IN THE MATTER: of the Resource Management Act 1991 (**RMA**)

AND

IN THE MATTER: Proposed Plan Change 2: Pukehangi Heights to the Rotorua District Plan under Part 5, Sub-Part 5 – Streamlined Planning Process and Schedule 1 Part 5 of the RMA

STATEMENT OF EVIDENCE OF PETER MORLEY WEST ON BEHALF OF BAY OF PLENTY REGIONAL COUNCIL – HYDROLOGICAL BASIS FOR ANALYSIS

18 September 2020

Qualifications and Experience

1. My full name is Peter Morley West. I am a consulting engineer and Director of Blue Duck Design Ltd, a consultancy specialising in hydrological design and analysis of flood protection and flood prediction systems. I have held this position for 10 years, since August 2010.

2. Prior to this I was employed by the Bay of Plenty Regional Council as Environmental Engineer for 5 years starting in May 2005; and Graduate Engineer for the period starting October 2003.

3. I have 16 years experience in the field of hydrological engineering including supporting local government regulatory RMA processes. I've provided expert witness evidence to several consent hearings and environment court hearings.

4. I hold a bachelor's degree in Engineering: B.E. (Hons) in Natural Resources Engineering from Canterbury University.

5. I am a Chartered Professional Engineer (CPEng) in N.Z. and an International Professional Engineer (IntPE). My CPEng practice area description includes river catchment hydrology, river modelling and flood forecasting, flood protection and erosion protection design.

6. My professional memberships include:

    - Chartered Member of Engineering New Zealand (CMEngNZ)
    - Member of the New Zealand Hydrological Society

7. I have read the Expert Witness Code of Conduct set out in the Environment Court's Practice Note 2014 and I agree to comply with it. I confirm that the issues addressed in this statement of evidence are within my area of expertise, except where I state I am relying on the specified evidence of another person. I have not omitted to consider material facts known to me that might alter or detract from my expressed opinion.

Background and Scope of Evidence

8. My evidence relates to the hydrological modelling of the plan change proposal in the context of the wider Utuhina Stream catchment. I will cover:

a) The establishment of the calibrated hydrological model of the wider Utuhina Stream catchment;

b) The selection and recommendation of appropriate rainstorm scenarios to be used for assessing effects of the proposed development;

c) Development of a method to assess the stormwater effects in the context of currently permitted future urban land development in the catchment;

d) Performance-checking of the potential on-site storm water detention ponds identified by RLC;

Utuhina Stream Catchment Hydrological Model

Summary: A calibrated hydrological model was established that provides an underlying connective framework to detailed hydraulic modelling components in the Utuhina Stream catchment. This model was used in the PC2 modelling of environmental effects.

9. In 2019 I was engaged by the Bay of Plenty Regional Council (BOPRC) to establish a hydrological model of the Utuhina Stream catchment. The BOPRC team refers to this as the NLR model. In this statement I refer to the Hydrological Model or sometimes The Model when the meaning is clear. The model is intended to be used for flood forecasting purposes, and to support design investigations within the catchment. Details of the model and its calibration are included in my report to BOPRC dated 26 September 2019, which is appended to this statement at Appendix 2.

10. The model calculates runoff from rainfall at 122 separate sub-catchments within the wider Utuhina Stream catchment, based in part on their soil types and ground covers. Stream flows from runoff are tracked through a network of routing branches to Lake Rotorua.

11. The model estimates stream flows over time at every point in its network, however due to its mathematical basis, it does not estimate water levels directly. The intended use of this type of model is to provide inflows at the boundaries of (one or more) detailed "hydraulic" models that resolve the water levels and flows at a finer resolution using a more explicit mathematical representation

12. For the PC2 plan change, this hydrological model has been used as the wider connective framework to support detailed modelling of storm-water networks (by WSP

for RLC) and of stream channel networks (by DHI for BOPRC). The hydrological model connected with the DHI stream-and-flood-plain model is often called the GUCM (Greater Utuhina Catchment Model) within the collaborative modelling teams. A map showing how the various models are configured to interact during the PC2 design scenarios is shown as ***Figure 1*** in Appendix 1.

13. The model was calibrated against 5 large flood events, using raingauges and weather-radar to determine the magnitude, timing, and distribution of rainfall intensities within the observed storms. For example a map of the storm rainfall totals observed by raingauge-corrected radar for the April 29 2018 storm are shown in ***Figure 2***.

14. The model's calibration performance was evaluated by comparison with the rated flow from the stream gauge on the Utuhina Stream at Depot Street. For example, a comparison of model flows against rated observed flows for the April 29 2018 flood is shown in *Figure 3*.

15. The model's calibration was further refined in collaboration with DHI who's model of the lower stream reaches includes an explicit representation of the stream channel's hydraulic dynamics. This resulted in a change for several of the upper catchment soil parameters. The updated table of soil parameters is appended to this statement (Appendix 3).

16. The model is not constrained as to how rainfall is applied, however a synthetic rainstorm generator is included that has been used to run design simulations for the assessment of effects of the PC2 development. The rainstorm profile selected is a 72 hour long fully-nested storm (***Figure 4***). Spatially it has a circular plan-form that is centred over the plan change area. The size of the rainstorm is explicitly determined. The intensity, duration, probability and spatial aspects of this storm have been determined in direct accordance with HIRDS v4 (NIWA 2018). *Figure 5* shows an example of the spatial storm pattern. This is the spatial distribution of the 1 hour duration component of a storm centred over the upper catchment. Note for the plan change modelling we centred the storm over the plan change area itself.

17. ***Figure 6*** shows the model discharge results at the location of the Utuhina stream recorder at Depot Street for the 1%AEP current climate and 1%AEP 3.68degrees climate scenario. Note that the current climate scenario peak flow result of 55 m3/s is almost exactly the same as the 1%AEP design stream flow calculated by flow gauge

statistics (as shown in Peter Blackwood's evidence). Also of note in ***Figure 6*** is the magnitude of increase in flood stress that these lower reaches are expected to experience in coming decades.

Rainstorm Scenarios

18. **Summary: The rainstorm scenarios used in the PC2 modelling were agreed to be appropriate. However it is important to ensure that future mitigation design adopts a similar suitably rigorous approach. Details of future methodology should be controlled within the plan change provisions.**

19. Earlier versions of the RLC s42A report and the WSP Stormwater Report expressed the view that the hydrological analysis of the plan change was "overly conservative" due to the use of a 72 hour long nested rainstorm as a design scenario.

20. The basis for these statements was addressed in detail at the 25 August Stormwater Expert Witness Caucusing. On exchange of information it was agreed by all that the analysis was not overly conservative but "appropriately conservative" and that the WSP Stormwater Report would be amended accordingly.

21. Despite this agreement in caucusing, storm scenarios remain an active issue, featuring in the evidence of both Mr Liam Foster, and Mr Mark Pennington. In several places the WSP Stormwater Report asserts that the use of this storm profile is "conservative" and makes recommendations to seek alternatives for future modelling work. I consider that "conservative" is misleading and that the analysis is "appropriately conservative". In my opinion plan change provisions should ensure that a similar suitably rigorous methodology is applied for any future analysis.

22. I understand that further assessments of effects of this plan change are still required to be made in the future. Without a further full-catchment hydrological assessment of the full PC-area development, **current PC2 provisions do not ensure that the actual mitigation will be as effective as the hypothetical measures** presented by WSP; or that cumulative effects of the final development will be adequately assessed.

23. I believe that it is within the scope of the plan change provisions to include guidance and/or requirements for the methods to be used for such future assessments. To support the hearing panel on this aspect I intend to present information regarding storm scenarios.

24. I want to make the following points:

(a) In-cautious or conflicted selection from a plethora of "industry standard" methods can easily mis-represent the hydrological effects of land development.

(b) The Utuhina stream catchment and its tributaries and sub-catchments form a complex dynamic environment that responds to multiple facets of storm behaviour, making effects assessment complicated.

(c) Fully comprehensive assessment of effects is not entirely possible from one single storm profile, and so a degree of conservatism is required;

(d) A high degree of care should be exercised in determining an appropriate storm scenario methodology for future analysis. This degree of care should be ensured through plan change provisions.

25. There are many methods for applying rainfall to design of stormwater management systems. Some of these are presented in the conference paper referred to in the evidence of Mark Pennington (Groves et al 2020). The paper's lead author also wrote the WSP Stormwater Report for this plan change. The paper points out that depending on which method is selected, for a given development scenario a wide range of pond sizes will result. All of the methods assessed in that study are industry standards. Some of the (hypothetical) designs presented in the paper resulted in under-sized detention ponds. These represent a design failure for any flood impacted communities downstream.

26. As presented in the WSP Stormwater Report (introduced into evidence as appendix to Mr Foster's statement) analysing the 72 hour rainstorm resulted in increased detention pond sizes over WSP's preferred 24 hour storm (s2.2.3 p13). The overall increase was from about 6 hectares to 14 hectares. This indicates that the system is indeed sensitive to storms longer than 24 hours. As would be expected because the ponds' residence times are much longer than 24 hours. Clearly if longer storms are impactful on design, and they occur naturally, then we should design for them.

