
Review of Kāpiti Coast flood hazard management reports

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Executive summary

Awa Environmental Ltd (AWA) have produced a series of reports that utilize the TUFLOW numerical model to project future flooding levels and flows for catchments. This modelling was undertaken to improve the Council's ability to simulate the district's flood hazard for flood management.

Considering the model calibration, validation and application for assessing present flood hazard:

- The TUFLOW HPC 2023-03-AB model used is an appropriate model for the intended purpose. The model was not verified, but since it is an industry standard, this is not considered an issue.
- The numerical model has been calibrated by adjusting model settings to achieve the best fit to measured and estimated flood data. However, it is clear that the data quality available for calibration was not consistently of a suitable quality.
- The process reported as validation in the draft reports involved an iterative adjustment of the model parameters to achieve a best-fit to the observations for selected storm events. This is not validation, but a further calibration. Validation involves assessing the goodness-of-fit of calibrated model predictions against an independent set of observations without modifying the model parameters. There is no evidence reported that this was done.
- No skill scores or goodness-of-fit statistics were reported for calibration or validation that would allow assessment of the applicability of the model results.
- The model is predominantly driven by rainfall depth across the model domain, which requires information on the rainfall frequency, depth and duration to determine the volume of water available.
 - Recorded rainfall within Kāpiti Coast District was used for calibrations, with estimates of frequency reported.
 - For model simulations used to produce maps, rainfall frequency-depth-duration distributions were provided by the NIWA High Intensity Rainfall Design System (HIRDS) V4 software. HIRDS combines measured rainfall with rainfall predicted by Regional Climate Models (RCMs), as 2 km by 2 km square grid cells covering New Zealand.
 - There was no assessment of the reliability of the HIRDS distributions for the Kāpiti Coast District compared to distributions determined directly from historical rainfall measurements.
 - No TUFLOW model calibration appears to have been performed using HIRDS data source

For assessing future flood hazard:

- It was assumed that apart from rainfall depth and sea level effects, all other factors affecting flood hazard would remain constant until 2130. This includes the influences of development on surface drainage and groundwater, the characteristics of the stormwater system, and the topography of the region. This is unlikely to be correct.
- HIRDS was used to project future rainfall frequency-depth distributions by scaling the 2018 HIRDS distributions by factors derived for projected future temperature for each frequency-duration pair evaluated.
 - Although the HIRDS documentation specifies that only the air temperature projections provided in the HIRDS manual should be used, AWA used different air temperature projections for their modelling.
 - The modelling was based on an extreme scenario (RCP8.5) and more extreme set of values representing the 83% percentile of that scenario (RCP8.5 H+). This was for the purpose of *stress testing* of the stormwater management system. It is not a plausible scenario for assessing flood risk.
 - The scaling used assumes that there is a strong relationship between air temperature and rainfall depth. Historical data indicates that rainfall depth is not significantly influenced by air temperature, but is strongly affected by topography, and sea surface temperatures and wind patterns in the Tasman Sea. The resulting rainfall depth projections should be considered unreliable.
- The methodology used did not include any assessment of the risk.

While the flood maps for 2030 may be reasonable, albeit biased towards extreme scenarios and a small increase due to the assumed temperature increase. They predominantly represent the current situation apart from any effect from using HIRDS instead of historical measured rainfall data. However, the model predictions should be validated and skill cores and/or goodness-of-fit statistics provided to allow assessment of the reliability of these maps.

- The HIRDS 2018 frequency-depth-duration curves are estimated from a combined dataset of measured data, and RCM projections derived from six CMIP5 Global Climate models by merging all scenario projections (RCPs 2.6, 4.5, 6.0, and 8.5). The validity of this dataset for Kāpiti Coast District should have been tested, particularly since it is known that HIRDS does not reliably

estimate rainfall depths for areas of significant topographic changes, such as the upper catchment of rivers and streams with the district.

The flood maps for 2130 are not considered reliable projections and should not be used to identify areas subject to specified levels of flood risk. The reasons for this are:

- The absence of validation goodness-of-fit statistics make it impossible to assess the uncertainties in the modelled future flood hazard due to the propagation of errors in the model calibration.
- There is no information to assess the probability of the scenarios used occurring. In particular, the modelling focussed on extreme scenarios (RCP 8.5 and RCP 8.5 H+) which are now recognised as implausible.
 - The HIRDS software manual specified that only the scenarios used to develop the frequency-depth-duration distributions should be used for projecting future flood depth. The values used by AWA differed significantly from the those specified for HIRDS
- It is likely that there will be changes to the behaviour of floods in the future due to development, changes to the stormwater system, or natural changes to the surface and groundwater drainage due to events such as an earthquake.
- There is no assessment of the actual likelihood of the predicted flood events occurring, which is required to define the flood risk.
 - The Annual Exceedance Probabilities (AEPs) shown on the maps represent the frequencies of the rainfall depths from the 2018 HIRDS estimated distributions. It has not been demonstrated that scaling those values by temperature is a reliable predictor of the AEP in 2130.

Introduction

The Kāpiti Coast District Council (KCDC) commissioned a Flood Hazard Study and Model Re-Build from Awa Environmental Ltd (AWA) to improve the Council's ability to simulate the district's flood hazard for a variety of purposes as set out in the Scope of Work¹. Various reports were produced as drafts by AWA. KCDC opened the drafts produced by AWA for public submissions.

The focus of the modelling was the stormwater systems, and most reports were for "catchments" that reflect the networks and discharge points of the stormwater systems, and do not necessarily follow natural surface freshwater catchment boundaries. A report summarising the overall methodology was also produced.

I was asked by Coastal Ratepayers United (CRU) to prepare this review to allow CRU to respond to the request for submissions, focussing on four reports:

- The methodology report (Kāpiti Flood Hazard Management Methodology Report);
- The catchment of the Mazengarb Stream (Mazengarb Model Build Report);
- The urban Paraparaumu Beach "catchment" (Paraparaumu Beach Model Build Report); and
- The Waikanae "catchment" (Waikanae Model Build Report).

CRU specifically requested that my review focus on:

- The quality of AWA's modelling, any third-party modelling, and their integration with respect to the appropriateness of the models used to realistically model Kāpiti Coast's flood hazard risks, and identification of any major gaps, e.g. missing drivers of risk or sources of mitigation;
- The various data sources used, their appropriateness, and the steps taken to address their limitations.
- The parameterization, and model calibration, validation and verification;
- The assumptions made in building the models and in their use, highlighting where these are likely to be unrealistic/unwarranted in the context of a flood hazard risk assessment.
- Model validation, and sensitivity and uncertainty analysis undertaken. Redoing or replicating AWA's work is not expected, although any high-level reassessment would also be appreciated.

