Westport - flood forecasting roadmap for evacuation warnings

Prepared for West Coast Regional Council

June 2019

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NIWA CLIENT REPORT No: 2019115CH
Report date: June 2019
NIWA Project: ELF19507

Quality Assurance Statement		
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	Formatting checked by:	Rachel Wright
	Approved for release by:	Helen Rouse

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Executive summary

A new integrated family health centre is to be built in Westport and, as Westport is vulnerable to flooding, eight hours flood warning is required to enable patients to be moved safely if a flood large enough to cause flooding of Westport is forecast. NIWA has received Envirolink funding to help West Coast Regional Council explore this issue. This report explores the feasibility of implementing a flood-forecasting system capable of provide accurate prediction of flooding with an 8-hour lead time. The report investigates different options and provides details of a recommended solution, as well as costs and a roadmap for implementation. The main conclusions are:

- A forecasting system could be created that will predict a flood at Westport eight hours in advance with enough accuracy to be used for triggering evacuations.
- The current hydrological network is adequate to inform a model, but a further telemetered rain gauge at Buckland Peaks would give more information on rainfall in the Paparoa range, an area of high importance for flood forecasting.
- The favoured modelling solution is a distributed, physically based hydrological model of the Buller River catchment driven by telemetered rain data from all rain gauges in and around the catchment as well as gridded rainfall forecasts to extend the forecast lead time. Telemetered flow records from throughout the catchment should be used for data assimilation to improve model accuracy.
- Flow thresholds for triggering flood warnings, especially for downstream areas of the city, should vary depending on forecast sea level (tide and storm surge). Accurate sea level forecasts are already produced by NIWA.
- The MetService rain radar at Hokitika could provide qualitative information on rainfall spatial variability, but due to its distance from the catchment the achievable accuracy of quantitative radar rain rate estimation is uncertain.
- It is recommended that the forecasting system should have a target accuracy of 70% or greater probability of detection (POD) and 30% or lower false alarm ratio (FAR).
- The estimated setup cost to implement the recommended forecasting roadmap is $55-90,000, with estimated annual costs of $10 - $35,000, not including WCRC staff time and maintenance of the gauge network (excluding GST).
- A backup to the base telemetry server, or other backups to the gauge network or telemetry system (if required) has not been costed.
- The flood warning system could be operational from 30 June 2020.

1 Introduction

A new integrated family health centre is to be built in Westport and, as Westport is vulnerable to flooding, eight hours flood warning is required to enable patients to be moved safely if a flood large enough to cause flooding of Westport is forecast. This Envirolink funded report for the West Coast Regional Council (WCRC) investigates whether a model can be created that will predict a flood eight hours in advance and if not, what warning time could be expected. The report examines whether any new hydrological sites are required to assist the modelling and advises on the most appropriate modelling solution including what real time data can be used. The solution needs to be accurate and robust to give confidence in its use, so the level of confidence in the model needs to be stated.

This report also provides the estimated cost to implement the solution, including any new hydrological sites, if required, and recommends the type of model and the inputs necessary. WCRC also require the costs of software, modelling and maintenance and advice on the time frame between completing any hydrological sites and the implementation of the model. Thus, this report is a roadmap of how to proceed with a flood warning system to give eight-hours' notice rather than providing a turn key solution. The report was funded by Envirolink medium advice grant C01X1831.

The report will be used by the WCRC to enable decision making around prioritising of work programmes, and civil defence planning. Further, the report will be used by Westport 2100, a community group, which will be convened in early 2019 to start the process of 100-year+ planning of hazard mitigation in Westport.

1.1 Scope

The project addresses the following:

- Can a model be created that will predict a flood in the Buller River eight hours in advance? If not, what is the best-case warning timeframe that could be expected?
- What are the site build requirements including number of sites, location of sites, and composition of sensors?
- What is the most appropriate modelling solution (rainfall runoff, routing, forecast driven routing) not necessarily EcoConnect or NIWA tools but a review that proposes the best road map for WCRC? How could WCRC utilise gridded rainfall, radar, real time gauges, and a better calibrated catchment to predict flooding and display the predictions in a usable way linked to the telemetry network?
- What level of confidence is expected from the model or system – this will be used for evacuation purposes so needs to be accurate and robust;
- What is the potential cost to implement this solution (not a model but a road map for site numbers and locations, type of model and required inputs/costs/levels of reliability/accuracy) by 30 June 2020, including build costs, software, modelling and maintenance?
- Advice on timeframe between finishing sites and implementation of modelling.

1.2 Report structure

Following this introduction, Section 2 of the report reviews background information regarding the level of flood hazard, sources of flooding, and existing monitoring and forecasting systems. Required forecast specifications are detailed in Section 3, and potential flood forecasting approaches are identified in Section 4. Section 5 contains a detailed technical analysis of historic gauge data and rainfall forecasts to better understand the achievable forecast lead time and accuracy. The purpose of this analysis is to address the core question of whether it is feasible to provide the required lead time and accuracy, as well as to investigate what the preferred approach should be.

Section 6 summarises the findings of sections 4 and 5 by tabulating the advantages and disadvantages of different potential forecasting systems. Section 7 draws on this summary to provide conclusions regarding the feasibility of forecasting, as well as recommendations for a forecasting solution and a roadmap to implementation, including cost estimates.

2 Background

2.1 Flood hazard for the integrated family health centre

Duncan and Bind (2014) used 2-dimensional hydrodynamic flood modelling to predict flood extents and depths in Westport. They show that flooding would occur at the health centre site during a 1/50 annual exceedance probability (AEP) river flood, equating to 8920 m^3/s peak flow (McKerchar 2004, as revised in Duncan and Bind 2014) and 1.44 m peak sea level coinciding with the flood peak. 1.44 m is the MHWS10 sea level (sea level exceeded by 10% of all tides). This combination of river flood and tide produces flood hazards around the proposed health centre classified as "Low" (indicating shallow flowing water or deep standing water indicating that able-bodied adults should proceed with caution) or "Moderate" (indicating deep or fast flowing water dangerous for some, e.g., children). However, at this combination of river flood and tide the roads around the health centre are classified as having a "Significant" hazard that is dangerous for most people with deep, fast flowing water.

A more recent study by Gardiner (2017) who modelled several 1/50 AEP floods with differing bridge blockage (State Highway 6 bridge over the Buller River) and climate change scenarios confirmed Duncan and Bind's (2014) findings. Gardiner (2017) concluded that the health centre site has a low hazard rating with a large part of the property falling into the H1 category (i.e., is generally safe for people, vehicles and buildings) for the 1/50 AEP event based on the current climate with the surrounding streets in the H3 category (i.e., unsafe for vehicles, children and the elderly.)

For the design of a flood forecasting and warning system it is important to consider the ability to safely evacuate people to lower risk locations, either to higher ground in Westport or away from Westport via the Buller River Bridge to the west or the Orowaiti Estuary Bridge and causeway to the east. Duncan and Bind (2014) show that the eastern approach to the Buller River Bridge is too deep for safe vehicle passage for cars during floods greater than the 1/50 AEP flood and MHWS10 tide although may be passable for heavy 4WD vehicles. The Orowaiti Estuary Bridge and causeway would be passable for cars for the same flood and tide.

However, Duncan and Bind (2014) show that the roads between the health centre and the Orowaiti Estuary Bridge have a significant hazard rating indicating deep fast flowing water for the 1/50 AEP flood and MHWS10 tide level, whereas the 1/20 AEP flood (7800 m^3/s, 20year ARI) and MHWS10 tide level show only low and moderate hazard on those roads.

The health centre, along with the rest of Westport, will be flooded during extreme floods (1/50 AEP) and the frequency and magnitude of floods will increase with climate change and sea-level rise. There are however low flood risk areas to the east and west of the town which could provide a suitable alternative location for the health centre, thus eliminating the flood risk to the centre and its patients.

In summary, the critical issue for evacuation from the health centre is the flood hazard on the roads between the health centre and the Orowaiti Estuary Bridge. Thus, a prudent flood trigger level would be about 8400 m^3/s (~1/35 AEP), with consideration of the flood peak timing (flood peak and high tide coinciding) and level of the tide peak (including storm surge) to determine whether a flood warning should be issued.

2.2 Buller River flood sources

The Buller has a large catchment (6500 km^2), with much of the upper catchment in Tasman District (Figure 2-1). A significant proportion of the flood peak is known to originate in the lower Buller catchment, from catchments immediately to the east of the Paparoa and Mt William Ranges (Horrell and Henderson 2012). These lower catchments only make up 15% of the total basin area but experience high rainfalls and there is relatively little time between rain falling in these ranges and flood peaks arriving at Westport, so forecasting flows derived from these catchments is particularly challenging (Duncan and Bind 2014). The larger rivers draining into the Buller River from the Paparoa and Mt William Ranges are the Ohikanui and Blackwater Rivers from the south and Mackley (Orikaka) River and Cascade Creek from the north.

The flow contribution from the upper Buller catchment, from upstream of the Buller at Woolfs flow recorder, has a greater travel time so should be easier to forecast. The Inangahua catchment is quicker responding than the upper Buller catchment, but has greater travel time than the Paparoa Range/Mt William range rivers.

Further analysis of the relative flow contribution and travel time from different parts of the catchment is contained in Section 5.1: Analysis of gauge data.

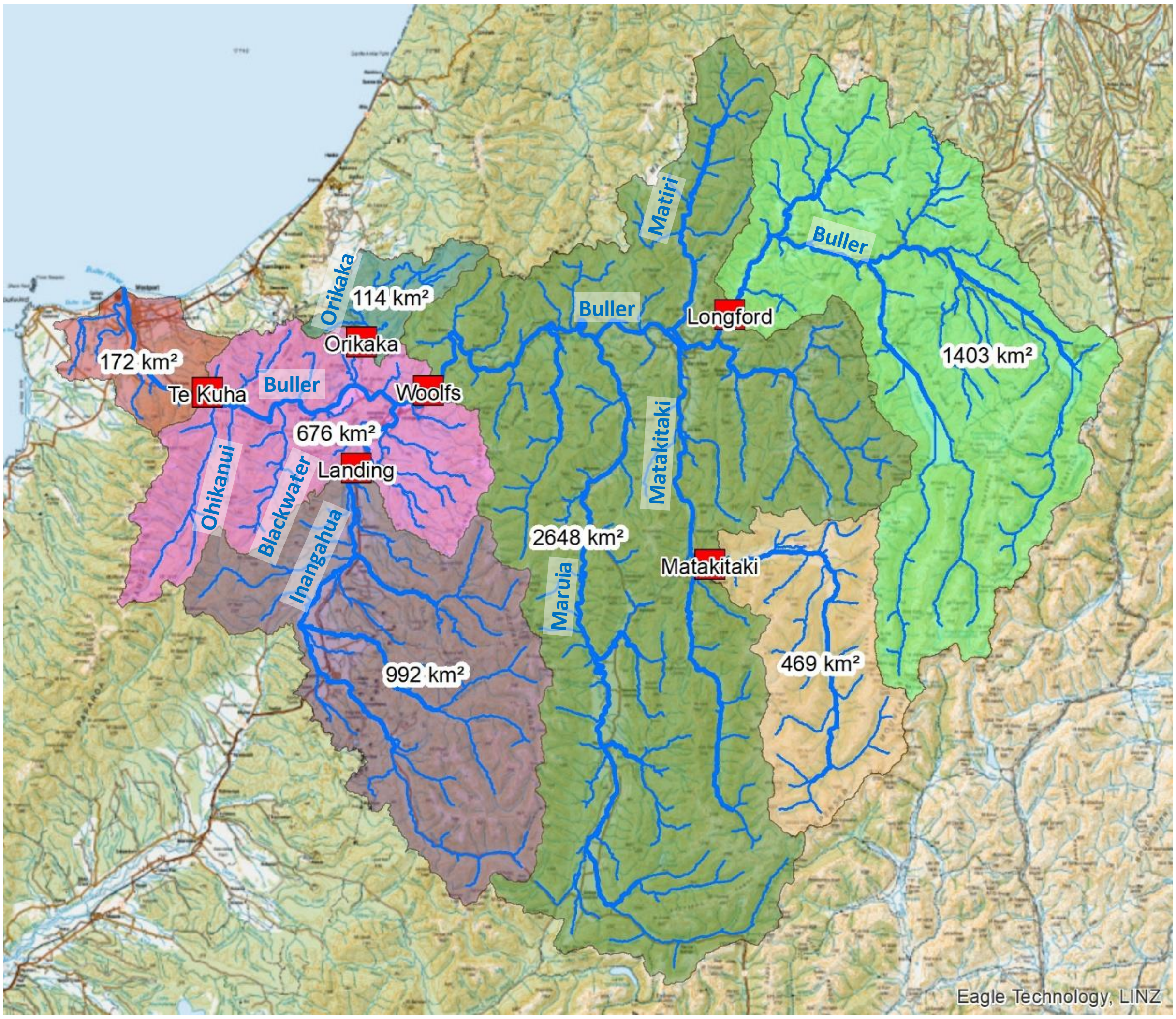

Figure 2-1: Buller River catchment and flow recorders. Coloured regions show the sub-catchment upstream of each flow recorder. Areas are given (in km^2) for each coloured region.

Modelling by Duncan and Bind (2014) shows that storm surge and tide timing do have an impact on flood severity in Westport, although the primary driver of flooding for most areas is peak flow in the Buller River. The effect of tides/surge on flooding should be considered by any forecasting system.

2.3 Current flood warning for Westport

The current flood warning system for Westport is based on the water level on the Buller River at Te Kuha about 13.5 km upstream of Westport and 1-1.5 hours flood wave travel time. A water level of 7.5 m (~3000 m^3/s) triggers an alert, when a watch is kept on water levels and flows at the Buller River at Te Kuha, Buller at Woolfs, and the Inangahua River at Landing water level recording sites. Flood warnings are based on the water levels at those sites, rainfall at Sirdar Creek at Paparoa, forecast rainfall, tide levels and the synoptic weather situation. The Sirdar Creek telemetered rain gauge is near the headwaters of the Ohikanui River which is a major contributor to Buller River flood peaks. Flood warnings are issued only if, in the judgement of WCRC and Buller District Council staff, the above factors indicate a warning is required (Duncan and Bind 2014).

2.4 Existing NIWA flow and tide forecasting systems for Westport

NIWA operates an environmental forecasting system that includes weather, river flow, sea level and sea state hazard forecasting called EcoConnect (Uddstrom 2011). Flow forecasting for the Buller River at Longford and the Buller River at Te Kuha, as well as sea level forecasting for Westport (combined astronomic tide and storm surge) are currently part of EcoConnect and available to WCRC (Cattoën et al. 2016c, Duncan and Bind 2014).

Flow forecasts start 48 hours ahead which gives enough notice of extreme events to allow residents to arrange an evacuation if necessary. Forecasts are updated every six hours and normally get more accurate in timing and magnitude of the flood peak as the forecasts get closer in time to the forecast peak (best range is 6-12 hours lead time). The flow forecasts assimilate the current instantaneous flow rate at each update. That is, the model state (soil moisture levels, etc.) and flow forecast are adjusted every six hours to reflect the current flow, making forecast initial conditions more accurate (Cattoën et al. 2016c; McMillan et al. 2013).

The Buller River EcoConnect flow forecasts use a TopNet hydrological model based on Strahler order 3 river/catchment data from the River Environment Classification version 2 (REC2) dataset (approximately 5-7 km river length of model resolution and about 10 km^2 sub-basin resolution, see NIWA 2019 for details of the REC2). The hydrological model simulates flow based on forecast rainfall from NIWA's NZCSM high resolution weather model. Verification showed that forecast flood peaks, using the current operational model in EcoConnect for a 4300 m^3/s flood at Te Kuha, were within 10% of the observed peak at a range of forecast lead times (Duncan and Bind 2014).

EcoConnect tide and storm surge forecasts for Westport are based on hydrodynamic modelling of storm surge driven by forecast weather (wind and pressure) data. While no assessment of forecast accuracy at Westport has been made directly (due to the influence of river flows on sea level), forecast accuracy was found to be good for the Charleston sea level recorder, approximately 25 km south of the Buller River mouth (RMSE = 0.04m, Lane et al. 2009), and is expected to be very similar for Westport.