27. There is no dispute that such storms occur just as frequently as shorter duration storms. Each component of the 72 hour nested storm that was used for this analysis is in direct accordance with statistical analysis of rainstorm probability carried out using local raingauges by NIWA. This is published by NIWA in their HIRDS web-based application and detailed in their report (NIWA, 2018).

28. What is questioned however is the nesting of storm components together to create a synthetic "nested" design storm. For example: WSP Stormwater Report 14/9/2020 s3.1.2.2 in Liam Foster's evidence:

> "*As a result, the use of 'nested' storms tends to produce much higher peak discharge when compared to either normalised storm hyetographs (based on typical observed storm events) (McConchie, 2019), flood frequency analysis using observed flow data, or other industry standard temporal patterns, like those identified within recent national guidance (NIWA, 2018)".*
>
> I disagree with part of this statement. The model results from the 72 hour nested storm used in this analysis show a very close agreement with the flood frequency analysis (demonstrated in 17 above). I do agree that nested storms tend to produce higher flows than many industry standard storms patterns. This is well addressed by WSP's Mark Groves outlined in my 25 above. My reading of his work is that he found that many industry standard methods would result in design failure for downstream communities.

29. Conventional nested storms do carry an additional improbability in that the various duration components all occur at the same level of likelihood. It is often pointed out that this doesn't happen in natural storms - which is strictly accurate. But something very similar to this <u>does</u> happen in natural rainstorms. ***Figure 7*** shows the embedded duration-component rain depths observed during the April 2018 Utuhina flood. The figure shows that most of the storm components fall within a narrow band of likelihood. This storm fell on the Utuhina catchment, and it had a 1 hour rainstorm (about 1-in-20 year probability) nested within a 2 hour rainstorm (about 35 year) nested within a 6 hour rainstorm (50 year) etc. The component probabilities are not perfectly aligned, as within the synthetic storm but similar enough to demonstrate that nesting shorter duration storm components within longer ones is what does happen within natural rainstorms - and therefore it is perfectly valid to ask how any stormwater management proposal performs when this occurs.

30. The Utuhina stream catchment, including the stream's tributaries and sub-catchments forms a complex dynamic environment that responds to multiple facets of storm behaviour. There are many different ways that flood-causing rain can naturally fall on the catchment. Some of these ways will test the proposal differently from others - showing different environmental effects.

31. Catchment response times are important: Small, fast storm-water sub-catchments in the urban areas respond more readily to the short-duration components of a storm,

while the longer forested upper-Utuhina subcatchments will respond more to the longer storm components. There are many subcatchments all of different sizes contributing to the Utuhina system. And it's not straightforward either - for example adding an effective detention pond to a small urban catchment will lengthen its characteristic response time from less than one hour to up to several days. Similar to natural storms, a design storm should include a range of both long and short duration components to test how these different subcatchments interact.

32. The storm timing is important, and whether the storm has multiple peaks: Urban sub-catchments along the lower Utuhina and Mangakakahi reaches are susceptible to late bands of rain falling towards the end of a storm, when the main stream channel is swollen, stopping them from draining. This storm profile is sometimes called "heavy ended" and is common in the Bay of Plenty. The increased duration of flooding in the lower river is one acknowledged negative effect of PC2 so representing this late-falling rain is important. ***Figure 8*** shows an example of very intense rain falling at the end of a rainstorm at Whakarewarewa which is near to the Utuhina catchment.

33. The storm timing is important in other ways too: Detention ponds are susceptible to early-falling rain, or rain on the previous day that can fill part of their storage volume before the main rainstorm intensity occurs. Early-falling rain also impacts ground moisture levels, increasing runoff rates. ***Figure 9*** shows an example of significant rain falling the day before the main storm. As presented at the expert witness caucusing, the amount of rain falling on 28 April in this example (the day before the main storm) is very closely reproduced in the first 24 hours of the 1% AEP 72 hour nested storm that was used in the PC2 analysis (the design hyetograph shown in ***Figure 4***).

34. The storm direction and rate of travel are important: Radar observations (for example ***Figure 10***) often show intense cells of rainfall tracking across the catchment, commonly missing nearby raingauges. This touches on the evidence of Mr Mark Pennington where he attempts to find a relationship between the Whakarewarewa raingauge and the Utuhina Stream recorder. The fact is that the raingauge is not in the catchment. Radar observations show that the bulk of storms affecting Utuhina Stream are not adequately represented by that raingauge.

35. Stream systems are most susceptible to storms that track in the direction of stream flow and at a similar speed to the stream's flow. Mobile design storms are not typically used in the stormwater design industry due to the small size of catchments

normally modelled. The Utuhina Stream catchment however is sensitive to storm track direction and speed of travel.

36. These storm features (31-3534) all occur frequently in natural rainstorms over the Utuhina catchment. All will produce a different set of environmental effects. However the practical reality is that computation is limited and modelling must be constrained to a small collection of **representative** synthetic events. The approach taken for the PC2 modelling was a widely-responsive storm profile (the 72-hour nested storm), run over a spectrum of probabilities from 10% AEP (10 year) current-climate to 0.2%AEP (500 year) with full climate change impact. In this way it is intended that most environmental effects would be fairly investigated.

37. In some ways the 72 hour nested storm used for this analysis is conservative: it carries an additional improbability in that the various duration components all occur at the same level of likelihood as discussed in 28 above.

38. As counter-point to 37 above: In some ways the storm is perhaps not conservative enough: it only has one peak for example; it is not heavy-ended; it does not travel in the direction of the stream. It is possible that analysis of these other storm aspects - all of which naturally occur in this catchment within the band of likelihood being studied - would reveal otherwise un-identified environmental effects of the proposed development.

39. However we are practically constrained to modelling only a limited number of representative scenarios. A high degree of care should therefore be applied to selecting these scenarios. An appropriate degree of conservatism is required to counter the limitation in 38 above.

40. The method details, such as rainstorm scenarios, for any future analysis should be controlled through this plan change process. The responsibility for confirming the appropriateness of the future methodology should be shared by the regulatory bodies according to their statutory roles.

41. I've been involved in the drafting of the suggested amendments to the plan change provisions by the Regional Council (in the evidence of Nathan Te Pairi). I support these amended provisions in particular the requirement for the Stormwater Management Plan mitigation design methodology to be signed off by the Regional Council. The reason for this is to ensure that any future proposal has mitigation measures at least as effective as WSP's hypothetical Mitigation Scenario 15. The

inputs into any future modelling work (as noted above in 26) can greatly affect the outcome of any modelled proposal and therefore should be controlled by the provisions. And also to ensure that a Stormwater Management Plan appropriately constrains future subdivision and discharge consents to ensure that cumulative stormwater effects of the plan change as a whole are managed at implementation stage.

Future Environment Scenario

Summary: The methodology used by BOPRC to assess the effects of the plan change in the context of permitted future urban development outside of the PC2 area is described.

42. Land alongside the lower Utuhina Stream and the lower reaches of its tributaries the Mangakakahi and Otamatea streams is currently at higher-than-acceptable flood risk. This is covered in evidence by Kathy Thiel-Lardon. Flooding in these areas is contributed to by runoff from urban areas, which are only partially developed with respect to that currently permitted by the district plan. To understand the environmental effects of the PC2 plan change in the context of this potential future environment, a special scenario was modelled. The collaborative modelling teams called this scenario the "City Future" scenario.

43. The currently existing environment "City Now" scenario is based on calibrated modelling - both for the WSP models of the stormwater networks, and the BOPRC modelling. In the urban areas, the precision afforded through these calibrations was low in both cases due to limitations of only one rated stream-flow gauge serving multiple stream tributaries, however literature guidance and engineering judgement were applied, and the models give realistic results.

44. The following notes relate to the permitted future urban development scenario within the BOPRC (GUCM) modelling. A GIS analysis was carried out that determined the zoned class of each land parcel in the catchment and applied impervious-surface percentages that were suggested by RLC's planning team as practical expectations for maximum future development. ***Figure 12*** shows a map of the resulting distribution of surface imperviousness.

45. Back calculation from calibration, based on assumed existing percentages of imperviousness in these catchments led to a pervious-surface proportional runoff coefficient of C=0.18. Impervious surface runoff was applied at C=0.85 based on

literature guidance (BOPRC Guideline 2012/02; DBH, 2011). A further GIS analysis was used to determine the sub-catchment blended percentage imperviousness by integrating that value from all of the land parcels within each subcatchment. Subcatchment runoff parameters were thus determined for the "City Future" scenario.