The TUFLOW model

The AWA reports state that the model used was TUFLOW version 2023-03-AB, which is available as TUFLOW Classic and TUFLOW HPC versions. It is clear from the reviews by BMT in Appendix A, that the

¹ Appendix A of AWA's Kāpiti Flood Hazard Management Mazengarb Methodology Report – Final Draft for Review

model used was TUFLOW HPC 2023-03-AB. This is an industry standard numerical model and suitable for the purpose of assessing hydrological processes for urban catchments.

The reviews by BMT focused on the technical aspects of the modelling, and identified a number of minor issues that were rectified. These reviews primarily considered the application of the model for hindcasting historical flooding events as described in the Methodology report².

However, for the purpose of predicting future flood hazard, it is necessary to have confidence that the model is reliably predicting the real world. This relies on three key components^{3,4}:

- Calibration – this involves adjusting model parameters (constants, coefficients, etc.) to match observed data, improving the model's agreement with real-world scenarios;
- Validation – this involves evaluating the model's ability to accurately represent the real world or a specific scenario, often by comparing its predictions with new, independent data not used during calibration;
- Verification – this involves ensuring that the model implementation accurately reflects the conceptual description of the model and its solution.

Note that validation does not involve adjusting the model parameters to match observations, and should involve quantification of the degree of agreement between the predictions and independent observations. Another key aspect of validation is an assessment of the uncertainties for the predictions, which involves determining the model skill or determining goodness-of-fit statistics⁵.

The explanation of the calibration and validation methodology for the TUFLOW models in the reports confuses validation with calibration, as indicated by the statement on page 45 for the Methodology report that says:

“Validation of the catchment models was an iterative process that involved aligning model results with recorded flooding observations. Adjustments were made to model parameters to achieve agreement between observed and predicted flooding ...”.

This is a calibration procedure, not validation. It is unclear if an iterative process was used for both the May 2015 and December 2021 events used for validation in the reports reviewed.

² Kāpiti Flood Hazard Management Methodology Report – Final Draft for Review

³ Thacker, B. H., Doebling, S. W., Hemez, F. M., Anderson, M. C., Pepin, J. E., & Rodriguez, E. A. (2004). Concepts of model verification and validation.

⁴ Refsgaard, J. C., & Henriksen, H. J. (2004). Modelling guidelines—terminology and guiding principles. *Advances in Water Resources*, 27(1), 71-82.

⁵ Gneiting, T., & Raftery, A. E. (2007). Strictly Proper Scoring Rules, Prediction, and Estimation. *Journal of the American Statistical Association*, 102(477), 359-378.

The Methodology report includes mention of additional validation for the Wharemauku upper catchment (steep hills), involving 4 additional historical storm events. The Wharemauku report was not included in this review.

It is clear from the Methodology report that the calibration was largely qualitative due to the lack of quantitative data on flood depths and extent. Further, the data available ranged from anecdotal data (descriptions and a few photographs) to instrumental rainfall and river level data. The variable data quality does not provide a useful assessment of the applicability of the predicted values for the purpose of assessing present and future flood risk. This is particularly problematic for the preparation of flood maps with specified levels of annual probability.

Although, modelling of future flood hazard was based on frequency-depth-duration curves estimated by the NIWA High Intensity Rainfall Design System (HIRDS) version 4⁶ software, and not from observational data within Kapiti Coast District, there appears to have no validation of the HIRDS rainfall estimates, or validation using known flooding events using the HIRDS estimated rainfall depths. If this was the case, it does not provide any confidence that the model can produce realistic predictions for future events.

Climate change effects are the only factors considered in the modelling that may affect future flood hazard. There is no assessment of what role climate change has had on historical and present-day flood hazard. It is probable that other factors have had, and will have, a role in determining flood hazard. The HIRDS software makes assumptions about the processes due to climate change affecting future rainfall depths that may not be valid for Kāpiti Coast District. This will be discussed further below.

There also appears to have been no validation of the effects due to tides and storm surges (tsunami inundation was not included in the modelling), and therefore provides no indication that the model can realistically simulate the effects of those processes.

Overall, I agree with BMT that the TUFLOW model is suitable for the purpose of simulating an urbanised catchment response to rainfall events. I also agree that the TUFLOW model is an improvement over the previous MIKE FLOOD models used by KCDC. However, I do not consider that the ability of the TUFLOW models to reliably predict the future behaviour of the catchments simulated has been demonstrated. Apart from the lack of validation, including an assessment of model skill, it is clear from the BMT reviews and the methodology reported that the future predictions are dependent on the

⁶ Carey-Smith, T., Henderson, R., & Singh, S. (2018). High Intensity Rainfall Design System, Version 4, Prepared for Envirolink. 73 p.

assumptions made by the modellers. These should have been addressed as part of the model methodology and the uncertainties explained and quantified.

The following sections will discuss some of the assumptions that I have concerns about.

Present rainfall depth-duration-frequency distributions

The Methodology report does not identify the rain gauge sites actually used for calibrations, although it presents a map of the locations used by HIRDS (see Table 1 below). For the model “validations” based on flood events in May 2015 and December 2021 and presented in the Mazengarb report, AWA used rainfall observations from 3 recording sites (Table 12, page 31, Mazengarb report): Paraparaumu Airport EWS, Te Horo Wetland at Shoveler Lagoon, and Waikanae Water Treatment Plant. The rain gauge measurements were interpolated between these sites using the standard Thiessen polygon method.

Only time series of rainfall depth appear to have been used, and there was no assessment of the frequency-depth-duration distributions that define the probabilities associated with rainfall depth. It is unclear how AEP values were determined for the rainfall depths used in calibration. Ideally the data for these sites would have been used to define the historical frequency-depth-duration extreme value distributions.

Since the HIRDS V4 software was used to predict future flooding, it should have been used to provide the rainfall depth inputs for the historic floods simulated for calibration. Ideally, the HIRDS frequency-depth-duration distributions should also have been compared with the historic distributions at the locations within Kāpiti Coast District that were used to derive the HIRDS estimates. This is because Carey-Smith et al (2018) identify a number of issues that primarily affect the tails of the distributions, which are the focus of this flood hazard modelling. This includes the presence of rapid changes in topography, as occurs between the cusped foreland lowlands and the hills rising into the Tararua Ranges. The headwaters of most natural catchments draining through Kāpiti Coast District are in the hills and ranges, where rainfall depth is likely to vary significantly at smaller spatial scales than the 2 km by 2 km smoothed grid used by HIRDS.