2.5 Hydrological monitoring

A map of the Buller River catchment showing the location of key hydrometric monitoring stations is shown in Figure 2-2. As parts of the upper catchment lie in Tasman District and border Canterbury, sites maintained by Tasman District Council and Environment Canterbury are included on this figure as well as sites maintained by WCRC and NIWA. All the operational sites marked have telemetered near-real time data available and could be valuable for inclusion in a flood forecasting system. We have assumed that WCRC would be able to negotiate access to data from all the marked sites for the purposes of flood forecasting (if it is not already available).

The adequacy of monitoring in the lower Buller River is of particular importance for flood forecasting because, as established in Section 2.2, this area contributes significantly to flood flows. There are several well-established stations in the lower Buller catchment of relevance for flood forecasting:

- The NIWA Buller at Te Kuha flow recorder provides the best measure of flood flows arriving into Westport. Its usefulness for flood forecasting is limited due to the short travel time from the site to Westport, but it is incredibly valuable for calibrating and validating potential forecasting systems. The site opened in July 1963.
- The WCRC Buller River at Woolfs and Inangahua at Landing flow recorders provide valuable data on flow arriving from the upper catchment. These sites opened in 1983.
- The WCRC Sirdar Creek at Paparoa rain gauge is well positioned to monitor rainfall in the Paparoa range at the head of the Ohikanui catchment. The rainfall record started 9 April 1986.

Horrell and Henderson (2012) and Duncan and Bind (2014) reviewed hydrometric monitoring and suggested continued monitoring of existing sites and the following additional sites:

- A telemetered water level recorder on the Ohikanui River.
- Installation of telemetered rain gauges in the Cascade Creek and Orikaka River catchments.

Following recommendations, recent improvements by WCRC include:

- New telemetered rain gauges have been installed at Orikaka at Plateaux Stream (commenced 27 June 2018) and Orikaka at Gorge (28 June 2018) in the Orikaka (Mackley) River catchment, and on the Brunner Range (commenced 9 February 2017);
- A water level recorder has been installed on the Orikaka River at Gorge and records started 28 June 2018.

However, the Ohikanui River water level has not proceeded because of lack of a suitable site and because backwater caused by the Buller River affects flow a long way upstream.

With the additional recently installed sites, coverage in the lower catchment is likely adequate for flood forecasting, however the northern part of the Paparoa Range represents a bit of a gap in the raingauge network. We have identified one potential additional raingauge site in the lower catchment at Buckland Peaks. This site would provide information on rainfall in the Northern half of the Paparoa Range, reducing forecast uncertainties due to rainfall variability between Sirdar Creek and the northern part of the range.

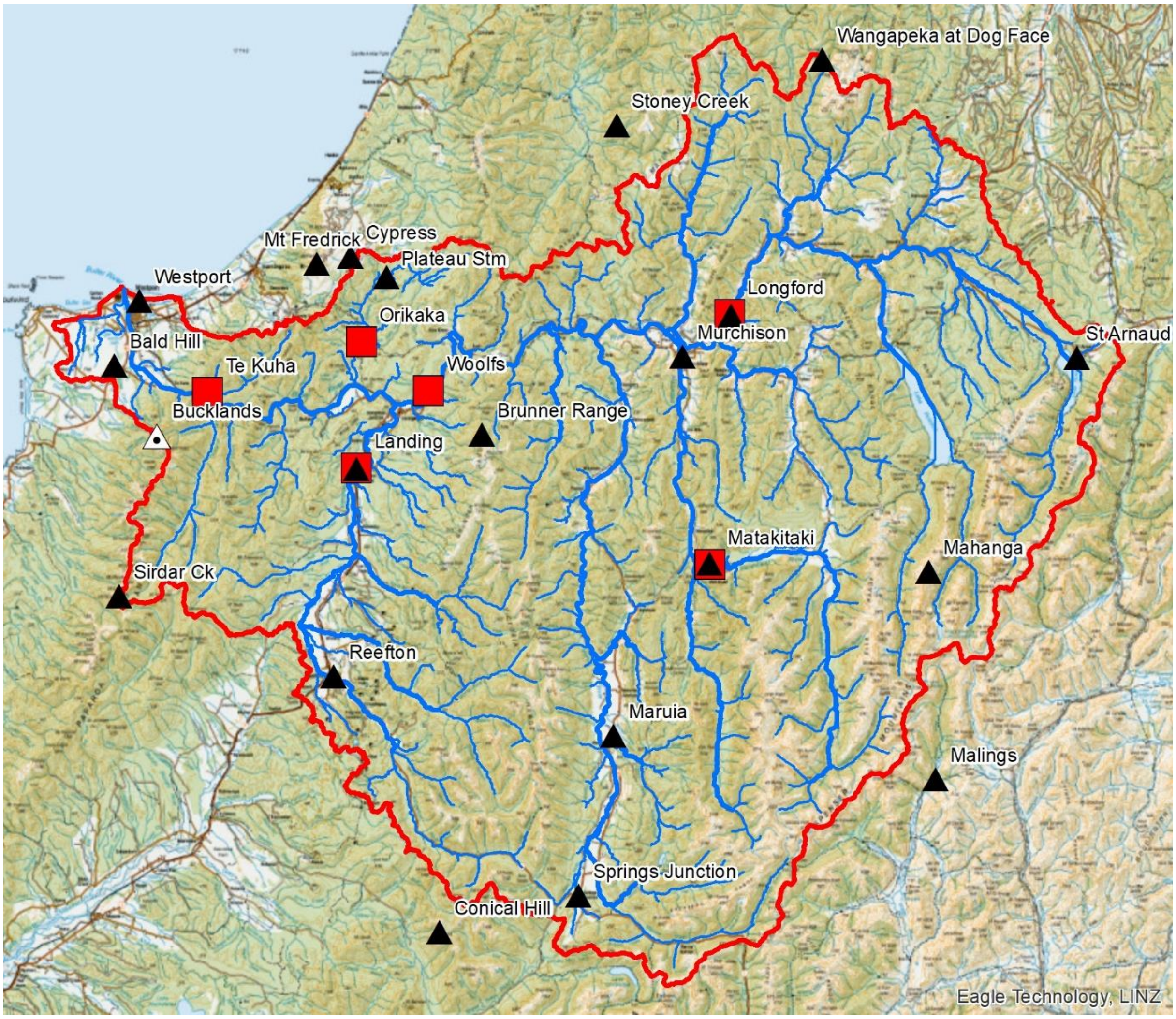

Figure 2-2: Location of rain gauges and flow recorders in the Buller River catchment. Operational rain gauges are marked by black triangles, operational flow recorders by red squares and potential additional rain gauge by open triangle. Note that the sites marked include WCRC, Tasman District Council, NIWA, and Environment Canterbury maintained sites.

2.6 Backup systems

Given that flood forecasting models rely on data from the water-level and rainfall recorders, it would be worthwhile considering duplicate systems to provide redundancy in flood situations:

- Is the distribution of rain gauges such that if one fails the forecast will not be compromised? Any model needs to be tested to determine the effect on model accuracy, if any of the rain gauges or water-level recorders fail. Depending on the results of the tests, duplicate systems may be required.
- If rain gauges are key, then should there be redundant rain gauges nearby? An additional rain gauge near the Sirdar Creek at Paparoa rain gauge should be considered given its likely importance to any flood forecasting system.
- There needs to be a system that keeps watch on the telemetry system to warn if data are no longer being received. An automatic backup is essential if the data are coupled to a rainfall-runoff model.

- There is a need to look at the performance of each site to see how reliable it is during storms. Any unreliable site should be duplicated or have duplicate sensors and/ or telemetry systems depending on the nature of the failure.

2.7 Key components for the flood forecasting roadmap

- The critical issue for evacuation from the health centre is the flood hazard on the roads between the health centre and the Orowaiti Estuary Bridge. A prudent flood trigger level would be about 8400 m^3/s (~35-year ARI).
- For most large floods a significant proportion of the peak flows originate from catchments immediately to the east of the Paparoa and Mt William Ranges.
- Current flood warning comes from the water level at Te Kuha (1-1.5 hours travel time to Westport) and the Sirdar Creek at Paparoa rain gauge.
- The current rainfall and water level recorder networks are adequate for informing flood models, but a new gauge at Buckland peaks would improve information on the spatial variability of rainfall across the Paparoa Range.
- An automatic backup for the telemetry server, analysis of data reliability during storms and duplicate systems for critical sensors/telemetry are recommended to increase reliability.

3 Required forecast specifications

Flood forecasts need to be **accurate, reliable** and provide enough **lead time** for action.

3.1 Forecast accuracy

Flood forecast accuracy refers to how well the forecast flooding corresponds to the actual flooding. There are many different metrics which can be used to assess the performance of a flood forecasting system (Hawkes and Whitlow 2005). Some of the most useful metrics for specifying target forecast requirements are False Alarm Ratio (FAR) and Probability of Detection (POD). Both metrics are calculated based on statistics of how well the forecasting system predicts whether key flood warning thresholds are crossed. FAR is defined as the proportion of flood warnings issued for which flooding did not occur, whereas POD is the proportion of actual flood events for which flood warnings were correctly issued. These metrics are calculated from the 'contingency table' (Table 3-1) using equations (1) and (2).

Table 3-1: Contingency table for computation of forecast performance metrics.

Threshold forecast	Flooding observed	
	Yes	No
Yes	a (hit)	b (false alarm)
No	c (miss)	d (correct)

$$FAR = \frac{b}{a+b} \quad (1)$$

$$POD = \frac{a}{a+c} \quad (2)$$

The subtleties of how POD and FAR are calculated from multiple forecasts issued at different times, when considering different lead times, can significantly influence the calculated scores. Further guidance on these details is provided in Robson et al. (2017).

Typical specifications for flood forecasting accuracy require, as an absolute minimum standard, that POD is greater than 0.5, and FAR is less than 0.5 (Hawkes and Whitlow 2005). A useful guide to interpreting forecast performance is given by Robson et al. (2017) and is reproduced in Table 3-2.

Table 3-2: Forecast accuracy grading based on POD and FAR scores. Reproduced from Table 6.1 Robson et al. 2017. Note, the final grade is defined as the best that can be achieved by both the POD and FAR scores; that is, the worse of the two individual grades.

Grade	Description	POD	FAR
1	Exceeds target	POD ≥ 0.8	FAR ≤ 0.2
2	Meets target	0.8 > POD ≥ 0.7	0.2 < FAR ≤ 0.3
3	Meets target with tolerance	POD (with tolerance) ≥ 0.7	FAR (with tolerance) ≤ 0.3
4	Does not meet target	0.7 > POD ≥ 0.5	0.3 < FAR ≤ 0.5
5	Significantly below target	0.5 > POD ≥ 0.3	0.5 < FAR ≤ 0.7
6	Poor	POD < 0.3	FAR > 0.7

The threshold flood flows for triggering evacuation of the health centre should only be exceeded infrequently (35-year ARI flood event, see Section 2.1), and during development of a forecasting system it is only possible to assess accuracy over the period for which data are available to generate hindcasts. As any forecasting system will likely rely on data from recently installed rain gauges, some installed as recently as June 2018 (see section 2.5) it will not be possible to generate meaningful accuracy statistics for the actual warning threshold. Instead a lower forecast threshold will have to be used for assessing model performance.

It is recommended that a flood forecast for Westport should be considered acceptable if it achieves a POD greater than 0.7 and FAR less than 0.3 for floods exceeding a flow threshold set such that approximately 10 measured floods exceed the threshold over the full period for which it is possible to assess model performance.

3.2 Forecast reliability

Forecast reliability is independent from its accuracy and refers to the forecast's ability to continue to operate effectively, even during severe weather or flooding. Any flood forecasting system developed for the Buller River needs to be robust to potential failures in the gauging, communication or power networks.

One way of quantifying reliability retrospectively is to calculate the proportion of forecasts for which the forecasting system was working effectively (Hawkes and Whitlow 2005).

$$Reliability = 1 - \frac{Number\ of\ forecasting\ failures}{Total\ number\ of\ forecasts} \qquad (3)$$

where 'Number of forecasting failures' counts the number of occasions when a forecast could not be made for whatever reason; and 'Total number of forecasts' is the total number of forecasts that would have been made over the same period if no forecasting failure had occurred.

As modes of forecast failure are often linked to weather and flooding it is likely better to focus on critical forecasts when considering the above statistic, for example by only including periods with two days of a specific high flow threshold being exceeded.

A retrospective analysis of reliability of different parts of the forecasting system could be undertaken to identify potential vulnerabilities. For example, if specific rain gauges were essential for the forecast operation then an analysis of historic reliability of real time data from a set of similar gauges could be undertaken to investigate the frequency and duration of failures. Typical targets for monitoring station (flow and rain gauge) reliability are:

> *"not more than 1.5 % (approx. 5 days) missing record in any twelve-month period and, for any station, not more than one calendar year in two shall have any missing record."* (Appendix A in Fenwick 2014)

The potential need for backup systems to be incorporated into the gauging network was discussed in Section 2.6.

3.3 Forecast lead time

Lead time refers to the amount of time between a flood warning being issued and the onset of flooding. Assessment of forecast lead time should assess the sum of all the different cumulative delays present in the forecasting system. Depending on the system this may include:

- Reporting frequency/latency of telemetered rain and river level gauges.

- Frequency of updates to weather forecast models, including the time taken for the models to process and results to become available.
- Time taken for hydrological/hydraulic forecasting models to run and the frequency with which model runs are carried out.
- Lead time provided by the forecasting model.
- Time taken for staff to interpret forecasts and decide whether to issue a warning.
- Time taken for flood warning to be communicated to recipients.

It is notable that the lead time provided by the forecasting model likely involves a compromise between accuracy and timeliness, as forecast accuracy is often higher at short lead times.

The required forecast lead time for the Westport health centre specified by WCRC is 8 hours. To be effective the forecast needs to achieve enough accuracy at this lead time. As forecast accuracy is best measured at the Te Kuha flow recorder, approximately 1 to 1.5 hours travel time upstream of Westport (see Section 2.3), 7 hours lead time is required for a flow forecast at Te Kuha.

3.4 Summary of forecast specifications

- Flood forecasts need to be **reliable**, **accurate** and provide enough **lead time**.
- Reliability can be calculated retrospectively from the proportion of forecasts for which the forecasting system was working effectively.
- Accuracy can be calculated from forecast performance metrics to provide a False Alarm Ratio (FAR) and Probability of Detection (POD). We recommend that a flood forecast for Westport should be considered acceptable if it achieves a POD greater than 0.7 and FAR less than 0.3 for floods exceeding a flow threshold.
- Lead time is the time between when a warning is issued and the onset of flooding, thus its assessment needs to include consideration of all sources of delay, such as latency of telemetry systems and time for forecaster decision making. WCRC have specified that eight hours lead time is required at Westport.

4 Potential flood forecasting approaches

In general, river floods can be forecast for a specific location in several different ways. The following sections give a brief overview of typical forecasting approaches and a discussion of their suitability for application to Westport.

4.1 Observed upstream flow/level

The most simple and reliable approach for flood forecasting is to use observed data from upstream flow/level recorders to trigger flood warnings. WCRC currently use this approach to generate flood alerts based on observed flows from the Buller at Te Kuha flow recorder. The disadvantage of this approach is that forecast lead time is limited to the travel time from the upstream recorder, in this case approximately 1 to 1.5 hours, significantly less than the desired lead time of 8 hours. Other flow recorders exist further upstream including Buller at Woolfs, and Inangahua River at Landing which could be used to provide accurate forecasts of flow from these parts of the catchments. However, on their own these gauges cannot be used to forecast flooding in Westport because, as described in section 2.2, the lower Buller flow peaks (which cause flooding in Westport) generally originate from catchments downstream of these recorders and often peak prior to these upstream recorders.