Detention Pond dynamic performance check

Summary: Following investigation, I can endorse the dynamic mechanism for mitigation measure detention pond solution

46. I carried out checks on the dynamic performance of a selection of detention ponds specified for representative mitigation (Mitigation Scenario 15) in the WSP Stormwater Report. Inspection of an earlier version (Mitigation Scenario 14) for the stormwater expert witness caucusing had found inappropriately long drain-down-times of up to 7 days.

47. The pond drain-down time performance criteria agreed at caucusing was that the lower volume (that served only by the primary outlet) would drain at least half its volume in 24 hours within the design storm scenario from when the secondary outlet stops discharging.

48. Details of SCS curve numbers, initial-abstraction rates, subcatchment areas, pond sizes, and pond outlet configurations were taken from the WSP Stormwater Report (September 14 2020). A separate SCS method hydrological response (for pond inflow) was run within my own software. Outlet discharge rates were determined for the range of levels based on the large-orifice inlet-controlled method. The inflow hydrograph was routed through the pond. The results (for example ***Figure 11***) compared closely with those provided by WSP with some tolerance for my necessary assumptions of unknowns: pond side-slope and pond surface curve number.

49. Following investigation I can endorse the dynamic mechanism for the mitigation measures detention ponds.

Conclusions

50. A calibrated hydrological model was established that provides an underlying connective framework to detailed hydraulic modelling components in the Utuhina Stream catchment.

51. A 72 hour nested rainstorm scenario was developed and was used to assess the cumulative effects of land development within the plan change area on flooding in the lower catchment. Expert witnesses agree that the scenario is appropriate for cumulative effects assessment.

52. The selection of appropriate rainstorm scenarios for modelling is essential to the validity or otherwise of any future assessment of effects (especially cumulative effects) in the plan change area; and should be controlled in the plan change provisions to ensure that actual mitigation measures perform as effectively as the hypothetical ones presented.

53. The methodology used by BOPRC to assess the effects of the plan change in the context of permitted future urban development outside of the PC2 area is described.

54. Checks on the dynamic performance of flood mitigation detention ponds have been carried out and found to be in order.

DATE 18 September 2020

Peter Morley West

REFERENCES

Groves, M, Hellberg, B, Shicker, B and Bird, W, *Does your detention meet your intention?,* Water New Zealand Stormwater Conference, August 2020.

Hydrological and Hydraulic Guidelines, BOPRC Guideline 2012/02, Table 5.2

NZ Building Code Documents E1 Surface Water 2011

NIWA, August 2018, High Intensity Rainfall Design System - version 4, NIWA Client Report Number 2018022CH

Appendix 1: Figures

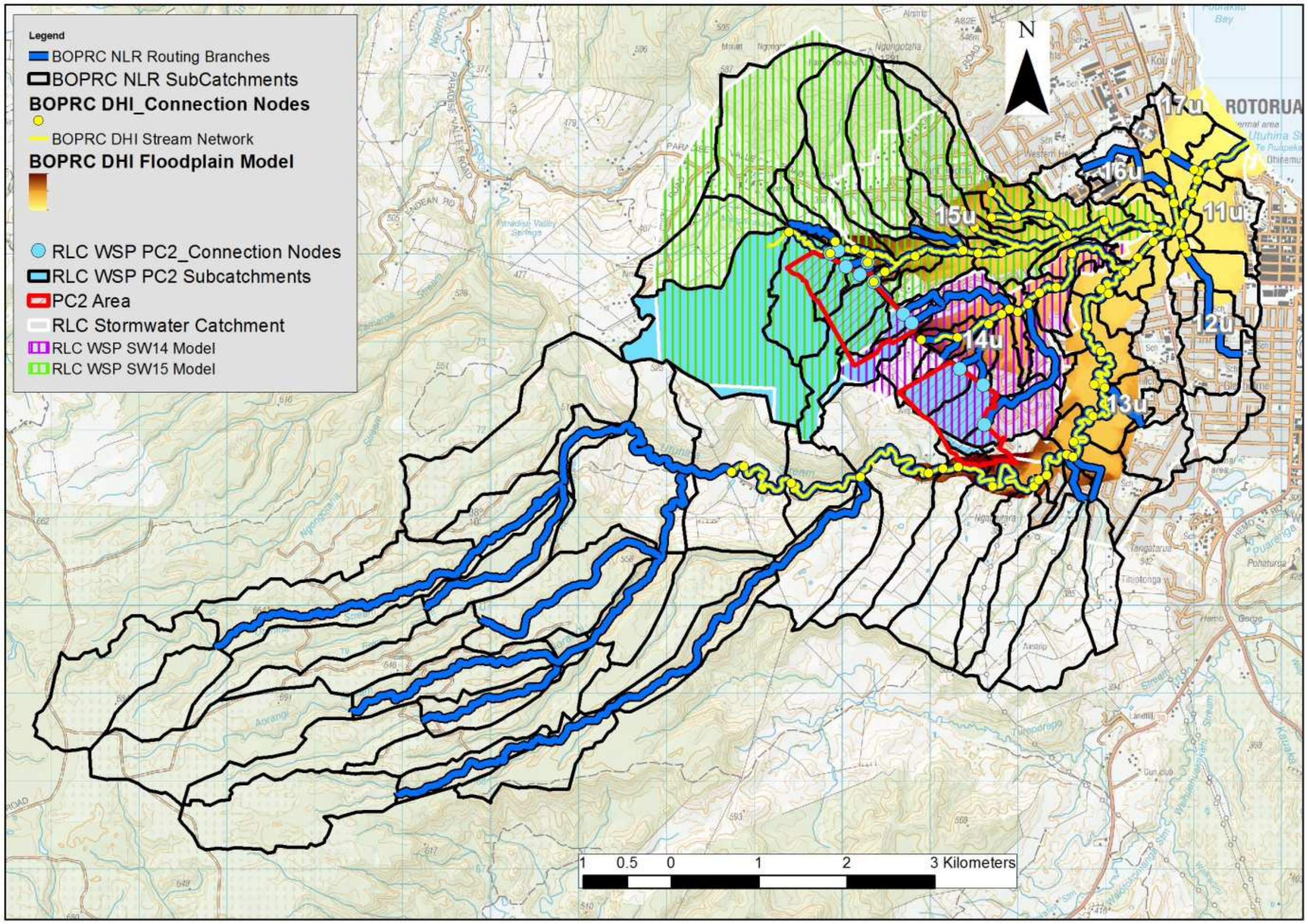

Figure 1: Map showing collaborative modelling layout with BOPRC Hydrological Model (black polygon subcatchments and blue routing branches; BOPRC hydraulic model by DHI (yellow floodplain area and yellow stream channel network); RLC hydraulic model by WSP (coloured polygon catchments). Also showing PC2 area with red polygons.