Further, it is my experience based on studies of flood risk and landslide triggering for the Auckland, Waikato and Bay of Plenty regions, that even for areas with small topographic changes the HIRDS estimate can deviate markedly from historical data, particularly for low probability extremes.

Future rainfall depth-duration-frequency distributions

Predictions for future events used the HIRDS estimated rainfall depths. No calibration or validation appears to have been performed for model runs using HIRDS, even though it was recognised that there are significant spatial variations in rainfall across the Kāpiti Coast District during single rainfall events.

Table 1 lists the rainfall observation stations located within Kāpiti Coast District and the record periods that are used by HIRDS V4. This list includes the stations used by AWA for the May 2015 and December 2021 events (highlighted). Note that the HIRDS analysis did not include data after 2016. The longest time series are for stations that only recorded daily rainfall totals, which limits rainfall intensity distributions to 5-, 4-, 3-, 2- and 1-day durations. Shorter duration analyses are possible for stations with sub-daily (12-, 6-, 2- and 1- hours) and sub-hourly (30-, 20- and 10-minutes, but not considered by AWA). The available sub-daily records cover from 6 to 47 years.

The observed rainfall data from the stations listed in Table 1 were adjusted to provide the data used by HIRDS, as follows:

- Monthly maxima are determined for the standard rainfall durations used by HIRDS as discussed above. Maxima derived from daily data are adjusted to account for timing differences between the standard day, and the rainfall event (rainfall for an event may be partially recorded in adjoining days). This adjustment scales up the rainfall total by 1.030 to 1.148 depending on the number of days, with the largest adjustment for 1-day durations.
- Sites less than 500 m apart (e.g. for Paraparaumu Airport) were merged. If the data overlap in time, the largest rainfall values at any site are retained in the merged dataset.

It is clear from Table 1, that no sites have sufficiently long records to allow determination of the low probability extreme events normally considered for risk assessment, such as the 1% Annual Exceedance Probability (AEP) value. The other issue that is evident when the sites are plotted on a map (Figure 14, page 21, Methodology report) is that they are not uniformly distributed through Kāpiti Coast District. Ideally the frequency-depth-duration distribution should be available and well constrained at all locations of interest.

HIRDS generates frequency-depth-duration distributions by fitting Generalised Extreme Value (GEV) distributions to depth-duration and frequency-depth data from the available measurement sites, after making adjustments as summarised above. The resulting GEVs are filtered by various criteria to produce a subset of regional distributions that are mapped onto a 2-km square grid, combined with the corresponding values for any merged observation site within any grid cell. The regional distributions are used to estimate rainfall depths for required return periods for specific event durations.

Table 1 — Summary of the instrumental rainfall observation sites within Kāpiti Coast District used by HIRDS V4, with the sites also used by AWA for the Mazengarb report highlighted. The data availability at daily, sub-daily and sub-hourly time intervals are indicated.

Site ID	Site Name	Latitude	Longitude	Daily Coverage	Sub-Daily Coverage	Sub-Hourly Coverage
49908	Whareroa at QE Park	-40.9737	174.9763	2002-2015 (10y)	2002-2015 (10y)	2002-2015 (10y)
57106	Otaki at Depot	-40.7698	175.1444	1993-2015 (23y)	1993-2015 (23y)	1993-2015 (23y)
58004	Waikanae Water Treatment Plant	-40.8882	175.0723	1995-2015 (21y)	1995-2015 (21y)	1995-2015 (21y)
58005	Te Hapua Wetland at Shoveler Lagoon	-40.8134	175.0783	2010-2015 (6y)	2010-2015 (6y)	2010-2015 (6y)
58103	Mangaone at Transmission Line	-40.8360	175.1703	1993-2015 (21y)	1993-2015 (21y)	1993-2015 (21y)
59007	Akatarawa at Warwicks	-40.9575	175.0768	1981-2015 (35y)	1981-2015 (35y)	1981-2015 (35y)
59104	Waiotauru at Kapakapanui	-40.9273	175.1638	1993-2015 (23y)	1993-2015 (23y)	1993-2015 (23y)
59201	Penn Ck at McIntosh	-40.9171	175.3095	1993-2015 (23y)	1993-2015 (23y)	1993-2015 (23y)
E04891	Kapiti Island	-40.8546	174.9316	1961-2016 (48y)		
E04991	Paraparaumu Aero	-40.9070	174.9840	1951-2016 (66y)	1956-2002 (47y)	1956-2002 (46y)
E04992	Paekakariki North	-40.9690	174.9770	1973-1986 (11y)		
E04994	Paraparaumu Aero AWS	-40.9070	174.9840	1992-2016 (25y)	1995-2016 (22y)	
E04995	Paraparaumu EWS	-40.9039	174.9844	1996-2016 (21y)	1996-2016 (21y)	1996-2016 (21y)
E05711	Otaki 1	-40.7640	175.1450	1893-1969 (76y)		
E05713	Otaki Temuera St	-40.7600	175.1340	1971-1984 (14y)		
E05714	Otaki East	-40.7600	175.1690	1980-1991 (12y)		
E05717	Te Horo Jonelle	-40.7900	175.1580	1992-2016 (25y)		
E05802	Waikanae Waterworks	-40.8894	175.0720	1970-2016 (47y)		
E05803	Te Horo Beach Puruaha	-40.8080	175.0790	1995-2008 (14y)		
E05811	Te Horo Longcroft	-40.8170	175.1480	1969-2016 (48y)		
E05812	Te Horo Marycrest	-40.8200	175.1050	1970-1980 (10y)		
E05901	Paraparaumu Wairere	-40.9110	175.0100	1971-1988 (13y)		
E05908	Paraparaumu Valroa	-40.9410	175.0100	1981-1986 (6y)		

The frequency-depth-duration curves derived by HIRDS can deviate from the curves derived directly from the observations, particularly at the tails of the distribution. HIRDS V4 employs an extra adjustment to the derived distributions to minimize discontinuities caused by the more extreme observations, which is intended to reduce this deviation.

Carey-Smith et al (2018) estimated the uncertainty for the estimated rainfall depths and found that the uncertainty increased faster than increasing depth with decreasing exceedance probability. It was noted that the greatest uncertainties were associated with low probability, short duration events. They

only provided low resolution contour plots for the entire country for their uncertainty results, so it is very difficult to assess the uncertainties for Kāpiti Coast District.

