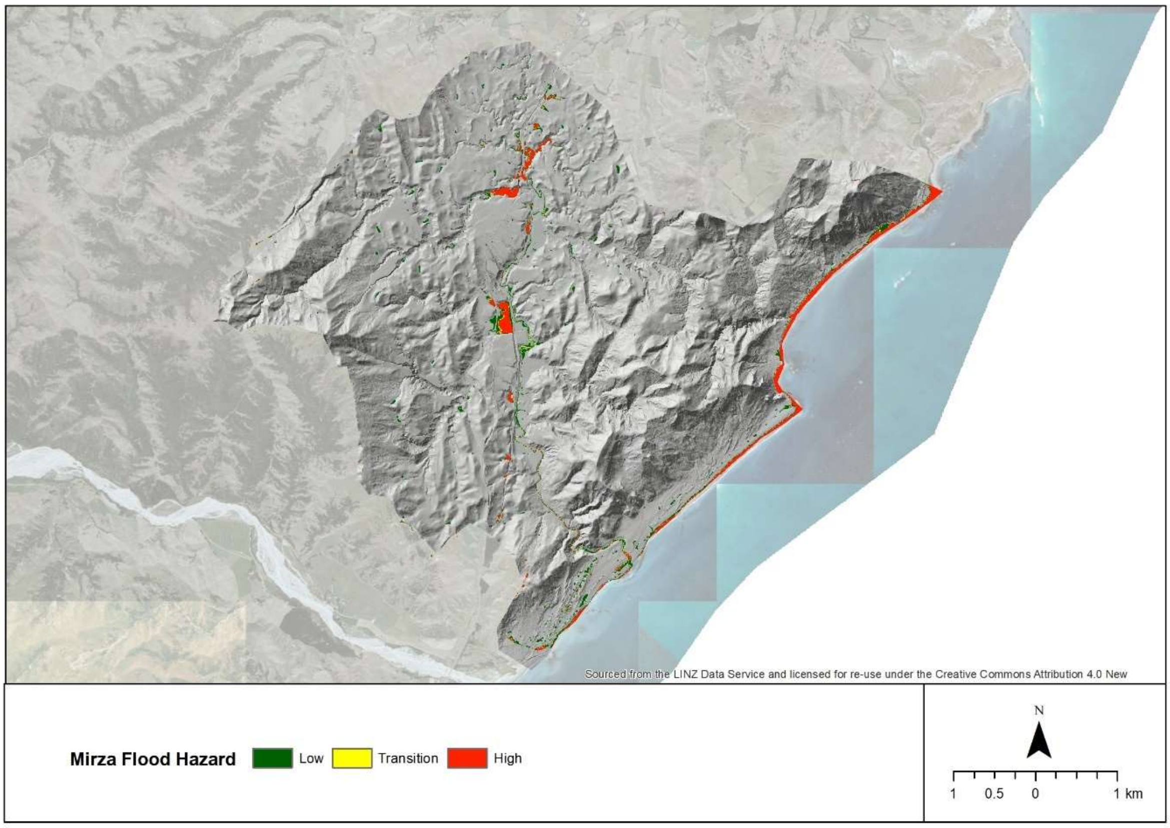

Figure 4-13: Flood hazard map during a 1% AEP 6-hour rainfall event in the Mirza catchment.

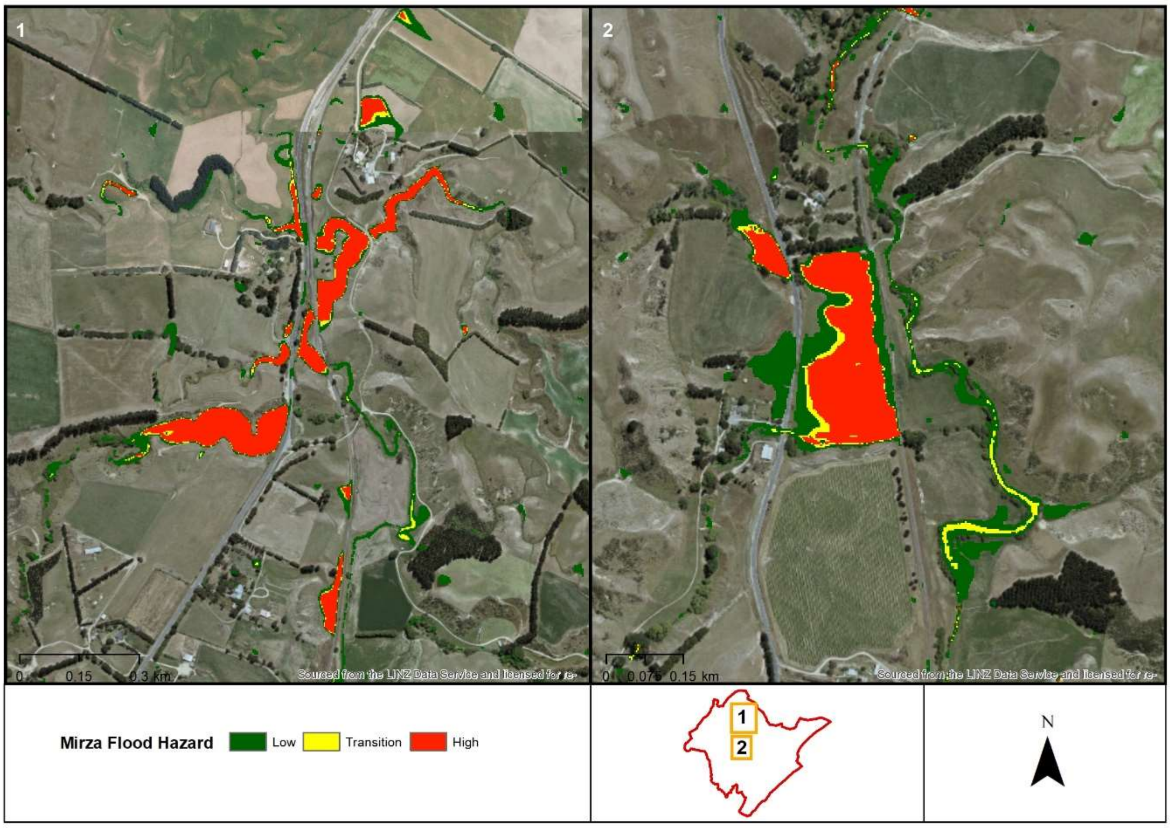

Figure 4-14: Flood hazard map during a 1% AEP 6-hour rainfall event in the north of the catchment (left) and around the embankment which protects the vineyard to the south (right).

WAIMA CATCHMENT

The flood hazard has been quantified for the Waima catchment during a 1% AEP 24-hour duration design rainfall using the maximum depth and velocity maps. Typically, the flood extent follows the floodplain. The upper half of the catchment is characterised by steep-sided, narrow valleys that confine the flood extent.

Water depth

Within the Waima catchment there are a couple of notable topographic pinch points in the upper catchment (Figure 4-15). Here the floodwaters deepen as water builds up behind the constriction formed by the narrowing of the steep valley sides (Figure 4-16). In the lowland part of the catchment, the floodplain widens, and overall depths are reduced.

