Impacts of Climate Change on Urban Infrastructure & the Built Environment

A Toolbox

Tool 2.1.3: Hydrological modelling of present-day and future floods

Authors

J. Sturman[1], H. McMillan[2], S. Poyck[2], R. Ibbitt[2], J. Walsh[2], R. Woods[2], A. Tait[1] and E. Hreinsson[2]

Affiliations

[1] NIWA, Private bag 14901, Wellington

[2] NIWA, PO Box 8602, Christchurch

Contents

1. Introduction

1.1 Background

It is expected that future increases in heavy rainfall due to climate change will greatly impact river flow and river flooding in New Zealand. The IPCC Fourth Assessment Report (2007) found that floods in New Zealand are "very likely" to become more frequent and intense, resulting in increased risk to major infrastructure including failure of flood protection measures. The pattern of rainfall over New Zealand will also change, e.g. Eastern areas expected to become drier, Western areas expected to become wetter, leading to regional variations in flood risk changes.

As detailed in the [Tool 2.1.1] the second step in estimating the effects of climate change on river flood flows is to estimate the change in flood flow. The Ministry for the Environment's Tools for Estimating the effects of Climate Change on Flood Flow manual (MfE, 2010) provides a range of methods in order to do this and these methods will be discuss in this report.

1.2 Purpose of Tool

To use estimates of future heavy rainfall intensity, temporal and spatial variation [Tool 2.1.2] and estimate the corresponding river flood flows.

2. Methods

2.1 Simple screening methods for determining future river flows

Simple screening methods generally offer less confidence in making forecasts for events that fall outside the range of historical observations (MfE 2010). This is because they are less sophisticated in their representation of real-world processes and they are restricted to their use of historical data. The following section presents two commonly utilised empirical screening methods: the US Soil Conservation Service (SCS) and unit hydrograph methods and the Rational Method.

The US Soil Conservation Service (SCS) and Unit Hydrograph methods

The unit hydrograph method converts a hyetograph (a graph of the distribution of rainfall over time) into a hydrograph (a graph showing changes in river flow over time) for a chosen catchment. In comparison the SCS method utilizes land-cover related parameters to relate peak flood flow to rainfall.

The Tools for Estimating the Effects of Climate Change on Flood Flow manual (MfE, 2010, section 4.2.1) presents the TP108 model as an example of a standard model for computing design flood hydrographs in small catchments and this information is provided below.

TP108 is a standard model for computing design flood hydrographs in small catchments in the Auckland region (Auckland Regional Council, 1999). It has been used outside the region, but it must be stressed that the model was not developed to do so. Also note that it is currently being updated by the Auckland Regional Council to GD2009/001.

A key input to TP108 is the 24-hour rainfall total, P, which is mapped for the Auckland region (Auckland Regional Council, 1999). The formula for event run-off is:

Q = (P – Ia)2 / (P – Ia + S)

where:

- *Q is run-off depth (millimetres)*
- *P is rainfall depth (millimetres)*
- *S is the potential maximum retention after run-off begins (millimetres)*
- *Ia is initial abstraction (millimetres), which is 5 millimetres for permeable areas and zero otherwise.*

The retention parameter S (measured in millimetres) is related to catchment characteristics through:

S = (1000/CN – 10) 25.4.

The value of the curve number (CN) ranges from 0 for zero run-off to 100 for complete run-off; its value depends on a catchment's characteristics. The TP108 method for estimating CN values is given in the TP108 manual (Auckland Regional Council, 1999, section 2.2 and Appendix B). Note that TP108 does not give detailed guidance on how to adjust CN values for the effect of antecedent conditions, but does mention they influence CN values.