Climate change

The effects of climate change are incorporated into HIRDS V4 by scaling the rainfall depths by an augmentation factor for each event duration and return period combination. The augmentation factors for different rainfall event durations and frequency (expressed as annual return period, which is the reciprocal of the AEP) are shown in Figure 24 on page 13 of the Methodology report. This is the same as Table 6 on page 44 of Carey-Smith et al (2018), and it is included below in Figure 1. These augmentation factors were estimated from Regional Climate Models (RCMs) downscaled from six CIMP5 Global Climate Models (GCMs). The criteria for the selection of these six models is not given, but it was noted that there are biases in the resulting precipitation data that involves the extreme rainfall events.

The derivation of the augmentation factors assume that historical precipitation GEV distributions were stationary (did not change over time), and that future GEV distributions will be non-stationary. The GEVs estimated from the RCMs differed from the GEVs estimated from historical data, but the spatial patterns of rainfall depth looked similar when plotted using a logarithmic scale. Carey-Smith et al (2018) state that based on maps of percentage change in rainfall depth per degree of warming across New Zealand that:

“... increases in rainfall depth are more common than decreases (particularly for RCP8.5), but the spatial pattern of these changes is very different for the different simulations. Not only are the spatial patterns different between the 6 different driving models, but they also vary across the different RCPs for the same model.”

These results indicate that there are different regional responses to climate change for rainfall depth. Carey-Smith et al (2018) spatially smoothed the predicted changes to rainfall depth to derive the single augmentation factors for each duration-frequency pair in their Table 6 (which involved combining results from different RCP scenarios and biased the factors towards RCP8.5 which projected the largest temperature change). The smoothing process means that it is not possible to distinguish different HIRDS estimates of future climate change impacts by RCP scenario in Figure 1.

With respect to the regional variations in augmentation factors, Carey-Smith et al (2018) state:

“While these regional patterns appear coherent and may have some physical explanation (for example more intense tropical storms in the future may lead to the most extreme events becoming more intense in Northland and Coromandel), the large regional variability between RCM simulations does not allow us to say with confidence that these patterns are correct. Until further research has confirmed or updated these patterns, it is not appropriate to estimate climate change augmentation factors for the HIRDS surfaces on a regional scale, however users

should be aware that in reality some regions of New Zealand may have larger increases than others.”

Table 6: Percentage change factors to project rainfall depths derived from the current climate to a future climate that is 1 degree warmer.

DURATION/ARI	2 YR	5 YR	10 YR	20 YR	30 YR	40 YR	50 YR	60 YR	80 YR	100 YR
1 HOUR	12.2	12.8	13.1	13.3	13.4	13.4	13.5	13.5	13.6	13.6
2 HOURS	11.7	12.3	12.6	12.8	12.9	12.9	13.0	13.0	13.1	13.1
6 HOURS	9.8	10.5	10.8	11.1	11.2	11.3	11.3	11.4	11.4	11.5
12 HOURS	8.5	9.2	9.5	9.7	9.8	9.9	9.9	10.0	10.0	10.1
24 HOURS	7.2	7.8	8.1	8.2	8.3	8.4	8.4	8.5	8.5	8.6
48 HOURS	6.1	6.7	7.0	7.2	7.3	7.3	7.4	7.4	7.5	7.5
72 HOURS	5.5	6.2	6.5	6.6	6.7	6.8	6.8	6.9	6.9	6.9
96 HOURS	5.1	5.7	6.0	6.2	6.3	6.3	6.4	6.4	6.4	6.5
120 HOURS	4.8	5.4	5.7	5.8	5.9	6.0	6.0	6.0	6.1	6.1

Table 7: As in Table 6, but showing the variability that could be expected across New Zealand based on the Regional Climate Modelling results.

DURATION/ARI	2 YR	5 YR	10 YR	20 YR	30 YR	50 YR	100 YR
1 HOUR	9.8 – 17.5	10.6 – 18.1	10.7 – 18.5	10.7 – 18.8	10.7 – 18.9	10.7 – 19.1	10.7 – 19.4
2 HOURS	9.2 – 18.0	9.9 – 18.4	10.0 – 18.7	10.1 – 19.0	10.1 – 19.1	10.1 – 19.3	10.1 – 19.6
6 HOURS	7.5 – 14.9	8.0 – 15.4	8.3 – 15.9	8.4 – 16.4	8.5 – 16.6	8.5 – 17.0	8.5 – 17.4
12 HOURS	5.7 – 13.5	6.5 – 13.9	6.8 – 14.2	7.1 – 14.5	7.2 – 14.8	7.3 – 15.1	7.3 – 15.4
24 HOURS	4.0 – 11.9	4.6 – 12.0	4.8 – 12.1	4.9 – 12.2	5.0 – 12.3	5.1 – 12.5	5.2 – 12.8
48 HOURS	2.6 – 11.0	3.1 – 11.1	3.3 – 11.2	3.4 – 11.3	3.4 – 11.3	3.4 – 11.4	3.5 – 11.5
72 HOURS	2.1 – 10.5	2.6 – 10.6	2.7 – 10.8	2.8 – 10.9	2.9 – 11.0	2.9 – 11.1	2.9 – 11.2
96 HOURS	1.7 – 10.0	2.2 – 10.2	2.4 – 10.5	2.5 – 10.7	2.6 – 10.9	2.6 – 11.0	2.7 – 11.2
120 HOURS	1.3 – 9.6	1.9 – 9.7	2.1 – 10.0	2.3 – 10.2	2.3 – 10.4	2.4 – 10.5	2.4 – 10.7

Figure 1 – Tables 6 and 7 from Carey-Smith et al (2018) showing the augmentation factors and uncertainty ranges for projected changes in rainfall depth in response to a 1°C warming.

While it was not stated, the results presented in the report also show some areas may have lower increases than others. A table of estimated uncertainties was included in the report (Table 7) and is included in Figure 1.

It is evident that HIRDS projects larger percentage changes to rainfall depth for short duration rainfall events, than for long duration rainfall events. Table 6 also indicates an increase in rainfall depth for all extreme rainfall events, even though the RCMs projected decreased rainfall depth in some regions.

Short duration events involving extreme rainfall depths are usually associated with intense small-scale convective features such as thunderstorms and mesoscale storms (mesoscale or weather bomb). These have a localised effect limited to a few catchments.