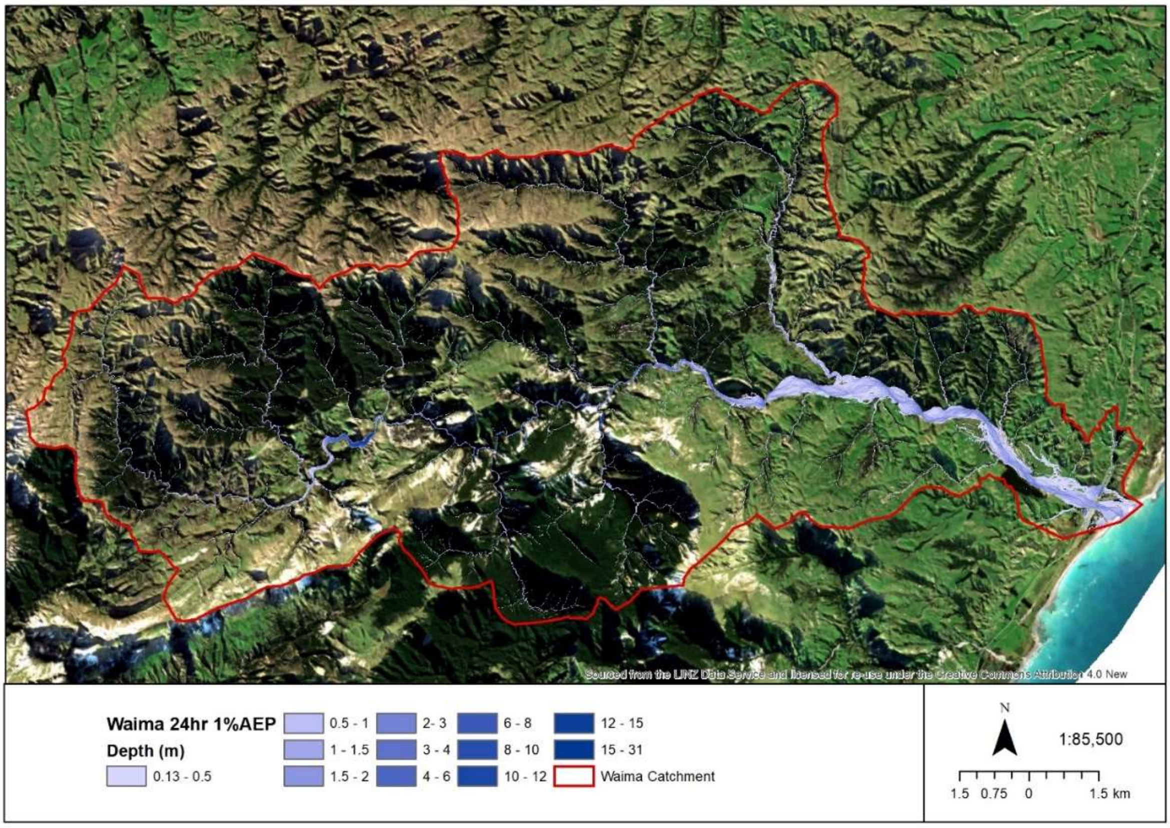

Figure 4-15: Maximum water depth during a 1% AEP 24-hour rainfall event in the Waima catchment.

Velocity

Waima experiences the highest velocities of the three catchments (*Figure 4-17*). Velocities tend to slow behind topographic constrictions but increases as flow passes through (Figure 4-18). The highest velocities are seen in the mid-catchment where the river sides are both the steepest and narrowest. Velocities are highest through the main channel, slowing as floodwaters move across the floodplain and surrounding land (Figure 4-18).

Overall Flood Hazard

Flood hazard is generally low throughout this catchment (Figure 4-19). The main areas of high flood hazard are behind topographic pinch-points (Figure 4-20). In these areas, floodwaters build up and inundate the surrounding floodplain. However, the flooding is limited to a relatively small area given the surrounding topography.

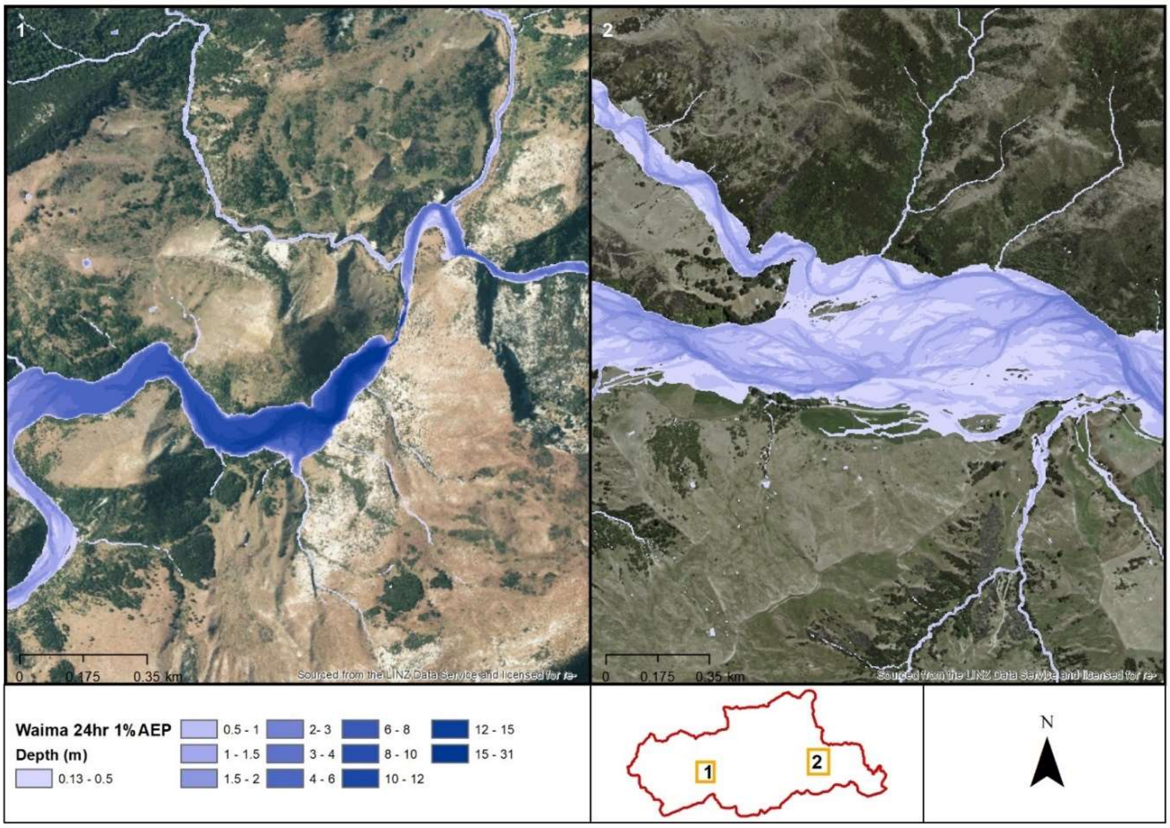

Figure 4-16: Maximum water depth during a 1% AEP 24-hour rainfall event is highest around topographic pinch points in the upper catchment (left). Maximum water depth is lower over the floodplain in the lower catchment (right).