The remaining steps of TP108 convert the run-off depth (Q) into a flow hydrograph by assuming a particular temporal pattern for the storm rainfall and estimating a characteristic lag time for the catchment to respond to rainfall. In a screening approach, these calculations will be assumed to be the same for both the current and future climates and are not discussed further here. In a more sophisticated approach, *you might consider whether the temporal rainfall pattern or initial abstraction might change, but this level of detail is generally not appropriate when the method is used as a screening tool.*

To use this method as a screening tool in the Auckland region, apply it once with the current 24-hour rainfall from the map in the Auckland Regional Council guidelines (Auckland Regional Council 1999), and apply it a second time with: (i) the rainfall changed to reflect the expected changes in rainfall described in section 3.2; and (ii) the CN value changed to reflect any available information on how antecedent conditions may change with climate. Thus, the extreme daily rainfalls might be approximately 8 per cent higher by 2040, since extreme rainfall is expected to increase 8 per cent per degree of warming, and approximately 1 degree of warming is expected by 2040 in many parts of New Zealand. Tables 1 and either 2 (for 2040 estimates) or 3 (for 2090 estimates) from this manual can be used with this method.

The Rational Method

The Rational Method is a common technique used in engineering hydrology and it can also be used as a screening tool for predicting changes in flood flow. The Tools for Estimating the Effects of Climate Change on Flood Flow manual (MfE, 2010) presents the formula for the Rational Method as:

$$Q = C\, i\, A / 3.6$$

where:

- *Q is the estimate of the peak design discharge in cubic metres per second*
- *C is the run-off coefficient*
- *i is rainfall intensity in millimetres per hour, for a duration equal to the time of concentration of the catchment*
- *A is the catchment area in square kilometres.*

2.2 Advanced methods for determining future river flows

There are many advanced methods available for deriving river flows from rainfall data. Most of these methods can be divided into storage-routing models and catchment hydrology models.

Storage-routing models

These models estimate the direct effects of rainfall on river flow and run-off, and hence can be used to investigate scenarios of future rainfall changes. The methods are less concerned with the physics of the rainfall-run-off process and instead represent the downstream flow of water through linked reservoirs. Two common examples of these models are HEC-1and RORB. These two models are discussed in more detail in section 4.3.1 in the Tools for Estimating the Effects of Climate Change on Flood Flow manual (MfE, 2010).

Catchment hydrology models

This is the most advanced method for investigating the effects of climate change on river flow estimates. Catchment hydrology models range from simpler, catchment-scale, data-based models to fully distributed, physically based catchment hydrology models, such as TopNet or MIKE SHE. The latter may offer highly detailed representations of a catchment including topography, soil and land use. For more detailed information see section 4.3.2 in the Tools for Estimating the Effects of Climate Change on Flood Flow manual (MfE, 2010). The following three case studies all use the TopNet model to estimate the effect of projected changes in rainfall on river flows and floods. See [Tool 2.1.2] for details of the methods used to estimate the future rainfall changes.

2.3 Choosing the right decision tool

The process diagram below (Figure 2.1) provides basic guidance on selecting the most appropriate method based on simple questions relating to the particular study. It shows only the most common methods. For more detailed guidance with advantages, disadvantages and data requirements for all possible methods, refer to Table 6 of MfE (2010).