The travel time from Woolfs to Te Kuha is approximately 2.5 to 3 hours based on analysis of hydrographs. The travel time from Inangahua at Landing to Te Kuha is longer and varies depending on storm direction. Typically Landing peaks many hours before Woolfs and the flood peaks recorded at Landing are on average 0.46 the size of those recorded at Woolfs.

4.2 Rainfall thresholds

Rainfall thresholds can be used to trigger flood warnings based on rainfall data, for example if rainfall total exceeds 110 mm in 6 hours a flood warning could be issued. By using observed rainfall rather than flow it is possible to extend lead time. If accurate forecast rainfall data is available (see sections 4.4, 4.5 and 5.2) lead time can be extended much further than when only using observed rainfall data. Whilst this approach has been used effectively in many catchments it neglects factors such as the influence of antecedent catchment wetness or spatial/temporal variability in rainfall on flood peak flow. These limitations mean it generally works best in small flashy catchments which respond to short duration high intensity rainfall. For larger catchments with longer time of concentration and multiple sub-catchments or significant influence of antecedent wetness (i.e., the Buller), these weaknesses can reduce forecast reliability.

It is possible to develop rainfall thresholds which vary depending on antecedent catchment wetness (for example a second (lower) threshold is used if the catchment has received more than 50 mm in the 48 hours prior to the current event). However, with a catchment as complex as the Buller it is likely to be challenging to develop accurate variable thresholds due to spatial differences across the catchment.

For Westport it is our opinion that, while simple rainfall thresholds such as that given above can provide a “heads up” notice of potential extreme floods, they will not provide enough reliability for an evacuation warning because of differences in rainfall response between events caused by antecedent conditions and the spatial-temporal distribution of rainfall across the catchment.

4.3 Rainfall radar

Rainfall radar resolves the spatial variability of rainfall processes and can therefore be an effective alternative to rain gauge measurements. Rainfall radar is available for the lower Buller catchment from the MetService radar 6-7 km SE of Hokitika situated at an altitude of 351 m.

The coverage over the Paparoa Range and up to the Mt William range is good, but there is attenuation in the lowest radar beam by hills at the southern end of the Paparoa Range. The beam is not completely blocked over the Paparoa Range, so precipitation is still able to be seen and there is useful radar data over the Paparoa Range and beyond (Chris Noble, Manager Severe Weather Services, NZ MetService, pers. comm.).

Rainfall estimation from radar (i.e., using a Quantitative Precipitation Estimate (QPE) scheme to convert radar reflectivity to rainfall), is best within 120 km of the radar itself – at that range the lowest beam is near 2 km high (plus the height of the radar itself), so will be starting to overshoot lower level precipitation (especially at distances farther from the radar). The closest part of the Paparoa Range is approximately 90 km from the radar, Westport is about the 120 km, and Mt William about 130 km. (Chris Noble, Manager Severe Weather Services, NZ MetService, pers. comm.).

There are some emerging methods with dual-polarised radars (such as the Westland radar) which could be used to minimise the impact of beam blocking. However, the Westland radar is C-band. This means there will be attenuation limitations in heavy, widespread rain and when there is localised heavy rain directly over the radar site.

4.4 Nowcasting and radar forecasts

Post-processing methods can be used to extend the operational usefulness of radar observations to provide more timely warnings with short response times. Consultancies such as Weather Radar New Zealand Ltd[1] have previously worked with regional council and MetService radar datasets to provide Quantitative Precipitation Forecasts (QPF) for radar nowcasting and rainfall-runoff models targeted at flood forecasting (Sutherland-Stacey et al. 2011; Sutherland-Stacey et al. 2016; Sutherland-Stacey et al. 2019).

Radar nowcast QPF are generated using the Short-Term Ensemble Precipitation System (STEPS) (Bowler et al. 2007) to provide ensemble estimates of possible rainfall distribution over the 2-6 hour period following the most recent radar data. This would extend the lead time beyond what could be achieved using observed rainfall only. The frequency of updates can be as short as radar updates (e.g., every 10 minutes with only a few minutes of latency). These ensemble rainfall forecasts are typically based initially on advected radar rainfall observations that are gradually blended with a Numerical Weather Prediction (NWP) model to extend the rainfall predictions a few hours into the future.

The Bureau of Meteorology of Australia have implemented the use of radar-based ensemble rainfall forecasts to provide enhanced flood forecast and warnings in Australia (Velasco-Forero et al. 2019). Overall STEPS ensemble rainfall skill (performance) is better than NWP rainfall forecasts for the first 2 to 3 hours and then comparable to the NWP skill for larger lead times. From an operational perspective, STEPS has the key advantage to provide updated ensemble of rainfall forecasts to flood forecasters every few minutes. However, when small time intervals are used it can lead the forecast to have overlapping rainfall bands.

[1] http://www.weatherradar.co.nz/home

A first step for WCRC could involve contracting a suitable provider to assess the performance and limitations of the existing MetService radar system for the Buller catchment by analysing the complete radar archive to date (Sutherland-Stacey et al. 2017). A second step based on a suitable contractor's advice could be to consider further radar hardware such as mobile high-resolution radars being developed and researched at Weather Radar NZ (Sutherland-Stacey et al. 2011; Sutherland-Stacey et al. 2018).

4.5 Weather forecast rainfall

Rainfall forecasts from numerical weather models can be used to extend forecast lead times by accounting for future rain that has not yet fallen.

Rain forecast patterns from a high-resolution weather model (1.5 km) provide more accurate distributed information than large scale weather models (greater than 5 km resolution) (Cattoën et al. 2016c). The convection-permitting nature of a high-resolution weather model and its better orographic representation are key to representing localised storms more accurately over steep and high ground (Cattoën et al. 2016c).

As part of its multi-hazard forecasting tool EcoConnect, NIWA operationally runs such a high-resolution weather model called NZCSM (New Zealand Convective Scale Model). The weather forecast provides updated gridded rainfall forecast every 6 hours out to 48-hour lead times. Rainfall values can be provided half hourly, hourly and for specific station locations with model output statistics corrections (Carey-Smith 2018).

However, although NZCSM is the highest resolution model running operationally in New Zealand, its 1.5 km resolution still causes substantial smoothing of the steep slopes common in New Zealand mountains. Therefore, orographic rainfall is likely to be underestimated in some cases, including in the Buller catchment. Weather forecast models are also well known to underestimate heavy rainfall and overestimate light rainfall or drizzle (Blacutt et al. 2015; Cattoën et al. 2016a; Cattoën et al. 2016b; Cattoën et al. 2016c; Helmis and Nastos 2012; Shroder et al. 2007), even when annual totals are approximately correct, and often require bias correction before use in a rainfall-runoff model (Cattoën et al. 2016b; Cattoën et al. 2018). In June 2017, NIWA upgraded NZCSM by implementing a new dynamical core for seamless atmospheric prediction called ENDgame. This addition improves explicit gravity wave representation and aids in atmospheric forecasting of orographic rain in fast moving extreme events.

NZCSM is a deterministic model i.e., it simulates a single best estimate forecast of future weather with no consideration of uncertainty. Ensemble modelling involves simulation of multiple possible future weather scenarios (ensemble members), capturing potential uncertainty and allowing better forecasting of extreme events. NIWA is currently testing a new operational weather ensemble implementation NZENS, which simulates 18 members out to 2.5 days at 4.5 km resolution over New Zealand (Figure 4-1). An ensemble of weather models should significantly improve forecast accuracy in terms of spatial and temporal rainfall distribution during extreme events. An example of the development of "probability of exceedance" forecasts of hourly (or daily) rainfall totals exceeding some defined threshold are defined in Figure 4-2. It is expected that the new ensemble forecast capability will be available in EcoConnect within the next financial year (2020).

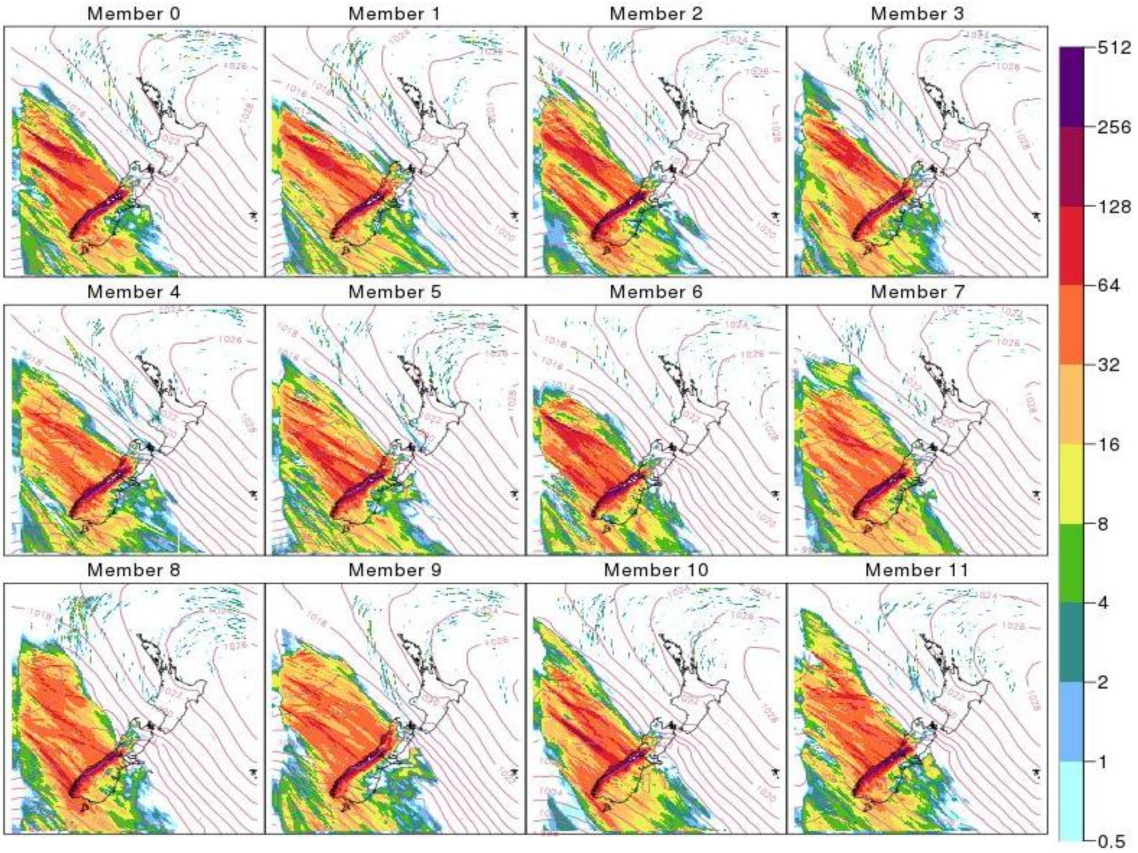

Figure 4-1: Rainfall totals for the 24-hour period ending 0000 hrs NZST on 27 March 2019 from NIWA's new downscaling ensemble forecast system, NZENS. This rainfall event broke several national rainfall records, notably on the Cropp River (near Hokitika) where 1086mm of rain fell in 48 hours.

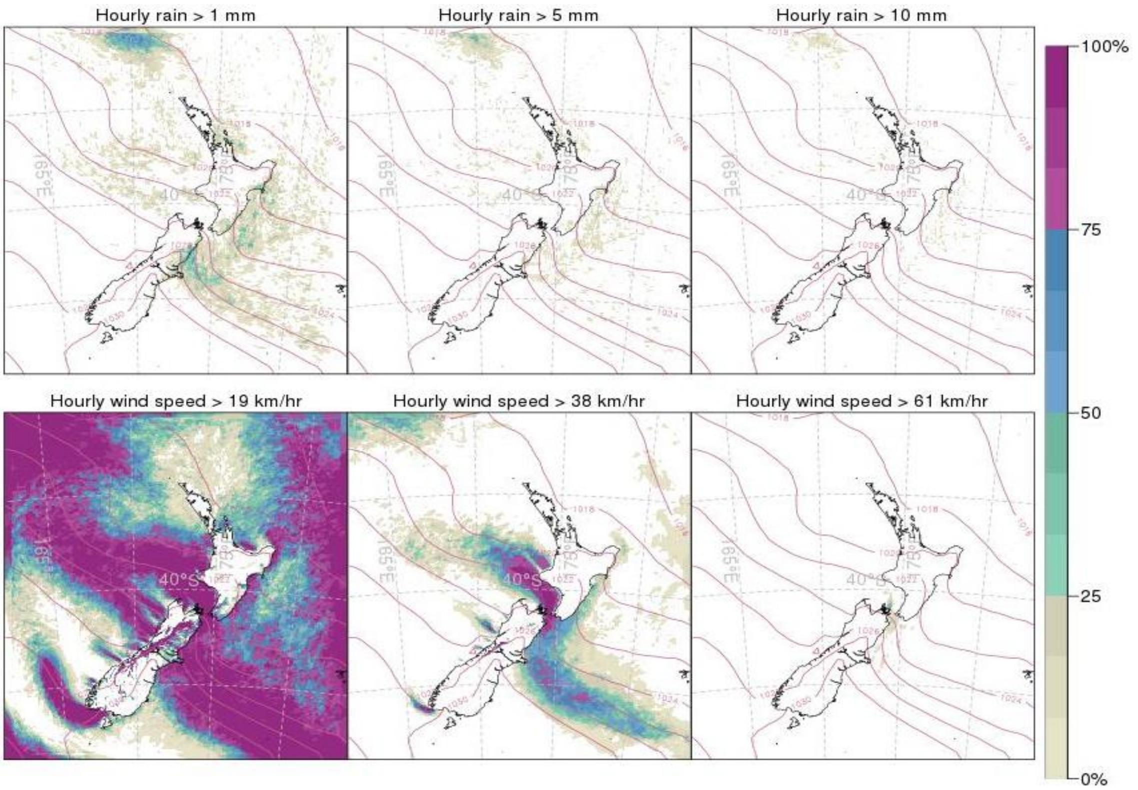

Figure 4-2: Example plots of early Probability of Exceedance products derived from NZENS forecast data. The top row shows probabilities of rainfall in the hour up to 0800 NZST on 6 April 2019, exceeding three predefined thresholds. The bottom row shows exceedance probabilities for winds speeds. Probabilities are calculated from all available NZENS members.

4.6 Hydrological (rainfall runoff) models

Hydrological models generate predictions of river flow based on rainfall data. Hydrological models are typically calibrated to observed flow data at a downstream flow recorder. They are much better able to capture the effects of antecedent catchment wetness and spatial/temporal variability in rainfall as it moves across a catchment compared to simple rainfall thresholds.

As with rainfall thresholds, the lead time provided by hydrological models depends on the source of rainfall data. Using observed rain data, forecast lead time is limited to the travel time from the upper catchment. The Sirdar Creek at Paparoa rain gauge is well sited to represent rain falling in the Ohikanui River catchment which generates a large part of the flood peaks observed at Westport. The gauge has been in place since 1986 so there is good data availability to calibrate a hydrological model for this catchment.

Hydrological modelling based on rainfall observed at the Sirdar Creek at Paparoa rain gauge and observed river flows could possibly provide 8-12 hours flood warning for Westport for floods from this source. Utilising forecasts of future rainfall could allow much longer lead times but introduces an additional source of uncertainty. This is discussed further in section 5.2.

There are many potential hydrological models which could be applied for forecasting in the Buller catchment. Models can be grouped into empirical black box models, lumped conceptual models, or distributed physically based models (Refsgaard and Knudsen 1996). Empirical models do not explicitly incorporate physical processes but instead rely on being fitted to long periods of observational data. As such they are not necessarily reliable outside the range of parameters for which they have been calibrated. This means they are not appropriate for predicting larger, infrequent floods in the complex Buller catchment where rainfall data are available for few floods of the severity which is desired to be forecast (approximately 1/35 AEP, see section 2.1). The Buller catchment covers a large area with high vertical relief, and spatially varying rainfall patterns and hydrological response. This complexity means that distributed physically based modelling is likely required to accurately predict flows. The resolution of such models needs to be high enough to adequately capture the spatial variability in rainfall and topography within the catchment. Based on our experience of hydrological modelling in West Coast catchments, it is our opinion that the model will require a sub-basin resolution of between approximately 10 km^2 (Strahler order 3 in the REC2 river network, NIWA 2019) and 1 km^2 (Strahler order 1 in the REC2 river network, NIWA 2019). Many different distributed physically based models are available. Distributed hydrological models applied within New Zealand include TopNet and MIKE SHE.

