The Urban Impacts Toolbox: An example of modelling the effect of climate change and sea level rise on future flooding.

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Abstract

This paper presents good practice methods for flood risk assessment under climate change in urban areas of New Zealand, following techniques selected from the "Impacts of Climate Change on Urban Infrastructure and the Built Environment Toolbox" (see the first paper in this special issue and NIWA, MWH, GNS and BRANZ, 2012). A case study evaluating flood risk in Westport is used to demonstrate the methods. Hence this paper has a dual purpose to explain the modelling methods and to provide a flood risk assessment for Westport under selected climate change scenarios.

We show how physically-based climate, hydrological and hydrodynamic models can be used together to simulate changes in meteorological and hydrological processes under future climates, and evaluate the effect of those changes on projections of flood inundation and risks to people and assets. Using a historic 1-in-50 year event as a baseline, we predicted how the severity of that event would change under each climate scenario. Statistically downscaled projections from Global Climate Models were used to define appropriate adjustments to the historical rainfall and temperature measurements. Using the hydrological model TopNet, this data was used to simulate flood hydrographs at the Te Kuha gauging station upstream of Westport. The resulting hydrographs predicted for the future time period 2080-2099 correspond to events in the current climate with recurrence intervals of 78, 98 and 113 years for the B1, A1B and A2 IPCC SRES scenarios respectively. The flood hydrographs provided upstream boundary conditions for a 2D hydrodynamic model simulating inundation of the Buller floodplain. Predictions for inundated area increase from 50% of Westport town in the current climate to 67%, 70%, and 72% for the B1, A1B and A2 scenarios for the 2080-2099 time period. Resulting maps of inundation depths and velocities allow detailed planning for mitigation of flood events. We used the hazard assessment tool RiskScape to calculate the impact of the flood on people and assets (buildings, contents and vehicles) within the inundated area. The predictions showed that under the A1B 2080-2099 scenario, present day Westport could expect risk to life classified as 'Medium' or greater to 560 people, building damage of $72M and contents damage of $68M.

1 Introduction

Flooding is the most frequent natural hazard in New Zealand (MfE, 2008b), and flood risk cannot be avoided. Under climate change, rainfall events in New Zealand are forecast to become more intense, causing greater storm runoff and a decrease in the protection afforded by measures such as levees (IPCC, 2007). Urban environments are particularly vulnerable to extreme weather and flooding events, as has been found internationally (e.g. Hall et al., 2005). A key finding of the NZ government's recent review of flood risk management was that good information on the nature of the flood hazard was crucial to management of the flood risk (MfE, 2008b).

This is backed up by Regional Council RS&T Strategy documents which state that more research is needed for 'development and implementation of updated techniques for modelling and mapping to determine the economic risk of river flood hazards that are applied consistently regionally and nationally' (Regional Council Science Advisory Group, 2011b) and 'to provide a more robust and defensible position to address hazard risk more effectively, and to give decision makers confidence' (Regional Council Science Advisory Group, 2011a). Therefore the aim of this paper is to demonstrate a good practice method for science-based flood risk assessment, following the methods outlined in the "Impacts of Climate Change on Urban Infrastructure and the Built Environment Toolbox" (NIWA et al., 2011) and introduced in Tait et al. (2012; this issue). The results of such a process are designed to help city, district, regional and central government identify opportunities and reduce the impacts of flooding under climate change.

The location chosen for this study was Westport, which is particularly vulnerable to flooding because it is on the flood plain between the Buller River and the Orowaiti Estuary, an old channel of the Buller River that carries a substantial flow during large floods. Westport is vulnerable to inundation from a combination of river floods and high sea levels. It is therefore important to understand whether climate change could lead to any further increase in flood risk for Westport. This research builds on previous work for the Buller, including initial work commissioned in 2003 by the Buller District Council to quantify the extent of Westport's flood hazard and the MfE (2005) report examining the effects of simulated climate change. Since then, the climate change guidance, hydrodynamic model and recommended flood risk assessment method have all been updated, leading to the need for a revision of flood risk guidance.

The approach used in this study is to use a baseline rainfall scenario, adjusted for predicted climate change impacts on precipitation, as input to a hydrological model coupled to an inundation model and a risk and impact assessment tool. The use of a hydrological model to transform rainfall predictions to runoff predictions for flood risk assessment is a well-established method (e.g. Cameron, 2006; Cameron et al., 2000). It is important to extend the method to include 2D hydrodynamic modelling and mapping of flood inundation, to determine the spatial extent of flood risk and to promote objectives such as the use of soft engineering solutions (e.g. floodplain restoration) and community awareness. Hence, coupled hydrological and hydrodynamic modelling is becoming more common (Anselmo et al., 1996; Hsieh et al., 2006; McMillan and Brasington, 2008; Pappenberger et al., 2005). Introduction of the results into a GIS framework may ease the uptake and interpretation of spatially-explicit findings (Meyer et al., 2009; Thumerer et al., 2000).

The further addition of a module for vulnerability and damage assessment can be used to calculate the social and economic impacts of floods, for example using information on building use or value (Apel et al., 2004; Merz et al., 2004). Urban-specific criteria may include population and vulnerable groups, differentiated residential land use classes, areas with social and health care needs and ecological indicators such as recreational urban green spaces (Kubal et al., 2009), and can also allow for 'intangible' damages such as disruption (e.g. ten Veldhuis and Clemens, 2010). In this case the NZ-specific "Risk-Scape" tool is used (Schmidt et al., 2011).

The remainder of this paper is structured as follows. The IPCC climate scenarios used in the study are summarised, with a description of the Global Climate Models and downscaling techniques used to determine the local effects on the NZ climate. The case study location (Westport and Buller River) is introduced. An overview of the modelling method is then given, before each step in the modelling process is described in detail alongside the corresponding results. These steps include the rainfall scenario; hydrological model development, calibration and application; hydrodynamic modelling; and vulnerability and damage assessment. The paper concludes with a summary of assumptions and uncertainties in the modelling process, and a discussion of possible alternative model choices.