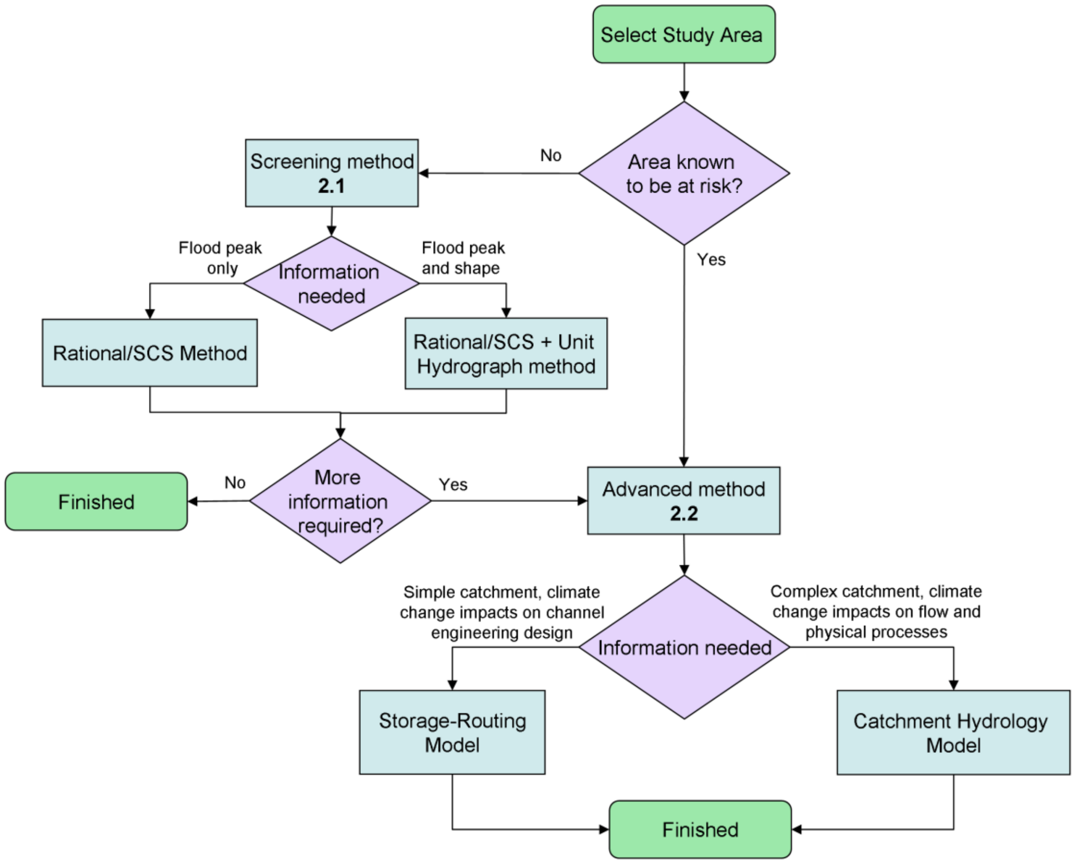

Figure 2.1: Process diagram providing guidance on choice between the most commonly used methods for modelling impact of climate change on future river flow

3. Case study examples

3.1 Impacts of Climate Change on Floods for the Heathcote River

The method used for estimating the effect of climate change on Heathcote River (Christchurch) flood risk is as follows. First we estimated the effect of climate change on rainfall using the design event approach [see Tool 2.1.2]. The rainfall depth was based on rainfall statistics provided by Griffiths et al. (2009) and the temporal pattern of rainfall was taken from an observed severe rainfall event The simple screening approach outlined in MfE (2010) was used to calculate the effect of various climate scenarios on the design event.

Then we used a hydrological rainfall-runoff model (a TopNet model of the Heathcote calibrated to 8 flood events) to convert these changes in rainfall to changes in river flow [see this section]. Each design rainfall was used as input to the rainfall-runoff model, to produce a different flood hydrograph for each climate change scenario.

Lastly, a hydraulic model was employed to assess impacts on flood inundation [see Tool 2.1.4]. Each flood hydrograph was used as input into the hydraulic model.

For more information on this case study, see [Toolbox Overview and Case Study Examples].

Catchment Hydrology Model

The TopNet catchment hydrology model was used in this case study. The model operates in three steps: 1) input data is managed and disaggregated (i.e. spatially from station data or gridded data to the sub-catchment scale, and (if necessary) temporally from daily to hourly rainfall data); 2) When the precipitation for the catchment is calculated, the water balance is solved for each sub-catchment. The physical quantities that are updated in this stage are canopy storage, soil storage, aquifer storage and overland flow storage. A detailed description of this step can be found in Clark et al. (2008); and 3) streamflow (kinematic wave) routing, using a one-dimensional Lagrangian kinematic wave routing scheme, in which runoff produced by each sub-catchment is routed through the stream network to the basin outlet (Clark et al. 2008).

