CALIBRATION OF RUNOFF-ROUTING MODELS FOR THE PORT HILLS CATCHMENTS

M. Passier (AECOM New Zealand Ltd), S. Williams (AECOM Australia Pty Ltd), T. Parsons (Christchurch City Council / Innovate Consulting)

ABSTRACT

Christchurch City Council developed the city-wide flood models to assist with response to the city's increased flood risk following the Canterbury earthquakes. The project developed new hydraulic models for Avon and Heathcote Rivers and Sumner Stream.

The steep, mostly non-urbanised Port Hills catchments of the Heathcote River comprise around 4,000ha of the total Heathcote River catchment area of around 12,300ha, generally with loess soils overlying volcanic rock. The hillside catchments are a significant element of the river hydrology. Historically, the Port Hills response has been heavily influenced by antecedent conditions, with a dry state resulting in large initial losses and a wet state leading to a significant runoff response. Flow records also show an extended tail following rainfall events. This understanding was tested during development of a reliable hydrological model of the system.

Previous hydrological calibration efforts for the hillside catchments were mixed due to the limited available data and the methodologies applied.

The objectives of the city-wide modelling demanded resolution of the urban drainage network, which is predominantly in flat areas of the city. Direct rainfall (rain on mesh) within the hydraulic model was considered to be the most practical hydrological approach to support the level of detail of the hydraulic model, and the rain on mesh methodology was initially considered in detail for the hillside catchments. Initial calibration trials with a wide range of rain on mesh model parameters for the Bowenvale and Hoon Hay Valley gauged catchments showed a poor correlation between recorded and modelled flow for the June 2013 and March 2014 large rainfall events.

A trial of XP-RAFTS and RORB non-linear runoff-routing models was subsequently undertaken using the Bowenvale and Hoon Hay gauged catchment data. The XP-RAFTS and RORB models more successfully predicted stream flow at the monitoring sites than the rain on mesh approach. The models were calibrated using a set of catchment storage parameters common to the two events and the two gauged catchments. The RORB model was adopted in the city-wide project as the preferred methodology for deriving stream flow estimates from the hillside catchments.

The XP-RAFTS and RORB runoff-routing models evaluated in the study are not widely used in New Zealand, but are well established and widely applied in catchment studies Australia-wide. Accordingly, there are limited published regional parameters or methods for parameter estimation available for NZ catchments.

The available flow data at the Bowenvale and Hoon Hay monitoring sites allowed derivation of catchment storage parameters for the RORB model applied in the city-wide modelling project. Good calibration was achieved using those models for the steep, non-

urbanised gauged catchments in Christchurch, where calibration of previous hydrologic models has proven challenging.

The use of non-linear runoff-routing models, including XP-RAFTS and RORB models investigated in this study, offer additional tools that may be used to resolve rainfall runoff response in NZ catchments. Further investigation of gauged catchments in NZ would support the understanding of regional relationships for parameter estimation, and may support wider use of the models for estimation of rainfall runoff in ungauged catchments.

KEYWORDS

Hydrology, rainfall, runoff, model, Christchurch

PRESENTER PROFILE

Sally Williams

Sally is a Principal Engineer at AECOM Australia. She is a chartered engineer with over 15 years' experience in hydrologic and hydraulic modelling. Sally's recent work includes development of city-wide flood models for Christchurch region following the 2012-2013 Canterbury earthquakes. She hasn't seen snow in almost 10 years.

Mark Passier

Mark is a Principal Engineer at AECOM New Zealand. Mark has over 14 years' experience in civil and environmental engineering. He was the project manager leading delivery of the Heathcote River and Sumner stream models developed as part of the city-wide modelling project.

1 INTRODUCTION

The Port Hills are a defining feature of Christchurch. They are the most apparent topographic feature of the otherwise flat city. The Heathcote River meanders through the fringe of the city's flat land near the base of the hills. Surface runoff from the hillside catchments is a significant contributor to the river flows, so understanding of the rainfall runoff processes from the hillside catchments is imperative for flood prediction within the Heathcote catchment.

There are established hydrological models for estimating surface runoff from the Port Hills catchments, however the calibration accuracy has not been consistently well resolved and there remains uncertainty in prediction of peak flow, volume and hydrograph rising and falling limb characteristics. The application of rainfall to the models has contributed to uncertainty of the existing modelling methodologies, because of a pronounced rainfall gradient on the hillside catchments.

Christchurch City Council (Council) established the city-wide flood modelling project to develop detailed models for flood estimation across the entire city; the project included an investigation of alternative methods for hillside hydrology. The urban drainage network was represented in a high level of detail in the hydraulic model of the Heathcote River catchment, which supported use of rain on mesh (direct rainfall) as the hydrological method in the flat areas of the city. However, initial calibration trials for steep gauged catchments of the Port Hills showed poor results when using the rain on mesh approach.

A trial calibration using the non-linear runoff routing models XP-RAFTS and RORB was undertaken and provided more favourable results. The RORB model was subsequently adopted as the preferred methodology for estimation of surface runoff from the steep Port Hills catchments.

The RORB model has not been used widely in New Zealand. It is a network model that was originally developed in by the Monash University Department of Civil Engineering in 1975, and it retains widespread use in Australia. The historical development and theoretical basis of the RORB model are well documented within the user manual and Australian Rainfall and Runoff Guidelines (ARR, 2016).

Following an overview of the context of the city-wide flood modelling project and previous analytical assessments of Port Hills hydrology, this paper details calibration of the RORB model to two gauged catchments of the Port Hills, Christchurch.

2 DEVELOPMENT OF CHRISTCHURCH CITY-WIDE FLOOD MODELS

The city-wide flood models will be used to inform development of the Land Drainage Recovery Programme (LDRP) and the Long Term Plan (LTP) as well as assess impacts of the Canterbury Earthquake Sequence (the earthquakes) and a wide range of other activities including regulatory compliance for buildings. The aim of the modelling project is to deliver updated river catchment models for ‘flat land’ Christchurch.

The challenges that were facing Council included variability of existing model construction across the city, uncertainties with post-earthquake applicability of pre-existing models (including calibration, representation of topography, stormwater network invert levels, and potential hydrological differences) and historical challenges with model prediction of runoff from the Port Hills, particularly understanding the strong influence of antecedent rainfall on recorded flows for less significant events (Williams, 2005).

In addition to the modelling challenges described above, there is a steep rainfall gradient across the Port Hills catchments. Orographic effects are highlighted by steeply graded rainfall isohyets evident in Council design guidance (WWDG, 2011). Traditionally, model parameters are derived based on calibration to the flow recorded at a single gauge and then these parameters are applied widely across all Port Hills catchments, because available data would not support a more refined approach.

The three rainfall gauges within or near to the Bowenvale Valley have been used to derive the design rainfall isohyets with median annual 24-hour rainfall depths of 74.5 mm, 68 mm and 66.1 mm for Upper Bowenvale, Mid Bowenvale (now closed) and Bowenvale Flume, respectively (Griffiths, et al. 2009). Historical hydrological assessments undertaken for and by Council have had to tackle issues with rainfall distribution. Simplifying assumptions have been previously applied (e.g. excluding particular rainfall gauges, delineation of large catchments). Hydrological models and methods that have been tested include DHI Mouse Model-B, Unit Hydrograph and regional models (Williams 2005).

3 ANECDOTAL UNDERSTANDING AND PREVIOUS MODEL ANALYSIS OF PORT HILLS HYDROLOGY

3.1 ANECDOTAL EVIDENCE

Historically, a ‘rule of thumb’ for the Port Hills catchments has been that 20 mm of rain needs to fall on a ‘dry’ catchment prior to saturation of the loess soils and notable runoff being generated. This was exemplified by the 12 October 2000 event during which minimal flows were recorded at the Bowenvale flume in the first 5.5 hours of the event, within which time 22 mm of rain fell. But high flows followed, with a peak flow of approximately 6 m^3/s after a subsequent 50 mm of rain. There was very little rain in the 5 day period that preceded that event. This contrasts with the 17 July 1996 event, when runoff was generated soon after first rain fell. There was approximately 47 mm rain in the 5 days period that preceded that event.

A long tail which is evident in stream flow hydrographs following significant rainfall events also indicates significant storage of water within the catchment either above or below the ground surface.