Different future climate change scenarios can influence the projected rainfall depth through the choice of temperature change used to scaling the augmentation factors. However, Carey-Smith et al (2018) include the following caveat about the use of Table 6 for projecting future rainfall depths:

“It is important that the temperature data used to estimate future augmentation factors be from the same source as that used to model the changes in extreme precipitation observed in the RCM simulations”.

This means the six CIMP5 GCMs that were downscaled for the RCMs used to derive the augmentation factors should be used to project temperature changes. Table 8 from Carey-Smith et al is provided (shown in Figure 2 below) to indicate what temperatures should be used for corresponding IPCC scenarios. According to the Methodology report (Table 16, page 13 – Figure 3 below), AWA did not use the values specified in Table 8.

Table 8: New Zealand land-average temperature increase relative to 1986—2005 for four future emissions scenarios. The three 21st century projections result from the average of six RCM model simulations (driven by different global climate models). The early 22nd century projections are based only on the subset of models that were available and so should be used with caution.

	2031—2050	2056—2075	2081—2100	2101—2120
RCP 2.6	0.59	0.67	0.59	0.59 (4 model avg)
RCP 4.5	0.74	1.05	1.21	1.44 (5 model avg)
RCP 6.0	0.68	1.16	1.63	2.31 (CESM1-CAM5 only)
RCP 8.5	0.85	1.65	2.58	3.13 (3 model avg)

Figure 2 – Table 8 from Carey-Smith et al (2018) summarizing the projected temperature changes that should be used for HIRDS V4 to project future rainfall depths. Note the caveat for the 2101-2120 projected temperatures

Table 16. Projected temperature changes based on statistical downscaling for NZ context (MfE, 2018)

AREA	SOURCE	CLIMATE CHANGE SCENARIO	SUMMER (°C)	AUTUMN (°C)	WINTER (°C)	SPRING (°C)	ANNUAL (°C)
Wellington in 2030	Awa extrapolation	Base					0.4
Wellington in 2100	MfE 2018	RCP 8.5	3.1	3.1	3.2	2.7	3.0
Wellington in 2120	MfE 2018	RCP 8.5	4.0	3.9	3.7	3.3	3.7
Wellington in 2130	Awa extrapolation	RCP 8.5M					3.7
Wellington in 2130	Awa sensitivity analysis	RCP8.5H+					4.0

Figure 3 – Table 16 from the AWA Methodology report. Note that the temperature changes used differ from those specified by Carey-Smith et al (2018).

It would be more useful for KCDC to use the frequency-depth-duration curves determined from the measurements at the stations listed in Table 1 and use these to identify a plausible sequence of rainfall depths as input into TUFLOW. Given that the depths are derived from a probability distribution, they will have known exceedance probabilities. If deemed necessary, then the potential effects of climate change can be applied by scaling the probability distributions. The scale factors can incorporate all significant drivers affecting the rainfall intensity and depth, and do not have to be restricted to temperature.

Rainfall response to increasing temperature

It is assumed by HIRDS and the RCMs that rainfall depths will increase with increasing temperature as indicated by the Clausius-Claperyon relationship, which is simplified to a 7% increase in maximum possible atmospheric water content with a 1°C rise in temperature^{7,8}. Strictly, the relationship determines the maximum vapour pressure produced by the evaporation of water at a given fluid temperature (may be referred to as the saturation vapour pressure). However, evaporation is not solely a function of air temperature (strictly the fluid temperature), and amount of precipitation is dependent on the absolute humidity (mass of water vapour per unit volume of moist air, or mass of water vapour per unit mass of dry air), which is related to the relative humidity. The relative humidity is the ratio of

⁷ Douville, H., Qasmi, S., Ribes, A., & Bock, O. (2022). Global warming at near-constant tropospheric relative humidity is supported by observations. *Communications Earth & Environment*, 3(1), 237.

⁸ Adam, D. (2023). What a 190-year-old equation says about rainstorms in a changing climate. *Proceedings of the National Academy of Sciences*, 120(14), e2304077120.

actual vapour pressure to saturation vapour pressure and hence can be converted to the absolute humidity.

Relative humidity for New Zealand is typically less than 100% (but can exceed 100% (super saturation) in some situations. Stats NZ (Tatauranga Aotearoa) maintain a series of climate and weather indicators, including monthly mean daily rainfall and extreme rainfall⁹. NIWA also provide climate data summaries including mean monthly temperatures and relative humidity¹⁰. Global climate indicator data, including for New Zealand, are also available from GlobalDataLab¹¹. Data for all available climate/weather indicators from the 30 stations used by Stats NZ were downloaded, and Figure 4 plots the mean relative humidity at 9 am against the mean monthly air temperature.

As can be seen from the trend line in Figure 4, there is a statistical trend of increasing relative humidity with increasing temperature. However, the rate is $\sim 0.2\%$ per degree, and the trend line is not statistically significant ($r^2 \approx 0$). Looking at the indicator sites used, the highest average relative humidity occurs at Milford Sound, and the lowest occurs at Lake Tekapo (which is lower than Scott Base in Antarctica with an average monthly air temperature of -19.4°C). The pattern in Figure 4 is predominantly a function of orographic effects (orographic lift increases relative humidity, and vice versa for descending air masses), and proximity to a water source.

Figure 5 shows time series of the overall annual mean relative humidity for New Zealand, and for Wellington, between 1990 and 2020. There is no statistically significant trend over this time, although the magnitude of the interannual variability appears to be increasing. The variation in relative humidity appears to track the Southern Oscillation Index, that changes in ocean and atmospheric circulation affect relative humidity for New Zealand.

These data suggest that relative humidity and rainfall for Kāpiti Coast District are not responding significantly increasing air temperature (much less than the 7% per $^\circ\text{C}$ assumed due to climate change), but is responding to fluctuations in sea surface temperature (which is reasonable as strictly the Clausius-Claperyon relationship is based on the fluid temperature and not the gas temperature), and possibly the wind stress over the Tasman Sea (which affects evaporation rates). Carey-Smith et al (2018) also noted that the six RCMs used to develop HIRDS were forced by sea surface temperature (Section 4.1, page 35).