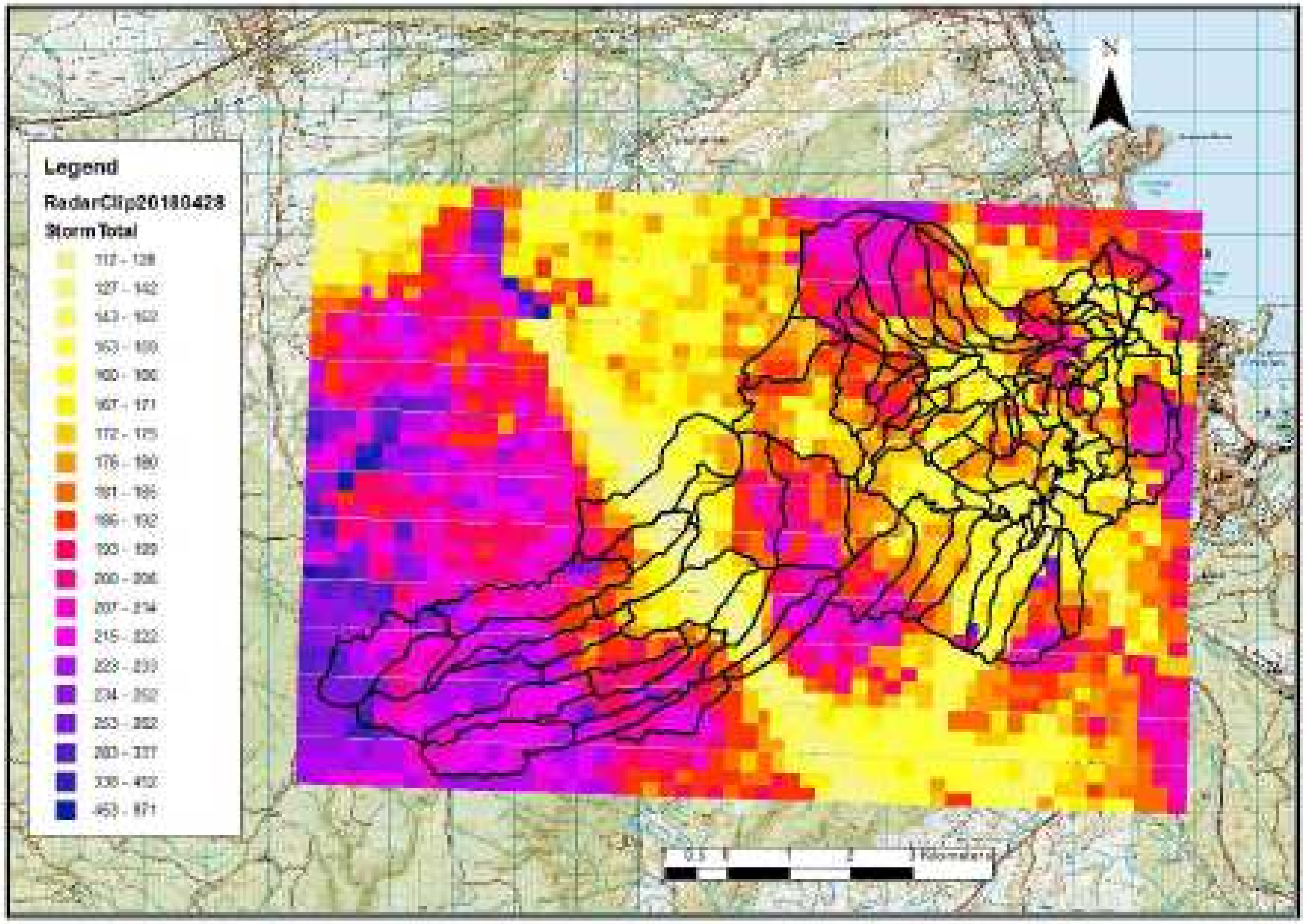

Figure 2: Storm total rainfall radar observations (mm) for April 28 - 30 2018.

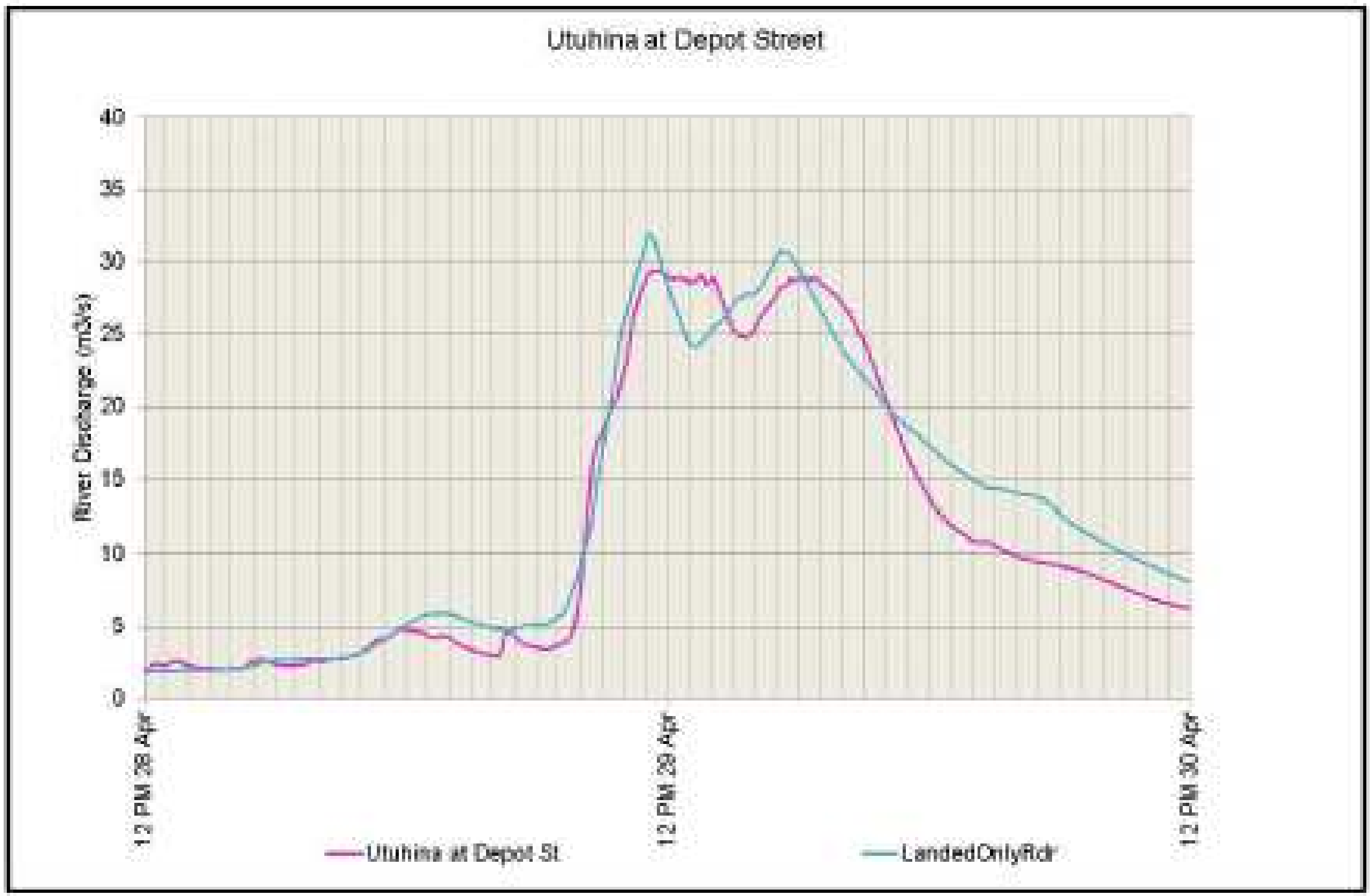

Figure 3: Model discharge results at Depot Street stream gauge on Utuhina Stream for April 29 2018 (blue line) overlaid with stream gauge rated flow hydrograph (pink line).

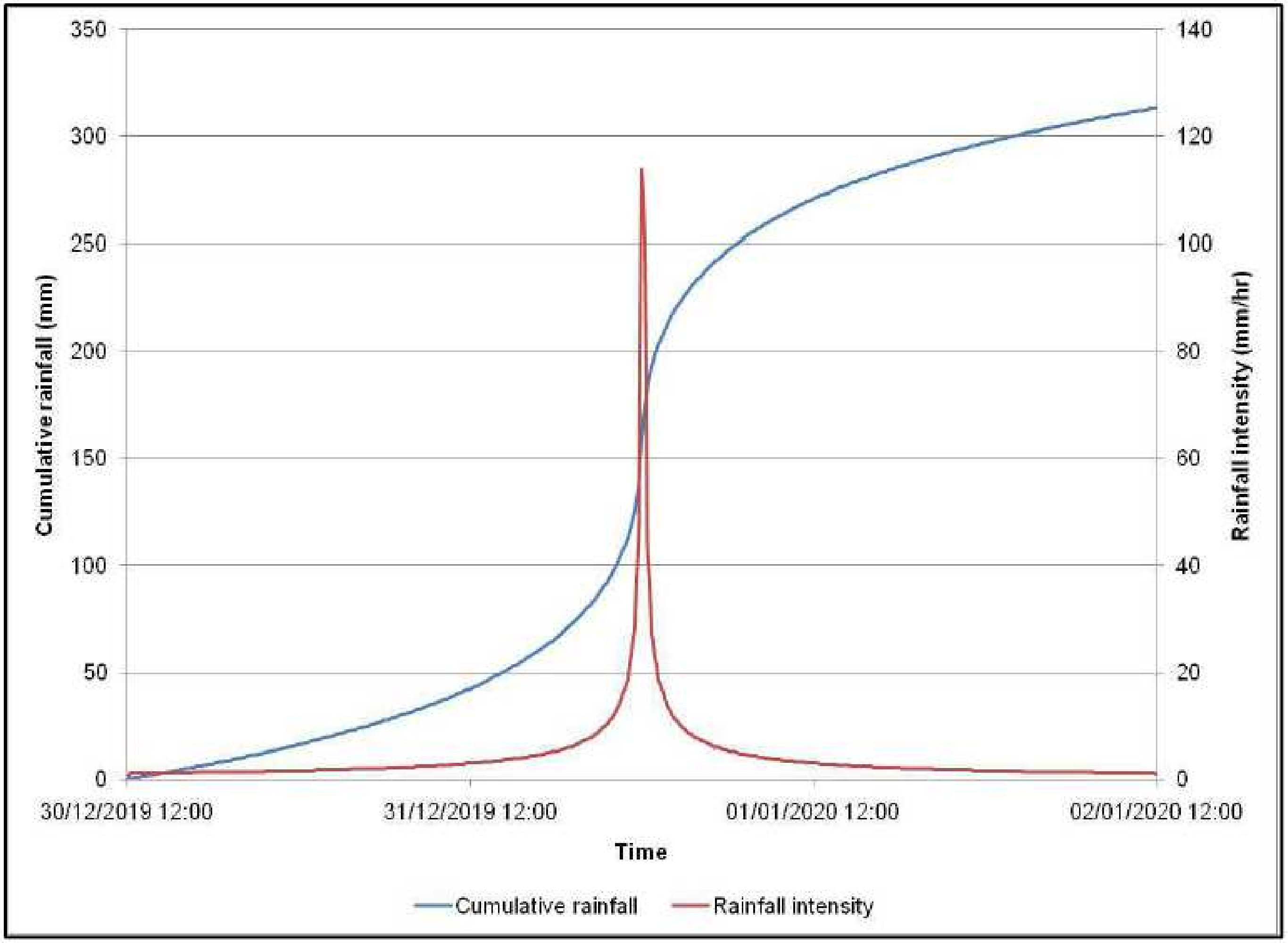

Figure 4: 72 hour nested storm hyetograph for 1% AEP current climate scenario.