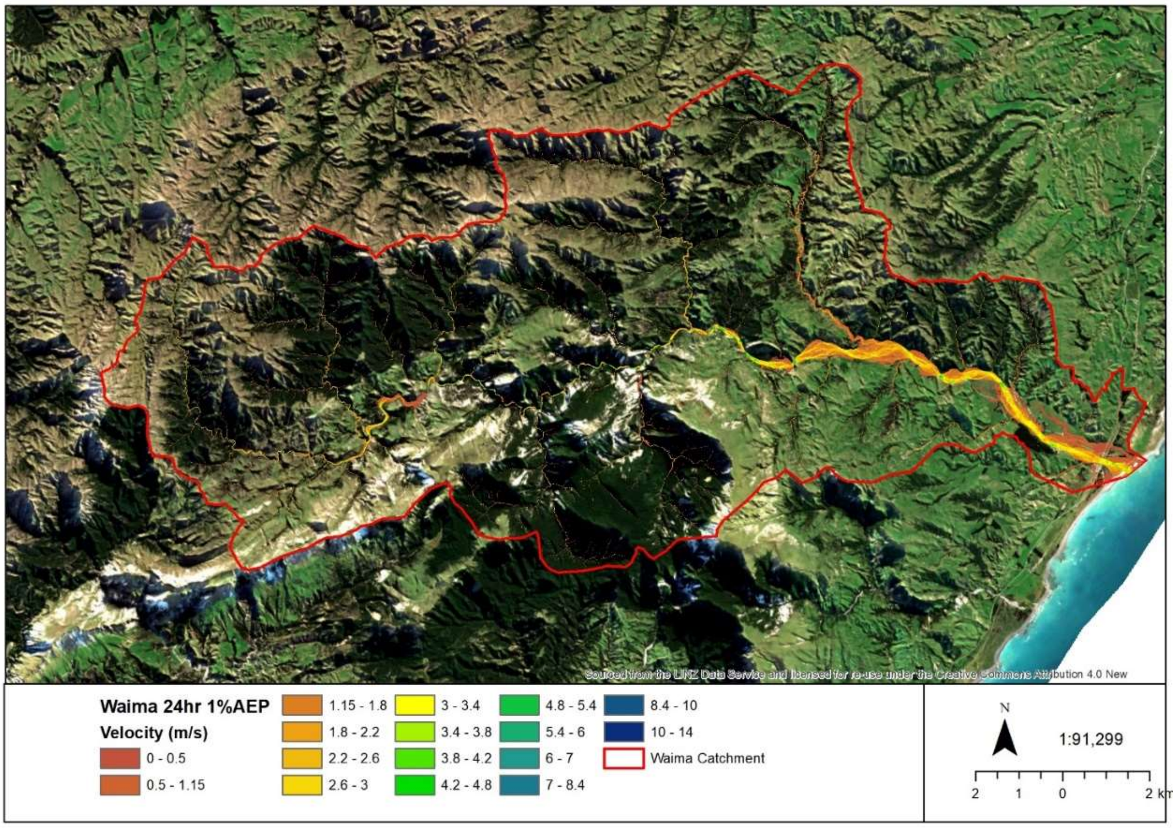

Figure 4-17: Maximum velocity during a 1% AEP 24-hour rainfall event in the Waima catchment.

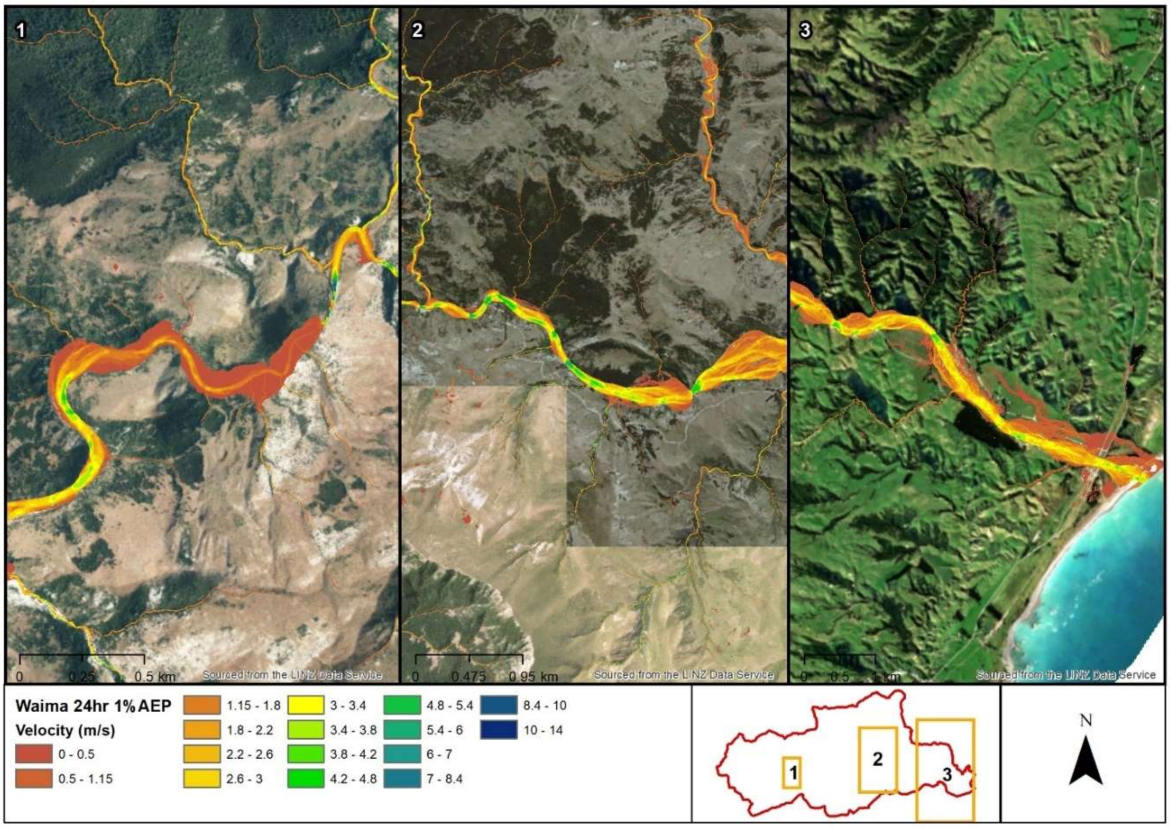

Figure 4-18: Maximum velocity during a 1% AEP 24-hour rainfall event in the upper catchment where velocities slow behind topographic constrictions (left). Velocities are highest in the steep and narrow mid-catchment (middle) and through the main channel towards the river mouth (right).