⁹ <https://www.stats.govt.nz/indicators/extreme-rainfall/>

¹⁰ <https://niwa.co.nz/climate-and-weather/climate-data-and-activities>

¹¹ <https://globaldatalab.org/>

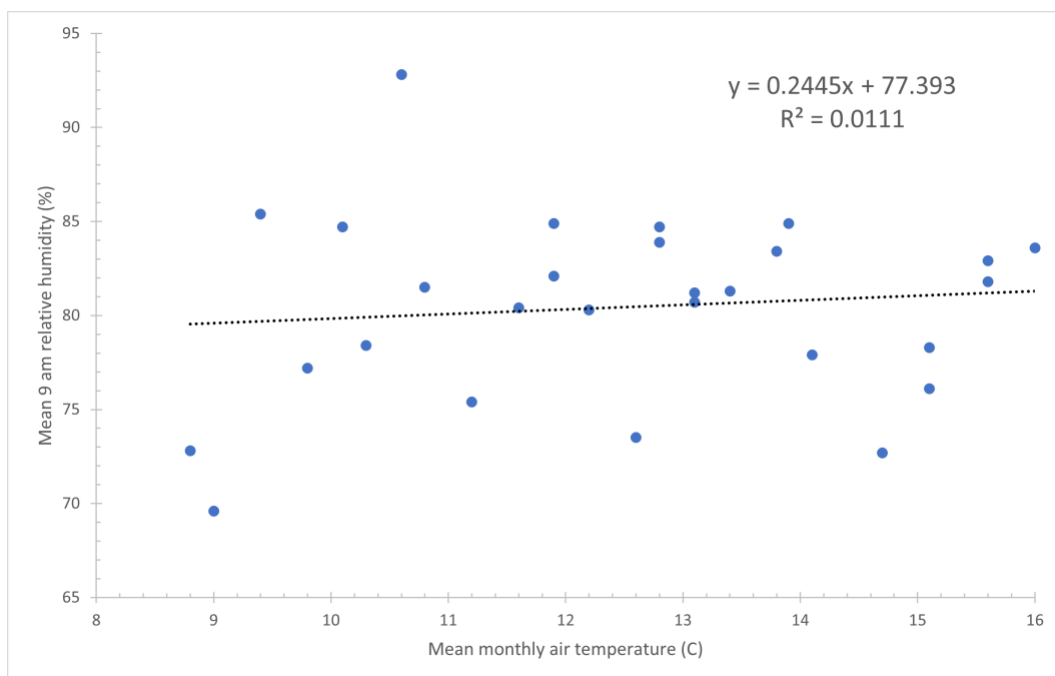


Figure 4 – Mean 9 am relative humidity (%) versus mean monthly air temperature (°C) for the 30 indicator sites used by Stats NZ to monitor climate change. Data from Stats NZ and NIWA.

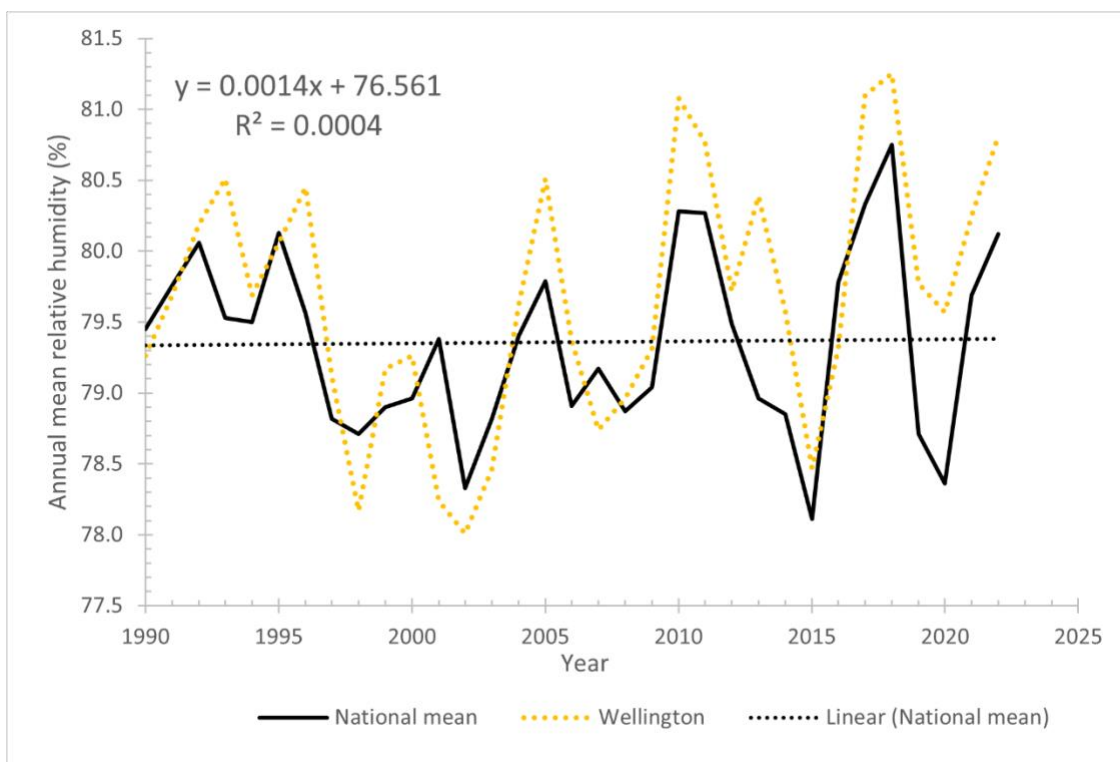


Figure 5 – Annual mean relative humidity (%) for 1990 to 2020 for New Zealand overall, and Wellington. Data from GlobalDataLab.

However, although there do not appear to be trends in relative humidity, it is worth considering studies that have specifically looked for trends in rainfall for the Greater Wellington Region. Woolley et al (2020)¹² provide an analysis of historical data for extreme winds, rainfall, MSL pressure, and dew point temperature. Chappell (2014)¹³ provides a summary of the weather and climate of the Wellington Region that updates earlier summaries but doesn't assess long-term trends.

Some trends have been determined by StatsNZ and are available on their website¹⁴, which includes trends for extreme rainfall defined as the maximum daily rainfall, and wet days where the rainfall exceeds the 95% percentile of the daily rainfall distribution. The trends are analysed for 30 stations across New Zealand, which includes Wellington, but no locations within the Kāpiti Coast District. For the period 2013-2022, Wellington had an average daily maximum rainfall of 67.6 mm and on average 25.4% of the annual rainfall occurred on very wet days. Wellington showed no trend in extreme rainfall over the period 1960-2022).