Model Calibration

The TopNet model was calibrated using rainfall data relating to eight flood events. The rainfall data were taken from 5 surrounding raingauges, and interpolated onto the catchment using the inverse distance method. The rainfall depths were also corrected according to the differences of average annual rainfall between the gauges and the catchment. The rainfall data were used as input to the hydrological model and the measured and modelled flows were compared at the Buxton Terrace gauge site at the outlet of the catchment. The model parameters were then adjusted to produce the best fit between the modelled and measured data. The results of the calibration are shown in Figure 3.1.

The model was validated (i.e. a test independent from the calibration) using 110 years of rainfall data measured at the botanical gardens in Christchurch. The rainfall was distributed within the catchment according to the pattern of average annual rainfall (Tait et al, 2006). For validation the return periods of the different floods were verified.

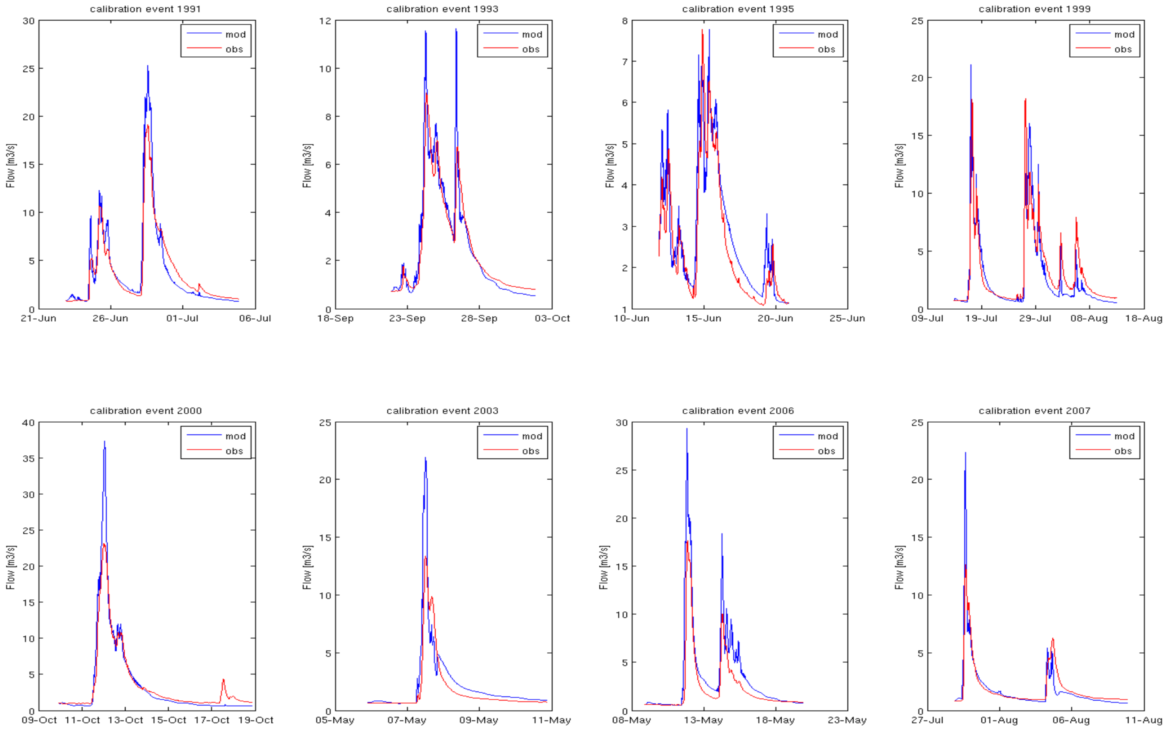

Figure 3.1: Results of the calibration of TopNet for eight flood events in the Heathcote catchment. Each graph shows time on the x-axis and flow on the y-axis. For each event, the measured flow is shown in red and the modelled flow is shown in blue.

Climate Change Impacts on Flow

To assess the impact of changes in rainfall due to climate change, we repeatedly ran the calibrated Topnet model of the Heathcote catchment with different rainfall events corresponding to the climate change scenarios described in [Tool 2.1.2]. Each of the simulated hydrographs for the Heathcote River at Buxton Terrace was provided as input to the hydraulic model of flood inundation [see Tool 2.1.4 for inundation results].