2 Climate Scenarios

A range of climate scenarios are used in the flood risk assessments in this paper. Climate scenarios describe different world futures, including assumptions about technological and economic development, globalisation, population growth and land use, to determine future greenhouse gas emissions. Four emissions families were described in the Special Report on Emissions Scenarios (SRES; Nakićenović and Swart, 2000), and these are summarised in Table 1. While Table 1 classifies the emissions scenarios between ‘Low’ and ‘High’, it is worth noting that recent research suggests that global emissions since 2000 track most closely along the high A1FI scenario, although the period is too short to constrain any long term trends in emissions because of significant inter-annual variability (Sanderson et al., 2011).

To understand how New Zealand precipitation patterns and depths will evolve under the climate change scenarios, Global Climate Models (GCMs) are used to simulate the behaviour of the global atmosphere and oceans. From the 17 GCMs that were initially analysed, 12 were found to be significantly more accurate in predicting New Zealand climate based on tests using historical data, and hence are used here (Mullan and Dean, 2009). The GCM projections must be downscaled to reproduce orographic effects and other local-scale rainfall patterns. Statistical downscaling is the most common method, as it is computationally inexpensive, and can therefore be used relatively easily for ensemble simulations (MfE, 2008a). It consists of the formulation of regression equations to link GCM predictions to local observations of precipitation and temperature. The method which has been used in New Zealand is described in more detail in the Climate Change Effects and Impacts Assessment Guidance Manual (MfE, 2008a), also Mullan et al. (2001). With this method, rainfall and temperature changes relative to the current climate are obtained on a monthly timescale and a 5 km spatial scale (MfE, 2010). Possible alternative downscaling methods exist and are discussed in Section 7, however statistical downscaling is currently considered the most robust method for New Zealand studies.

Emissions Scenario	Description	Summary
A1	Rapid economic growth, global population that peaks mid-century, rapid introduction of new and more efficient technologies	
A1FI	Fossil intensive energy sources	**High**
A1B	Balance of fossil / non-fossil energy sources	**Medium**
A2	Global population increases continuously, economic and technological development is regionally oriented	**Medium-High**
B1	An integrated world with global solutions to economic, social and environmental stability.	**Low**
B2	A world that emphasises local solutions to economic, social and environmental sustainability	**Low-Medium**

Table 1: Summary descriptions of the SRES emissions scenarios used in this study

3 Case-study Catchment

The Buller River catchment (Figure 1) has a catchment area of 6350 km^2 and a mean flow of 454 m^3s^{-1} at the gauging station located at Te Kuha, a few kilometres upstream of the Buller flood plain where Westport is located. The sources of the Buller River are Lakes Rotoiti and Rotorua and rivers draining the Southern Alps. However, the main source of floods are the tributaries immediately upstream of Te Kuha that drain the rugged Paparoa and McWilliams Ranges as they intercept moisture-laden winds crossing the Tasman Sea. The Buller River at Te Kuha has the largest estimated flood peak in New Zealand of 12,700 m^3s^{-1} in 1926.

4 Method Overview

An overview of the method used in this study is as follows:

(1) A historical flood event (approximately 1-in-50 year) was chosen as the baseline flood scenario. Rainfall and temperature data relating to this event were extracted from NIWA's Virtual Climate Station Network (VCSN).

(2) Monthly adjustments to the historic rainfall and temperature data were calculated for each climate change scenario from statistically downscaled GCM projections.

(3) A hydrological model was developed and calibrated for the Buller using the Topnet model (Clark et al., 2008).

(4) The future rainfall/temperature data were used as input to the Buller hydrological model to produce a simulated flood hydrograph for each climate change scenario.

(5) These flood hydrographs, in combination with projections of sea level rise, were provided as input for a 2D hydrodynamic model used to estimate flood inundation.

(6) Damage estimates to buildings associated with the projected inundation levels were estimated using the tool 'RiskScape' (Schmidt et al., 2011; www.riskscape.org.nz).

Each of these steps will now be explained in detail, with the results given at each stage.