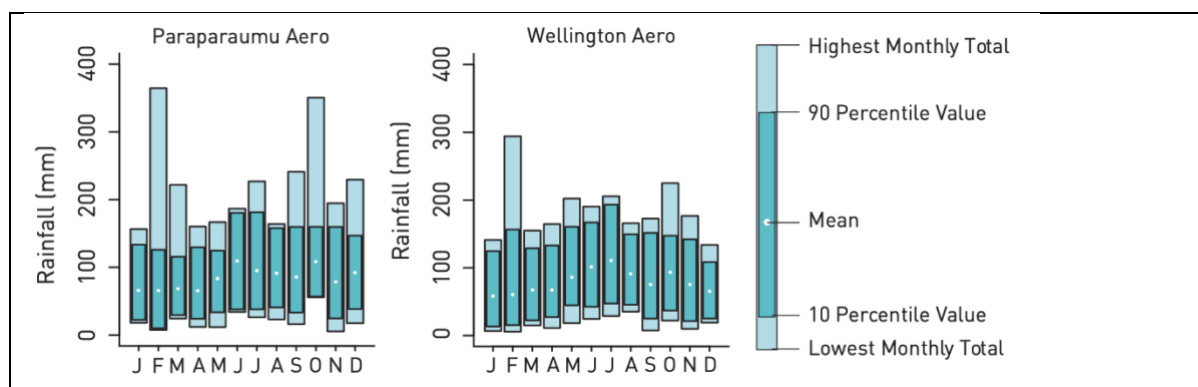


Figure 6. Monthly variation in rainfall for Kāpiti Coast (Paraparaumu Aero) and Wellington (Wellington Aero) for the period 1981-2010. (part of Figure 11, Chappell (2014)).

Chappell (2014) showed that there are spatial differences in rainfall for the Greater Wellington Region. Unfortunately, Chappell (2014) uses different definitions for extreme rainfall and so the data they present cannot be readily compared to the StatsNZ results. Figure 6 compares the distribution of monthly total rainfall between Paraparaumu and Wellington Airports. The data suggest that Paraparaumu is more affected by atmospheric river events than Wellington (Prince et al, 2021¹⁵; Reid

¹² Woolley, J.-M., Turner, R., Rampal, N., Carey-Smith, T., Yang, E., & Pearce, P. (2020). Historic climate extremes analysis for the Wellington Region. Report prepared for Greater Wellington Regional Council, NIWA Client Report 2020089AK. 77 pp.

¹³ Chappell, P. R. (2014). The climate and weather of Wellington, 2nd Edition. NIWA Science and Technology Series, Number 65. NIWA, Wellington: 39 pp.

¹⁴ <https://www.stats.govt.nz/information-releases/new-zealands-environmental-reporting-series-our-atmosphere-and-climate-2023/>

¹⁵ Prince, H. D., Cullen, N. J., Gibson, P. B., Conway, J., & Kingston, D. G. (2021). A Climatology of Atmospheric Rivers in New Zealand. *Journal of Climate*, 34(11), 4383-4402

et al, 2021¹⁶), resulting in episodic intense rainfall events during the tropical cyclone season from September to April. Pearce et al (2017¹⁷) include the summary information from Chappell (2014) and provide some analysis of long-term trends. Overall, their results indicate that there has been no significant change in extreme rainfall for the Greater Wellington Region since the 1920s associated with climate change.

Woolley et al (2020) undertook an analysis of historic rainfall for composite rainfall records at Kelburn, Wellington Airport, Paraparaumu Airport and Masterton using different criteria specified by the Greater Wellington Regional. The analysis was undertaken by the High Intensity Rainfall Design System (HIRDS) and should be constrained by observations for sites used to derive the HIRDS rainfall distributions. However due to the different criteria and the adjustments made to observations by the HIRDS analysis, the Woolley et al (2020) results should be viewed with caution.

From Woolley et al (2020) Kelburn had the longest record covering the decades from the 1870s to the 2010s, while Paraparaumu's record started in the 1950s. Paraparaumu recorded the highest average annual number of rain events exceeding 5 mm within 10 minutes. Kelburn recorded the highest average number of events for all other criteria. Paraparaumu ranked second for intensities from 10mm/30min to 50mm/12hour, third for 60mm/day, and fourth for all higher thresholds. All four stations displayed large interdecadal variations that made identifying any trends difficult. The only possible trends recognised were for short duration intensities (10-60 minutes) at Kelburn. Looking at the metadata available on NIWA's climate database for the Kelburn rainfall data suggests that the apparent trend may be due to changes to instrumentation and the data collected (Sub-daily measurements started in 1940). In particular, the observations show a large step change around the 1980s that produces the apparent trend.

Other studies (Salinger & Griffiths, 2001¹⁸; Griffiths, 2007¹⁹, 2013²⁰; Griffiths et al, 2014²¹) have not found any consistent trend between historic extreme rainfall and temperature for New Zealand. Griffiths (2007) specifically compared the warmer 1950-2004 period to colder earlier data, and found small changes linked to variations in the frequency of westerly winds but not air temperature. These variations in wind patterns are associated with ENSO, SAM and PDO (Griffiths, 2011). Harrington &

¹⁶ Reid, K. J., Rosier, S. M., Harrington, L. J., King, A. D., & Lane, T. P. (2021). Extreme rainfall in New Zealand and its association with Atmospheric Rivers. *Environmental Research Letters*, 16(4), 044012

¹⁷ Pearce, P., Fedaeff, N., Mullan, B., Sood, A., Bell, R., Tait, A., Collins, D., & Zammit, C. (2017). Climate change and variability - Wellington Region, Report prepared for Greater Wellington Regional Council. NIWA Client Report 2017066AK, NIWA, Auckland. 192 pp

¹⁸ Salinger, M., & Griffiths, G. (2001). Trends in New Zealand daily temperature and rainfall extremes. *International Journal of Climatology: A Journal of the Royal Meteorological Society*, 21(12), 1437-1452.

¹⁹ Griffiths, G. M. (2007). Changes in New Zealand daily rainfall extremes 1930 - 2004. *Weather and Climate*, 27, 3-44.

²⁰ Griffiths, G. (2011). Drivers of extreme daily rainfalls in New Zealand. *Weather and Climate*, 31, 24-49.

²¹ Griffiths, G. (2013). New Zealand six main centre extreme rainfall trends 1962-2011. *Weather and Climate*, 33, 76-88.

Renwick (2014²²) found similar small changes when comparing 1950-1979 to 1980-2009. There is also a strong correlation between mean annual rainfall and the frequency/magnitude of extreme rainfall events, so an increase in mean rainfall in the future may be associated with a higher frequency/magnitude of extreme rainfall. However, historic mean annual rainfall shows interannual to multi-decadal variations, but no long-term trends.