The current climate was simulated using a specific event (from 2 January 1980) which was selected to be representative of the type of event that can produce severe floods. Climate scenarios were simulated by increasing or decreasing all hourly rainfall amounts in the storm by the same scale factor. The scale factor was chosen to produce the daily rainfall total for the desired ARI and climate scenario [see Tool 2.1.2 for more information]. TopNet was then used to simulate the river flow and potential flood that would result if the resulting rainfall occurred at Christchurch Gardens and rainfall totals over the rest of the catchment continued to be distributed within the catchment according to the pattern of average annual rainfall.

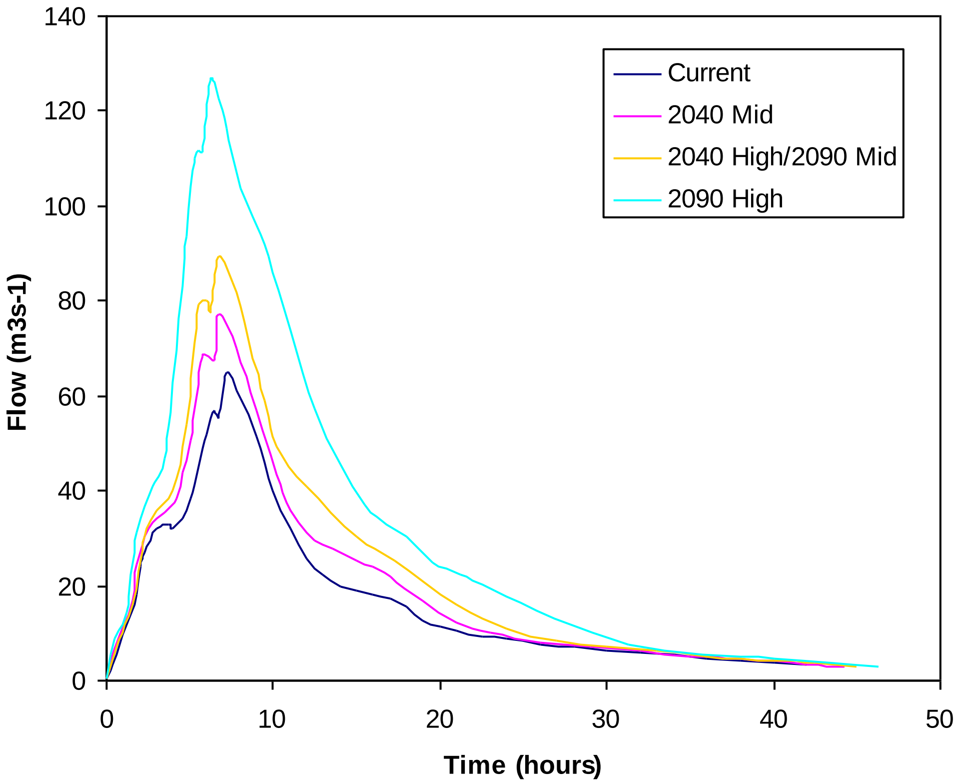

Figure 3.2: Modelled hydrographs at Buxton terrace for 1-in-100 year rainfall events for the current climate and two future periods (2040 and 2090) for two different emissions scenarios (Mid scenario A1B and High scenario A2).

The output hydrographs modelled by TopNet are shown in Figure 3.2. These predictions are for a 1-in-100 year event at Buxton Terrace, which is the tidal limit of the Heathcote. When these flows are used as input into the hydraulic model [Tool 2.1.4], flows at all minor tributaries contributing to the Heathcote must also be modelled. The flow at the Bowenvale tributary was calculated internally by TopNet. All other tributary flows were calculated as scaled versions of the Bowenvale flow, using a method derived in a previous study.