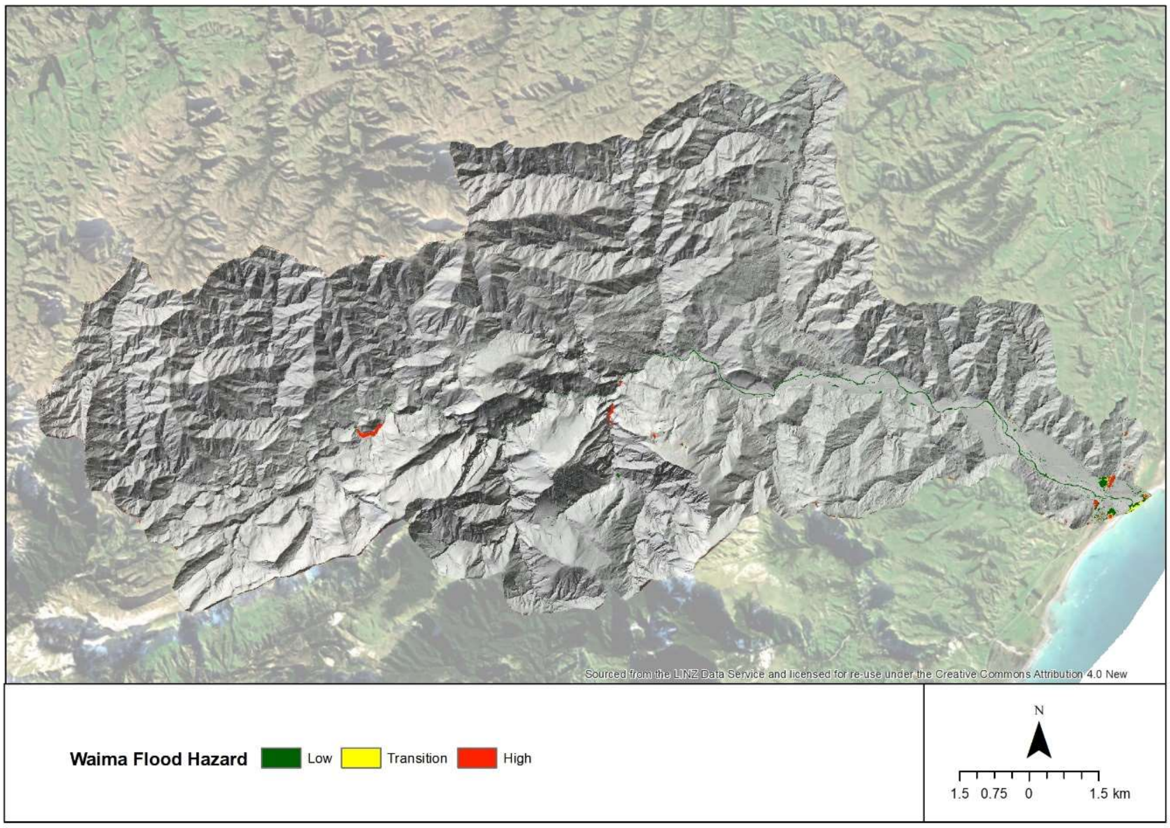

Figure 4-19: Flood hazard map during a 1% AEP 24-hour rainfall event in the Waima catchment.

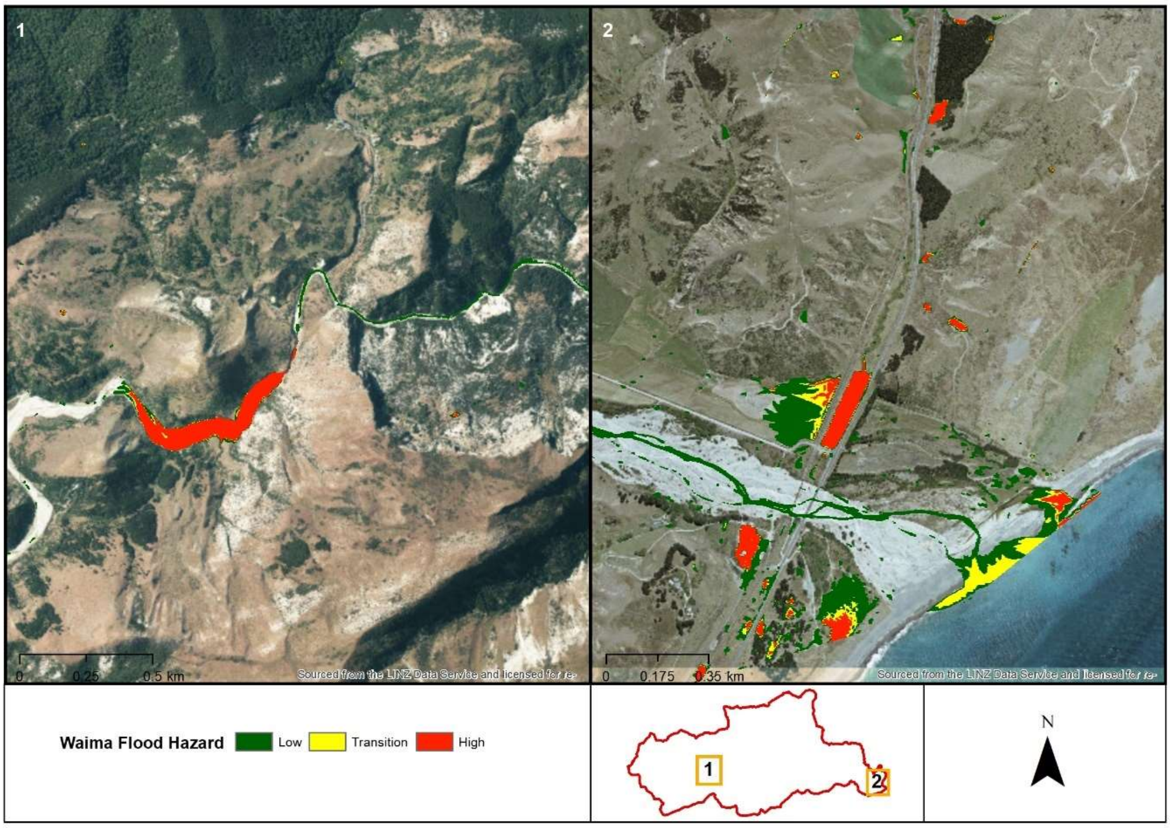

Figure 4-20: Flood hazard map during a 1% AEP 24-hour rainfall event in the upper catchment behind topographic pinch points (left) and near the river mouth (right).

Near the river mouth, floodwaters flow over surrounding land, but the flood hazard is low because of the lower velocities and depths. There are, however, smaller pockets of high flood hazard where water is constrained by roading infrastructure in this area (Figure 4-20).

4.3 Erosion and deposition analysis

Bed shear stress is the force of moving water acting against the bed of the channel. In TuFlow™, the bed shear stress is calculated by the equation below: where ρ is density, g gravity, V velocity, n Manning's n and y depth.

$$\text{Metric Units: } \tau_{bed} = \frac{\rho g V^2 n^2}{y^{\frac{1}{3}}}$$

To initiate the movement of grains on the bed of the river, the bed shear stress must exceed the critical shear stress (a function of the Reynold number and particle size). Typically, increased bed shear stress promotes erosion whereas a reduction in bed shear stress promotes sedimentation; with larger bed shear stresses having the capability to move larger grain sizes.

Figure 4-21 shows a relationship between particle size and critical shear stress. Figure 4-22 shows the relationship between particle size and critical erosion velocity; where the critical erosion curve shows the minimum velocity required to lift a particle of a certain size. Depending on the relationship between particle size and velocity, different 'conditions' are recognised i.e. fluvial transportation, erosion, and sedimentation (Figure 4-22).