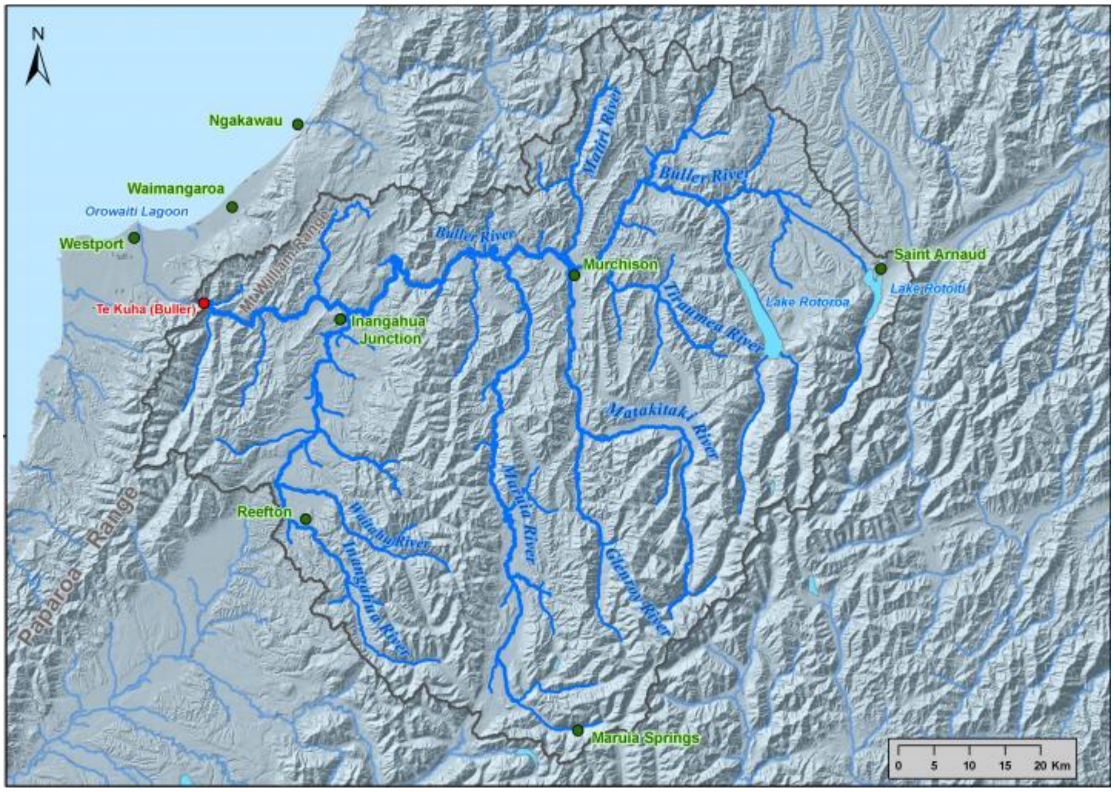


Figure 1: Map of the Buller Catchment showing locations of Westport and flow gauging station at Te Kuha.

5 Results

5.1 Rainfall and temperature data from historical flood event

A historical flood event was chosen to represent the type of extreme flood event of interest for the Buller catchment. The flood occurred on 31 August 1970 when the peak flow at Te Kuha was measured at 8480 m^3s^{-1}. Rainfall and temperature data for this event were extracted from the VCSN. These data are interpolated from climate station records onto a 0.05° lat/long (~5x5 km) grid over the whole of New Zealand (Tait et al., 2006). Daily values of rainfall and minimum and maximum temperature from all the VCSN grid points within the Buller catchment were used. A bias correction was applied to the rainfall grid based on a previous study which compared total volumes of rainfall and river flow on a multi-year basis, and gave percentage corrections required to the VCSN rainfall data required to ensure water balance was maintained in the catchment (Woods et al., 2006). Finally, the daily rainfall values were disaggregated from daily to hourly time steps using hourly data from the Greymouth Airport climate station to distribute the rainfall within each 24-hour period.

5.2 Rainfall and temperature data for Climate Change Scenarios

In this study, 3 emissions scenarios and 2 different time periods were chosen to cover a wide range of possible futures. The emissions scenarios used were B1, A1B and A2 (see Table 1), and the time periods were 2030-2049 (referred to as 2040) and 2080-2099 (referred to as 2090). Monthly rainfall and temperature adjustments to be applied to the historical data were available from statistically-downscaled GCM projections. Hence these adjustments were used to produce projected hourly and temperature data for each future scenario.

In this study a 'best-case scenario' estimate of future flood risk was required, in the light of large projected monthly rainfall changes. Hence two variations were made to the usual procedure for adjustment of daily rainfall data outlined in (MfE, 2010). Firstly, there was no change made to the number of rain days in the record and no increase in the most extreme rainfall volumes, which are usually done to simulate changes in extremes suggested by dynamic downscaling results from NIWA's Regional Climate Model. Secondly, the monthly rainfall changes for 2040 and 2090 were smoothed using six-month averaging. Two averaging periods were chosen: June–November and December–May. Each month within the two periods was assigned the corresponding six-month average temperature and rainfall changes. Due to these variations of the standard method, the results must be considered as low estimates of the future flood risk.

5.3 Hydrological model development and calibration

Model Description

The hydrological model used in this study is NIWA's TopNet model. This model is a semi-distributed rainfall-runoff model with explicit spatial representation of the Buller catchment according to subcatchment boundaries. Subcatchments are defined based on Strahler order; the model resolution used here was at Strahler order 3. Within each subcatchment, the model simulates the waterbalance using TopModel concepts (Beven and Kirkby, 1979) to simulate expansion and contraction of saturated areas contributing to surface runoff. Once runoff reaches the stream network, it is routed to the basin outlet using a one-dimensional Lagrangian kinematic wave routing scheme. TopNet is widely used in hydrological applications in New Zealand (e.g. McMillan and Clark, 2009; Poyck et al., 2011; Woods et al., 2009) and a detailed description of the model equations can be found in Clark et al. (2008).

Model Calibration

TopNet requires a range of model parameters to describe the physical characteristics of each subcatchment, such as soil hydraulic conductivity, infiltration capacity and overland flow velocity. Initial estimates for the parameters are made for each subcatchment based on the New Zealand River Environment Classification (Snelder and Biggs, 2002), the New Zealand Land Resource Inventory and the New Zealand Land Cover Database (Newsome et al., 2000). During the calibration process, the model parameters are adjusted to optimise the model's ability to simulate observed streamflow records. To reduce the dimensionality of the parameter estimation problem, the spatial pattern of the parameter values is preserved, but the values are adjusted uniformly using a spatially constant set of parameter multipliers.

In this case, calibration was performed by running the Topnet model for the hydrological year 1998 - 1999 for ten thousand different parameter multiplier sets, sampled across the parameter space. Model input data (rainfall and temperature records) were extracted from the VCSN as previously described. We selected the fifty best-performing sets, i.e. those that produced the highest Nash Sutcliffe Efficiency (NSE; Nash and Sutcliffe, 1970) when compared against observed streamflow at Te Kuha. TopNet was then run fifty times for a longer period 1990 - 2007 with those selected parameter sets and the optimal set was chosen based on visual comparison between modelled and observed streamflow as well as NSE (the chosen parameter set had NSE of 0.788 which was the highest score among all the parameter sets). As a final step, these optimised parameter values were tested using a model run for the 31 August 1970 flood event. Two adjustments were made to ensure the best fit for (a) timing and (b) magnitude of the flood peak.

a) As with the calibration procedure described in the previous paragraph, hourly rainfall data from the climate station at Greymouth Airport were used to disaggregate the VCSN rainfall from daily to hourly time intervals, however uncertainty arises since this timing may not hold throughout the catchment. In this case, a three hour delay in rainfall patterns was found to optimise timing of the flood peak.

b) The value for overland flow velocity was decreased (from 0.057 to 0.050 ms^{-1}) in order to optimise the simulated peak flood discharge.