3.2 PREVIOUS MODELLING ANALYSES

Several investigations were undertaken during the 1990's and early 2000's to support engineering work undertaken at Sibleys and Scotts drains in the Bowenvale Valley to better manage extreme storm flows from the Port Hills catchments. The historical hydrological work was summarised by Williams (2005), who also considered the calibration of two modelling approaches: Mouse Model B and MOUSE UHM for the April 2000 flood event. Williams concluded that constant or proportional loss models could not easily replicate the Port Hills hydrology and a variable continuous loss model incorporating antecedent conditions should be applied. He recommended the use of Mouse Model B for future works in the Bowenvale catchment as well as wider application to the Port Hills and derived a set of recommended calibration parameters.

Further work by Wong (2015) adopted the parameters recommended by Williams and a similar Mouse Model B with Horton's infiltration loss model approach. For design event simulations, Horton's initial and ultimate infiltration losses of 10 mm and 0.5 mm/hr were adopted, plus an additional storage loss of 2 mm. Wong also compared his model to the flow hydrograph for the March 2014 flood event but was unable to create a good match with either the Upper Bowenvale or Bowenvale Flume rainfall hyetographs as inputs, even with larger losses of 10 mm and 5 mm/hr applied within Model B.

It is noted that these previous models did not resolve subcatchments and rainfall distribution in detail. A single catchment of approximately 320 hectares was used to represent the entire area upstream of the Bowenvale Valley gauge. Rainfall records from the Upper Bowenvale gauge were discounted due to the high depth totals; pluviography records for the Bowenvale Flume rain gauge were applied to the entire catchment area.

3.3 HILLSIDE HYDROLOGY USING RAIN-ON-MESH

The potential benefits of direct rainfall (rain on mesh) hydrology for the city-wide flood model were considered by the project team. The Sumner and Heathcote hills catchments were modelled with a direct rainfall approach. That approach allowed for the consideration of the spatial variability in rainfall and catchment topography in significant detail. However, during testing, oscillations were discovered in the flow hydrographs extracted near the base of the hillside terrain. The oscillations prevailed for all further testing work using the rain on mesh approach within the anticipated range of model parameters.

Testing outside of the usual range of model parameters (e.g. Manning roughness) and evaluation of the stabilising effects of changes to the model structure and parameters was undertaken to confirm a preferred approach to implementation of rain on mesh in the city-wide flood modelling project.

Satisfactory stability of flow hydrographs extracted near the base of the hillside terrain was achieved in simulations that represented the hillside terrain with ground slope reduced by a single order of magnitude from the actual slope. The model results with the modified catchment slope were compared to the Bowenvale gauge data and the Wong (2015) model for the 2014 flood event to assess its overall performance against the recorded data and the accepted calibration of the existing model. The results were comparable to the outcomes from Model B hydrology (Wong, 2015), which did not provide a good prediction of the gauge recorded data.

The model output hydrographs closely followed the rainfall hyetograph characteristics, with a uniform hydrograph lag following peaks and troughs of the rainfall pattern. Despite excellent stream network representation, the rain on mesh approach did not model subcatchment and reach storage in a way that provided a good representation of catchment storage, expressed as hydrograph lag and decay.

It remained unclear how important the anecdotally perceived subsurface flow routing was for the calibration events and therefore the team tested some more traditional surface runoff-routing models.

4 CALIBRATION OF RORB MODELS OF PORT HILLS CATCHMENTS

4.1 CALIBRATION SITES AND AVAILABLE DATA

The flow monitoring data at the Bowenvale and Hoon Hay gauge sites provide two locations on the Port Hills for calibration of catchment flow models. There are a number of rainfall gauge site across the city, although only a single active gauge is located at higher elevation on the Port Hills within the Heathcote catchment; the Upper Bowenvale gauge. Figure 1 shows the location of the flow and rainfall monitoring sites.

Table 1 summarises key characteristics of the catchments upstream of the flow monitoring sites. The catchments are essentially steep, non-urbanised rural catchments.

Figure 1: Site Location

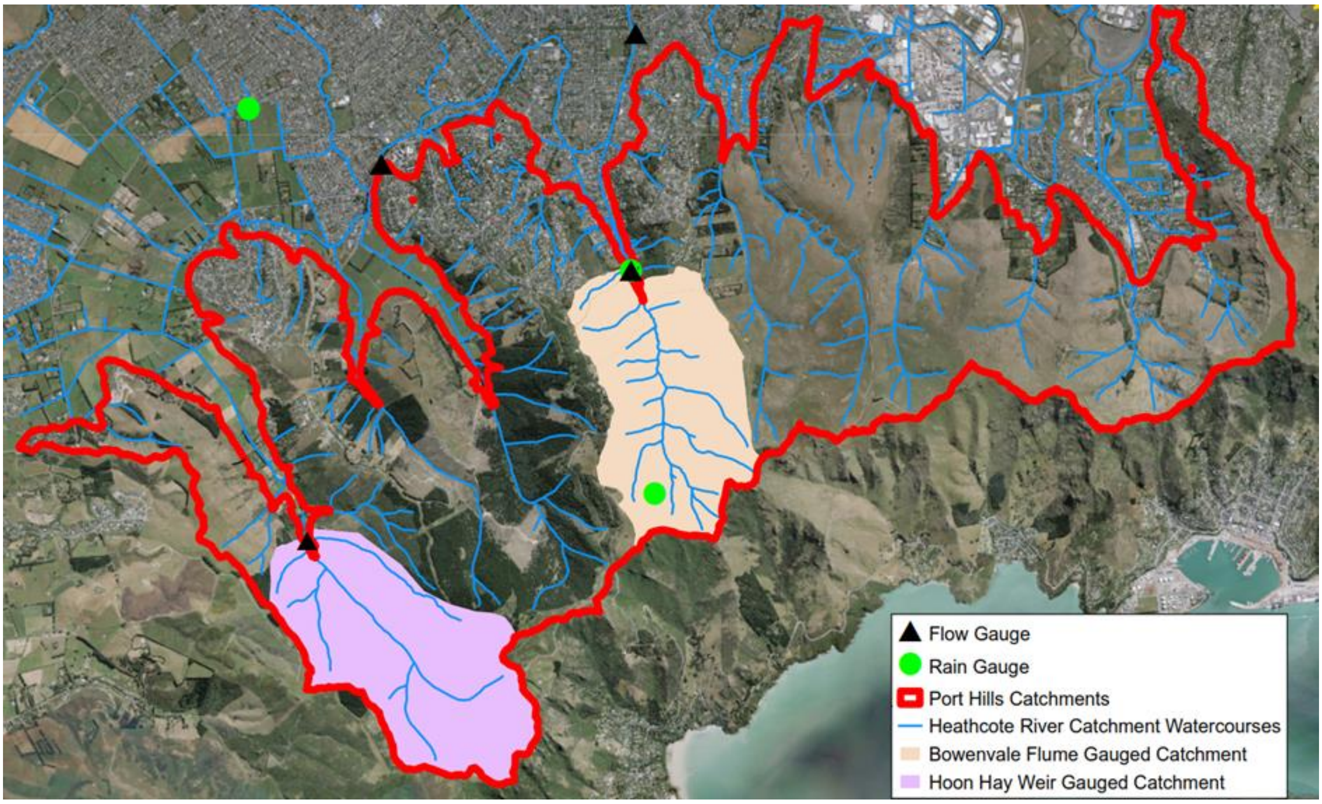


Table 1 Characteristics of Port Hills gauged catchments

Catchment	**Total catchment area (ha)**	**Average reach slope (%)**	**Indicative roughness (Manning's n)**
Bowenvale	320	34	0.2
Hoon Hay	470	21	0.2

The calibration events considered in the city-wide modelling project included the following:

- June 2013 event: 15 June 2013 19:00:00 to 18 June 2013 00:00:00
- March 2014 event: 04 March 2017 08:00:00 to 05 March 2014 13:00:00

Streamflow data was available for the Bowenvale site for both the March 2014 and June 2013 events, however a period of equipment malfunction between 04 March 2014 11.15 pm and 05 March 2014 2.45 am makes the record incomplete for that event. Streamflow data for the Hoon Hay site was available only for the June 2013 event.

These events were selected as they occurred after the Canterbury earthquakes and there was significant surface flooding during the events, making them suitable for wider hydraulic model calibration.

4.2 RAINFALL AND STREAMFLOW CHARACTERISTICS OF THE CALIBRATION EVENTS

4.2.1 CALIBRATION EVENT RAINFALL AND GAUGED FLOWS

The characteristics of rainfall received during the two calibration events are summarised in Table 2 (below). The June 2013 event was a much longer event with lower rainfall intensity as compared with the March 2014 event. The pronounced rainfall gradient between Upper Bowenvale and Bowenvale Valley locations is evident from comparison of the rainfall intensities and cumulative rainfall totals shown in Table 2.