Cattoën et al. 2016c noted that long term water inflows and outflows did not balance in the Buller catchment when calibrating a hydrological model to rainfall station data (for example Sirdar Creek station). However, this may not be a major issue for a calibration only focused on large flood events, provided different sources of rainfall data are consistent (i.e., no biases between rain gauge and forecast rainfall if both are being used).

4.7 Sea level dependant flow/rainfall thresholds

Reliable sea level forecasts including the effects of tide and storm surge are already available for Westport (see Section 2.4). As flooding from the Buller River is influenced by backwater effect from the sea, the high tide level and tide timing with respect to flood peak arrival time are important to include in any flood forecasting system. The simplest way to explicitly include sea level is to make the flow threshold for triggering flood warnings dependant on the forecast sea level. Hydro-dynamic modelling using the existing flood mapping model (Gardner 2017) could be used to derive appropriate thresholds for different sea levels.

A further potential development of this approach is to forecast flood levels in Westport, or flood inundation, based on an interpolation of results from previously computed hydrodynamic simulations for a range of peak flow / sea level scenarios (Chiaverini et al. 2016).

4.8 Hydrodynamic modelling of flood levels

Incorporating a hydrodynamic model into the forecasting system to simulate the interaction of flows and tides would enable forecasting of flood levels on the Buller River in Westport. This would allow the use of flood level thresholds (rather than flow thresholds) for the triggering of flood warnings. The model would explicitly simulate the combined effect of forecast river flow and sea level timeseries, allowing a more accurate prediction of the resulting flood severity.

A simple 1D hydrodynamic model (rather than the existing 2D flood mapping model) would be required to ensure the model was fast and reliable enough to run as part of the operational forecasting system. The model would likely need to extend from Te Kuha to the coast and include the Orowaiti Estuary. Utilising a hydrodynamic model would only be possible with a flow forecast derived from a hydrological model, as simple rainfall threshold approaches would not predict a timeseries of river flow, required for input into a hydrodynamic model.

4.9 Summary of identified forecasting options

Potential forecasting options include:

- Comparing observed upstream flows against a threshold.
- Comparing observed rainfalls against an intensity/duration threshold based on the catchment time of concentration.
- Using rainfall radar over the catchment to estimate the spatial distribution of rainfall intensity over the lower part of the Buller catchment.
- Using nowcasting and radar forecasts to predict rainfall intensity across the catchment for the next 2-6 hours.
- Using forecast rainfall from numerical weather models to predict rainfall intensities at longer lead times.
- Using hydrological models to predict river flow from rainfall. Hydrological modelling could be combined with rain data from gauges, radar, or weather forecasts.
- Developing sea level dependant flow/rainfall thresholds to include the effect of sea level on river flooding.
- Using a 1D hydrodynamic model to predict flood levels on the Buller River in Westport from forecast flows and sea levels.

A more detailed analysis of some potential elements of the Westport forecasting system, and how they influence forecast lead time and accuracy, is contained in Section 5. The advantages and disadvantages of all the forecasting options are then summarised in Section 6, including conclusions on their usefulness for Westport. Based on that summary, Section 7.2 details a recommended forecasting methodology.

5 Analysis of potential forecast lead time and accuracy

5.1 Analysis of gauge data

5.1.1 Calculated time of travel

The Sirdar Creek rain gauge is at the head of the Ohikanui River catchment. Duncan and Bind (2014) calculated that the time of concentration (the time from rain falling at the head of the catchment to river response at the bottom of the catchment) for the Ohikanui River was 2.5 hours. This calculation was based on the Ramser – Kirpich method of estimating time of concentration from catchment parameters. Including the travel time along the Buller River from the Ohikanui confluence past Te Kuha to Westport gives a total travel time from the Sirdar Creek rain gauge to Westport of approximately 3.5-4 hours.

5.1.2 Analysis of historic floods

Concurrent data from the Sirdar Creek at Paparoa rain gauge and the Te Kuha, Woolfs and Landing flow sites are available from April 1986. The ten largest floods during this period were analysed to investigate:

- The rainfall recorded at Sirdar Creek prior to each event.
- The relative contribution of the catchments upstream of Woolfs and Landing flow recorders, as well as the 790 km^2 catchment between those recorders and Te Kuha.
- The time between flow peaking at Woolfs/Landing and the flow peaking at Te Kuha.
- The time between rain falling at Sirdar Creek and flood peak at Te Kuha.

Table 5-1: Summary of rainfall and flow during the largest floods recorded since 1986. For simplicity all analysis is based on hourly mean flow and hourly total rainfall accumulation data.

	Peak flow (hourly average)				Sirdar Creek peak rainfall accumulation			
	Te Kuha	Woolfs	Landing	Residual*	48 hour	24 hour	3 hour	1 hour
Date	(m³/s)	(% of Te Kuha peak, hours lead time†)			(mm, hours lead time‡)			
15-Jul-2012	7907	52% (0)	21% (3)	31%	348 (0)	242 (4)	50 (8)	19 (10)
13-Jun-1993	7740	44% (3)	22% (3)	34%	214 (0)	156 (0)	36 (2)	20 (2)
20-May-1988	7765	65% (4)	32% (11)	16%	264 (10)	194 (2)	77 (17)	28 (18)
28-Dec-2010	6984	58% (1)	33% (8)	26%	271 (0)	247 (0)	63 (15)	24 (17)
22-Nov-1994	6472	55% (0)	20% (0)	26%	187 (0)	181 (1)	38 (15)	15 (15)
8-Nov-1994	6326	59% (2)	26% (22)	24%	183 (14)	132 (39)	37 (50)	14 (51)
27-Oct-1998	6014	64% (0)	31% (7)	22%	126 (8)	118 (5)	32 (11)	13 (12)
3-Jan-2013	6002	59% (0)	30% (4)	26%	207 (0)	160 (5)	38 (9)	17 (11)
11-Sep-2013	5929	53% (1)	35% (10)	25%	227 (0)	185 (2)	67 (15)	33 (16)
9-Jul-2018	5756	55% (0)	47% (6)	5%	199 (0)	131 (0)	42 (36)	20 (36)

* The difference between the peak flow recorded at Te Kuha and the peak of the combined Woolfs and Landing flows, expressed as a percentage of the peak flow recorded at Te Kuha.

† The time from flow peaking at individual gauges (Woolfs/Landing) and peaking at Te Kuha. A value of zero indicates that flow peaked at Woolf/Landing either before, or at the same time, as flow peaked at Te Kuha.

‡ The time from the end of the peak rainfall accumulation period at Sirdar Creek rain gauge until flow peaked at Te Kuha

For the ten floods the analysis showed that:

- The proportion of peak flow derived from the catchments upstream of Woolfs and Landing flow recorders, and from between these recorders and Te Kuha, varied significantly between different events, indicating that the spatio-temporal distribution of rainfall is having a big influence on the flood generating mechanism.
- Te Kuha peak flows were up to 50% greater than the combination of flow recorded at Woolfs and Landing, confirming the importance of forecasting flow from the Paparoa and Mt William ranges.
- In several events the flow peaked at Te Kuha at the same time or prior to the flow peaking at Woolfs due to the influence of inflows from the Paparoa and Mt Williams ranges.
- Antecedent conditions likely have a significant effect on flood response in some events, which had lower rainfall totals but were preceded by significant rain.

The variability in contribution from the different parts of the catchment, as well as the variability in rainfall patterns and response, is shown graphically in Figure 5-1 and Figure 5-2.

Figure 5-1 shows the largest flood since 1986 at Te Kuha, peaking at 7980 m^3/s, close to the threshold of 8400 m^3/s mentioned in Section 2. For that flood approximately 31% of the peak flow came from the catchments downstream of Landing and Woolfs. The combined flow from Woolfs and Landing sites peaked at the same time as Te Kuha. The Sirdar Creek rain gauge recorded steady heavy rain over a period of 36 hours leading up to the peak.

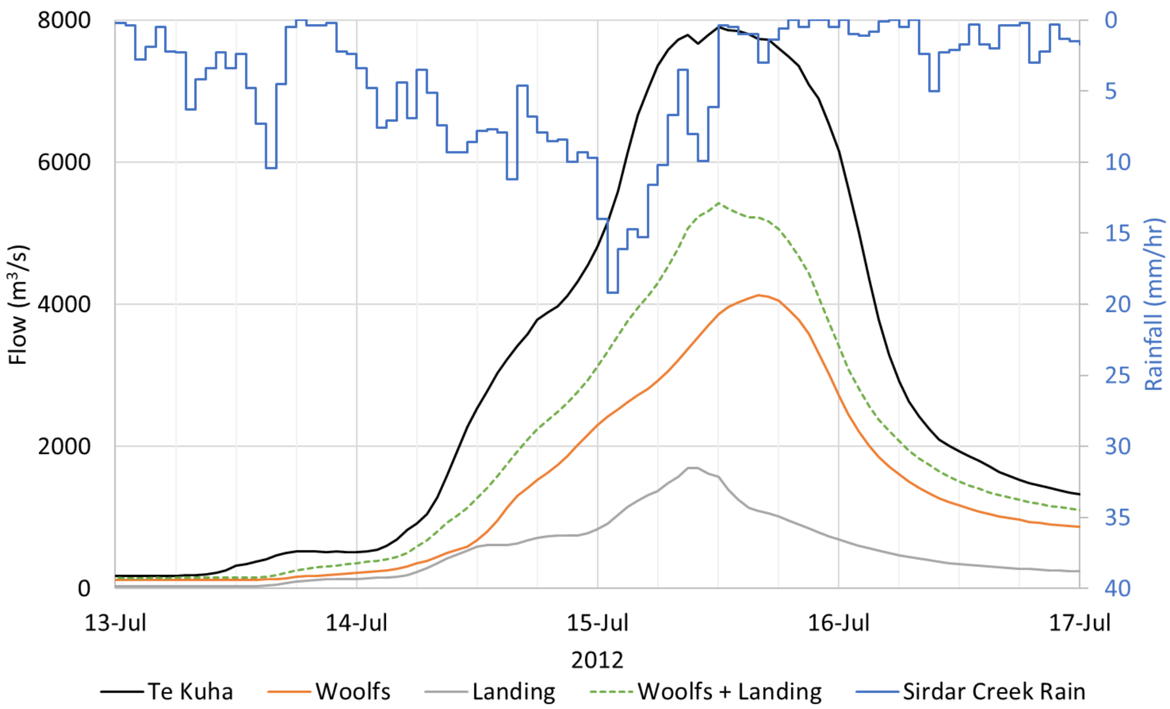

Figure 5-1: Lower Buller flow and rain during the July 2012 7980 m^3/s flood.

Figure 5-2 shows flood hydrographs and hyetographs for the recent flood of nearly 6000 m^3/s when there was data available for the newly installed rain gauge at Orikaka at Plateau. There are several points to note:

- The rainfall intensities at Orikaka at Plateau were greater than those at Sirdar Creek but showed a similar pattern.
- The high intensity rainfall from 6am to 6pm on 7 July resulted in only a small flood peak (1500 m^3/s) at Te Kuha. This is likely because the catchment was relatively dry and flows from the catchments above the Woolfs and Landing flow recorders were still low (collectively only 700 m^3/s).
- The lower Buller catchment had relatively little contribution to the main peak, which was driven primarily by the combined flows from Landing and Woolfs, which peaked 3 hours before the peak at Te Kuha.

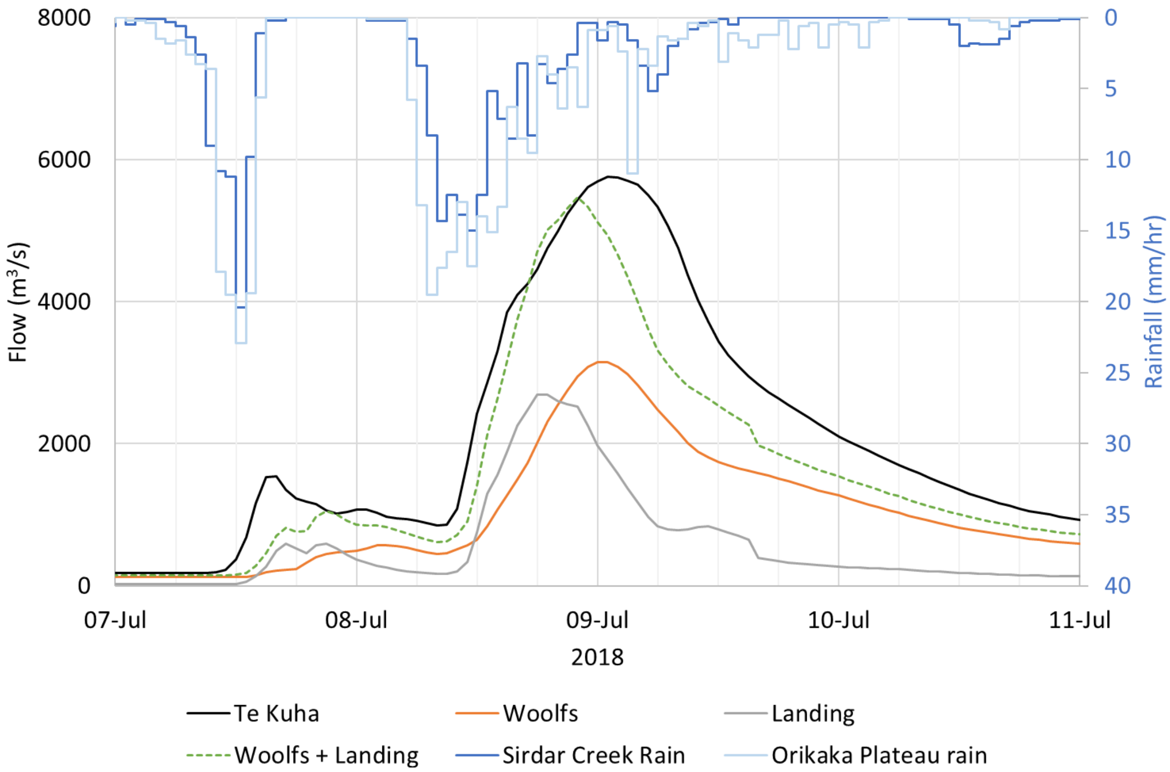

Figure 5-2: Lower Buller flow and rain during the flood of 8-9 July 2018.

5.2 Forecast rainfall

Historical rainfall forecasts in the Buller catchment on the West Coast have been evaluated to understand performance and limitations of using rainfall forecasts in the Buller catchment. A practical methodology has been developed to provide insight into timing errors associated with forecasts of heavy rainfall events.

Comparing the performance of forecast storm rainfall depths with observed rainfall depths and comparing forecast with observed timing of rainfall allows errors due to timing to be isolated from errors in forecast magnitude.

For locations in the Buller catchment, it was found that timing errors dominate for periods less than around 3 hours, whereas for periods of 6 hours and greater, the errors in forecast magnitude become more important than timing errors.

5.2.1 Distribution of hourly rain amounts

A rain rate histogram representing the hourly rainfall distribution over the observed record for Sirdar Creek in the Buller catchment is shown in Figure 5-3. This figure compares the observed and modelled frequency of occurrence of events in a series of rain rate bins. At Sirdar Creek, the model tends to under-forecast light rain events (although the dry events are slightly over-forecast) and very heavy rain events, while moderate rain rates (for this location) of between 5 and 20 mm/hr are forecast about right. The discrepancy in the largest rain rate bin is due to a single observed event of 180 mm/hr at 9pm on 2 November 2014.