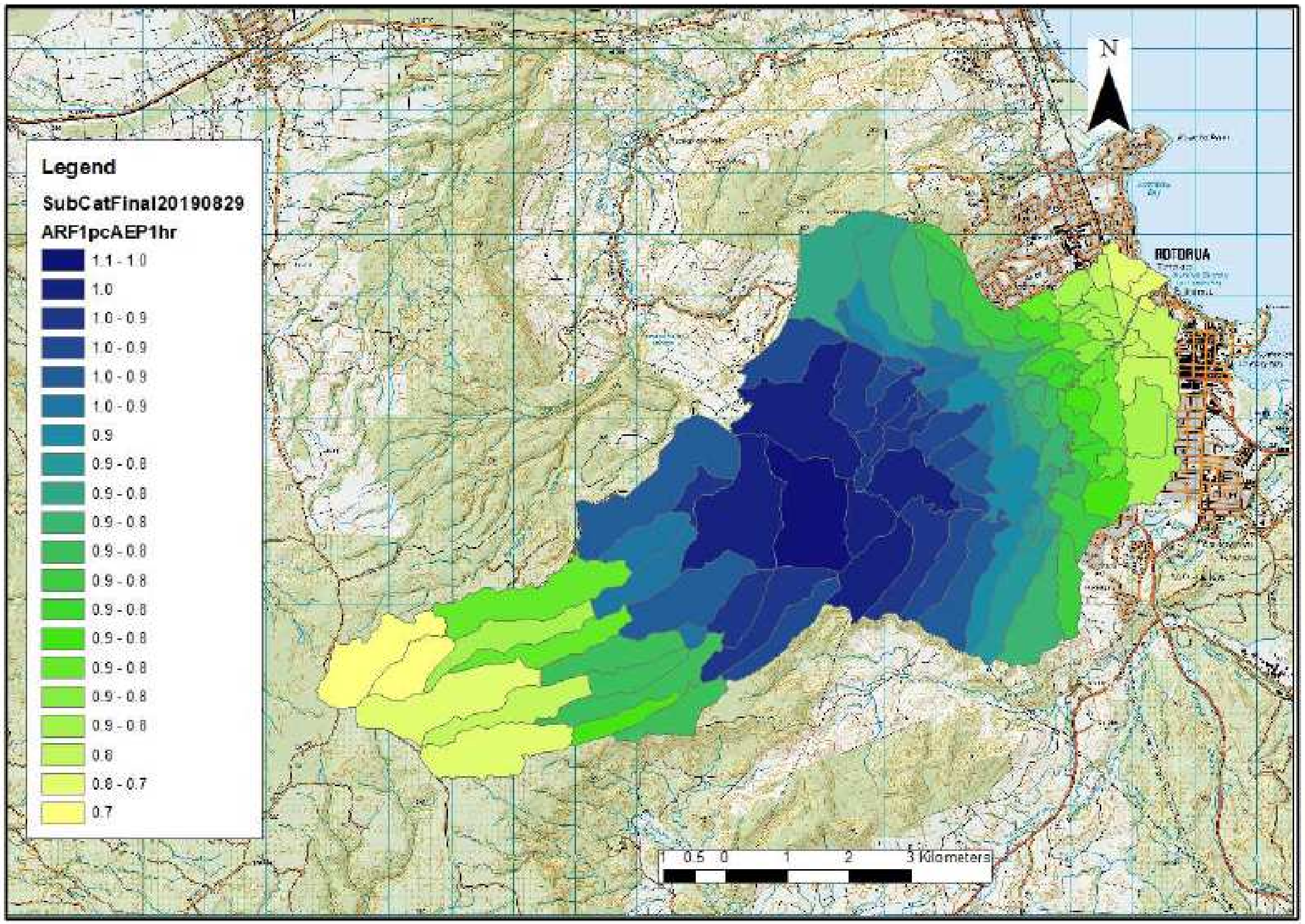

Figure 5: Spatial storm patter showing the 1 hour duration 1% AEP raindepth component of the storm as applied to each model subcatchment as a proportion of the raw HIRDS v4 value for that subcatchment's centroid location.

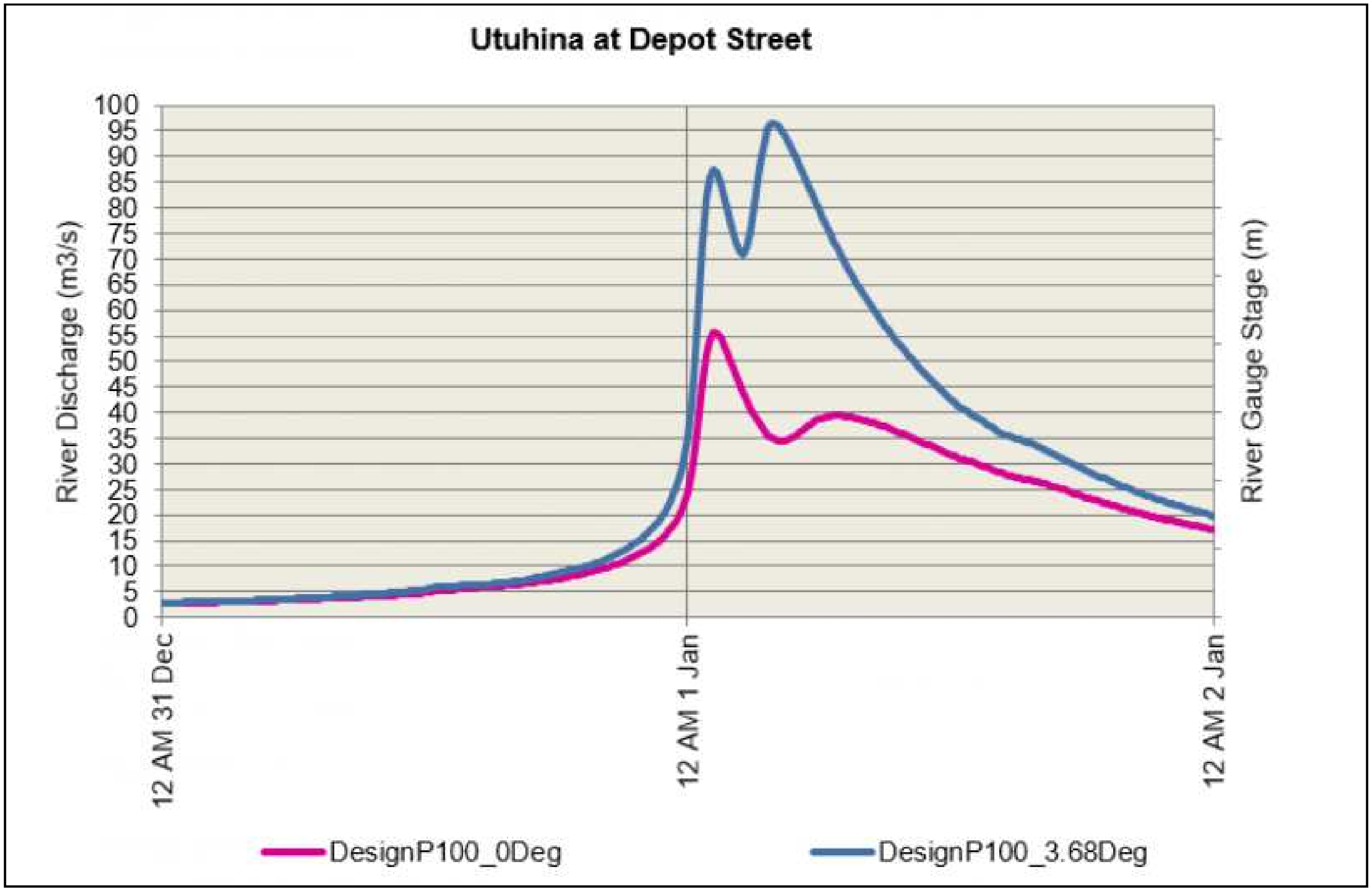

Figure 6: Hydrological model results for Utuhina Stream at the Depot Street gauge. Showing results for the 1% AEP (100 year) 72 hour nested storm centred on the PC2 plan change location, travelling on a bearing due north at 2 metres per second.