We note here that by optimising the model calibration for the 1970 flood, we assume that the 1970 rainfall-runoff relationship will hold under future scenarios. Refer to Section 6 for discussion and justification of this and other hydrological model assumptions.

5.4 Estimation of future flood flows

The current and projected future rainfall and temperature data for the flood event were used to drive the calibrated TopNet model. Table 2 shows the peak 24-hour (9am-9am) rainfalls and the resultant peak flow, Annual Exceedance Probability (AEP) and Average Recurrence Interval (ARI) for each scenario. The simulated hydrographs for Te Kuha are shown in Figure 2.

5.5 Inundation Modelling

This study used a pre-existing calibrated 2D hydrodynamic model (Hydro2de; Beffa and Connell, 2001) for the Westport area. The model was revised in 2009 after a LiDAR survey facilitated the compilation of a more accurate digital elevation model (DEM). The use of 2D models is a resource hungry exercise, both for its data requirements and the expertise and computing power required to carry out the modelling. It is more appropriate where there are extensive assets to protect or a high probability of loss of life from flooding. Such models provide a strong advantage for flood risk mapping in complex urban areas where they are capable of providing a dynamic representation of water transport onto and around the floodplain. There are, however, many sources of uncertainty related to such 2D models; these are reviewed in Section 6. The data requirements for the model are as follows.

Climate Scenario	**Period**	**Peak rainfall (mm/day)**	**Peak flow (m^3s^{-1})**	**AEP for current climate**	**ARI (years) for current climate**
Base	Current	350	8500	0.0213	47
B1	2030-2049	362	8805	0.0152	66
A1B	2030-2049	368	8977	0.0132	76
A2	2030-2049	370	9083	0.0122	82
B1	2080-2099	371	9017	0.0128	78
A1B	2080-2099	381	9319	0.0102	98
A2	2080-2099	387	9512	0.0088	113

Table 2: Projected changes to the peak flood flow in the Buller catchment for each future scenario.

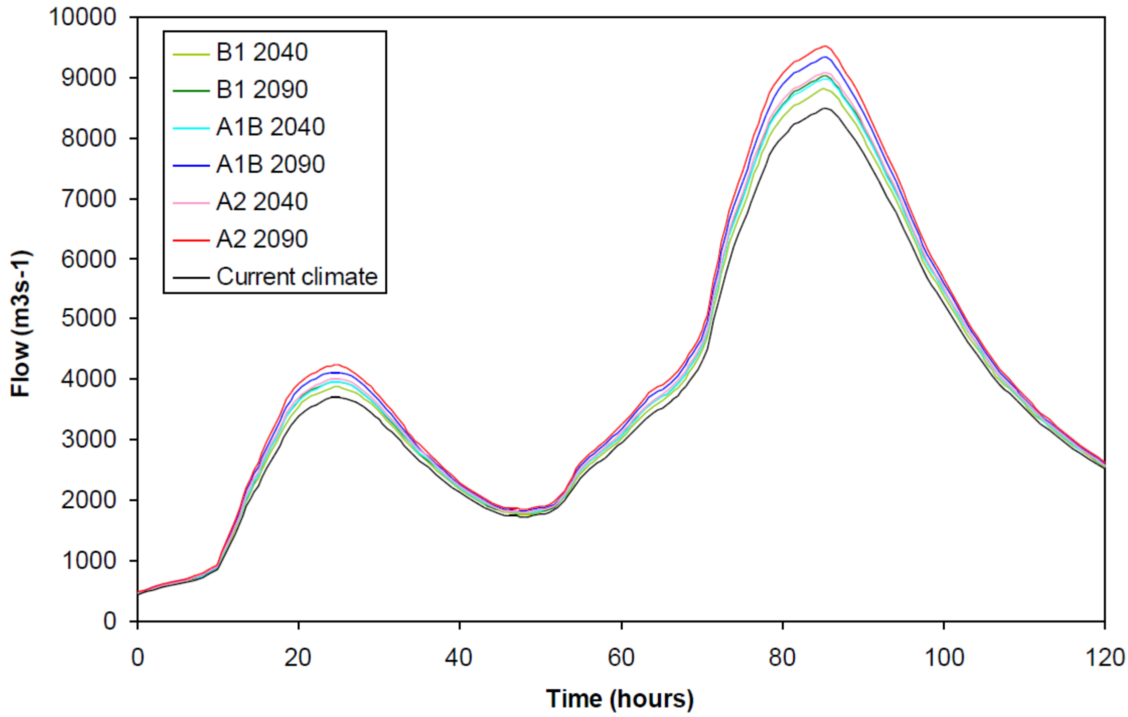


Figure 2: Modelled hydrographs at Te Kuha for the current climate and two future periods (2040 and 2090) for three different emissions scenarios (Low Scenario B1, Mid scenario A1B and High scenario A2).

Digital elevation model (DEM)
The Westport DEM covers the whole of the Buller River flood plain and is bounded by hills to the south, terraces to the east and west and by the sea to the north. The DEM was derived from airborne LiDAR which cannot detect underwater areas, and therefore bathymetry of wet areas such as rivers, lakes,

swamps and ocean was added. The original topographic data was resampled to provide mean elevation for the required size of computational cell, taking care to ensure that critical levels such as the top of the stopbanks or the bottom of narrow channels were preserved. The DEM cell size is 4.7 m square. Undertaking inundation modelling at very high resolution enables flow to be represented at the scale of individual buildings, and hence a correspondingly detailed exposure analysis (Ernst et al., 2010).

Hydraulic roughness
Hydrodynamic models require a roughness value for each computational cell. Roughness values for the Buller floodplain were obtained from calibrated remote sensing data.