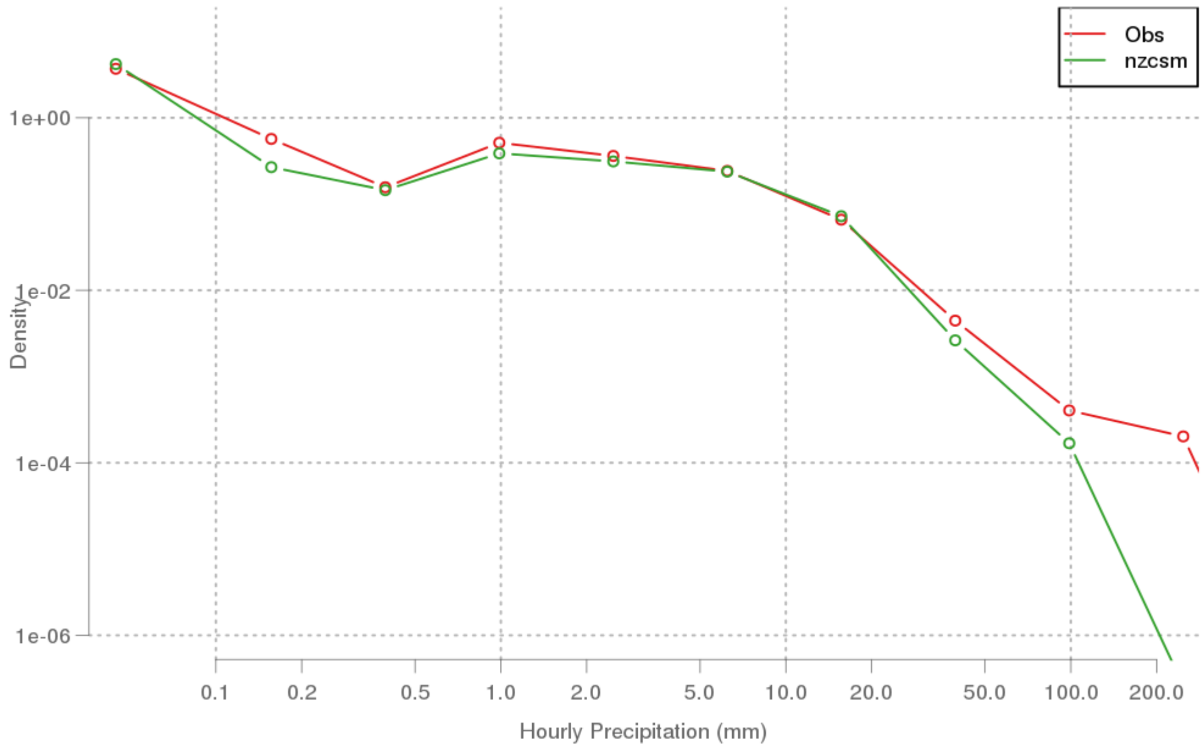

Figure 5-3: Observed and modelled rain rate histogram for Sirdar Creek, West Coast. Plot compares observed rain rates with those forecast by NIWA's 1.5km forecast model (NZCSM) for the period from 27 April 2014 to 29 June 2017.

5.2.2 Accuracy of hourly rainfall forecasts

To better assess the accuracy of hourly rainfall forecast we created a set of performance diagrams shown in more detail in Appendix A. The diagrams plot the probability of detection (POD), the success ratio (1-FAR, the false alarm rate), the Critical Success Index, and the forecast bias.

Figure 5-4 and figures in Appendix A all show that, for higher rainfall thresholds in particular, the categorical bias scores are very good. This mirrors what is shown in the rain rate histogram in Figure 5-3 and means that on average NZCSM gets the number of heavy rain events correct, even if they are not at the correct time.

Further analysis detailed in Appendix A suggests that the ability for the model to get timing right at the hourly scale could be improved. At the 3-hourly scale the difference is much smaller showing that the performance is better at this time-scale.

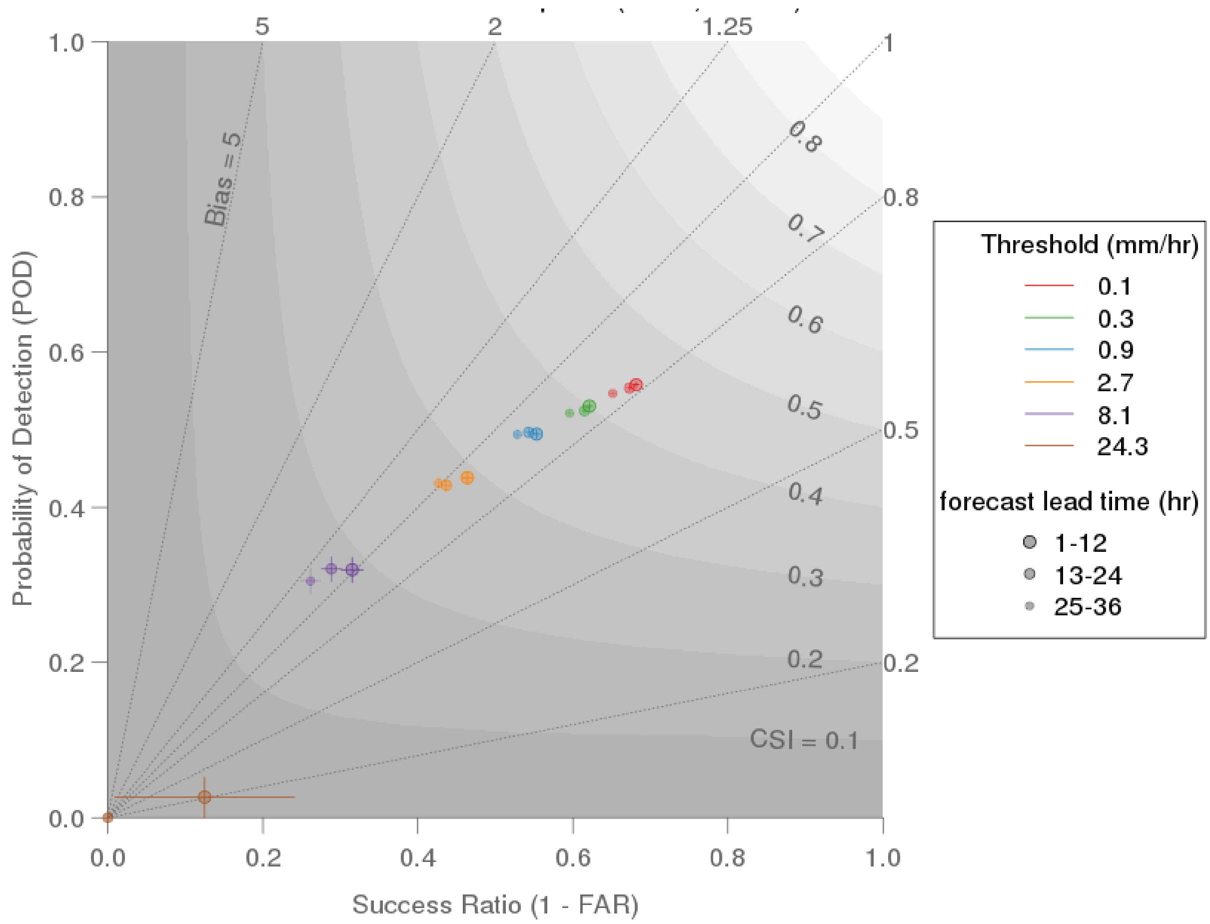

Figure 5-4: Performance diagram comparing hourly accumulations of rainfall with observations from exactly the same time. NZCSM Forecast compared against data from the Sirdar Creek rain gauge over the period 27 April 2014 to 29 June 2017. The colours represent increasing rain amount hourly thresholds. The performance is split at 3 different groups of forecast lead times depicted by the size of the plot symbols. The cross in the dots represent error estimates due to the number of events in sample (e.g., there are larger error estimates for larger thresholds with less frequency in the forecast archive). The Critical Success Index which combines the Probability of Detection (y-axis) and False Alarm Rate (FAR) is shown by shaded contours. The categorical bias is shown by dotted grey lines. A perfect forecast should lie in the top right corner and an unbiased forecast will always lie along the 1:1 line.

5.2.3 Forecast rainfall events at station locations

Some of the heaviest rain events during the NZCSM archive period have been plotted to show the observed versus forecast rain for a single model forecast covering 'events' for 2017 (Figure 5-5) and in Appendix B for 2014, 2015 and 2016. In many cases the high resolution convective-permitting model does quite well, particularly from 2015 onwards (although in a few, the event is completely missed). However, when the observations have a very large peak, the model often does not fully capture the extent of its magnitude.

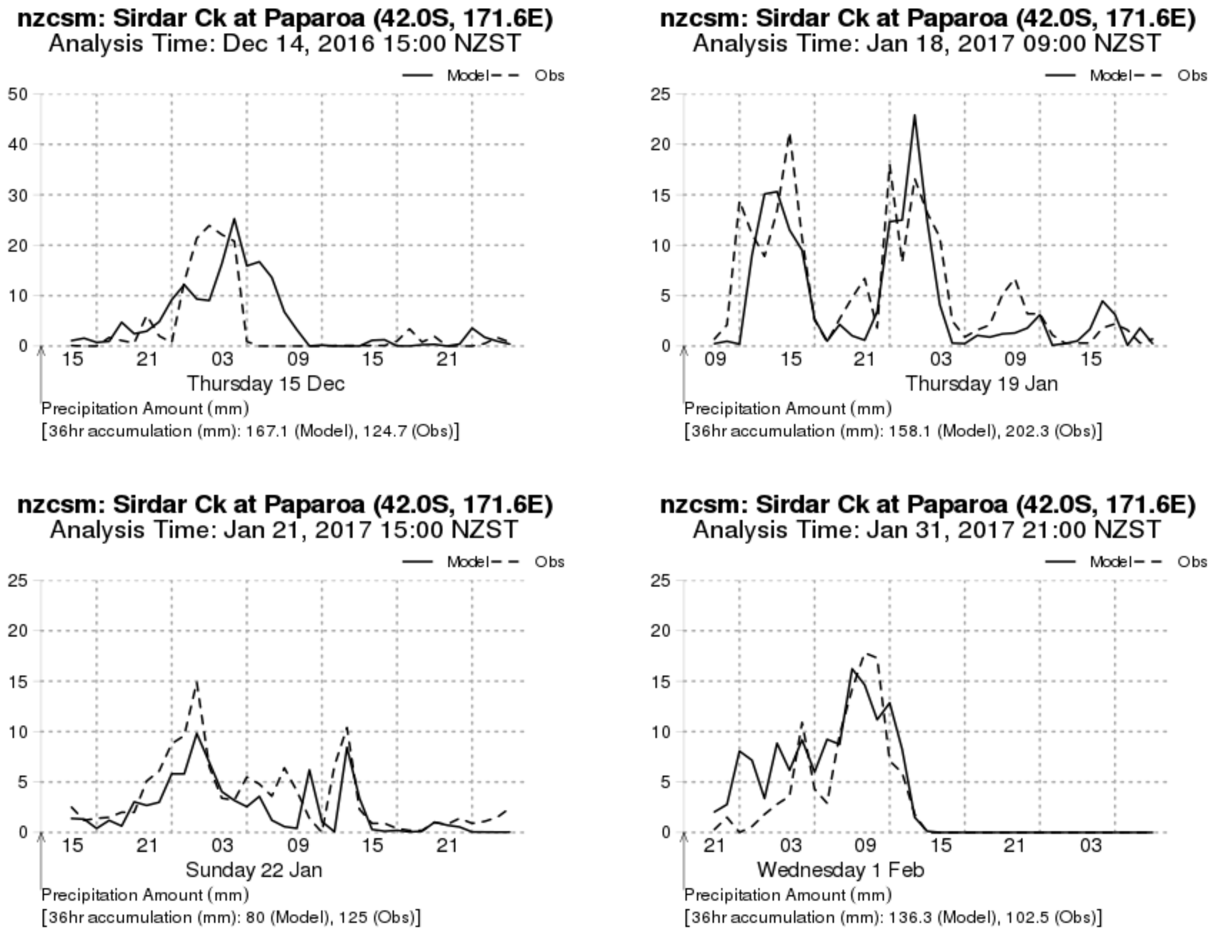

Figure 5-5: Rainfall forecast time series versus observed data in 2017.

5.2.4 Rainfall forecast averaged over the Buller catchment.

During a selected flood event in January 18th and 19th 2017—where the rainfall forecast performed well at Sirdar Creek at Paparoa station (top right plot in Figure 5-5)—we compared cumulated rainfall depth from station data, from NZCSM forecasts and the cumulative runoff depth observed in the Buller catchment (Figure 5-6 and Figure 5-7). By comparing observed runoff totals with forecast rainfall and runoff totals, we can test the forecast data in volumetric terms over the catchment area (Cattoën et al. 2016a); for example, if input rainfall depth is less than output runoff depth, forecasting models will not be able to close the water balance preventing accurate rainfall-runoff modelling. We tested the rainfall and runoff depths performance in each of the two nested catchments (Buller at Longford and Bullet at Te Kuha).

The total accumulated rainfall depth for the Sirdar Creek at Paparoa station reached 204 mm over 48 hours (Table 5-2). It is the second highest rainfall totals behind the Wangapeka at Biggs Top with 256 mm. In comparison, for the Buller catchment (Buller at Te Kuha) the observed runoff depth reached 87 mm over the same period. The average cumulated rainfall forecast depth over the catchment, at 97 mm, is only slightly above the observed runoff—suggesting an overall under-estimation of forecast rainfall totals at the catchment scale by the high-resolution convective scale weather model. A similar picture emerges from the Longford sub-basin of the Buller Catchment (Table 5-2).

Table 5-2: Rainfall and runoff depths over a 48-hour period for the January 18th -19th 2017 flood event.

Total depths over 48 hours	Te Kuha	Longford	Wangapeka at Biggs Top	Sirdar Creek at Paparoa
	Runoff (mm)		Rainfall (mm)	
Cumulated observed runoff/rainfall depth	87	29	256	204
Cumulated catchment average/point location rainfall forecast depth	97	36		
Cumulated catchment runoff forecast depth	56	13		

Although the station rainfall forecast performance is good for this flood event-with only a slight underestimation at the hourly timescale at the Sirdar Creek at Paparoa station (Figure 5-5), the overall accumulated catchment rainfall forecast is notably under-estimated when compared to observed runoff. As a representative case study, this flood event illustrates the nonlinearity and compounding effect of small rainfall forecast under-estimations during high intensity rainfall events in the West Coast.

To better account for uncertainties in initial conditions and precipitation model forecasts, the use of real ensemble weather forecasts will provide more robust predictions in the Buller catchment to ensure the accurate amount of rainfall depth is forecast for flood warning purposes.

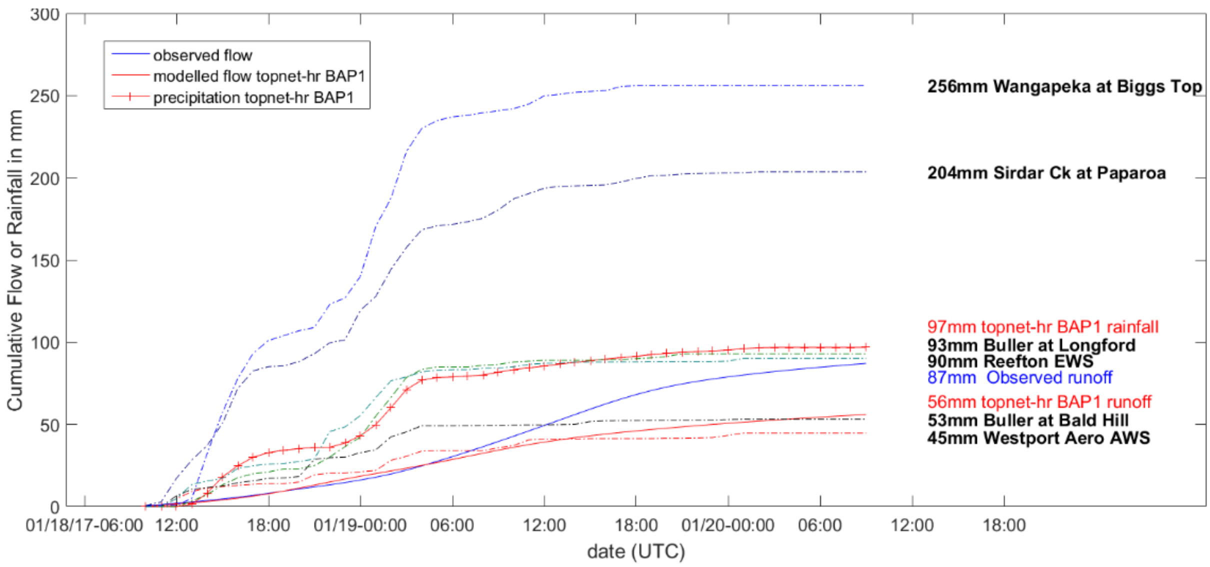

Figure 5-6: Rainfall and runoff depth for the Buller at Te Kuha catchment during the January 18th and 19th 2017 flood event.