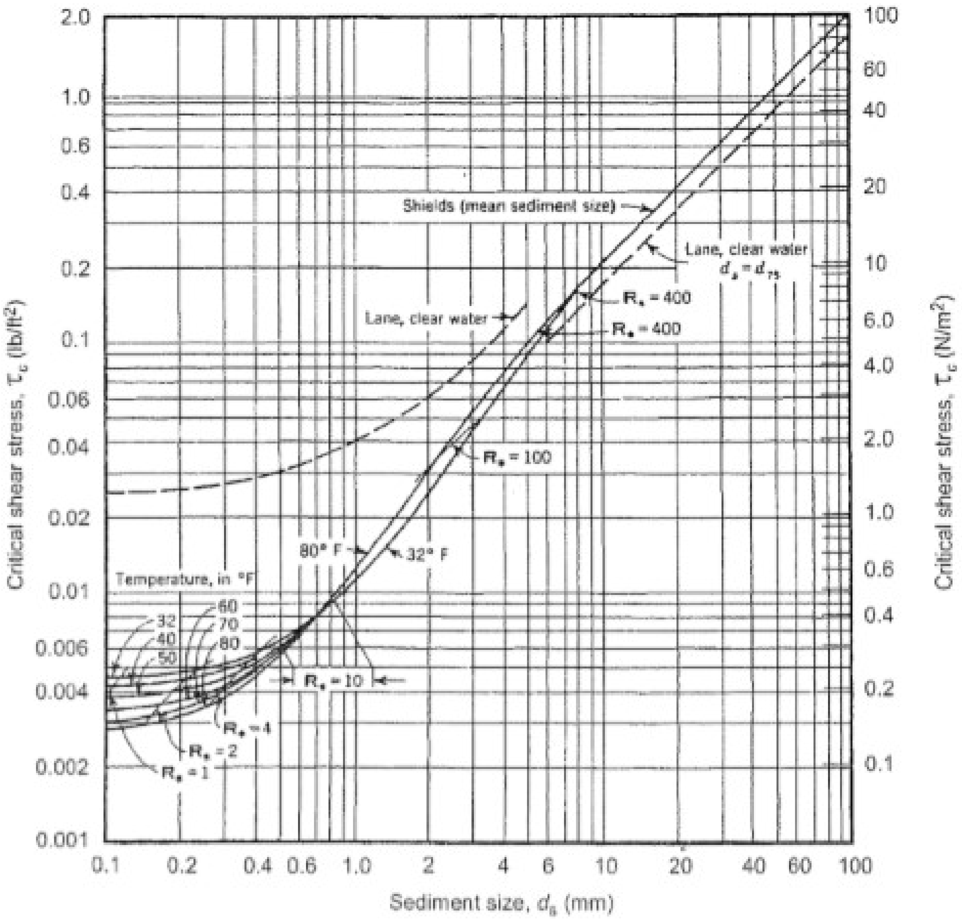

Figure 4-21: *Relationship between particle size and critical shear stress for uniform material with a specific gravity of 2.65. It is important to note that these conditions for the initiation of movement are not exact. The threshold for particle motion may also be affected by the cohesion, packing and sorting of the material.*

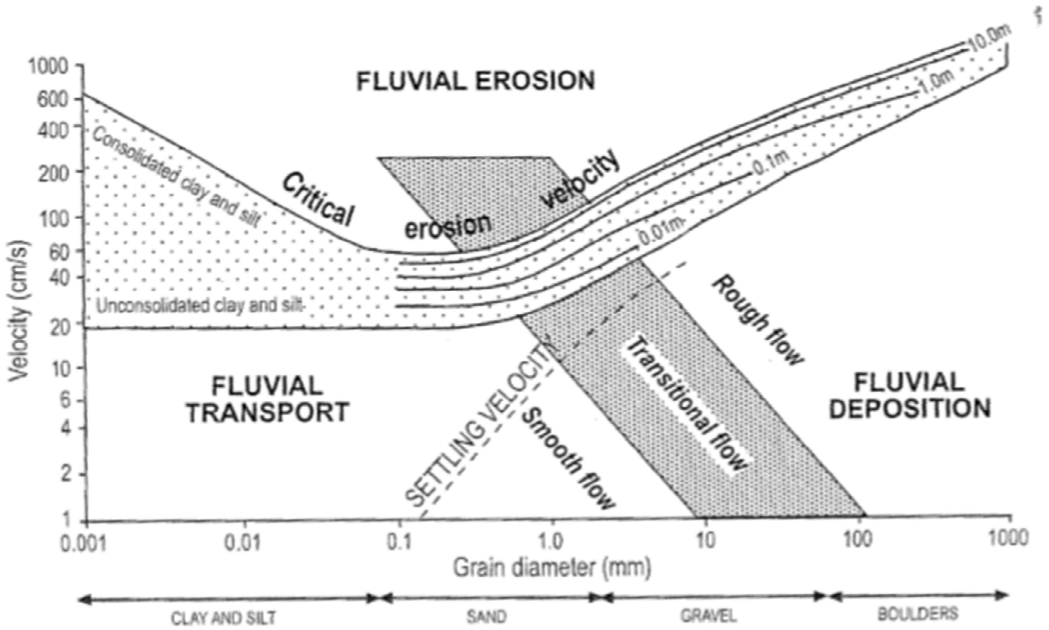

Figure 4-22: *Relationship between particle size and critical erosion velocity for uniform material with a specific gravity of 2.63. Because local flow velocity varies with distance from river bed, threshold conditions are illustrated for velocities measured distances of 0.01, 0.1, 1.0 and 10m above the bed.*

While there are many factors influencing erosion, transportation, and sedimentation these graphs, in combination with the bed shear stress results, can be used to give an indication of the grain sizes that could be moved and areas of sedimentation and erosion that may occur throughout the three catchments.

Understanding sedimentation and erosion processes within a catchment can be important for a number of reasons including water quality, deposition build up (effecting ecology, vegetation, and channel conveyance capability), scour, and erosion (effecting land stability).

With this in mind, the bed shear stress results have been analysed to provide a better understanding of the sedimentation processes within each catchment.

FLAXBOURNE CATCHMENT BED SHEAR STRESS

The maximum bed shear stress during this event (Figure 4-23) gives an indication of the erosion and sedimentation processes within the catchment.

Within the Flaxbourne catchment, the highest bed shear stresses i.e. the areas most prone to erosion, occur in the narrow deep channels of the mid-catchment (Figure 4-24, left). Shear stresses reduce as the river moves through the lower catchment, where the river widens and velocities slow. There are some areas of higher bed shear stress in the main channel, particularly where tributaries converge (Figure 4-24, middle) and towards the river mouth (Figure 4-24, right). Lower shear stresses, where deposition is more likely, occur on the floodplain where the flood water spreads out.