Figure 2 and Figure 3 present the recorded streamflow hydrographs and rainfall hyetographs at the Bowenvale Flume site for the June 2013 and March 2014 events, respectively. There is no flow record for a period of equipment malfunction during the March 2014 event (04 March 2014 11.15 pm and 05 March 2014 2.45 am). Based on the rainfall hyetographs at Bowenvale Flume and at Upper Bowenvale it is considered likely that this period of malfunction coincided with peak flow at the gauge site.

Figure 4 shows the recorded streamflow hydrograph at Hoon Hay weir for the June 2013 event. Since there is no rain gauge within the Hoon Hay area the hyetograph recorded at the Bowenvale Flume gauge is shown for comparison with the flow hydrograph.

Table 2 Summary of calibration rainfall characteristics

Calibration event and gauge location	Event duration (hrs)	Total rainfall depth (mm)	Average rainfall intensity (mm/hr)	Maximum 1 hr intensity (mm/hr)
June 2013 Upper Bowenvale	77	111.4	1.45	5.0
June 2013 Bowenvale Valley		83.2	1.08	5.4
March 2014 Upper Bowenvale	29	271.2	9.35	17.8
March 2014 Bowenvale Valley		163.0	5.62	11.0

Figure 2: Streamflow hydrograph (Bowenvale June 2013)

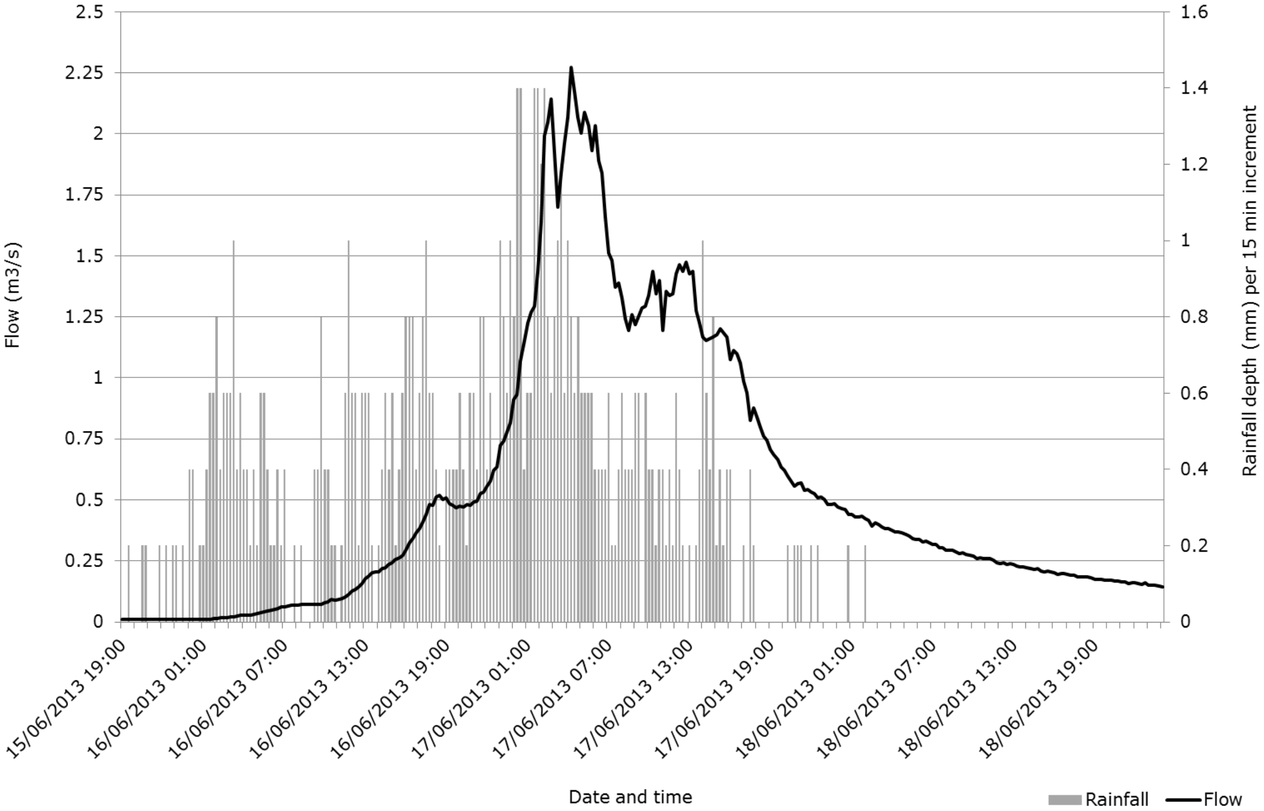


Figure 3: Streamflow hydrograph (Bowenvale March 2014)

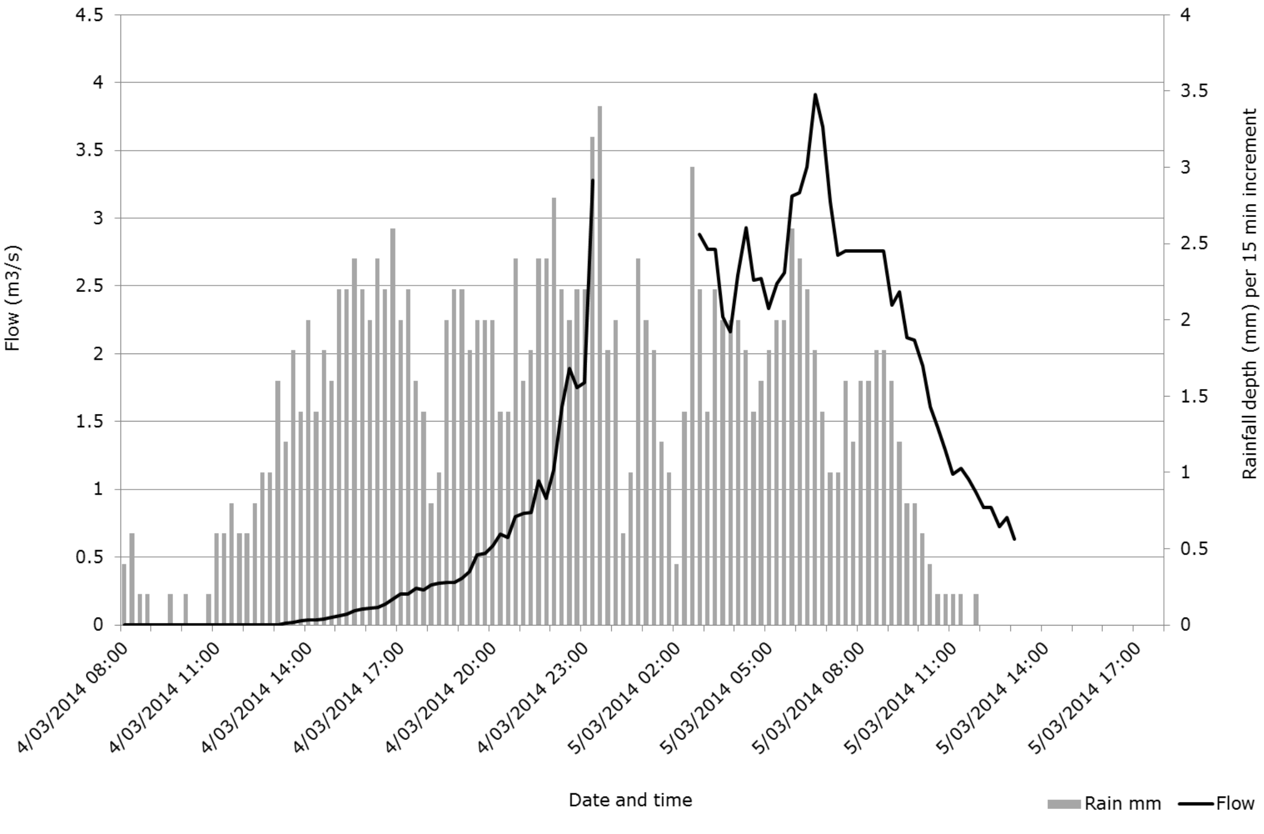
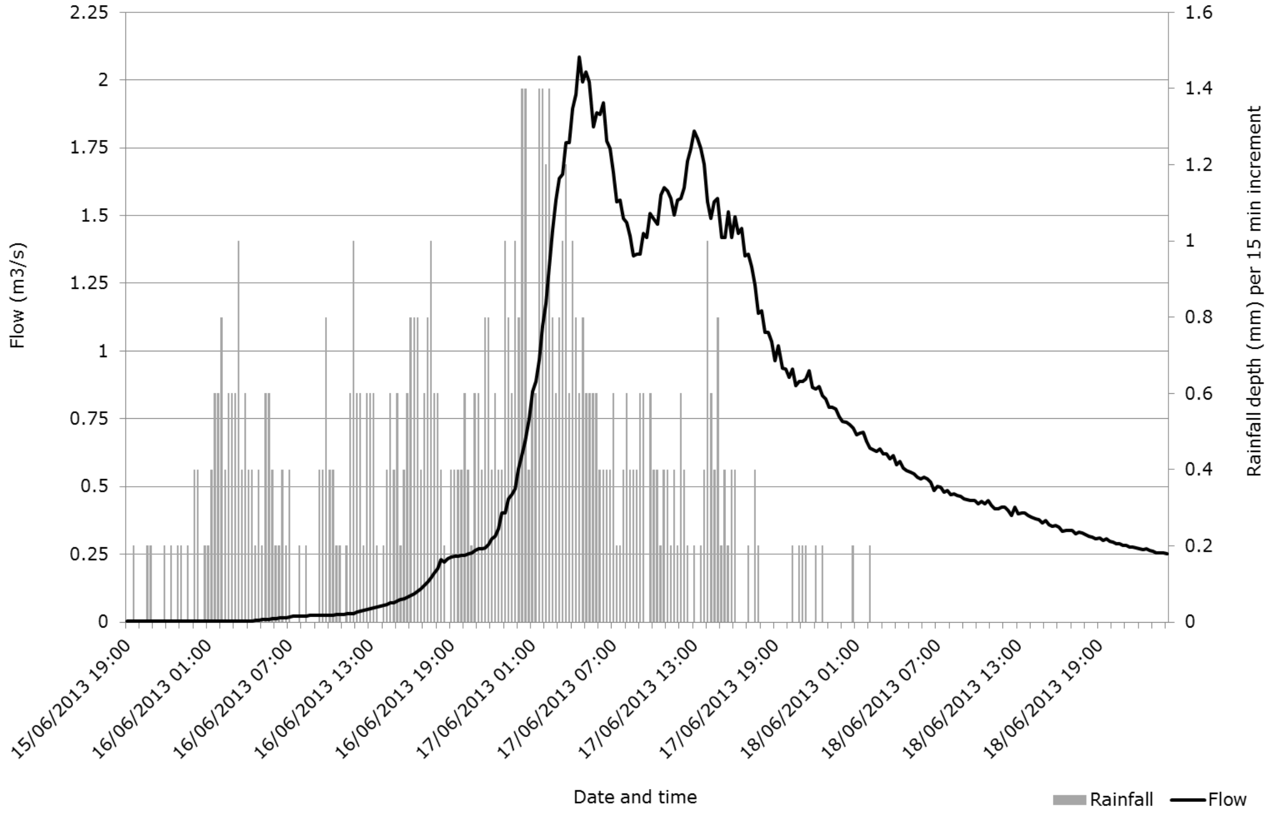