3.2 Heathcote experimental case study: Hydrological modelling of future floods using heavy rainfall derived from a weather generator and Regional Climate Model

As described in the previous [Tool 2.1.2], a Regional Climate Model coupled to a weather generator was used to produce 1000-year series of simulated rainfall and temperature for the Heathcote catchment. The series were available for current climate, and A2 and B2 future climate scenarios for a time period centred on 2090. To investigate the impact of climate change on river flow in the Heathcote, these series were used as input to the hydrological model TopNet. The model was calibrated as described earlier in this section.

For each climate scenario, the output from TopNet was a 1000-year series of river flows. The peak discharge of the largest flood in each year was extracted from the flow series, and used to create a magnitude-frequency diagram. However, at this stage, two issues were found.

(1) The daily rainfall total was not related in a simple way to the daily flow peak, as the pattern of rainfall within the day was equally important in controlling river flow.

(2) For the 'current climate' series, although the daily rainfall maxima produced by the method of Regional Climate Model bias-correction and weather generator were a good match to measured rainfall at the Botanic Gardens, the resulting flood flows could be very different. This was partly due to issue (1) and partly to the method of bias correction used.

For the above reasons, the simulated flood flows were not found to be suitable for flood risk assessment at this stage. The additional work needed to address these issues relates to a bias correction method which can correctly simulate not only daily rainfall totals, but also concurrently simulate the multi-day rainfall events which can lead to floods in the Heathcote. This research is currently ongoing in the FRST programme 'Regional Modelling of Climate Change'. Until the research is complete, further work in the Heathcote using this method could not proceed.

3.3 Estimating future flood flows at Te Kuha, Buller catchment

The hydrological model TopNet was used to produce time series of streamflow at Te Khua, Buller catchment, with temperature and precipitation as input data [see Tool 2.1.2]. A total of seven streamflow time series were produced for a flow event around 31 August 1970 for seven different set of input data:

1) Current climate

2) Medium emission scenario A1B, 2030-2049 (2040-Med)

3) Medium emission scenario A1B, 2080-2099 (2090-Med)

4) High emission scenario A2, 2030-2049 (2040-High)

5) High emission scenario A2, 2080-2099 (2090-High)

6) Low emission scenario B1, 2030-2049 (2040-Low)

7) Low emission scenario B1, 2080-2099 (2040-Low)

Calibration

Calibration was performed by running the Topnet model from 1998-04-01 to 1999-03-31 for ten thousand different parameter sets, sampled across the parameter space, and selecting the fifty best ones (in terms of root mean squared error and Nash Sutcliffe score for modelled streamflow at Te Kuha). TopNet was then run fifty times from 1990-04-01 to 2007-03-31 with these selected parameter sets and the best one chosen based on visual comparison between modelled and observed streamflow as well as root mean squared error and Nash Sutcliffe scores (the chosen parameter set had Nash Sutcliffe score of 0.788 which was the highest score among all the parameter sets).

Input data used in the calibration were the virtual climate station network (VCSN) interpolated rainfall and minimum and maximum temperature grids (0.05° lat/long, or ~5x5 km grid over the whole of New Zealand; Tait et al., 2006). 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). Rainfall values were disaggregated from daily to hourly time steps using hourly data from the Greymouth Airport climate station to distribute the rainfall within the 24-hour period.

Model runs for the <u>31 August 1970</u> flood event

The Topnet model parameters for the Buller catchment also needed to be adjusted to match the flood event as well as possible, as follows:

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. The hourly station data were shifted three hours back in time in order to get the timing of the flood peak right.

b) The value for overland flow velocity was decreased from 0.0574 to 0.0499 m/s in order to get the flood magnitude matching the observations. Other parameters were not changed.

After the model parameters had been changed to match the flood event, the model was run from 1970-01-01 past the flood event for each of the input data sets representing the seven different scenarios (including the current climate scenario). The tide used at the time of the peak flow was 1.618 m, which represents the Mean High Water Springs 10th percentile (MHWS10). 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). Table 3.1 shows the peak flow, AEP and ARI for each scenario. The projected changes to the peak flood flow are shown in Table 3.1, and the simulated hydrographs are shown in Figure 3.3.

Table 3.1: Projected changes to the peak flood flow in the Buller catchment for each future scenario.