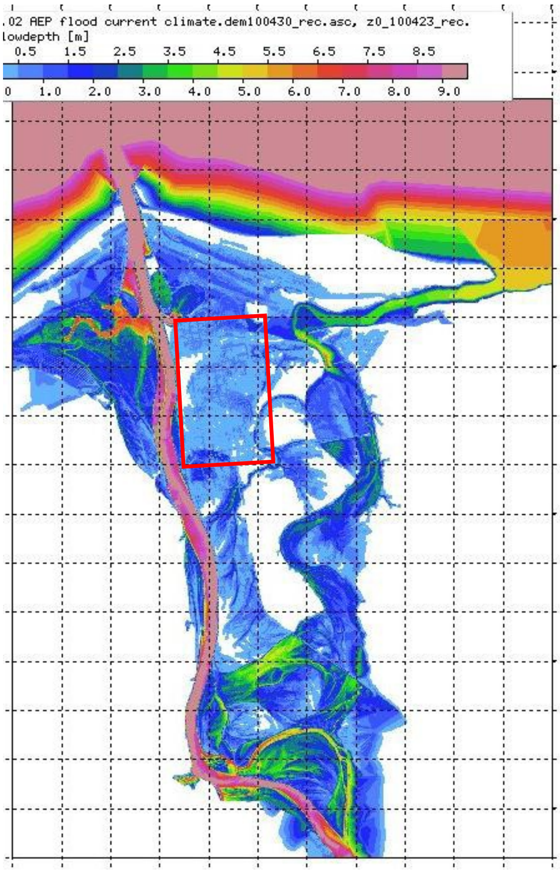
Bridges and culverts
Highway and railway bridges were incorporated into the hydrodynamic model where they could affect flood flows. The model requires the location of each side of the ends of bridges and bridge soffit levels. For culverts it requires the levels and location of the ends of the culvert, its diameter or width and height.

Model verification and calibration
Hydrodynamic models require verification against observed flood events and possible re-calibration. Corrections are achieved by changing hydraulic roughness values or digitally altering the DEM to ensure that it correctly represents the true topography during a flood. The Buller case was calibrated using water levels measured in the town during the August 1970 flood.

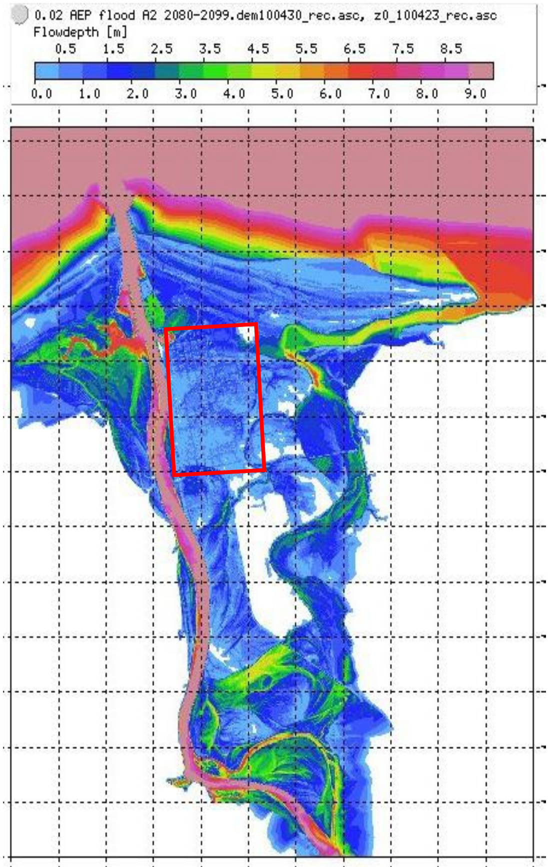
Tide levels
The Buller River at Westport is low-lying and close to the sea, so state of tide and any effect of climate change on sea-level needs to be taken into account. The base tide used for the simulations is the 1.618 m mean high water springs tide (MHWS10), i.e., the tide that is exceeded 10% of the time. The tide value was taken from the NIWA open ocean tide gauge at Charleston ~25 km south west of the Buller River. For the future scenarios, the tide was enhanced by either 0.4 m (the 2030-2049 period) or 0.8 m (the 2080-2099 period), consistent with guidance in MfE (2008). In the simulations, tide and flood peaks were assumed to be coincident. This assumption is consistent with the long, broad flood peaks typical of the Buller, which are therefore likely to include a high tide period. For this study, no account was taken of the effect of storm surge, although previous work has suggested a coincidence of storm surge with river floods in the Buller River in winter (Wild et al., 2004).

Results
The hydrodynamic model produces grid files of water depths, depth averaged velocity, and duration of inundation for each model cell at each time step, and the maximum value during the flood event. The figures below show the maximum values. The extent and depth of inundation on the Buller floodplain is shown for the current climate (base) case and the most extreme climate scenario in Figure 3.

The model results can be used to calculate derived statistics such as the percentage of the Westport urban area which is inundated. The designated urban area is shown in Figure 4 and the values are given in Table 3. The model could be used to explore potential mitigation options by digitally modifying the DEM to add flood banks, deepen or widen channels, or constructing flood bypass channels. The model would then be rerun to demonstrate the effectiveness and residual risk of such protection measures. An example of such adaptation testing in the case of a 1D model for rapid assessment is demonstrated in Keenan and Oldfield (2012; This issue).



3a. The maximum extent of inundation and water depth (in metres shown as a colour scale) of the Buller River flood plain for the current climate with a flood peak of 8500 m^3s^{-1} and coincident tide peak of 1.618 m. The red box shows the approximate location of Westport.



3b. The maximum extent of inundation and water depth (in metres shown as a colour scale) of the Buller River flood plain for the A2 2090 scenario with a flood peak of 9727 m^3s^{-1} and coincident tide peak of 2.418 m. The red box shows the approximate location of Westport.

Figure 3: Inundation simulations for Westport under current and 2090 climate scenarios

5.6 Riskscape: Impacts of Flooding

In the last step of the flood risk assessment process, the Riskscape tool (Schmidt et al., 2011) is used to calculate the impact of the flood on assets situated on the floodplain. Riskscape estimates such as these are intended for use by local authorities and communities as they participate in discussions and decisions on different adaptation options (Refer to discussion in Section 6 of Tait et al., 2012; This issue) While Riskscape is a multi-hazard assessment tool, we focus here on flood hazard only. RiskScape requires input data on hazards, assets and vulnerability, as follows.