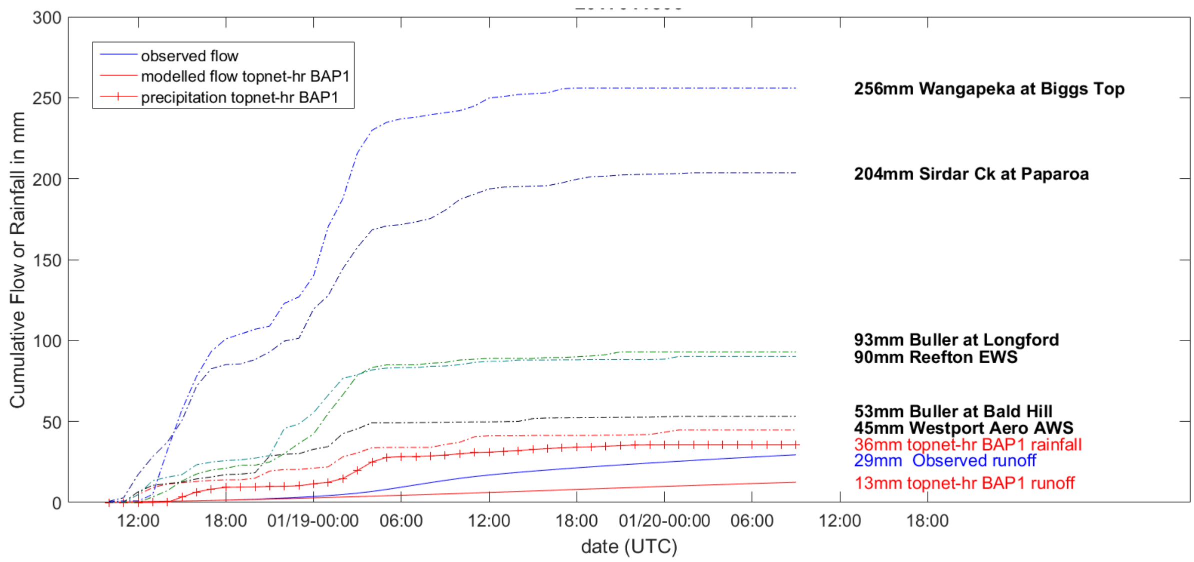

Figure 5-7: Rainfall and runoff depth for the Buller at Longford sub-catchment during the 18-19 January 2017 flood event.

5.3 Key findings from analysis of gauge data and forecast rainfall

Analysis of observed river flow and observed/forecast rainfall data has been used to assess the travel time and contribution to flood peaks from different parts of the Buller catchment, as well as the potential uncertainties present in forecast data. Key findings are:

- The estimated travel time for rainfall from Sirdar Creek to Westport is approximately 3.5-4 hours, so forecasts based on observed rainfall alone are unlikely to be able to provide the required 8 hour lead time for flows from the lower Buller catchment.
- Analysis of the ten largest flood peaks since 1986 in the Buller catchment showed:
  - The flood contribution from different parts of the catchment, the spatio-temporal rainfall patterns and responses to antecedent conditions vary greatly between events;
  - Flow contribution from the Paparoa and Mt William ranges makes up a significant part of the flood peak for many events and represents a forecasting challenge due to its shorter travel time.
- Rainfall forecast timing errors dominate uncertainty at periods less than around 3 hours. Errors in forecast magnitude become more important than timing errors for periods of 6 hours and greater.
- The NZCSM high-resolution weather model performs well for forecasting moderate rainfall events (between 5 and 20 mm/h), but under-forecasts heavy rainfall events.
- When rainfall is well forecast at a station location for a flood event, forecast rainfall totals at the catchment scale can be under-estimated. Using ensemble weather forecasts will be advantageous in the Buller catchment to better account for rainfall uncertainties during extreme flood events.

6 Summary of possible modelling solutions

Table 6-1 summarises the potential forecasting solutions for Westport based on combinations of the approaches described in sections 4.1 to 4.6. Advantages and disadvantages are identified for each potential forecasting solution, including conclusions from the analysis described in Section 5. Key points are:

1. Observed upstream threshold water levels at Te Kuha give only 1-1.5 hours warning of floods.

2. Observed rainfall station threshold exceedances can give 3.5-4 hours warning, but not all rainfall threshold exceedances would lead to floods because of variable antecedent initial conditions and uncertainty on areal extent of rainfall.

3. Nowcasting radar information (provided data are good enough), gives an additional 2-6 hours lead time (added to the 3.5-4 hours lead time possible with observed rainfall), however the achievable accuracy of radar calculated rainfall quantity is uncertain, due to the distance of the Hokitika radar from the catchment, and the blocking effect of the southern end of the Paparoa range. During flood events, this method could provide additional insights into rainfall patterns and the reliability of information derived from rainfall data from gauge stations. However, radar alone is unlikely to be able to provide adequate forecast accuracy.

4. Rainfall forecasts from numerical weather models will need bias correction but could provide rainfall exceedance thresholds out to a 48-hour lead time (helpful for regional council shift planning of staff during flood events).

5. Calibrated rainfall runoff (hydrological) modelling would improve flood forecast accuracy by incorporating the effects of antecedent conditions and variability in rainfall across the catchment.

6. Gridded rainfall forecasts coupled to a hydrological model would provide modelled flood thresholds out to 48 hours lead time. Use of real ensemble weather forecast would be advantageous for accurate uncertainty representation of extreme flood events.

7. The effect of sea/tide levels on flooding from the Buller river could be incorporated in two ways, either by having flow/rainfall trigger thresholds linked to sea levels (simple), or by developing a 1D hydrodynamic model of the lower reach of the Buller River (more complex but potentially more accurate).

All the potential forecasting systems involve automated analysis/modelling of real time data. Whichever forecasting system is selected will need to have a robust system for automatically carrying out this analysis and displaying information to forecasters. The display system will need to present timeseries of observed and forecast data to allow forecasters to make informed decisions regarding the likelihood of flood thresholds being crossed. Simple forecasting systems involving analysis of observational data can be handled by telemetry systems, such as WCRCs HydroTel system. For more complex forecasting systems involving the visualisation and integration of gridded data, and the automated running of hydrological or hydrodynamic models, other more specialist forecasting interfaces would be required, for example NIWA's Eco-connect system, the free software Delft-FEWS, or licensed software systems such as MIKE OPERATIONS. Whatever system is implemented consideration will have to be given to the robustness of the system and its communication links.

Table 6-1: Summary of potential forecasting solutions and the applicability for Westport. Solutions 1 to 8 represent potential fluvial flood forecasting systems, A and B are options for including the effect of sea/tide level on flood likelihood and could be carried out in combination with options 1-8

	Forecasting Solution	Forecast triggers	Lead time	Pros	Cons	Setup costs	Operating Costs	Conclusions
1	Upstream observed flow/level gauges	observed flow thresholds	~1.5h	High accuracy	Short lead time from Te Kuha. Not possible to forecast accurately from upstream sites as significant influence of lower catchment on flood peak.	none	Flow gauge maintenance	Insufficient lead time
2	Observed rainfall gauges	rainfall thresholds	~4h	Rain gauge network is reasonably good. Additional lead time compared to Solution 1	Ignores antecedent catchment wetness influence on runoff response. Ignores important influence of spatio-temporal variability in rainfall.	Development of rainfall thresholds.	Rain gauge maintenance	Poor accuracy as a result of excluding antecedent conditions and variability in rainfall distribution.
3	Observed rainfall + hydrological model	modelled flow threshold	~4h for flows from lower catchment, more for upper catchment.	Accounts for antecedent catchment conditions. Hydrological model can utilise information from upstream flow gauges (Woolfs & Landing)	Rain gauge data not fully representative of catchment rainfall (depending on spatial uniformity). Lead time limited to travel time from rainfall falling to flood arriving.	Model calibration	Rain/flow gauge maintenance. Server/model hosting.	May provide required accuracy. Not enough lead time for flows from lower Buller catchment.
4	Nowcasting radar	observed/ modelled rainfall thresholds	~4-10h	Good spatial rain representation for lower catchment. Frequent updates ~10-15mn	Ignores antecedent catchment wetness. Uncertainty over rain rate accuracy achievable due to distance from the radar site and blocking by the Paparoa Range (low elevation rainfall might be missed).	Initial assessment of radar suitability. Development/ calibration of QPF	Access to MetService radar data	Poor accuracy (antecedent wetness not accounted for). Radar useful to qualitatively understand spatial variability in rainfall.
5	Nowcasting radar + hydrological model	forecast flow thresholds	~4-10h	Good spatial rain representation for lower catchment. Frequent updates ~10-15mn	Uncertainty over rain rate accuracy achievable due to distance from the radar site and blocking by the Paparoa Range (low elevation rainfall might be missed). Need rain already formed to advect using nowcasting	Same as (4) + hydrological model calibration.	Access to MetService radar data Server/model hosting.	Accuracy of radar rain rates and potential for QPF uncertain without further analysis.
6	Rainfall forecast at station (MOS)	forecast rainfall thresholds	~48h (although accuracy lower at long lead times)	Longer lead times. Bias correction based on observed rain.	Ignores antecedent catchment wetness. Only point location information.	Forecast rainfall bias correction. Rainfall threshold derivation.	Access to NWP forecast (MetService, NIWA)	Good lead time but poor accuracy (antecedent wetness not accounted for).
7	Rainfall forecast at station (MOS) + hydrological model	forecast flow thresholds	~48h (although accuracy lower at long lead times)	Longer lead times. Bias correction based on observed rain. Hydrological model can utilise information from upstream flow gauges (Wolfs & Landing).	Forecast only updated every 6 hours. Higher uncertainties at longer lead times. Tendency to underestimate forecast rainfall at short lead time (0-6h).	Forecast rainfall bias correction. Hydrological model calibration.	Access to NWP forecast. Server/model hosting.	Good lead time but less accurate at short lead times than solution 3.
8	Gridded rainfall forecast (bias corrected) + hydrological model	forecast flow thresholds	~48h (although accuracy lower at long lead times)	Good spatial rain representation. Longer lead times. Hydrological model can utilise information from upstream flow gauges (Wolfs & Landing).	Forecast only updated every 6 hours. Higher uncertainties at longer lead times. Bias correction and model setup more complex. Tendency to underestimate forecast rainfall at short lead time (0-6h).	Forecast rainfall bias correction. Hydrological model calibration.	Access to NWP forecast. Server/model hosting.	Like solution 7 but captures spatial variability of rain over catchment better.
A	Sea level dependent warning thresholds	Forecast sea level + forecast rainfall/flow	Dependant on flow forecast approach	Accurate sea level forecast already available.	Unable to fully capture interaction with tide (i.e. coincidence of arrival time of peak flow and high tide).	Additional simulations using flood mapping model to identify thresholds.	Access to sea level forecast.	Simplest way of including effect of sea level on river flood forecast.
B	Hydrological model (solution no. 3, 5, 7 or 8) + Hydrodynamic model	Forecast flood level thresholds	Dependant on flow forecast approach	Explicitly includes effect of sea level and tide timing to improve accuracy.	Additional expense/complexity. Requires accurate prediction of flood wave arrival time (to be able to simulate interaction with tide accurately).	1D Hydrodynamic-model build and calibration.	Access to sea level forecast. Server/model hosting.	Allows accurate forecast of Buller flood levels rather than just flow.

7 Conclusions and recommendations

7.1 Conclusion regarding the feasibility of developing a suitable flood forecasting system

Buller River flood peaks affecting Westport can include a significant flow contribution from high intensity rainfall over the coastal Paparoa and Mt William Ranges in the lower Buller River catchment. This is a challenge for flood forecasting because there is a short travel time from rainfall falling to floods occurring for these coastal ranges. Forecasting flow from the Upper Buller catchment is also important, as it makes a major contribution to peak flow, but is likely to be easier due to the greater travel time for flows from the upper catchment.

Having analysed the range of forecasting options available and their strengths and weaknesses for application on the Buller River we conclude that it is possible to develop a forecasting system capable of providing lead time of 8 hours at the required level of accuracy.

The forecasting system should aim to achieve a 70% or greater probability of detection (POD > 0.7) and 30% or lower false alarm rate (FAR < 0.3) for floods exceeding warning thresholds. The analysis conducted for this report indicates that these targets are likely to be achievable, although this will remain uncertain until the forecasting system is implemented.

Whilst it is possible to provide an appropriate flood forecasting system, the integrated healthcare centre (along with the rest of Westport) remains at risk of flooding, and the frequency and magnitude of floods will increase with climate change and sea-level rise.

7.2 Recommended forecast methodology

The most-fit-for-purpose forecasting solution is a distributed, physically based hydrological model of the Buller River catchment driven by telemetered rain data from all rain gauges in and around the catchment (Figure 2-2) and gridded rainfall forecasts to extend the forecast lead time (combination of solutions 3 and 8 in Table 6-1). Telemetered flow records from throughout the catchment should be used for data assimilation to improve model accuracy. Flow thresholds for triggering flood warnings in different parts of the city can be based on the results of previous hydrodynamic modelling (Gardner 2017). Flow thresholds, especially for downstream areas of the city, should vary depending on forecast sea level (tide and storm surge; solution A in Table 3-1). Accurate forecasts of sea level are already produced for Westport by NIWA.

Hydrological modelling is required to achieve the required level of forecast accuracy because antecedent catchment conditions have a controlling influence on catchment response (see analysis in Section 5.1.2). It is recommended that a distributed hydrological model with high resolution (e.g., Strahler 1, sub-catchment area equal to approximately 0.5 km^2) is applied due to the high vertical relief and spatially varying rainfall patterns and hydrological response of the Buller catchment.

Inclusion of observed rainfall is required to achieve high accuracy at short lead times. Including forecast rainfall allows longer lead times and will be required to reliably achieve the target 8-hour lead time as well as to provide longer lead time forecasts to inform rostering decisions for forecasting staff. Inclusion of forecast rain data also provides a backup source of rain data in the event of one or more key rain gauges failing during a flood event (improving reliability). Including flow data from Woolfs and Landing flow recorders within the model (flow data assimilation) will improve the accuracy of the flow contribution from the upper catchment at shorter lead times. Woolfs is approximately 2.5-3 hours flood wave travel time from Te Kuha and travel times from Landing are longer.

Rainfall radar provides very valuable information regarding the spatial distribution of rainfall and we recommend that it should be used to aid flow forecast interpretation. For example, a qualitative inspection of radar data could inform a forecaster regarding whether rainfall only varies gradually across the catchment so gauge derived rainfall is likely to be representative of the wider catchment, or if rainfall is highly spatially variable and likely not well represented by gauge data. Despite the value of radar, we have not recommended that radar derived rainfall rates be included as direct inputs to the hydrological model as, without further analysis, we cannot be confident that quantitative rainfall estimates will be of sufficient accuracy. Our concerns regarding accuracy are because (1) the radar is located inland from Hokitika, 90-130 km away from the area where accurate rain data is most important for forecasting, and (2) the hills at the southern end of the Paparoa Range partially obscure the lowest beams of the radar, meaning that low elevation precipitation might be missed. Exploratory analysis of the radar data could be carried out to determine the likely accuracy which could be achieved for rainfall rate estimation over the coastal ranges of the Buller catchment.