Climate Scenario	Period	Peak flow (m^3/s)	AEP for current climate	ARI (years)	Tide enhancement (m)
Base	Current	8500	0.0213	47	0.0
B1 (Low)	2030-2049	8805	0.0152	66	0.4
A1B (Med)	2030-2049	8977	0.0132	76	0.4
A2 (High)	2030-2049	9083	0.0122	82	0.4
B1 (Low)	2080-2099	9017	0.0128	78	0.8
A1B (Med)	2080-2099	9319	0.0102	98	0.8
A2 (High)	2080-2099	9512	0.0088	113	0.8

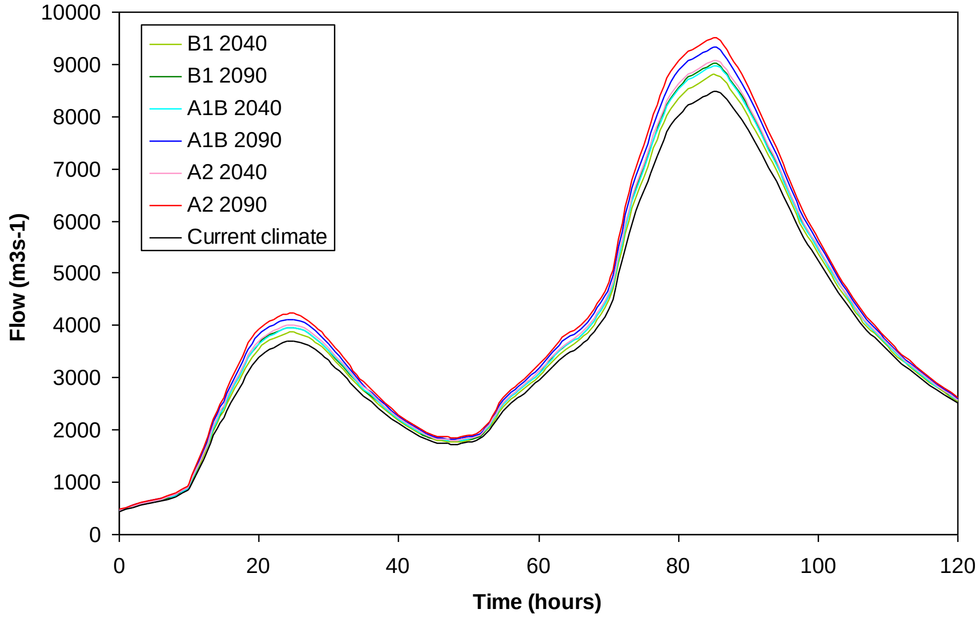

Figure 3.3: Modelled hydrographs at Te Kuha for the current climate and two future periods (2040 and 2090) for three different emissions scenarios (Low Scenarion B1, Mid scenario A1B and High scenario A2).

4. Data Needs

The data needs for hydrological modelling are strongly dependent on the type of model chosen, and the data availability for the catchment of interest should be a factor in the decision on which model type is most suitable.

For the climate change impacts assessment presented in the two case studies here, we used the distributed hydrological model, TopNet. The data requirements of TopNet are typical of this type of distributed, physically-based model. The model divides the stream network is divided into first order sub-catchments, and for each sub-catchment an underlying spatial data file is required which contains information about soil cover, soil depth, hydraulic conductivity, elevation (distribution), etc, as well as information about the river network, for example stream width, roughness, etc. The main sources of spatial data used for New Zealand applications of Topnet are the New Zealand River Environment Classification (Snelder & Biggs, 2002), supplemented with additional analyses of topographic data, the Land Resources Inventory (Newsome et al. 2000), and the New Zealand Land Cover Data Base (Willoughby et al., 2001).

The hydrological model also requires the input series of rainfall (see discussion of rainfall data availability in [Tool 2.1.2]), and input series of temperature (in order to estimate evaporative demand) and a measured series of flow in order to check the calibration of model parameters for the current climate.