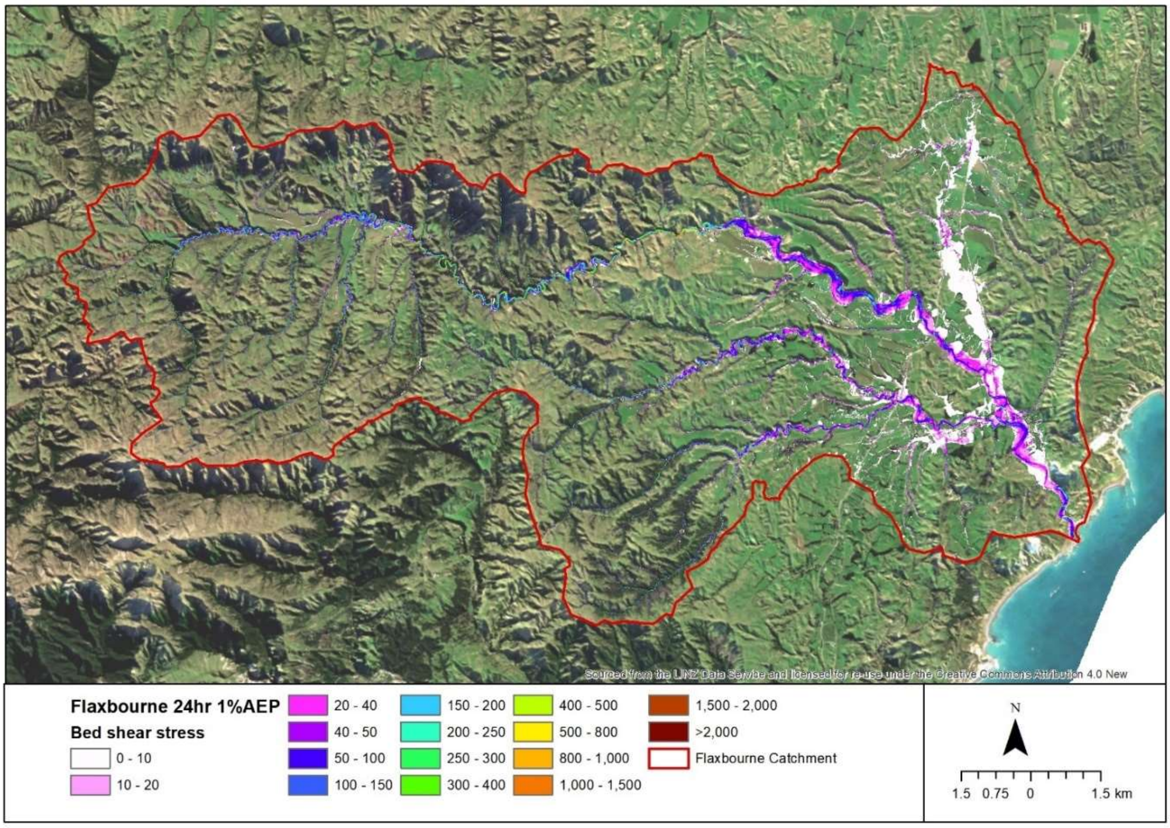

Figure 4-23: Maximum bed shear stress during a 1% AEP 24-hour rainfall event in the Flaxbourne catchment.

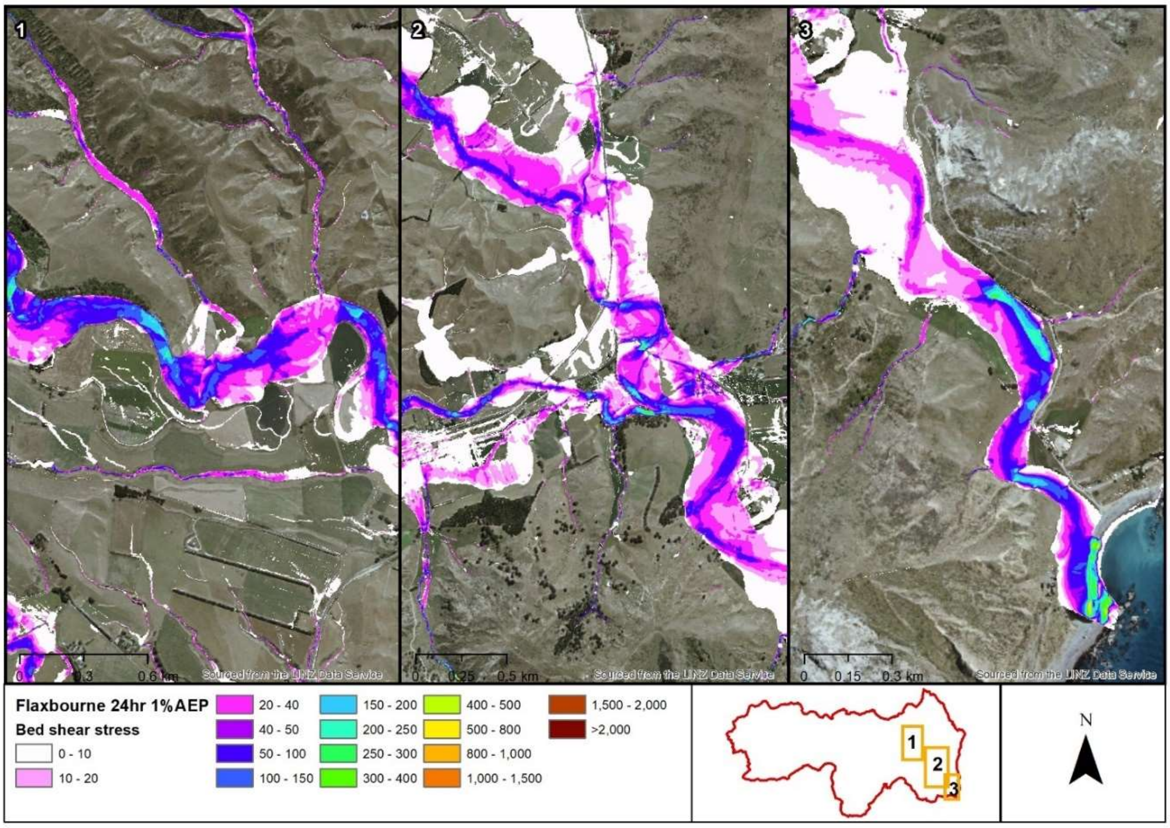

Figure 4-24: Maximum bed shear stress during a 1% AEP 24-hour rainfall event in the Flaxbourne catchment.

MIRZA CATCHMENT BED SHEAR STRESS

The maximum bed shear stress during the design event (Figure 4-25) gives an indication of the erosion and sedimentation processes within the catchment.

The bed shear stress results follow the expected distribution, with higher values in the narrower upper catchment tributaries, and lower bed shear stresses where the floodplain widens, and slower velocities are experienced. Compared to the other two catchments, the Mirza has lower bed shear stress and so will have less capacity to erode and transport larger material.

WAIMA/URE CATCHMENT BED SHEAR STRESS

The maximum bed shear stress during the design event (Figure 4-27) gives an indication of the erosion and sedimentation processes within the catchment.

The Waima/Ure has the highest bed shear stresses of the three catchments; with consequently greater erosional power capacity to move larger material. The higher shear stresses are seen in the steeper, narrower valleys and within the main river channel. Lower bed shear stresses, where deposition might be expected, can be seen on the lower floodplain.