Figure 4: Streamflow hydrograph (Hoon Hay June 2013)



4.2.2 ANTECEDENT RAINFALL

The June 2013 and March 2014 calibration events were, anecdotally, quite different in terms of antecedent rainfall and catchment conditions. The June 2013 event was considered to represent higher antecedent rainfall and 'wetter' catchment conditions in comparison to the March 2014 event.

The analytical appraisal of antecedent conditions, which informed the model calibration, considered the antecedent rainfall totals received over a range of periods prior to the calibration event and of the antecedent precipitation index (API). API is a useful indicator of the effects of antecedent rainfall at any point in time, based on rainfall over the preceding period. It acknowledges that the effects of antecedent rainfall decrease over time; more recent antecedent rainfall will have a stronger influence on catchment conditions than the rainfall which preceded it. The API uses an empirical decay factor, which is typically between 0.85 and 0.98. The assessment was based on a uniform decay factor of 0.95 based on Hill (2014), which does not account for potential seasonal variability.

The antecedent rainfall totals and API for the two events are shown in Figure 5 and Figure 6 (below). The figures offer the following understanding of the antecedent rainfall and its likely effects on catchment conditions prior to the calibration events:

- In the 60 day and 90 day periods prior to the calibration events, higher rainfall totals were received for the June 2013 event compared with the March 2014 event.

- In the 10 days prior to the calibration events, higher rainfall totals were received for the March 2014 event compared with the June 2013 event; negligible rainfall was received in the 10 days prior to the June 2013 event.

- The API was similar for the two events immediately prior to onset of rainfall used for model calibration, based on the assumed decay factor.

While the characteristics of antecedent rainfall are quite different, the effects of antecedent rainfall on catchment moisture condition are likely to be more similar than was presumed anecdotally. It is evident that the anecdotal knowledge of antecedent rainfall and its effects has some bias towards rainfall totals received over relatively long periods prior to the calibration events.

Figure 5: Antecedent rainfall and API (Bowenvale June 2013)

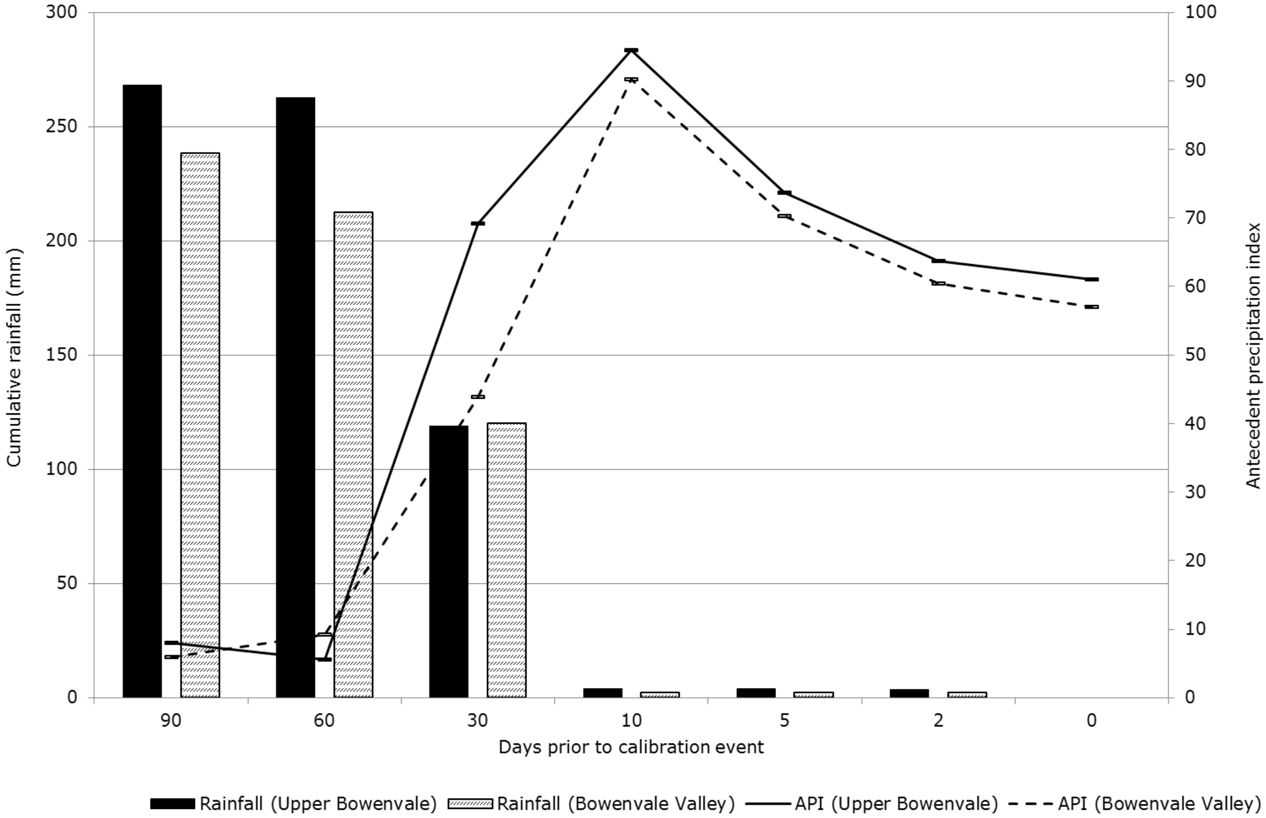
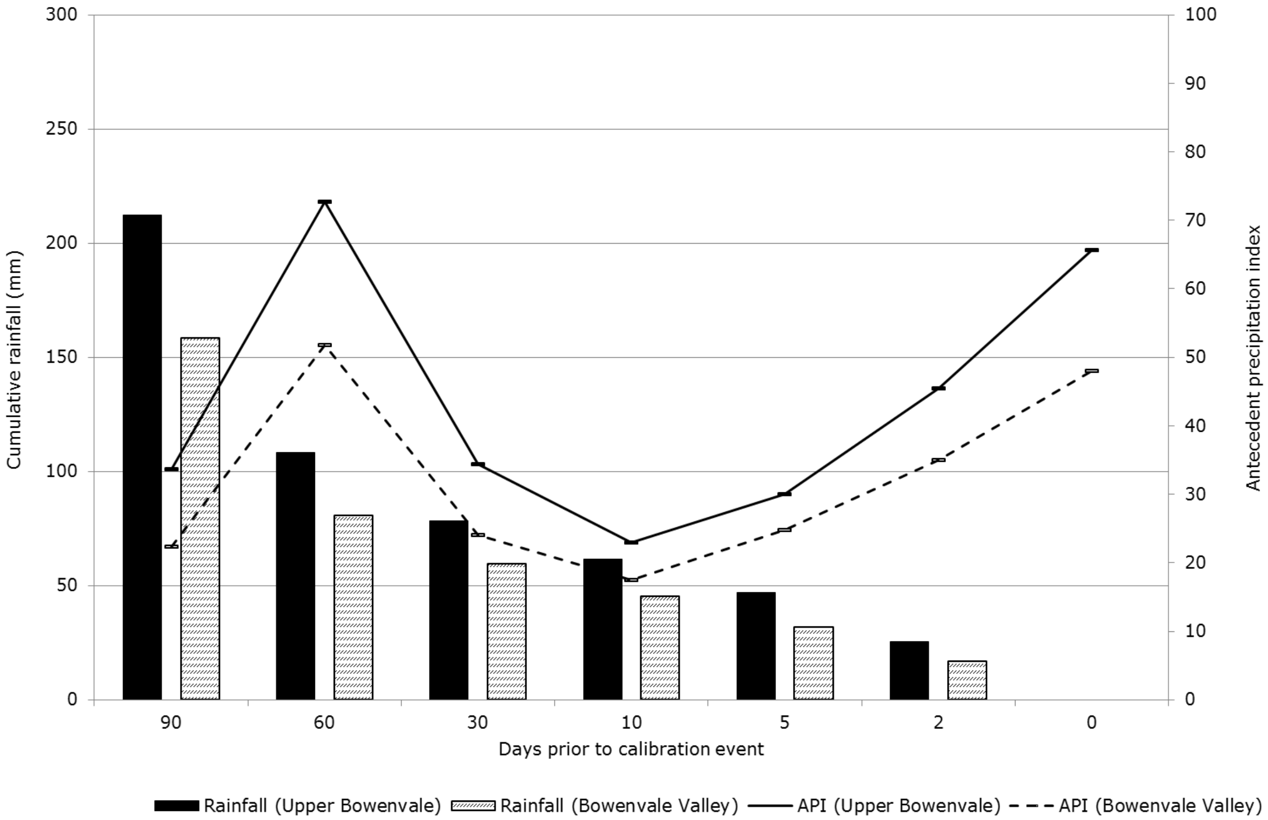