Considering the projected climate changes to extreme weather that may affect coastal processes for the Kāpiti Coast, Pearce et al (2017), Pearce et al (2019²³) suggested that rare, large extreme events are *likely* to increase in intensity due to more moisture being held in a warmer atmosphere (Clausius-Clapeyron assumption), with up to 25% increase in magnitude for Wellington and the southern coast under RCP8.5 in 2090. However, there was significant variation in the models considered, with most projecting less than $\pm 5\%$ change. Kāpiti Coast District may experience a larger increase in mean rainfall than Wellington in the winter.

Macara et al (2022²⁴) updated the analysis of Pearce et al (2019) for the areas west of the Tararua and Rimutaka Ranges, using the same CMIP5 GCM projections. Downscaling of CMIP5 projections was expected to be completed at some time in 2024 but does not appear to have been published. The 2022 update mostly included 5 more years of observations and didn't cover all of the extreme weather indicators, but did change the projections for heavy rainfall and 1% AEP extreme rainfall based on modelling historic rainfall (HIRDS):

- **Heavy rainfall** - Heavy rainfall events (99th-percentile of daily rainfall totals) are generally projected to become more severe in the future. By 2040, the magnitude of heavy rainfall events is projected to change by -1% to +12% (RCP8.5). By 2090, heavy rainfall event magnitude is projected to increase by 1-12% (RCP2.6) or 2-30% (RCP8.5)
- **Extreme rainfall** – Rare, extreme rainfall events are also expected to increase in both frequency (between two-fold and three-fold increases for various durations) and magnitude (up to 40% increase) based on the Clausius-Clapeyron assumption.

Overall, the projections of Pearce et al (2017) and Macara et al (2022) are consistent with Table 12.12 from the IPCC AR6 WGI report, which shows that projected changes are smaller than the present-day natural variability, although some events under the implausible RCP8.5 scenario may exceed natural variability by 2090. It should also be noted that the model projections are inconsistent with historic

²² Harrington, L., & Renwick, J. (2014). Secular changes in New Zealand rainfall characteristics 1950-2009. *Weather and Climate*, 34, 50-59.

²³ Pearce, P., Fedaeff, N., Mullan, B., Rosier, S., Carey-Smith, T., & Sood, A. (2019). Wellington Region climate change extremes and implications, Report prepared for Greater Wellington Regional Council. NIWA Client Report 2019134AK, NIWA, Auckland. 132 pp

²⁴ Macara, G., Woolley, J.-M., Sood, A., & Stuart, S. (2022). Climate change projections for west of Wellington's Tararua and Remutaka Ranges. Report prepared for Greater Wellington Regional Council, NIWA Client Report 2022069WN. 134 pp

records, which show there are no statistically significant long-term trends associated with climate change for indicators of extreme weather.

Hence, there is no compelling evidence that it is necessary to augment present day observed rainfall frequency-depth-duration distributions for projected climate changes before the 22nd Century as indicated by the IPCC AR6 WG1 report.

Sea level influences on flood hazard

Sea level affects flooding through direct inundation and effective changes to the base levels of the catchments. TUFLOW considers the base level effects.

The AWA approach to tidal effects, sea level changes, and storm surges appears to be the same as that in the Jacob's reports on coastal hazard vulnerability for the Kāpiti Coast. I have commented extensively on the problems with the Jacob's analysis, including the misuse of data and model predictions for areas outside the Kāpiti Coast as being representative of conditions within the coastal area of concern. These defects have been carried over to the AWA modelling, but I will not detail them again here.

AWA appear to have only considered the extreme IPCC scenarios, and the MfE more extreme RCP8.5H+ scenario (based on the 83rd percentile of the RCP8.5 model results). This is justified as a stress test for planning purposes, which is taken as being a worst-case scenario. The problem with the use of RCP8.5 and RCP8.5 H+ is that it is recognised internationally that they are exceptionally unlikely to virtually impossible, and not plausible. While KCDC may consider them to be acceptable for a planning stress test, they are clearly not consistent for the requirement to consider likely hazards for hazard assessment.

Other factors not considered for future flood hazard

Table 29 in the Methodology report summarises the model parameters adjusted during the calibration process AWA undertook for the catchments considered in this review. It identifies that the model results were sensitive to:

- Roughness of stream corridors
- Network improvements
- The topography as defined by the digital terrain model (DTM)

Issues with these aspects were also noted in the BTM review. The Methodology report also discusses issues with components of the models where the input data were problematic, such as groundwater. All the model components were assumed to remain constant for the next 100 years once the models were calibrated, apart from the rainfall depth and the base levels of the catchments. This is not a realistic assumption.

Firstly, it is likely that vertical land movement is likely to occur within the next 100 years due to local or nearby fault displacements during a seismic event, or due to slow-slip earthquake displacements. As demonstrated by the Canterbury and Kaikoura Earthquakes, these displacements can significantly alter the flood hazard. If the future flood hazard modelling is intended as a stress test for planning purposes, then it should include vertical land movement scenarios. This should include liquefaction, which is a recognised hazard in the KCDC district plan.

Secondly it is likely that the stream corridors, drainage network, and topography will be changed by development and redevelopment over the next 100 years (note how much has changed over the previous 100 years). The characteristics of the affected properties are also very likely to changes, which changes vulnerability and risk. There is no feasible way to predict what these changes will be.

Implications and conclusions

Without going into a detailed analysis, it should be obvious that the catchments will change over time in ways that may modify the flood hazard (including increasing and reducing the hazard), and that climate change is not the only driver of changing hazard (it may not be the most important either). These potential changes imply that it not possible to reliably predict the risk associated with future flood hazard very far into the future.

The AWA reports provide projections for 2030, which are essentially the present-day situation with a slight increase in rainfall depth. These projections would be reasonable if they considered likely events. This analysis could have been done with observed data and not included HIRDS projections. To provide more confidence in the projections, quantified validation results should be provided using the HIRDS rainfall depths used for the modelling. Ideally, the HIRDS rainfall depths will also be validated against measured rainfall depth distributions.

The other projections are for 2130, which is too far into the future to reliably estimate any of the input conditions for the models. Certainly, it is not possible to have confidence in the assumed values, as there are either no indications of their likelihood, or the uncertainties are too large.

While KCDC may wish to use the 2130 projections to inform planning for flood hazards, the maps produced do not have meaningful probabilities associated with them and should not be used to indicate flood risk for properties in the Kāpiti Coast District.