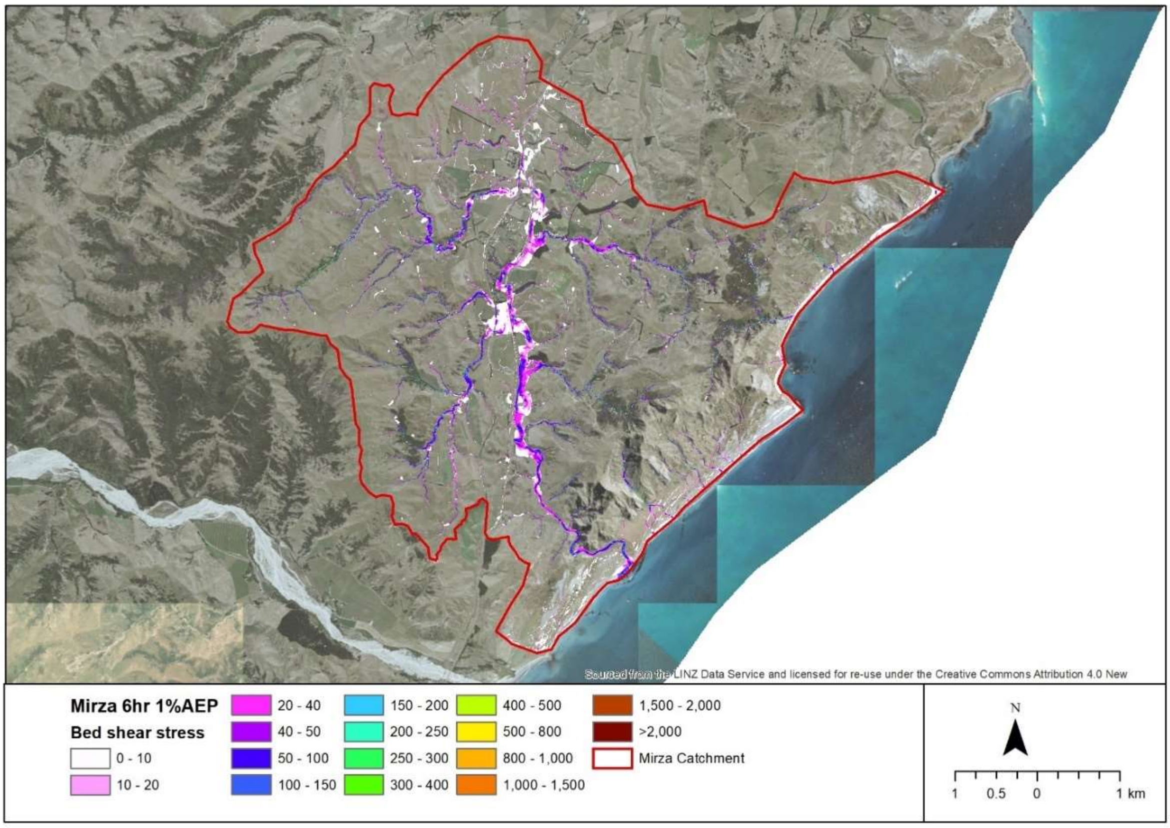

Figure 4-25: Maximum bed shear stress during a 1% AEP 6-hour rainfall event in the Mirza catchment.

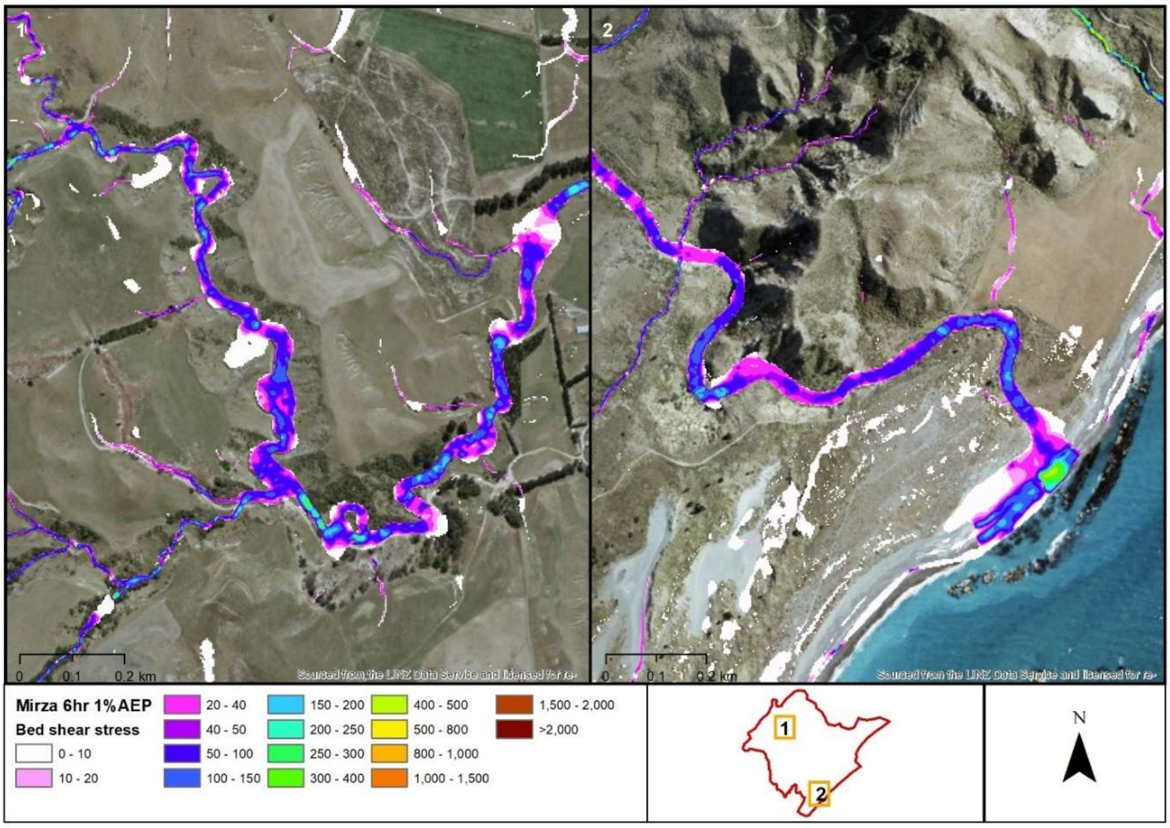

Figure 4-26: Maximum bed shear stress during a 1% AEP 24-hour rainfall event in the Mirza catchment.