Hazards

The Hazard Exposure describes the distribution and severity of the flood hazard in terms of the inundation depth, velocity and duration. While inundation depth is mandatory for estimating the consequences, the damage calculation can be done without velocity and duration. If not provided, flow velocity is assumed to be zero and duration is set to one day; however this would typically underestimate the impacts. If the risk is to be calculated, the recurrence interval for the flood must also be specified.

Climate scenario	**Period**	**Inundation in Westport. % area with depth >0.2 m**
Base	Current	51
B1	2030-2049	60
A1B	2030-2049	63
A2	2030-2049	64
B1	2080-2099	67
A1B	2080-2099	70
A2	2080-2099	72

Table 3: Percentage of the Westport urban area inundated under each climate scenario.

Figure 4: The red line encloses the area defined as Westport for the calculation of inundation.

Assets

Assessing an area's flood exposure requires a good understanding of the elements at risk within the study area. Elements at risk are spatially- and temporally-distributed assets which are valued by human society and under threat to be damaged by hazards (buildings, lifelines, business disruption, economic impacts, etc.) (Schmidt et al., 2011). The knowledge of the distribution of people, the location and function of critical infrastructure and the spatial extent, distribution and types of buildings, are the key to determining their exposure to floods and subsequently the possible impacts (Strunz et al., 2011). Indirect impacts also exist, such as loss of employment or recreation opportunities; refer to the discussion on direct and indirect costs in Keenan and Oldfield (2012; This issue).

Inventories for buildings, building contents, vehicle and people were created for Westport as part of the Urban Impacts Toolbox programme. Building attributes for residential, commercial and industrial building categories were surveyed in Westport and obtained from a combination of government building asset databases (e.g. Quotable Value, Buller District Council). Models were developed to assess building attributes where there were data gaps.

Vulnerability/fragility

The vulnerability description defines the way that an asset will react to exposure to a given hazard. Vulnerability refers to the potential for casualties, destruction, disruption or another form of damage or loss with respect to a particular element/asset. For example, a building's flood vulnerability is determined by its wall material, floor coverage and floor height. We recognise that other, wider definitions of vulnerability in terms of physical and social marginality and susceptibility may be appropriate for some applications or policy decisions. Riskscape primarily uses damage and fragility functions for the damage calculation process.

Damage functions for residential, commercial and industrial building categories are based on international case studies validated and refined using flood impact data collected from post-event field surveys in NZ (i.e. Manawatu, 2004; Lower Hutt 2004; BOP 2005 and Northland 2007). Damage is represented as a ratio of the replacement value of a building. Damage functions assign an average building damage ratio caused by a given flood depth and or velocity. Buildings are categorised based on their use, period of construction, number of storeys and building material and a different damage function is developed for each category.

The human susceptibility rating is adapted from Tapsell et al's (2009) model which combines hazard, exposure and mitigation information to estimate the risk to life. Due to an absence of casualty data from numbers of people exposed to flooding in past NZ events, the model output is also used to estimate the number of casualties experiencing different categories of impact. A probabilistic approach is used as even people with low risk may sometimes be injured. This approach was informed by reported casualty data from historic NZ flood events since 1900 and international case studies citing the relative ratios between deaths and injuries from flood events.

Impact Categories

RiskScape uses five impact categories that produce different measures of loss.

1. Human Losses, a measure of the detrimental effect on humans who are in or at this asset at the time of the asset's exposure to the hazard. Measured in number of people affected.

2. Damage State, a measure giving the extent to which the asset is damaged. Measured using five categories from 'Insignificant' to 'Collapse'.

3. Human Displacement, a measure of the extent to which humans and human activities are displaced by exposure of the asset to the hazard. Measured in number of days people are displaced.

4. Human Susceptibility, a measure of the susceptibility to injury (damage) of a hypothetical human present in or at this asset, based on the census deprivation index.

5. Reinstatement Cost, encompasses all direct costs caused by exposure of the asset to the hazard. Measured in dollars.

During the Riskscape analysis, the damage state was chosen as the impact category. The spatial resolution of the analysis was chosen at the individual building scale (although aggregated areas such as suburbs can also be used). For each climate scenario, Riskscape integrates the Hazards, Assets and Vulnerability information to calculate the damage incurred and show this information as maps. Example results are given in Figures 5 and 6 which demonstrate building damage state and structural repair costs estimated for the A1B climate scenario and 2090 time period.

Riskscape enables quantitative damage estimates to be output in tabular form. We show here examples using the moderate A1B climate scenario for the 2080-2099 time period. Information can be obtained on the absolute costs of building and content damage, percentage damage of the Westport asset base (Table 4), the simulated effects on people including casualties and people at risk (Table 5), and simulated buildings and contents damage by sector (Table 6). For clarity, the figures represent total costs/impacts, not increases over current levels. Corresponding results can be obtained for the other scenarios and time periods (not shown).