All rain data used in the hydrological model should be bias corrected based on observed river flow and the catchment water balance. A consistent approach to bias correction is important to ensure that the rain data used for model calibration and operational forecasting are consistent, and that data from different sources (e.g., numerical forecast data and gauge data) are consistent. In the future additional or modified data sources (for example radar QPF, improved numerical forecasts, or additional/changed gauge network) could be included within the forecasting system without model recalibration, provided the same bias correction approach is taken.

7.3 Roadmap for implementing forecasting system

The development of a forecasting system can be broken into several tasks. Taking a staged approach to delivery would allow the methodology to be adapted if required following completion of each stage. Tasks/stages required to develop the system would be:

1. **Assessment of monitoring reliability:** Assessment of gauge network reliability for flood forecasting (i.e., frequency and duration of gauge or telemetry system failures). If gauge reliability is deemed insufficient for forecasting (e.g., if it does not meet the quality criteria outline in Section 3.2) then improvements to system reliability or installation of backup systems should be considered for key rainfall (Sirdar Creek) or river flow gauges.

2. **Identify trigger thresholds:** Further hydrodynamic model simulations using the existing flood mapping model (Gardner 2017) should be carried out to identify appropriate flow threshold to trigger different levels of warning under different sea level/storm surge conditions.

3. **Hydrological model development:** Calibrating and validating a hydrological model based on historic observed rainfall and river flow data. Forecast accuracy should be assessed by calculating hindcast POD/FAR ratios.

4. **Incorporate forecast rainfall:** Bias correction of forecast rainfall, incorporation of forecast rainfall into the hydrological model and hindcast validation of forecast accuracy (POD/FAR) at different lead times.

5. **Operational forecasting system:** Implement the hydrological model in an operational forecasting system which can automatically process gauge and forecast data, run models, and display easy to interpret results to forecasters. The forecasting system should be made as robust as possible by including the capability to deal with site outages, delays to forecast data, etc. We recommend that the forecast system would be hosted in a managed server environment with built-in redundancy (ideally at a separate location).

6. **Forecast accuracy monitoring/improvement:** Once operational, ongoing monitoring of forecast performance should be undertaken. Depending on whether forecast accuracy meets target requirements for POD and FAR (see section 3.1) for an 8-hour (or greater) lead time, further improvements could be considered such as use of radar data, installation of additional rain gauges (e.g. at Buckland Peaks), or development of a hydrodynamic model to explicitly simulate tidal interactions.

7.4 Cost to implement forecasting roadmap

Accurate estimation of the cost to implement the recommended forecasting system is challenging, especially for operational costs as annual fees for data access, system hosting, etc., are dependent on agreements with suppliers. Below we have identified the main costs and, where possible, their likely magnitude. All estimated costs exclude GST.

The development/implementation costs of the forecasting system described above include:

- $5-10,000 for further hydrodynamic model simulations to identify flood warning flow thresholds accounting for sea level/storm surge.

- $50-80,000 for development, calibration and hindcast validation of a hydrological model based on observed rainfall and forecast rainfall, including data assimilation from flow gauges, assessment of accuracy at a range of forecast lead times and implementation in an operational system.

The annual operating costs include:

- Maintenance of the gauging network and telemetry systems WCRC records will provide the most accurate estimate of the cost of maintaining the existing network.

- Staff time for forecast decision making during events. We have not costed this element as we assume it is already covered as part of WCRC’s current operations.

- Annual fees for data access to quantitative numerical weather forecast data (and radar data if it is included in the system in the future). These operational costs are difficult to estimate as they are dependent on agreements with suppliers of forecast data (e.g. MetService/NIWA). They could potentially range from nothing up to a maximum of around $25,000 per year.

- Annual costs of operating/maintaining the forecasting system. We estimate annual maintenance costs of $10,000 per year on average to cover things such as periodic reviews of forecast accuracy, post event reviews, or periodic system upgrades.

Overall, the estimated set-up cost for implementing the recommended forecasting solution is $55-90,000, with estimated annual costs of $10-35,000, not including WCRC staff time and maintenance of the gauge network.

7.5 Time to model implementation

As the model would be primarily based on existing rain and flow gauges the flood warning system could be operational from 30 June 2020. As the record length of the recently installed Orikaka and Brunner range rain gauges (and any new gauges such as the potential Buckland Peaks rain-gauge) increases, the model should be re-validated (and if necessary re-calibrated) to improve model forecast accuracy (better POD and FAR statistics).

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Appendix A Forecast rainfall analysis

This appendix presents a more detailed forecast rainfall analysis to complement section 5.2 (Forecast rainfall) of the report.

Validation of historical rainfall forecasts in the Buller catchment on the West Coast have been performed to understand performance and limitations of using rainfall forecasts in the Buller catchment. The rainfall forecasts are part of NIWA's high resolution weather model archive generated with the convective scale NZCSM model (Cattoën et al. 2016a; Cattoën et al. 2016c). Since June 2017, NIWA has upgraded the NZCSM with improved atmospheric forecasting of orographic rain in fast moving extreme events. However, due to the more limited range of forecast archive of the upgraded model, the analysis below was performed with the previous model version which contains 3 years of archive.

A practical methodology has been developed to provide insight into timing errors associated with forecasts of heavy rainfall events. We compared rainfall forecasts from May 2014 through June 2017 against rain gauge observations at Sirdar Ck at Paparoa (210610).

Errors due to timing can be isolated from errors in forecast magnitude by comparing the performance of high temporal resolution forecasts (e.g., hourly) with observations.

For locations in the Buller catchment, it was found that timing errors dominate at periods less than around 3 hours, whereas for periods of 6 hours and greater, the errors in forecast magnitude become more important than timing errors.

Other validation metrics such as rain rate histograms, which compare the observed and modelled frequency of occurrence of events in a series of rain rate bins, have also been developed.

Accuracy of hourly rainfall forecasts

The following set of performance diagrams show the model's skill at forecasting rain amounts over a series of thresholds. These diagrams plot the probability of detection (POD) on the y-axis (the proportion of observed events [threshold exceedances] correctly forecast) and the success ratio on the x-axis (this is 1 – FAR, the false alarm rate, or the proportion of forecast events that did not occur). The Critical Success Index, which combines POD and FAR, is shown by the shaded contours and the categorical bias is shown by solid grey lines. A perfect forecast should lie in the top right corner and an unbiased forecast will always lie along the 1:1 line.

The six thresholds are chosen on a logarithmic scale such that the number of additional events included at each progressively lower threshold is of the same order of magnitude. The skill at three different groups of forecast lead times is shown on the figures and is depicted by the size of the plot symbols. The performance diagrams have been produced at the hourly and accumulated time scale (3, 6, and 12 hours).

Figure 5-4 compares each forecast with the matching hourly observation but combines forecasts into 12-hour groupings to calculate the categorical verification metrics. Figure A-1 also compares at the hourly time scale but allows forecasts and observations to be mis-matched in time anywhere within the 12-hour grouping. This allows the forecast model some leeway in getting the timing of the rainfall right while still requiring that the distribution of rainfall magnitudes within the 12 hours is still correct.

Further figures repeat the same concept but with progressively longer accumulation times; 3 hours, 6 hours and then 12 hours. For the final figure, the 12-hour forecast must match the observations exactly in time as the forecast grouping is also 12 hours. Note that the category thresholds change so that they match the length of accumulation time.

These figures all show that, for higher rainfall thresholds in particular, the categorical bias scores are very good. This mirrors what is shown in the rain rate histogram in Figure 5-3 and means that on average NZCSM gets the number of heavy rain events correct, even if they are not at the correct time.

The considerable increase in performance from Figure A-1 to Figure A-2 suggests that the ability for the model to get timing right at the hourly scale could be improved. At the 3-hourly scale the difference is much smaller (cf. Figure A-2 vs Figure A-3) showing that the skill is better at this time-scale. The 6-hourly figures (Figure A-4 and Figure A-5) did not add much additional insight.

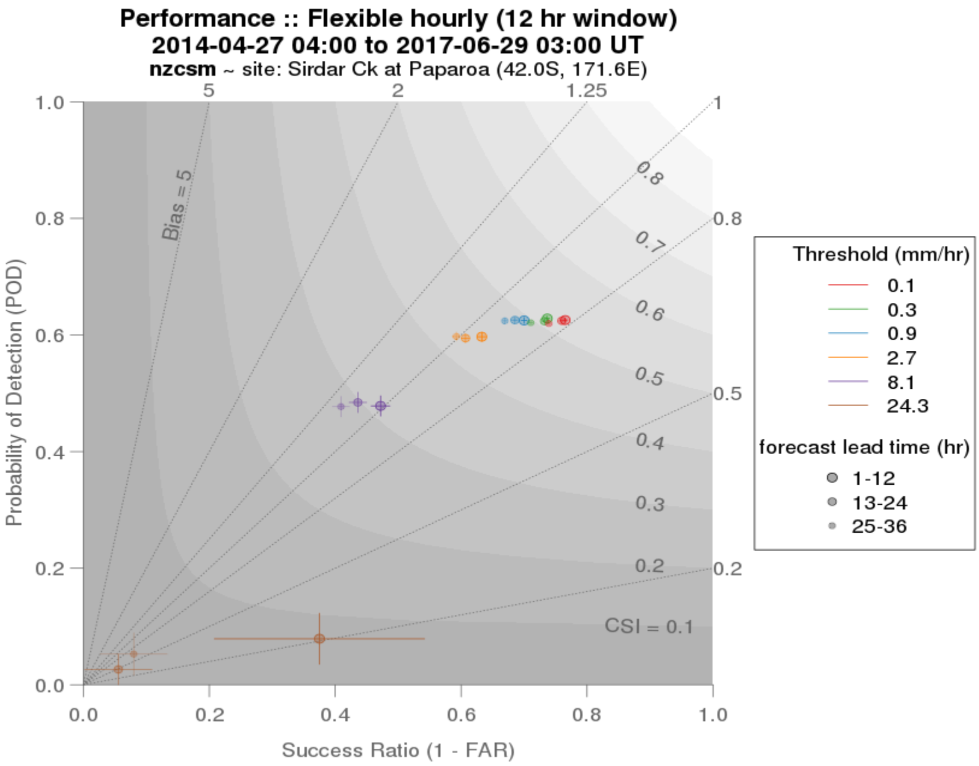

Figure A-1: Performance diagram comparing hourly accumulations of rainfall with observations anywhere within the 12-hour forecast verification window (see explanation of graph in Figure 5-4).

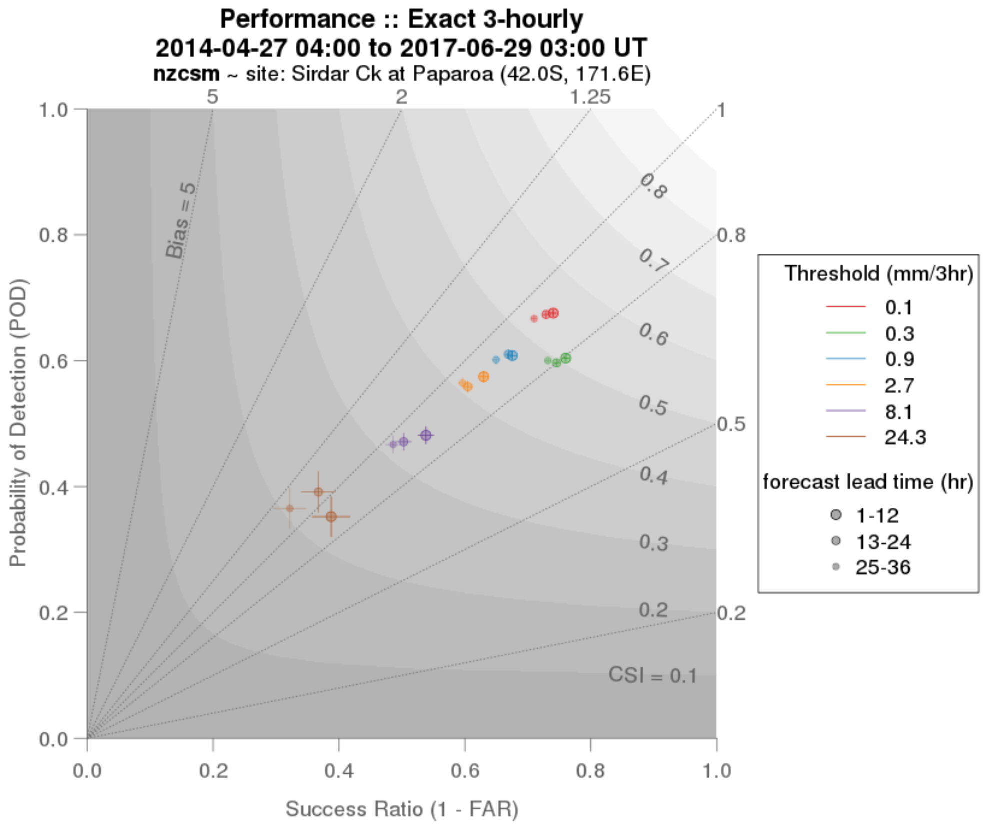

Figure A-2: Performance diagram comparing 3-hourly accumulations of rainfall with observations from exactly the same time (see explanation of graph in Figure 5-4).

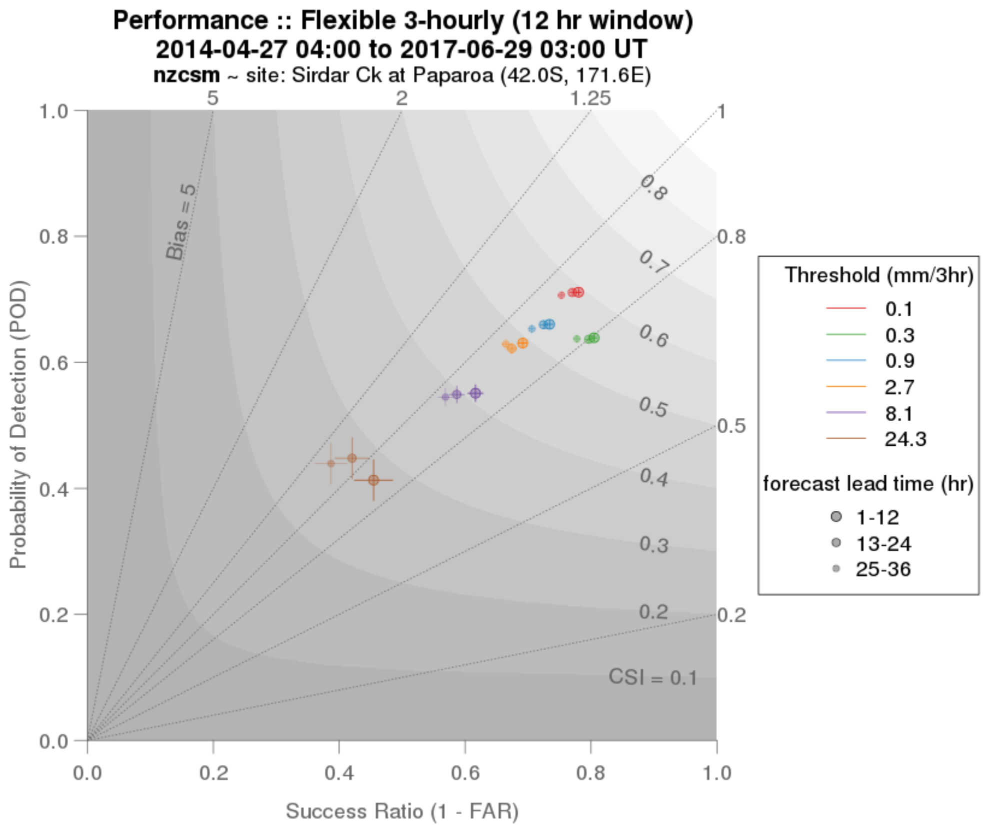

Figure A-3: Performance diagram comparing 3-hourly accumulations of rainfall with observations anywhere within the 12-hour forecast verification window (see explanation of graph in Figure 5-4).