Figure 6: Antecedent rainfall and API (Bowenvale March 2014)



4.3 RORB MODEL DEVELOPMENT

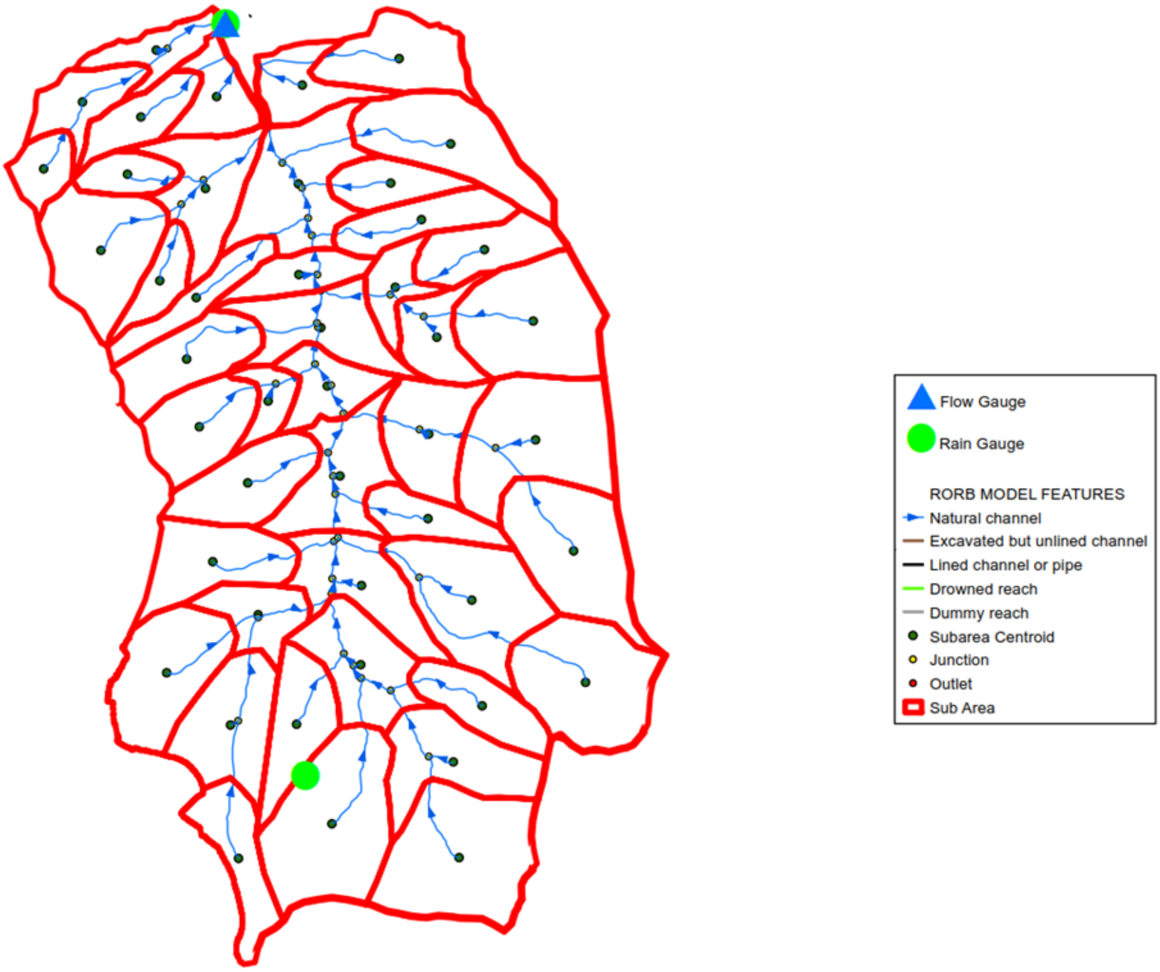
4.3.1 NETWORK SETUP

The network representation of the Bowenvale catchment RORB model is shown in Figure 7. The 320 hectare catchment area upstream of the gauge was divided into 46 subareas which are broadly similar in size.

Within each subarea the spatial rainfall distribution is assumed to be uniform and the overland flow hydrograph for each subarea is determined by converting the rainfall excess hyetograph at the catchment centroid into a direct runoff hydrograph. Each subarea hydrograph becomes an input to the stream network at the catchment centroid and is routed along the stream network to the catchment outlet at the Bowenvale Flume.

A key feature of the RORB runoff routing conceptualisation is that the translation and attenuation effects experienced by the runoff inputs on their way to the catchment outlet have to be represented in the routing through the stream links (reaches). The storage parameter (k) of the an individual routing element depends on the size of the total catchment being modelled and thus for wider application to the city-wide project, subarea sizes remained consistent across the Port Hills catchments, and also to ensure that, ideally, a minimum of four subareas contributed to each desired design hydrograph output location.

Figure 7: Subarea and reach representation within the RORB Model (Bowenvale Catchment)



4.3.2 INTERPOLATION OF MODEL RAINFALL INPUTS

The high rainfall gradient between the Upper Bowenvale and Bowenvale Valley rainfall gauges mentioned previously is apparent not only in the calibration rainfall data summarised in Table 2 (above) but also in the generalised design rainfall intensities in the WWDG (2011).