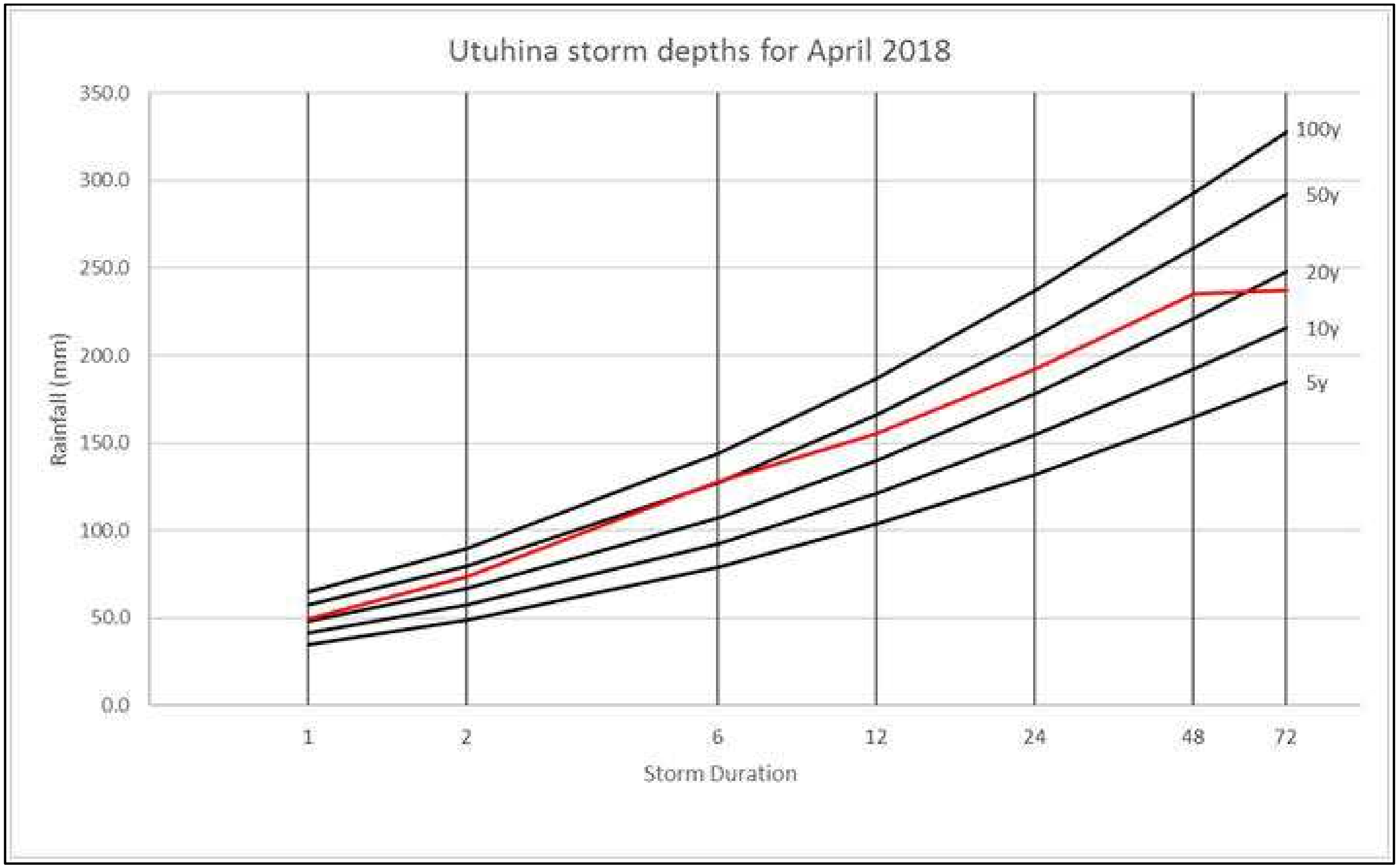

Figure 7: Storm depths in Utuhina catchment for April 2018 flood event. Black lines are HIRDs v4 values for the Pukehangi Plan Change Area. The red line is the rainfall depth over each nominal duration from the NLR model subcatchment that received the most intense rain.

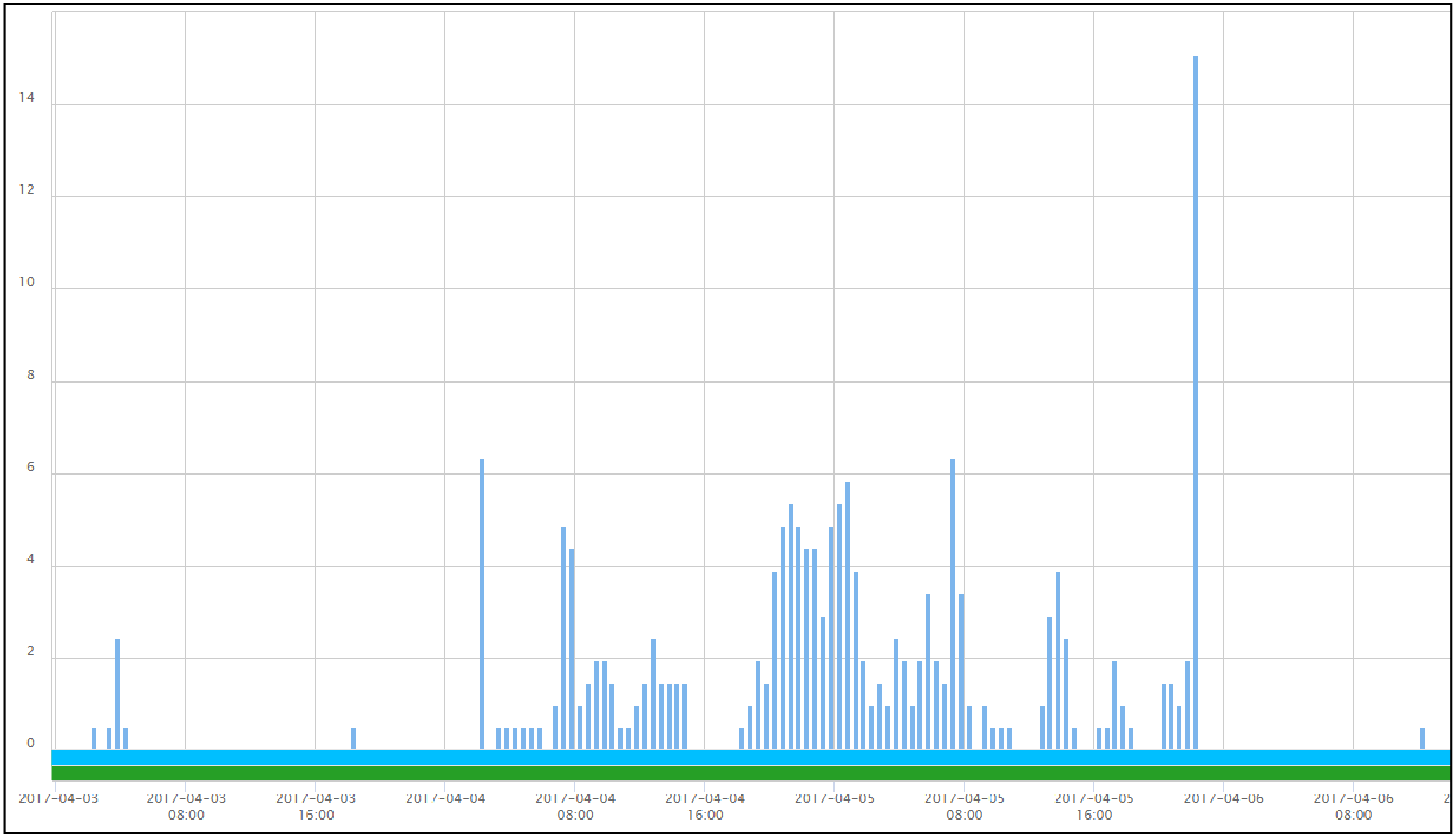

Figure 8: Rainfall observed at Whakarewarewa raingauge in Rotorua for 3-7 April 2017. Data is 15 minute depths.