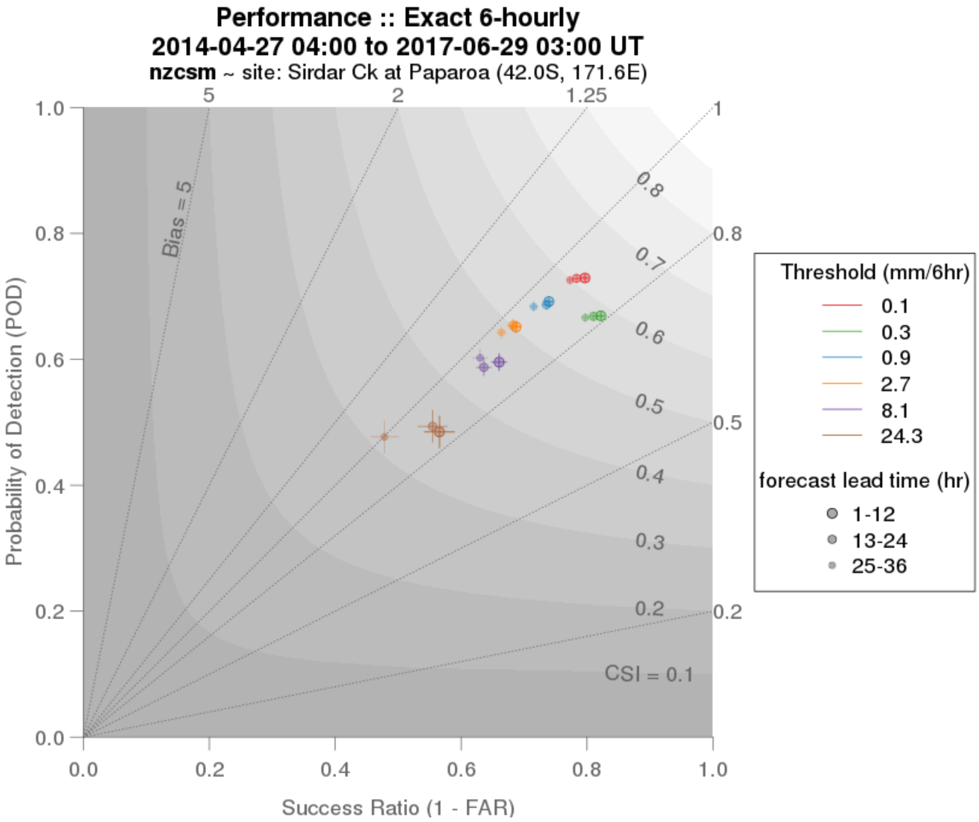

Figure A-4: Performance diagram comparing 6-hourly accumulations of rainfall with observations from exactly the same time (see explanation of graph in Figure 5-4).

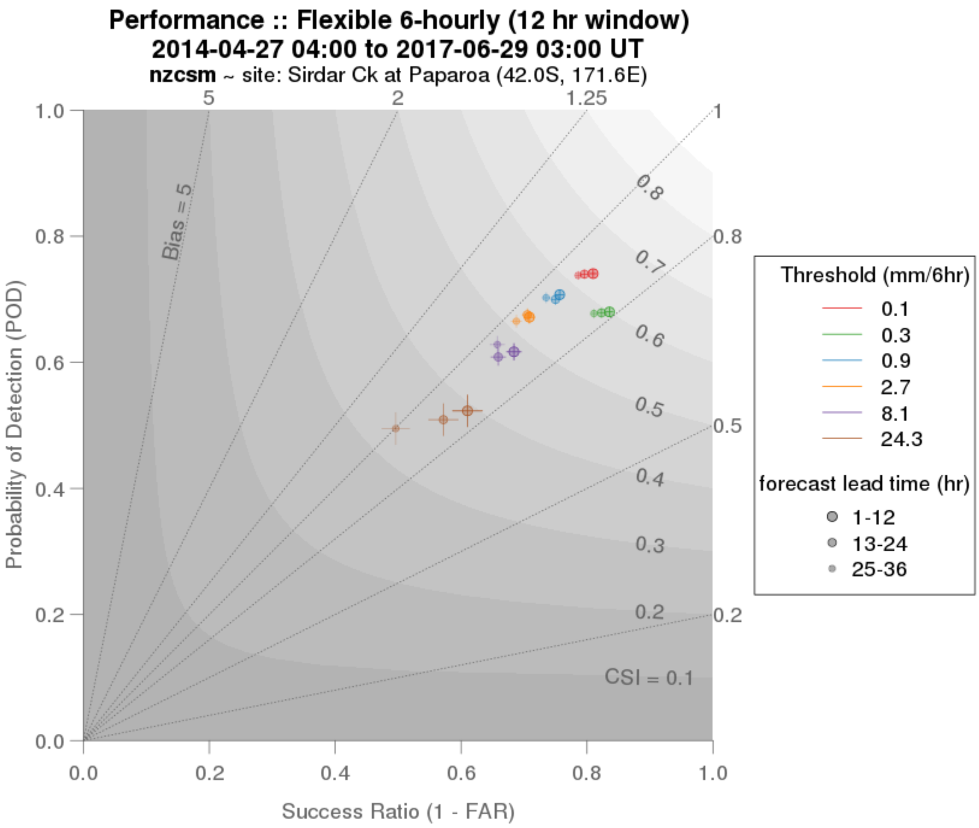

Figure A-5: Performance diagram comparing 6-hourly accumulations of rainfall with observations anywhere within the 12-hour forecast verification window (see explanation of graph in Figure 5-4).

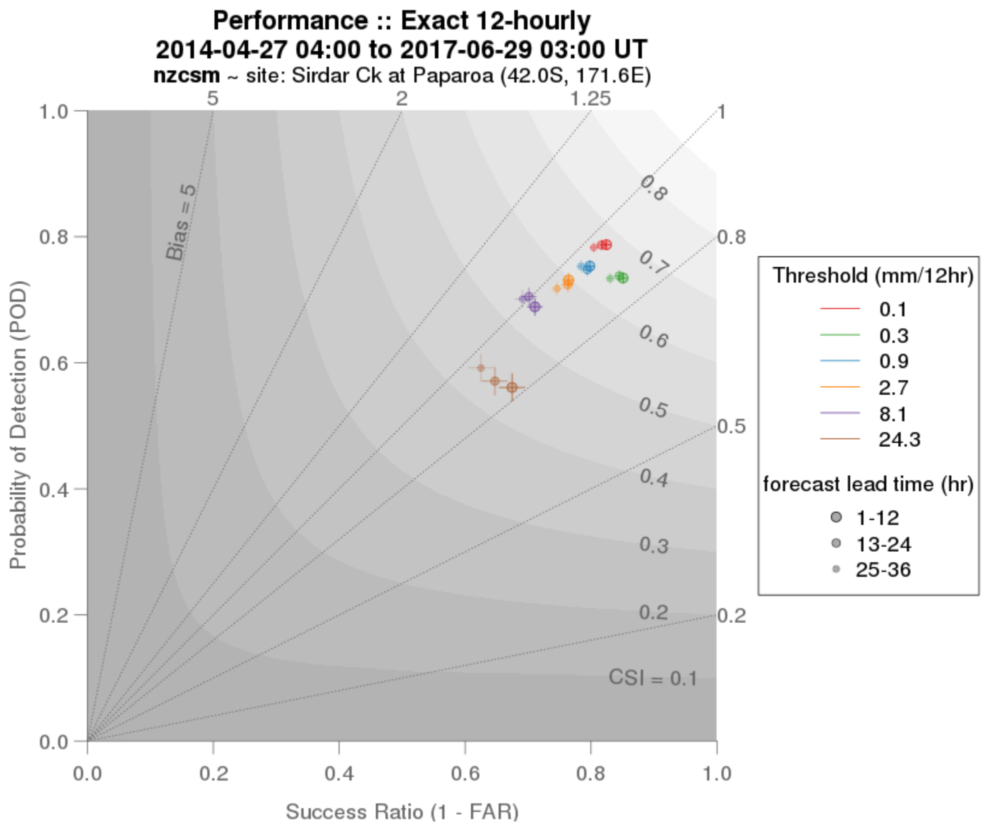

Figure A-6: Performance diagram comparing 12-hourly accumulations of rainfall with observations (see explanation of graph in Figure 5-4).

Appendix B Forecast rainfall events at station locations

Some of the heaviest rain events during the NZCSM archive period have been plotted to show the observed versus forecast rain for a single model forecast. 'Events' for 2017 are shown in Figure 5-5 in the main report. This Appendix shows events from 2014 (Figure B-1), 2015 (Figure B-2) and 2016 (Figure B-3).

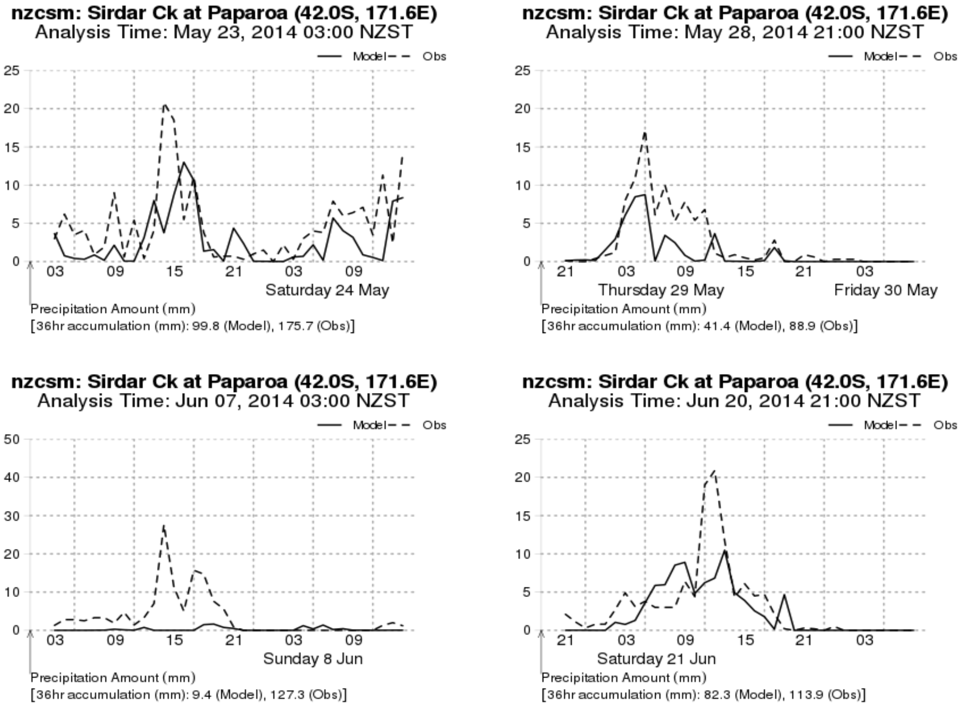

Figure B-1: Rainfall forecast time series versus observed data in 2014.

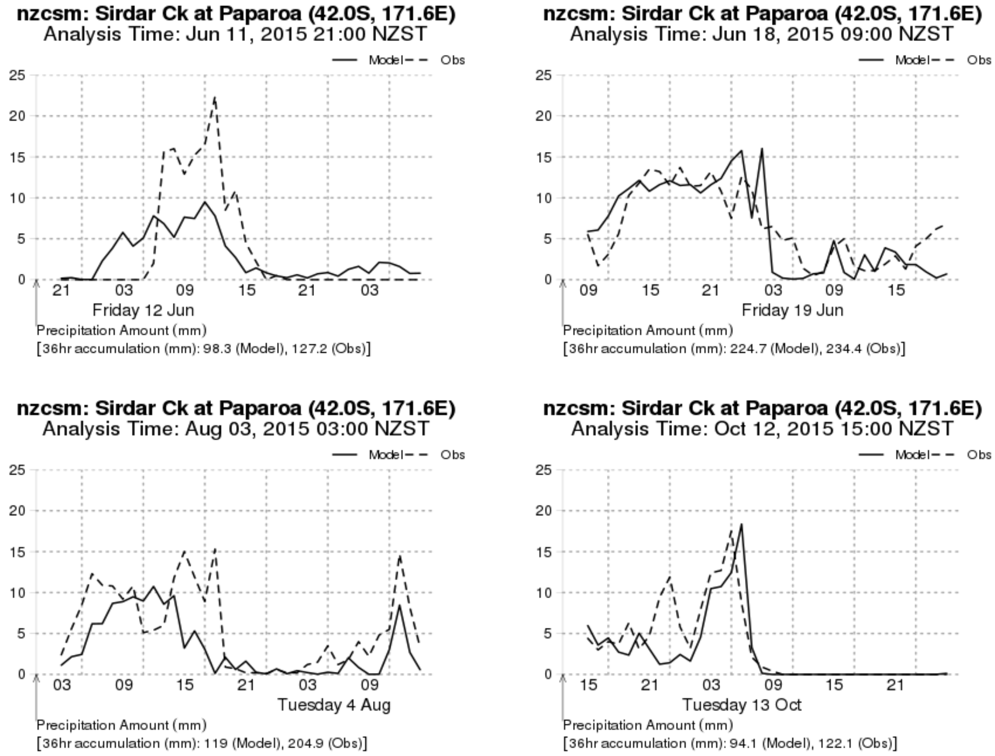

Figure B-2: Rainfall forecast time series versus observed data in 2015.

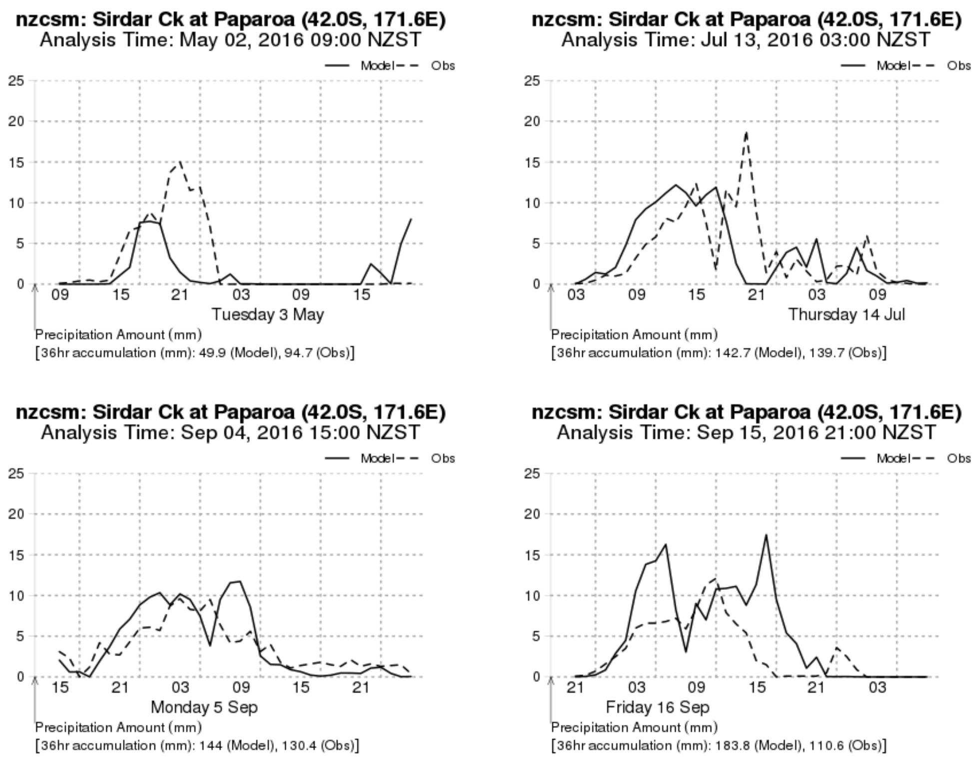

Figure B-3: Rainfall forecast time series versus observed data in 2016.