It is therefore presumed that a distinct rainfall gradient between higher elevations on the Port Hills and the flat areas of the city would be a characteristic of rainfall distribution in Christchurch in a general sense. To establish input rainfall time-series for model calibration, the individual rainfall time-series' from pluviographs located across the city were interpolated spatially to produce a two-dimensional rainfall time-series. The input rainfall time-series for each model subarea was then obtained from the two-dimensional time-series at the subarea centroid.

The approach made sound use of the available data and was compatible with both the rain on mesh and network runoff routing models used in the project. However, because there are few rain gauges located at higher elevations and there is a distinct rainfall gradient around the Port Hills, there is some remaining uncertainty around the accuracy of spatial rainfall inputs. The use of rain radar data to improve the accuracy of this spatial distribution was explored but was also subject to its own considerable uncertainty since the weather radar is located south of Christchurch and the Port Hills create a distinct ‘shadow’ effect on the radar images.

4.3.3 RORB MODEL ROUTING PARAMETERS

RORB applies a nonlinear routing formula ($S=kQ^m$) to describe the attenuation and decay of rainfall excess from a subarea. The parameters k and m, which relate the reach storage (S) to the flow (Q), are inputs to the RORB model which were determined through calibration of the model to observed flow hydrographs.

The exponent (m) expresses the degree of nonlinearity of the output hydrograph response and values in range 0.6-0.8 are typical.

The storage coefficient (k) represents the delay or lag time observed in the output hydrograph and is a function of catchment characteristics (kc) and reach characteristics (kr). Reach characteristics (e.g. length) are inputs into the model which are used to directly calculate the kr parameter. The catchment parameter, kc, is one of the most important variables in the RORB model and is best determined by calibration of the model to recorded data.

4.3.4 RORB MODEL LOSS PARAMETERS

Losses can vary dramatically across catchments. Often an initial loss dominates the loss processes and a smaller continuing loss persists through the storm. In order to determine the rainfall excess at each subarea, RORB applies an initial/continuing loss model approach.

It is noted that the Horton’s loss model, whereby the continuing loss decays exponentially with time, has previously been applied widely across the Christchurch region in preference to an initial/continuing loss model. For the poorly drained, low permeability loess soils of the Port Hills catchments the recommended Horton’s infiltration decay rate exponent in WWDG (2011) is 1.5 $x10^{-3}$. For a Standard Horton’s loss model, this makes the approximate time to decay to the ultimate constant infiltration rate approximately 1.5 hours. The two loss models are thus similar beyond of the initial 1.5 hours from the start of a given event/onset of decay for the recommended WWDG time decay value. However, the earlier calibration work undertaken by Wong (2005), established the much lower decay rate of $3.5x10^{-5}$, which would give rise to a greater difference between the two Horton’s methods.

As with the parameters kc and m, the initial and continuing loss values were determined with the RORB model based on fitting of parameters within a credible range to observed flow hydrographs.

4.4 RORB MODEL CALIBRATION

With little information to justify a spatial variation in storage and loss parameters due to soil variability across the Port Hills, and limited recorded data to calibrate such variations to, the aim of the calibration was to establish kc and m values which could be applied across all of the Port Hills catchments, with adjustment to kc based on catchment area where appropriate.

RORB has functionality to assist with the derivation of loss parameters for comparison with calibration data through the use of ‘FIT’ runs. In this mode the initial loss is nominated by the user and the program calculates the continuing loss rate by iteratively achieving a volume balance of rainfall-excess with measured surface runoff. This satisfies continuity, however volumetric errors in the input rainfall data will affect the values of the derived loss parameters.

With only two significant flood events used for model calibration and verification, the value of kc was initially determined based on fitting of the various model parameters to the recorded data for the June 2013 event at Bowenvale. The model was then verified against the larger March 2014 event, which had more uncertain data, and also against the runoff estimates for the June 2013 event in the Hoon Hay catchment.

A sequential approach was undertaken to determine the optimum fit of the four calibration parameters; kc, m, initial loss and continuing loss. The loss parameters were first adjusted to match the hydrograph volume and the routing parameters were next adjusted to optimise the hydrograph shape.

4.4.1 PARAMETER FITTING

The June 2013 flood event within the Bowenvale catchment was first investigated with the RORB network model. Initial and continuing loss values of 17.5 mm and 1.25 mm/hour indicated the best overall hydrograph volume match for that event. Corresponding optimum values of kc and m values of 2 and 0.8, respectively, were obtained. Figure 8 shows the calibrated model hydrograph compared with the recorded gauge hydrograph.

Figure 8: June 2013 Calibration Results [kc/m=2.0/0.8, IL/CL=17.5/1.25]

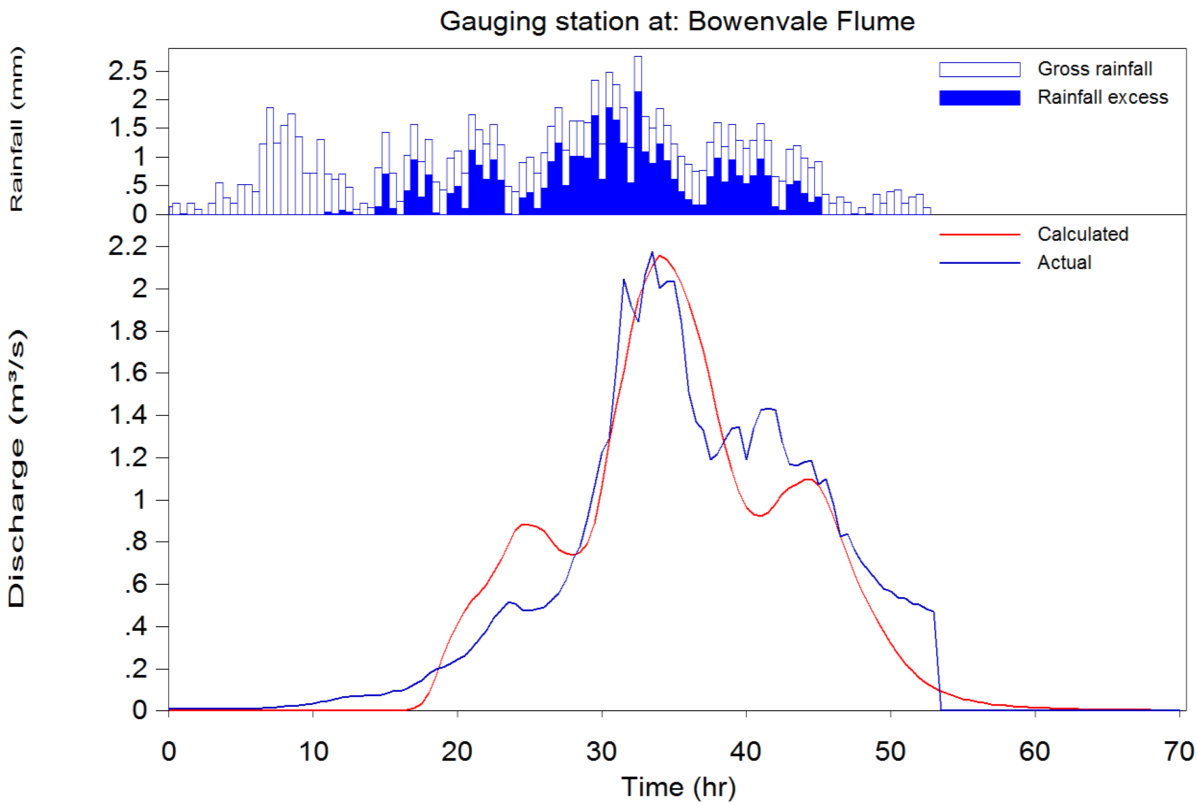


Table 3 summaries the key performance indicators for the model calibration result by comparing several important parameters from the hydrographs. The peak discharge and overall flow volume were predicted to within a 3% error margin. The time to peak and lag to peak were predicted to within half an hour; it is noted that the hyetograph inputs were in half hourly increments therefore any difference in these measures are reported at half hourly increments. The time and lag to the centre of mass of the hydrograph were predicted within less than an hour.