5. Assumptions and Limitations

These studies of the effects of climate change of river flows rely on estimating rainfall series under future conditions, and then using a hydrological model to transform the rainfall into a simulated flood peak. This process relies on a number of assumptions. We rely on the rainfall input series correctly representing a storm event of the future. The calculation of the rainfall series and the assumptions made are outlined in [Tool 2.1.2].

The use of a hydrological model assumes that the model perfectly represents the physical processes occurring in the catchment. There are always some cases where the model does not exactly reproduce the measured flow, and therefore there is uncertainty in the model parameters which should be identified during model calibration. It is beneficial to assess the uncertainty relating to the model simulations by using a range of possible model parameters rather than the single best parameter set. This type of analysis would demonstrate the range of possible flood flows expected for given future scenarios.

The future flood simulations also assume that the catchment remains unchanged between now 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.

6. References

Auckland Regional Council (1999) Guidelines for Stormwater Runoff Modelling in the Auckland Region. Technical Publication No. 108. Retrieved from http://www.arc.govt.nz/plans/technical-publications/technical-publications-101-150.cfm

Clark, M. P., D. E. Rupp, R. A. Woods, X. Zheng, R. P. Ibbitt, A. G. Slater, J. Schmidt, and M. J. Uddstrom (2008), Hydrological data assimilation with the ensemble Kalman filter: Use of streamflow observations to update states in a distributed hydrological model, *Advances in Water Resources*, 31(10), 1309-1324.

Clark, M. P., E. O. Hreinsson, G. Martinez, A. Tait, A. Slater, J. Hendrikx, I. Owens, H. Gupta, J. Schmidt, and R. Woods (2009), Simulations of seasonal snow for the South Island, New Zealand, *Journal of Hydrology (NZ)*, 48(2), 41-58.

Griffiths, G.A., Pearson, C.P., McKerchar, A.I. (2009). Review of the frequency of high intensity rainfalls in Christchurch. NIWA Client Report CHC2009-139, prepared for Christchurch City Council and Environment Canterbury, Christchurch, New Zealand, September 2009. 26pp.

IPCC. (2007). Summary for Policymakers. *In*: Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Solomon, S.; Qin, D.; Manning, M.; Chen, Z.; Marquis, M.; Averyt, K.B.; Tignor, M.; Miller, H.L. (Eds.). Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Available at http://ipcc-wg1.ucar.edu/wg1/Report/AR4WG1_Pub_SPM-v2.pdf.

Ministry for the Environment (2008) Coastal hazards and climate change: A guidance manual for local government in New Zealand. 2nd Edition. Revised by D. Ramsay and R. Bell (NIWA). Ministry for the Environment Publication No. ME 892, 127 pp.

Ministry for the Environment (2010) *Tools for estimating the effects of climate change on flood flow: A guidance manual for local government in New Zealand.* Woods R, Mullan AB, Smart G, Rouse H, Hollis M, McKerchar A, Ibbitt R, Dean S, and Collins D (NIWA). Prepared for Ministry for the Environment.

Newsome, P.F.J.; Wilde, R.H.; Willoughby, E.J. (2000). Land Resource Information System Spatial Data Layers. Technical Report. Landcare Research NZ Ltd., Palmerston North, New Zealand.

Snelder, T.H.; Biggs, B.J.F. (2002). Multi-Scale River Environment Classification for Water Resources Management. *Journal of the American Water Resources Association* 38: 1225\u2013 1240.

Tait, A., Henderson, R.D., Turner, R., Zheng, X., (2006). Thin plate smoothing spline interpolation of daily rainfall for New Zealand using a climatological rainfall surface. *International Journal of Climatology* 26(14), 2097-2115.

Willoughby, E.J.; Wilde, R.H.; McLeod, M.; Hewitt, A.E.; Webb, T.H. (2001). National soils database audit: a document describing Landcare Research soils data. *Landcare Research unpublished report*.

Woods, R.; Hendrikx, J.; Henderson, R.; Tait, A. (2006) Estimating mean flow of New Zealand rivers. *Journal of Hydrology (NZ)*. 45: 95-110.