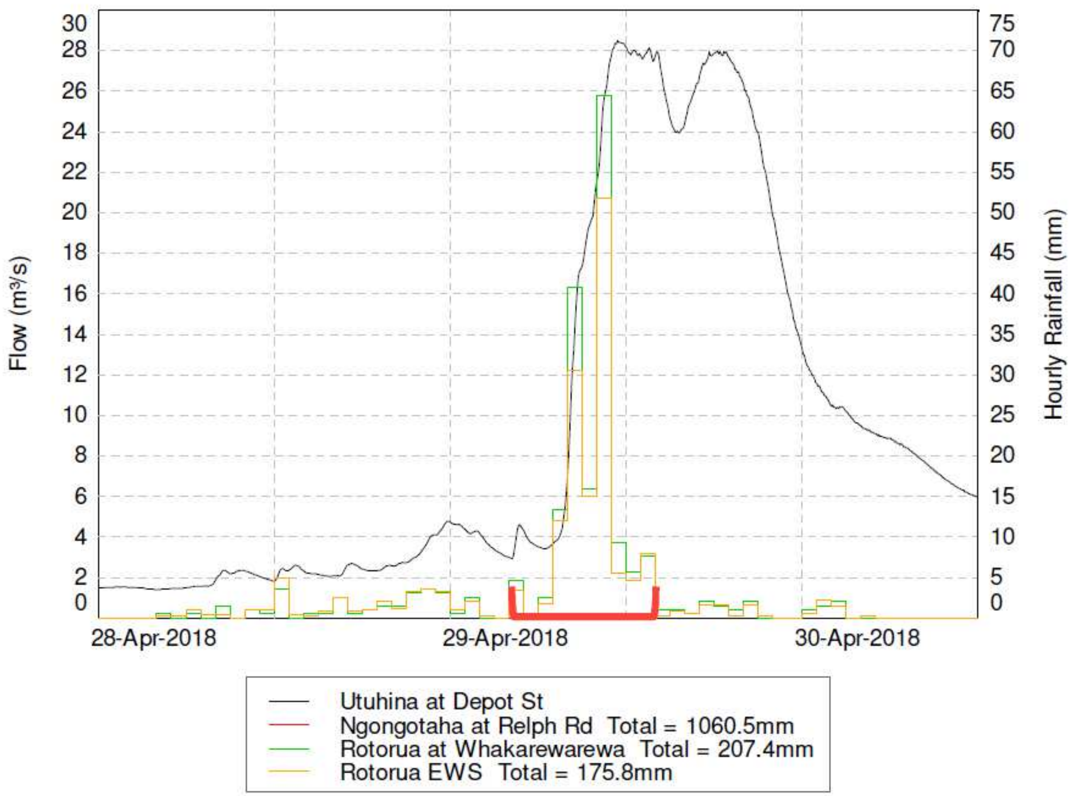

Figure 7: Largest flood event (29 April 2018) compared with nearest rain gauges to the catchment. Red brackets showing where 'bulk' of rainfall fell in an 8-hour window.

Figure 9: Figure from WSP Stormwater Report August 19 2020 version (since removed). Showing early rainfall (the day before) that is in almost direct accordance with that applied to the 1% AEP 72 hour nested storm.

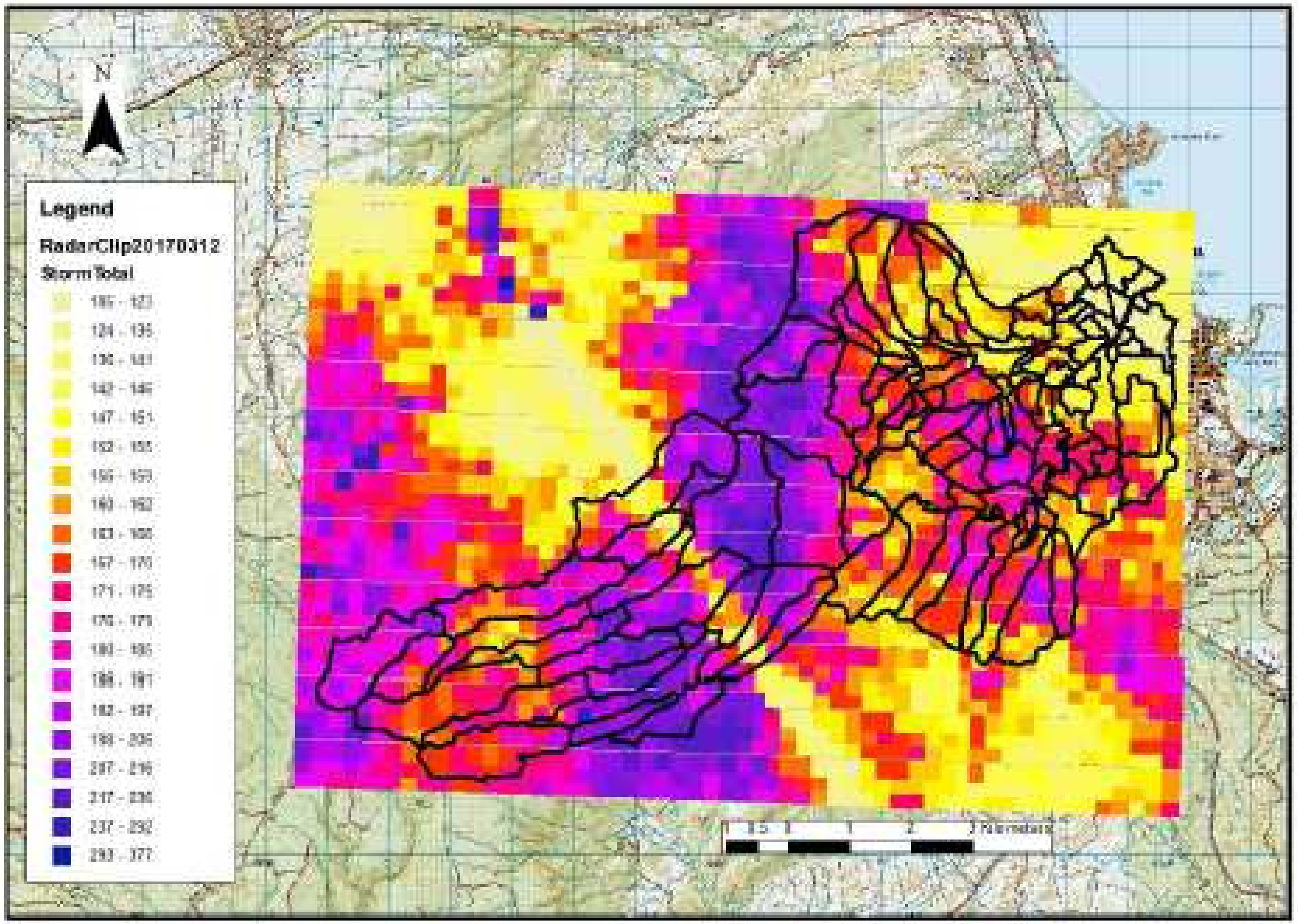

Figure 10: Radar rain plot showing the track of the March 2017 rainstorm in a southerly direction across the middle of the upper Utuhina catchment largely missing the Whakarewarewa raingauge (which is in the right of this picture).