Table 3 Calibration performance for key hydrograph parameters

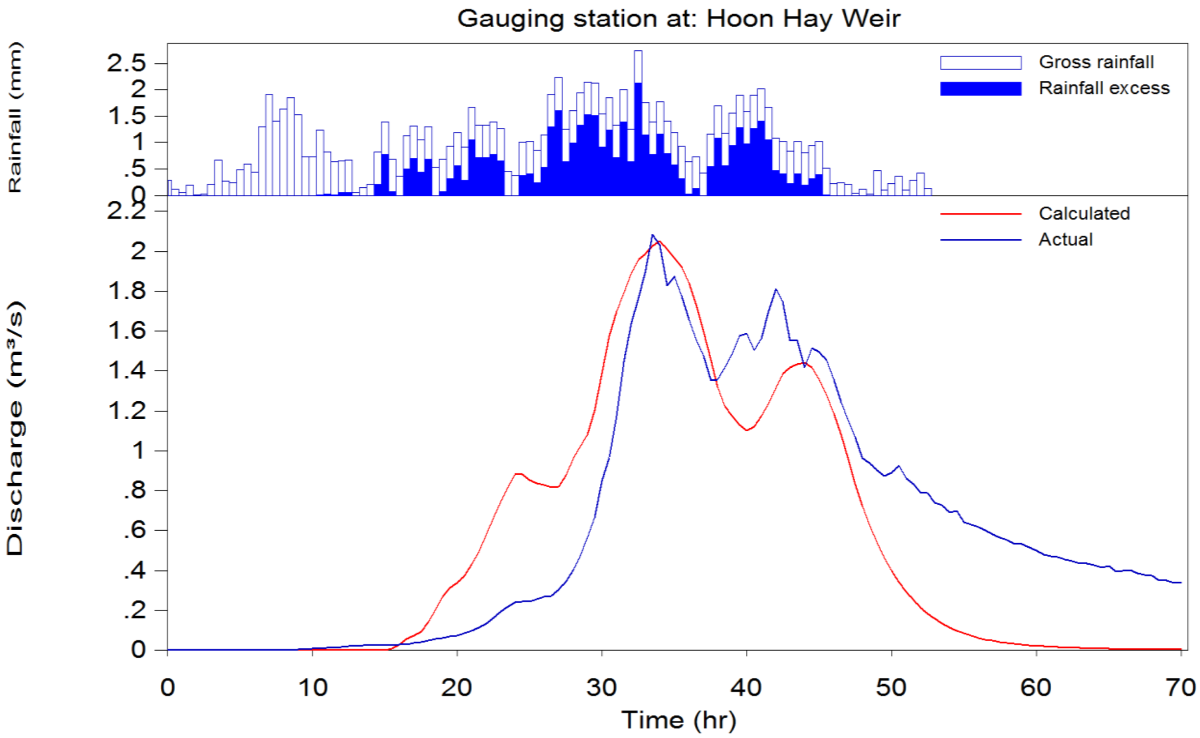
	Calculated	**Actual**	**Absolute Error**	**Error (%)**
Peak Discharge (m^3/s)	2.2	2.2	0.0	-0.8
Time to peak (hrs)	34.0	33.5	0.5	1.5
Volume (m^3)	0.12×10^6	0.13×10^6	-0.35×10^4	-2.8
Time to centroid (hrs)	35.4	36.2	-0.8	-2.3
Lag (mass)	4.6	5.5	-0.8	-15.3
Lag to peak (hours)	3.2	2.7	0.5	18.3

4.4.2 MODEL VERIFICATION

The model was verified through simulation of the June 2013 flood event for the nearby Hoon Hay catchment. This verification test was used to confirm the validity of the model for application to other catchments across the Port Hills. The same initial and continuing loss values (17.5 mm and 1.25 mm/hr) were applied to the catchment and the same kc/m values of 2.0/0.8 were also applied.

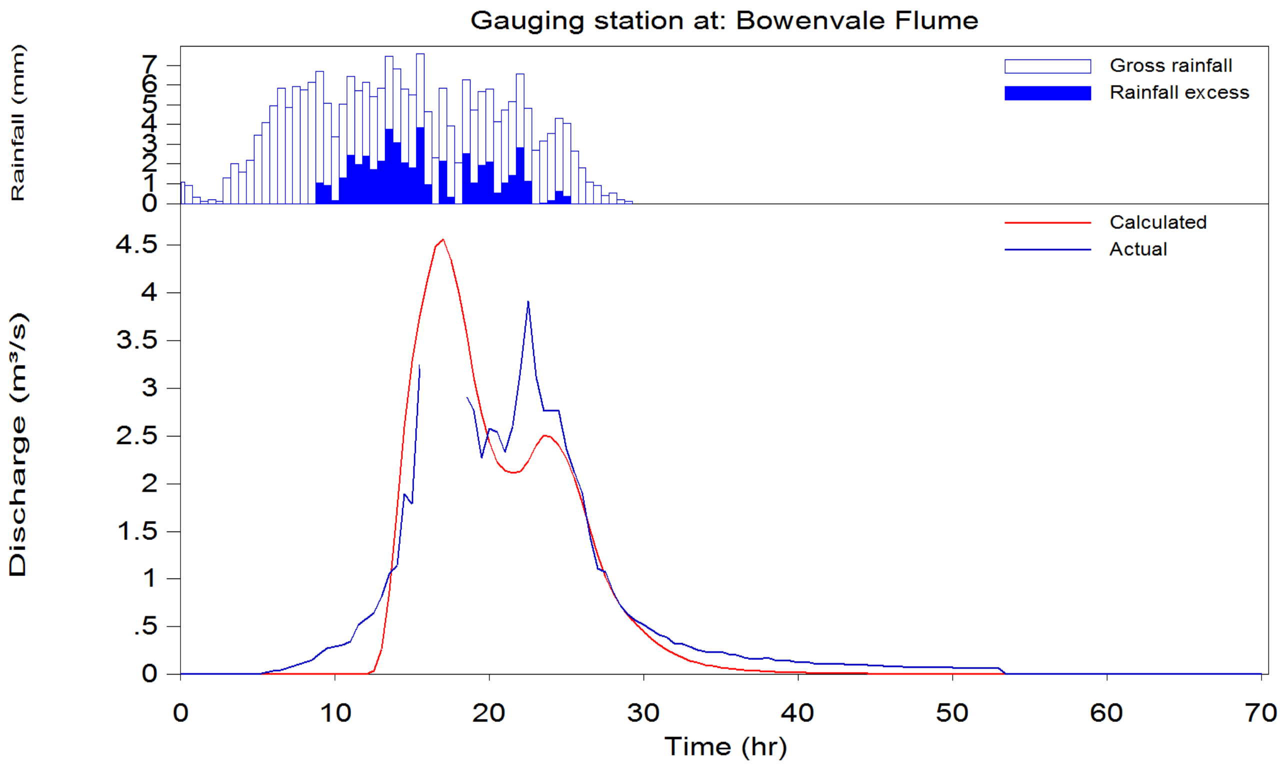
Figure 9 shows the comparison of the predicted and recorded hydrographs at the Hoon Hay weir gauge site. The model very accurately predicted the peak value of 2.1 m^3/s and the time to peak is predicted within half an hour (predicted at 34 hours versus a recorded value of 33.5 hours). The general hydrograph shape is matched and the volume is within 15% despite the model hydrograph rising and receding limbs being much steeper. The application of the calibrated model parameters to neighbouring catchments in the Port Hills was deemed appropriate based on the model verification using the Hoon Hay site data.

Figure 9: Model Verification: June 2013 Hoon Hay [kc/m=2.0/0.8, IL/CL=17.5/1.25]



The model was further verified through simulation of the March 2014 flood event for the Bowenvale catchment. As was shown in Table 1, this was a much shorter and more intense rainfall event as compared with the June 2013 event. Using the same loss parameters resulted in overestimation of the peak discharge with an error of over 150%. It was necessary to increase the initial loss and continuing loss values to large values of 60 mm and 7.5 mm/hr, respectively, to obtain a similar shape in the rising and receding limbs of the predicted hydrograph. It is not credible to compare volumes or peak flows for this event since there is missing data from the flow gauge during a significant period of the event. As noted previously, there also remains significant uncertainty in the spatial rainfall distribution for this event.

Figure 10: Model Verification: March2014 Bowenvale [kc/m=2.0/0.8, IL/CL=60/7.5]



4.4.3 MODEL SENSITIVITY ANALYSIS

In order to gain confidence in applying the model across several catchments and design events it was considered important to understand the sensitivity of the hydrograph outputs to the calibrated kc and m values.

The value of kc is theoretically related to the value of m. Consequently, a kc value determined with one value of m cannot validly be used with another value for the same catchment network model.

The RORB user manual suggests that if the m value is changed between runs, an approximate adjustment factor for kc is $(Qp/2)^{m-m'}$, where Qp is the peak discharge, m the old and m' the new value of the exponent. For the small peak runoff values characteristic of the Port Hills for the available calibration events, using this equation the value of kc for m values between 0.6 and 0.9 remains at 2.0.