6 Model Assumptions and Uncertainty

It is important to realise that when coupling a range of models (such as the climate, hydrological, hydrodynamic and risk models used here), that each link in the chain is subject to assumptions and uncertainty. These component uncertainties propagate through the chain to produce significant uncertainty in both the intermediate results (such as flood

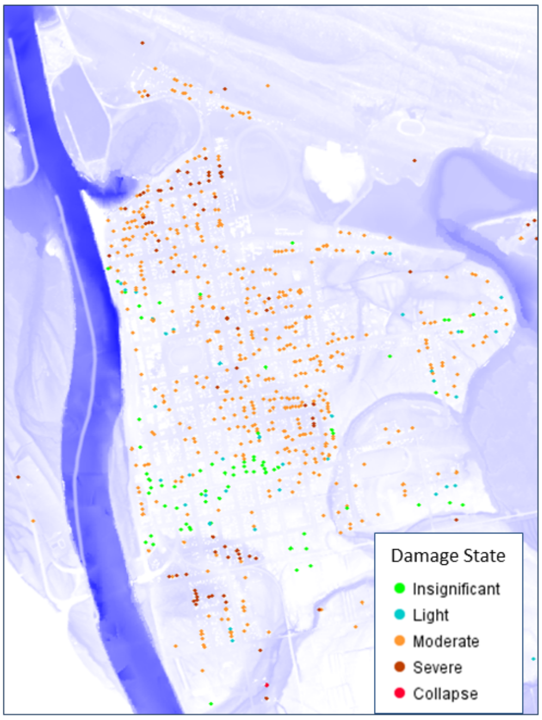


Figure 5: Riskscape screen shot for Westport inundation showing damage state of affected buildings for A1B 2090 scenario

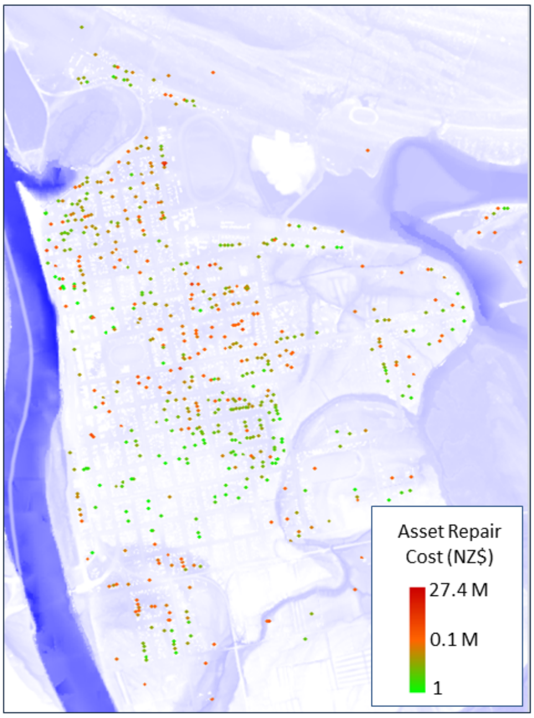


Figure 6: Riskscape screen shot for Westport inundation showing building / structural repair costs of affected buildings for A1B 2090 scenario.

Damaged		Absolute	% of Westport
Buildings damaged		1,216	43.9
$ content damage	$	68,078,427	14
$ content damage <1hr, no escape floor	$	50,306,107	10.3
$ content damage 1-6 hr	$	37,349,636	7.7
$ content damage > 6 hr	$	30,769,972	6.3
Loss of income	$	13,217,815	2.1
$ building damage	$	71,877,147	8.8
Vehicle damage (day)	$	11,297,311	31
Vehicle damage (night)	$	15,702,480	32.7
People in damaged buildings (day)		3,064	44.1
People in damaged buildings (night)		3,429	43.2

Building damage state	
Insignificant	56
Light	245
Moderate	863
Severe	51
Collapse	1

Table 4: Riskscape analysis of building damage in Westport under the A1B 2080-2099 flood event scenario.

	No Warning	Flood warning (mixed response)	Partial evacuation	Full evacuation
Casualties				
0 - No or light injury	2168	2176	2180	2181
1 - Moderate Injury	12	9	7	5
2 - Serious Injury	5	3	1	1
3 - Critical Injury	2	1	0	1
4 - Death	3	1	1	0
Risk to Life				
Low	1629	2000	2007	2185
Medium	378	153	182	4
High	178	36	0	0
Extreme	4	0	0	0

Table 5: Riskscape analysis of effects on people in Westport under the A1B 2080-2099 flood event scenario, for different assumed levels of flood warning.

Residential		
Residential buildings affected		1917
Residential buildings damaged		1101
Average damage ratio		0.237
Average building damage	$	48,731
Average content damage	$	49,513

Commercial, Industrial, agricultural sector		
Businesses affected		194
Average income loss	$	33,111
Businesses damaged		75
Average damage ratio		0.164
Average building damage	$	92,305
Average content damage	$	75,338

Education, health, community and other		
Number affected		78
Average income loss	$	87,106
Number damaged		40
Average damage ratio		0.224
Average building damage	$	282,524
Average content damage	$	197,852

Table 6: Riskscape analysis of building damage by sector in Westport under the A1B 2080-2099 flood event scenario.

peak and inundation extent) and the end result such as projected building damage or effects on people). Therefore, we found it important to state here the assumptions and uncertainties occurring at each stage. In future work it would be beneficial to assess the uncertainty, by using a range of possible model structures or parameters at each stage, enabling a range or distribution of possible flood risks to be determined. This would help to avoid the case where some aspects of uncertain model design, physical catchment characteristics or social futures are treated as fixed and may therefore unduly restrict the possible scenarios considered (Hulme, 2011; Lane et al., 2011). While this type of analysis is possible (e.g. Arheimer et al., 2011; McMillan and Brasington, 2008; Merz and Thieken, 2009), it is extremely computationally demanding as each additional model in the chain increases the dimensionality of the space of possible models.

Climate model assumptions

GCMs are designed to simulate long-term changes to the Earth's climate. The physical processes that result in extreme rainfalls that can lead to flooding are still not modelled well by most GCMs, as many of these processes occur on very small spatial scales. Choices based on expert judgement, such as those described in Section 5.2 to use lower estimates of the effect of climate change on extremes of daily rainfall, will affect (in this case reduce) the final flood flow predictions and must be taken into account during an impact assessment.

Hydrological model assumptions

The modelled future climate scenarios are based on alterations to the total rainfall while maintaining the hourly distribution pattern of the August 1970 flood. Similar daily rainfall totals with different hourly rainfall distributions can result in significantly higher flood peaks and volumes.