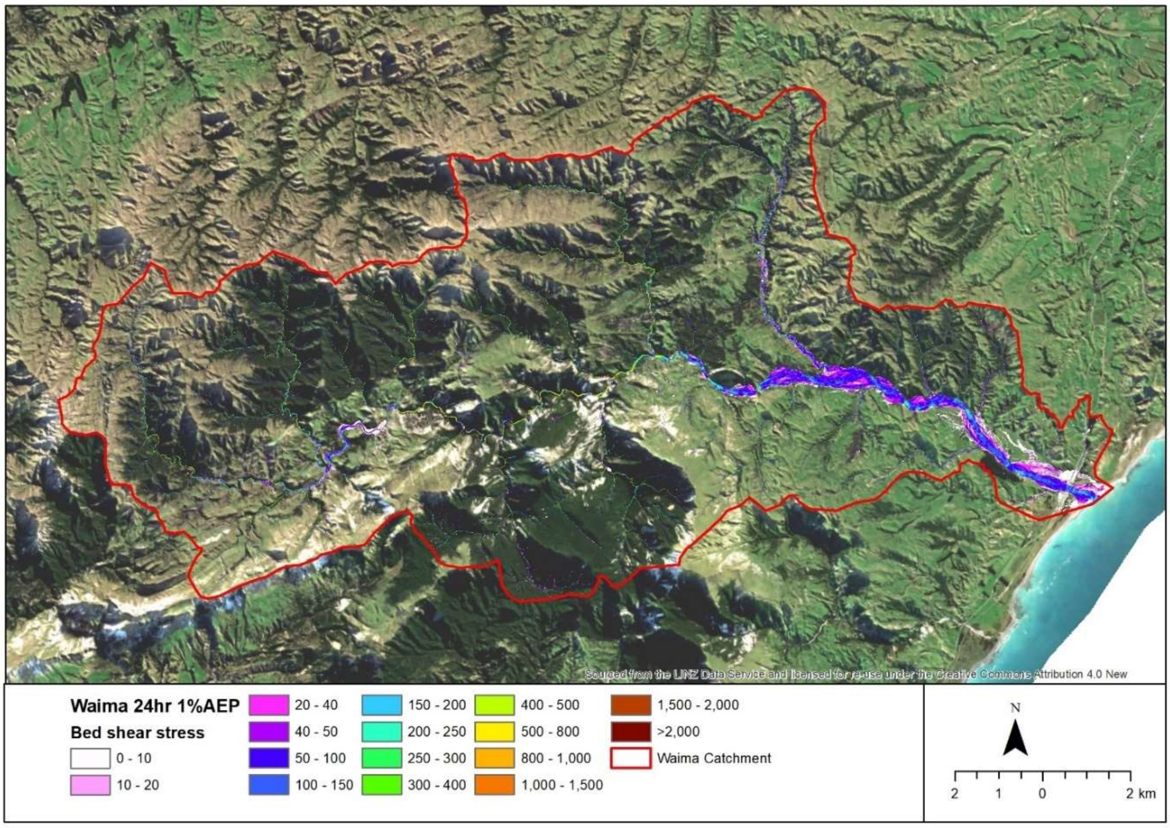

Figure 4-27: *Maximum bed shear stress during a 1% AEP 24-hour rainfall event in the Waima/Ure catchment.*

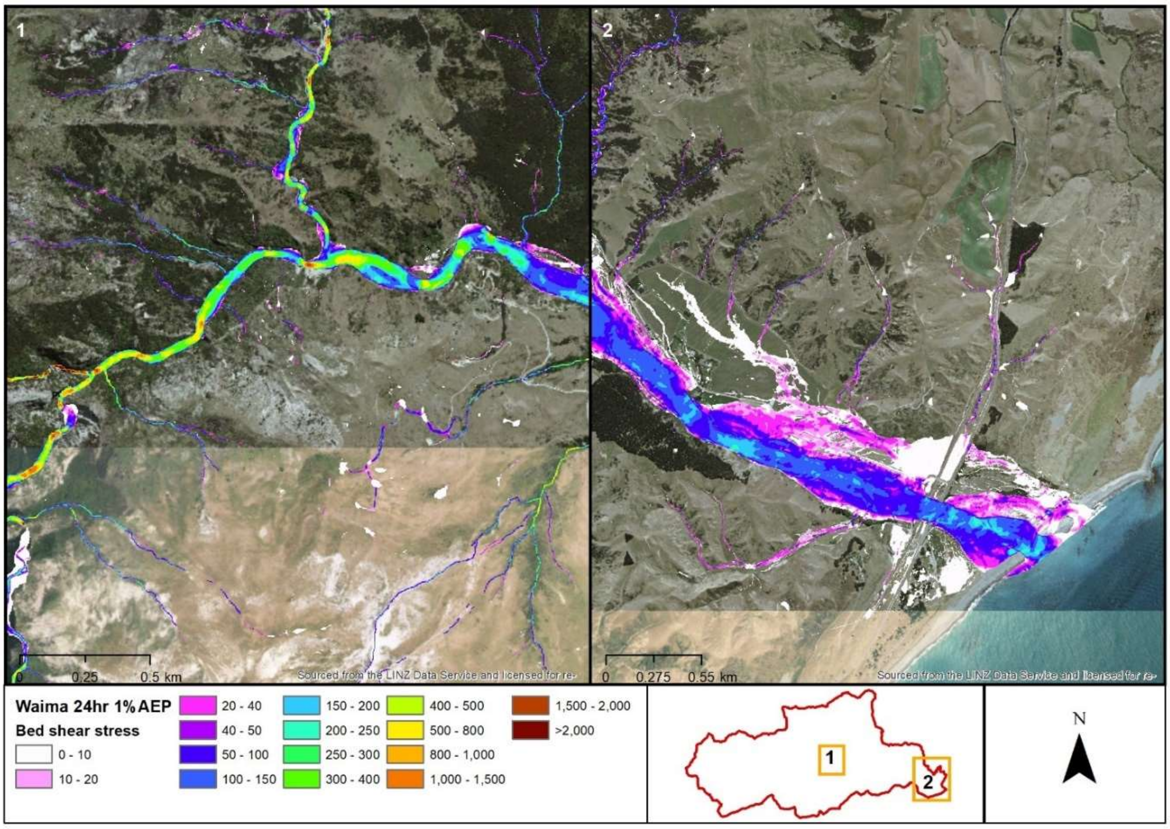

Figure 4-28: *Maximum bed shear stress during a 1% AEP 24-hour rainfall event in the Waima/Ure catchment.*

5 Conclusions and Recommendations

The flood hazard within the Flaxbourne, Waima/Ure and Mirza catchments following the Kaikōura Earthquake has been investigated using a 2-dimensional computational hydrological model (2-d model).

The flood extent was quantified during 1% AEP rainfall event, of the critical duration, within the Flaxbourne, Mirza, and Waima/Ure catchments. The bed shear stress was also derived to give an indication of the potential for erosion and sedimentation within each catchment.

The main findings include:

- Flooding is likely to occur on floodplains adjacent to rivers and streams, and immediately upstream of barriers across the floodplains, such as road or railway embankments;
- In some areas, flooding results from flow being restricted by drainage culverts under road and railway embankments. This causes flooding upstream of the culverts and flooding of SH1 and the railway;
- The natural topography can also restrict the flow, resulting in deeper flooding upstream of these pinch points;
- Bed shear stress is typically higher in the narrower, steeper sections within the upper catchment. Erosion is expected in these locations; and
- Bed shear stress is lower where flow spreads out across the floodplain. These areas may be affected by sediment deposition.

While best practise has been applied to develop this model, and obtain these results, confidence could be improved through additional work. To improve the validation of the results it is recommended that:

- Anecdotal information regarding known flood events be obtained and compared to the modelled flood extents and depths of inundation. This would increase confidence in the modelled outputs; and
- In the future, once more data are recorded from the Flaxbourne River at Corrie Downs, or if a larger flood event occurs, this data could be used to calibrate and validate the model.

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