The June 2013 flood event in the Bowenvale catchment was simulated with the RORB model using a kc value of 2.0 and m values varying between 0.6 and 0.9. Simulations with the kc value varied slightly but the m value remaining constant were also performed. Table 4 shows the results of these trials with the peak discharge error and volumetric error results shown for each scenario.

For fixed initial and continuing loss values of 17.5 mm and 1.25 mm/hr, respectively, Table 4 shows that the effect of varying m for a constant kc value of 2.0 is a relatively minor change in the peak discharge and overall volume, the hydrograph shape is naturally influenced more by the non-linearity parameter m. Table 4 also shows that varying the values of the initial and continuing losses has a much greater effect on the peak discharge and volume and therefore the selection of loss values for design event scenarios is critical for prediction of design flows.

Table 4 Sensitivity Test Results: Peak Discharge error (%)/Volume error (%) for each parameter set

Peak Discharge / Volume Error	**Initial (mm) / Continuing Loss (mm/hr)**		
Kc/m Parameters	**10.00/0.5**	**17.5/1.25 (calibrated parameters)**	**20.0/3.00**
1/0.8	43.0% / 66.0%	12.4% / -2.9%	-57.5% / -82.2%
2/0.6	19.6% / 66.0%	-11.5% / -2.9%	-77.1% / -82.2%
2/0.7	30.5% / 65.7%	-0.3% / -3.1%	-71.5% / -82.2%
2/0.8 (calibrated parameters)	29.9% / 66.2%	**-0.8% / -2.8%**	-69.3% / -82.2%
2/0.9	28.3% / 66.3%	-1.8% / -2.7%	-67.6% / -81.1%
3/0.8	10.0% / 0.5%	17.5% / 1.25%	20.0% / 3.0%

5 DEVELOPMENT OF REGIONAL RELATIONSHIPS FOR PARAMETER ESTIMATION

The use of rainfall runoff models like the RORB model applied within the city-wide project requires estimation of model parameters, and there are two basic approaches:

- If there is recorded streamflow and rainfall data for one or more events, parameters can be evaluated by calibration of the model against the recorded data; this was the situation for the city-wide modelling project.

- If recorded streamflow and rainfall data are unavailable, model parameters must be estimated from nearby catchments, regional empirical relationships or theoretically derived values.

The outcomes from the runoff routing models examined in the city-wide project demonstrate the useful role that RORB and similar models have for estimation of flood hydrographs for New Zealand catchments; and their immediate use for gauged catchments in New Zealand is unimpeded where the stream flow and rainfall data of the requisite quality is available.

However, the RORB model has not been used widely in New Zealand, so there is limited published data regarding parameter estimation for gauged catchments which could be used to guide application of the model to ungauged catchments. The opposite is true in Australia, where the RORB model is well supported by understanding of regional relationships for parameter estimation, such as those published in Australian Rainfall and Runoff, which enable confident and informed use of the model to ungauged catchments.

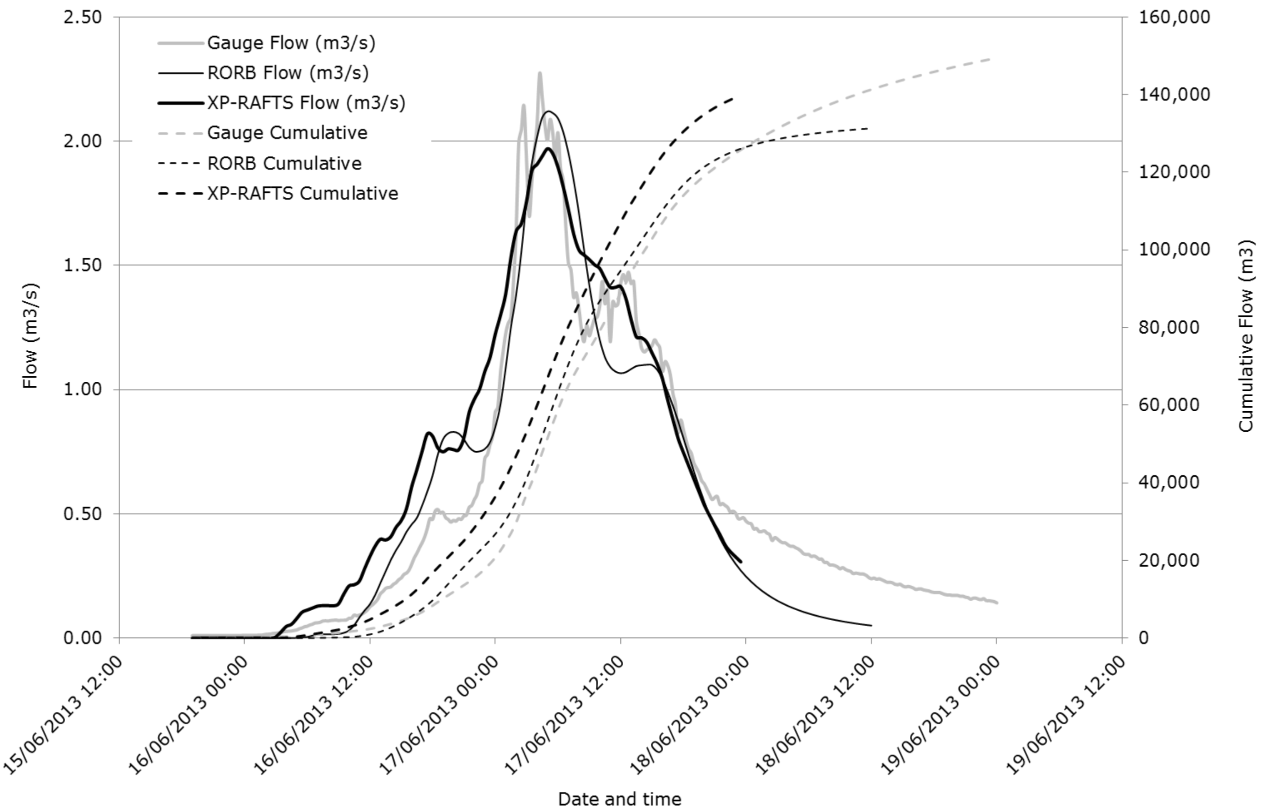
The outcomes and parameters of model calibration to the Port Hills catchments of Christchurch presented in this paper provide an initial understanding of parameters that may be applicable to catchments of that type. The understanding may be expanded geographically, to different catchment types, and over time to support the development of regional parameter relationships that would support more wide-spread and confident use of the model to ungauged catchments.

6 COMPARATIVE CALIBRATION OF XP-RAFTS MODEL FOR BOWENVALE CATCHMENT

A brief investigation of the potential use of the XP-RAFTS model was also undertaken as part of the city-wide modelling project. XP-RAFTS is a network runoff routing model and in that sense fits within the same category as the RORB model that was ultimately adopted. However, the XP-RAFTS model is conceptually different in its approach to runoff routing; the routing (storage) is applied to rainfall excess at the model subcatchment rather than at the model reach (as is the case in the RORB model).

Figure 11 (below) presents a comparison of the RORB model results against the XP-RAFTS model for a similar set of initial and continuing loss parameters and the same catchment delineation. Despite using a different runoff routing approach, the XP-RAFTS model was capable of similar prediction of stream flow.

Figure 11: Comparison of gauge recorded flow, RORB model and XP-RAFTS model results



7 CONCLUSIONS

A RORB model was adopted for estimation of runoff from the Port Hills catchments in Christchurch, as part of the city-wide modelling project.

The model calibration and validation demonstrates network runoff routing models of this type are capable of reasonably accurate prediction of flood hydrographs from the Port Hills catchments, and that the parameters developed for a given gauged catchment can be applied with reasonable confidence to catchments with similar characteristics and a similar model development approach was adopted.

Hydrograph prediction was sensitive to the loss parameters applied; initial loss and continuing loss in the case of the RORB model. The relatively low rainfall intensity of Christchurch, including the calibration events considered in the study, probably contributes to the apparent sensitivity. The calibrated catchment losses are high in relation to rainfall intensity.

The RORB and XP-RAFTS runoff-routing models are not widely used in New Zealand, and accordingly regional relationships for parameter estimation are not well developed. The outcomes and parameters of model calibration to the Port Hills catchments of Christchurch provide an initial understanding of parameters that may be applicable where catchment and rainfall characteristics are similar. Further investigation of gauged catchments in New Zealand would be required to support the understanding of regional relationships for parameter estimation and wider use of these models for estimation of rainfall runoff in ungauged catchments.

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