The use of a hydrological model relies on the model's ability to represent the physical processes occurring in the catchment. There are always some cases where the model does not exactly reproduce the measured flow, and there is uncertainty in the calibrated model parameters. The future flood simulations also assume that the catchment remains unchanged between the 1970 baseline event and the 2040 and 2090 time periods. If land-use change occurs (e.g. forestry is replaced by pasture) the catchment may react differently to heavy rainfall in the future. However, for the case study described here, the majority of the catchment area is native forest within the conservation estate. Hence, although some intensification of dairying practice has occurred on the lowland areas, this is not expected to have significant influence on flood magnitudes. This reasoning is backed up by a report prepared for Buller District Council (McKerchar, 2004) showing that flood frequency at Te Kuha has remained relatively unchanged when comparing recent records with early data (records from 1952 onwards and historical accounts from 1926).

Hydrodynamic model assumptions

The degree of inundation of Westport is very sensitive to the duration that the flood is overbank and hydrographs with different shapes and volumes (with the same peak flow) would result in different inundation depths and locations.

The models reported here have the MHWS10 tide peak aligned with the flood peak as discussed in Section 5.5. Higher or lower tides and their timing would result different areas and locations of inundation, e.g. in August 1970 the Buller River flood peak arrived at low tide and inundation was limited by the low tide, even though there was ~0.6 m of storm surge. Hydrodynamic models are additionally affected by uncertainties in boundary conditions, model parameters and bridge geometry (Pappenberger et al., 2006), and river morphological changes (Neuhold et al., 2009).

7 Model Choices

The flood simulations described in this paper rely on a series of choices of modelling method. At each stage, alternative model types could be used, and hence the flood risk assessment process depends on the expert knowledge of the practitioner to choose the most appropriate method. The Urban Impacts Toolbox (NIWA et al., 2011) used a second case study in the Heathcote catchment (Christchurch) to demonstrate some of the alternative choices. Some of these choices are well-established techniques, while others touch on the leading edge of research where improvements in physical process representation must be balanced against on-going research needs to improve understanding and performance of the method.

An example of alternative established methods is in the choice of current-climate rainfall scenario. In this paper, we used the measured rainfall associated with a historical flood event (here the August 1970 event). If a suitable historical event is not known, the High Intensity Design Rainfall System (HIRDS: http://hirds.niwa.co.nz) can be used to estimate extreme rainfall depths and durations. However, a limitation with using such "event-based" methods is that the model does not account for the catchment wetness condition prior to the event, which affects the ability of the catchment to store water and hence attenuate the flood peak. An alternative method which includes the effect of rainfall in the days, weeks and months prior to the extreme event is "continuous simulation". In this method, the current-climate rainfall scenario used is the complete historical series of measured rainfall in the catchment, as used for example by Poyck et al. (2011) to estimate impacts of climate change on water resources in the Clutha. The complete series can then be adjusted according to the climate change predictions, and then used to drive the hydrological model to simulate the associated flow series. Particular flood events from the flow series then become the input to the 2D hydrodynamic model.

The Heathcote case study also gave an example of a new/experimental method, where a Regional Climate Model (RCM) linked to a weather generator was used to estimate future climate scenarios. The RCM provides 'dynamic downscaling' to derive local climate effects from the GCM predictions by full simulation of the atmospheric processes that are significant to the creation of heavy rainfall events. The RCM allows for effects such as changes in storm tracks in future climates, as well as explicit modelling of changes in extreme rainfall, which are not simulated by the statistical downscaling methods used in this paper. An example of its use in NZ is given by McMillan et al. (2010). However, current limitations to the RCM method include a need for bias correction over multiple timescales, uncertainty caused by the limited availability of RCM runs (as each run in highly computationally intensive), and a limited number of statistical distributions fitted in the weather generator component. Current research to address these limitations will make the RCM method more widely applicable in future.

While two examples of alternative methods are given here, the reader is referred to the Toolbox (NIWA et al., 2011), introduced by Tait et al. (2012; This issue), and MfE guidance (MfE, 2010) for a fuller discussion.

8 Conclusion

This paper showed how climate, hydrological and hydrodynamic models can be used to predict the effects of future flooding and sea level rise on urban environments in NZ. A case study was undertaken to demonstrate the modelling methods by simulation of flood risk for Westport from the Buller River. Using a historic 1-in-50 year event (from 31 August 1970), projections from Global Climate Models were used to define monthly rainfall and temperature adjustments necessary to simulate climates for the time periods 2030-2049 and 2080-2099 and emissions scenarios B1 (Low), A1B (Medium) and A2 (Medium-High). The future rainfall and temperature data were used to drive a TopNet hydrological model which was developed and calibrated for the Buller. The hydrological model produced a simulated flood hydrograph associated with each climate scenario. The simulated flood hydrographs for the 2030-2049 time period correspond to events in the current climate with recurrence intervals of 66 years (B1 scenario), 76 years (B2 scenario) and 82 years (A2 scenario). For the 2080-2099 time period the recurrence intervals are 78, 98 and 113 years for the B1, A1B and A2 scenarios respectively.

These hydrographs, together with projections of sea level rise, were used as input to a 2D hydrodynamic model representing the Buller flood plain. The percentage of the Westport town area which is predicted to flood to depths of more than 0.2 m is projected to increase in such an event from 50% in the current climate, to 60%, 63% or 64% for the 2030-2049 time period in the B1, A1B and A2 scenarios respectively. For the 2080-2099 time period the percentages are 67%, 70%, and 72% for the B1, A1B and A2 scenarios. The final step was to use the multi-hazard assessment tool ‘RiskScape’ to evaluate the hydrodynamic model predictions in terms of loss to people and infrastructure. An example showed that under the A1B 2080-2099 scenario, Westport could expect risk to life of Medium or greater to 560 people, building damage of $72M and contents damage of $68M. The reduction in losses under different levels of flood warning could also be quantified.
In summary, this paper has demonstrated how the combined use of simulation and risk models enables flood risk assessment for a range of time periods and emissions scenarios. By providing projections of river discharge, maps of inundation depths and velocities, and effects on people and assets, the results will be valuable to many users across city, district, regional and central government.

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