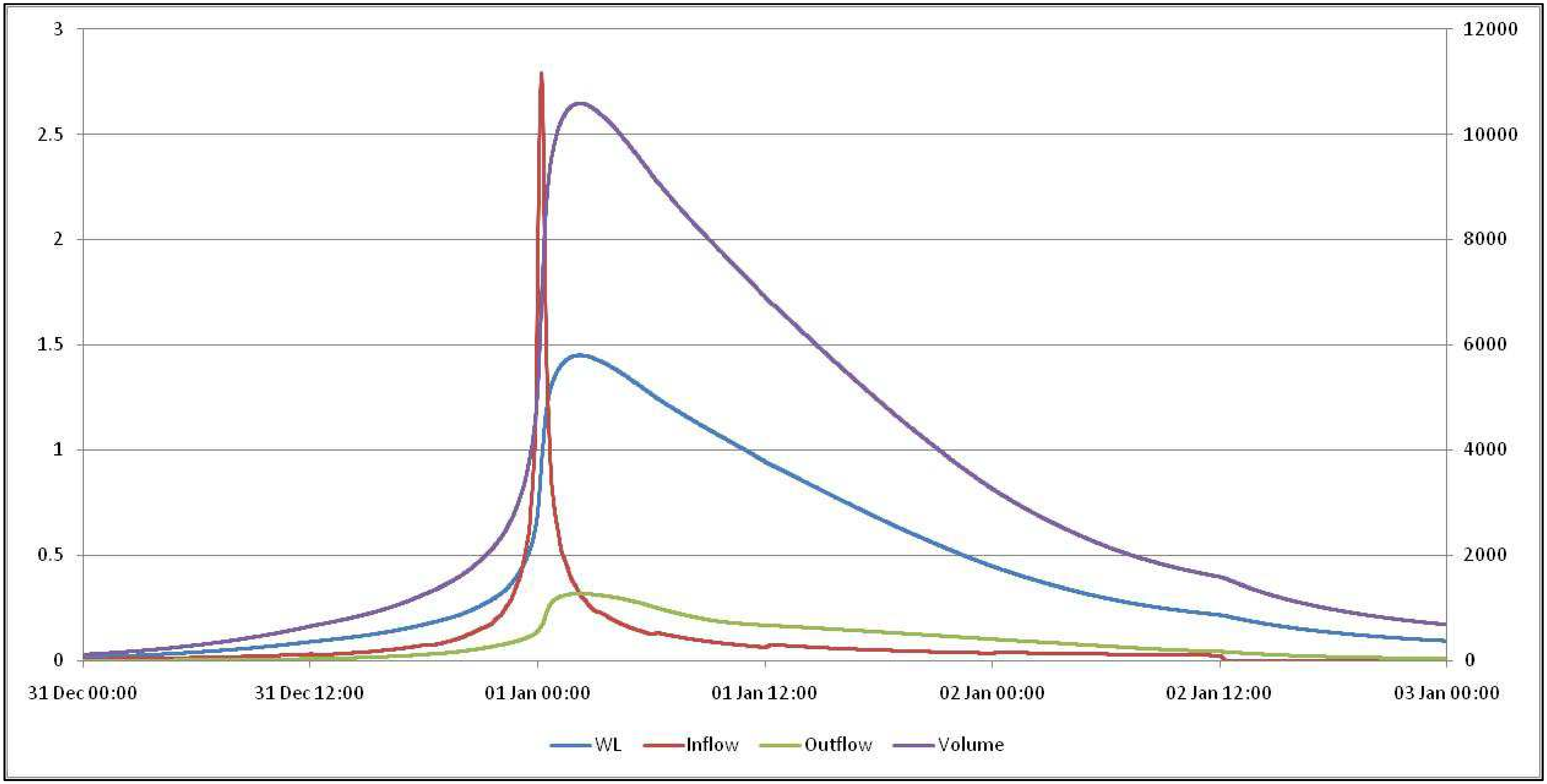

Figure 11: Example of pond routing check result - Pond 1 1%AEP 3.68 degreesCC

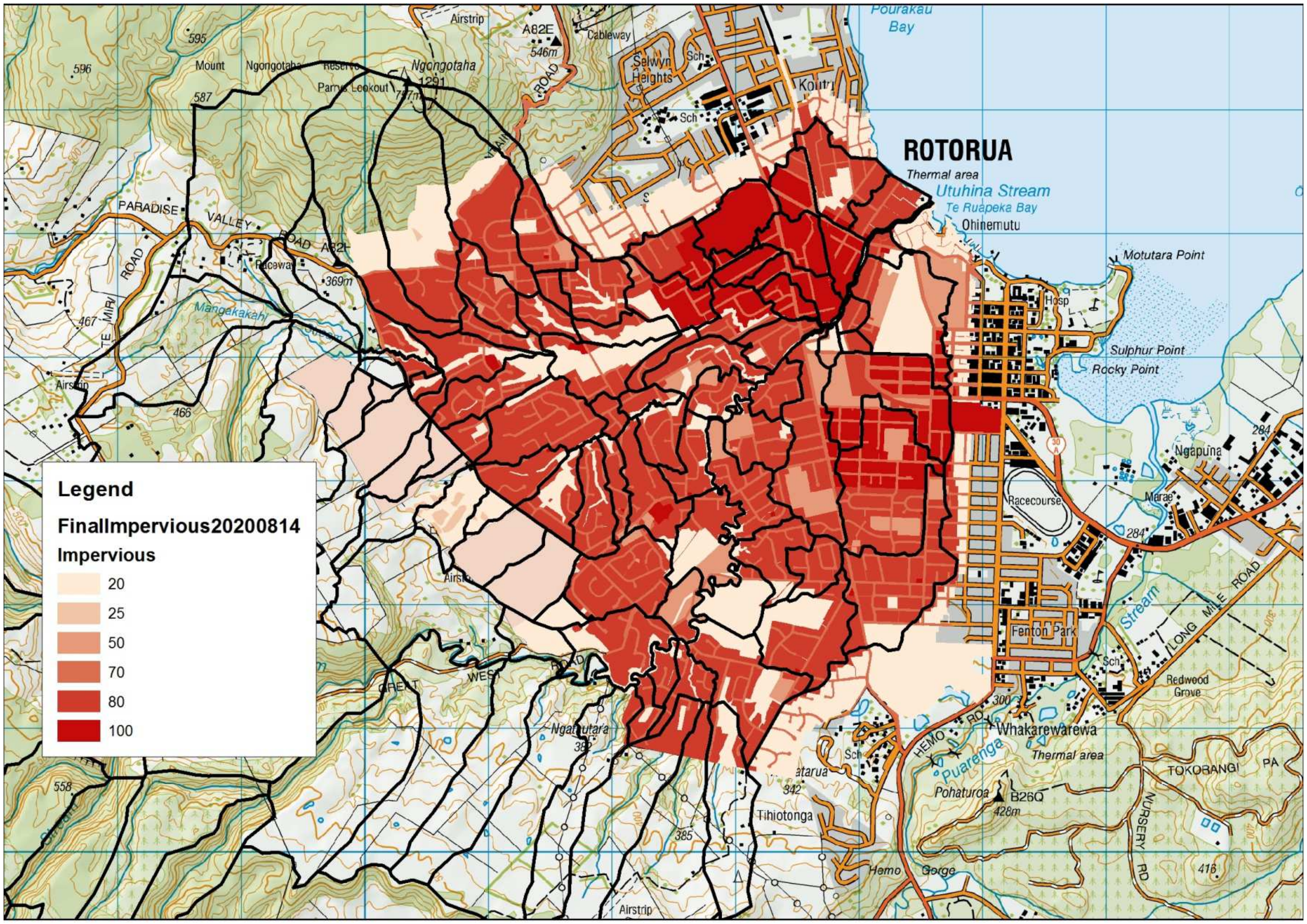

Figure 12: Map showing results of GIS exercise to determine permitted future impervious surface percentages in Utuhina urban catchments. Note some areas outside of the catchment (black polygons) are showing values but they are not included in the model and were in fact not analysed.

Appendix 2: Hydrological Model Report

BOPRC Flood Forecasting Systems

Utuhina Hydrological Model Establishment

26 September 2019

Peter West
Blue Duck Design Ltd

Blue Duck Design Ltd
Consulting River Engineers

Executive Summary

These notes document the establishment of a *Non-Linear Reservoir* (NLR) hydrological model of the Utuhina Stream catchment, Rotorua. The model covers the surface-water catchment of the stream to its discharge location into Lake Rotorua. It involves 122 subcatchment areas and 436 routing nodes along 60.1 km of stream-channel and piped routing branch network.

The purpose of the model is to determine the catchments' flow response to rainfall for use both in flood forecasting and in design. When used for design purposes, the model is intended to provide flow data at the boundaries of one or more hydraulic models (by others, using software such as InfoWorks or DHI's Mike). This flow data is generated at all routing nodes and subcatchment discharge locations. A hydraulic model would then resolve the detailed relationships between flows, water levels, waterway capacities, and storage volumes. When used for flood forecasting purposes, the hydrological model's built-in routing model is sufficiently accurate to predict flows at points of concern.

In flood forecasting mode the model operates automatically on a combination of rain-gauge observations, rain-radar inputs, and gridded forecast-rainfall estimates from NZ MetService's atmospheric weather prediction models. When used for design purposes the model has an in-built design-storm generator that delivers a spatially variable nested rainstorm consistent with NIWA's HIRDS version 4.

The model has been calibrated against the April 2018 flood event (peak measured at 29.5 m^3/s at Depot St gauge) and verified against the March 2017 event (29.4 m^3/s), the August 2014 event (31.1 m^3/s) and the January 29 2011 flood event (35.3 m^3/s). When run in design-mode the model predicts a peak discharge of 64.5 m^3/s at Depot Street in response to a 1% AEP rainstorm - compared to a statistical estimate of 55 m^3/s based on the gauge's historic flow record [1].

Software

The model is constructed in VBA programming language and uses Microsoft Excel as its primary user interface. Some support functions such as the design storm generator are constructed in the Excel workbook space itself.

NLR reservoir conceptual model; kinematic wave routing model

The Non-Linear Reservoir concept has been used to model subcatchment response to rainfall. The model involves 122 hydrological subcatchments. Each subcatchment is represented numerically by a conceptual reservoir for which specific discharge (q in mm/hour) is a function of storage depth (S in mm) in the reservoir. The function is non-linear and includes a proportional coefficient K and an exponential coefficient p:

$$q = \left[\frac{S}{K}\right]^{1/p}$$

Rainfall losses (to ground or elsewhere) were modelled at each subcatchment using a variation of the F1-RSA method. A proportional loss rate is applied that varies linearly between "initial" and "saturated" values relative to soil storage depths up to a nominated storage threshold (representing soil saturation).

A constant base-flow contribution is also included for each sub-basin. This is proportional to subcatchment area based on the river gauge base flows.

The channel routing and pipeline routing is modelled using the Kinematic Wave method [2]. This method is mass-conservative and based on Mannings Formula but assumes that the energy slope between each routing node is the same as the bed slope. Channels are represented by a limited subset of geometrically defined shapes. The shape used in the Utuhina model's open channels is parabolic with channel depth proportional to the channel wetted-perimeter squared. Stormwater pipelines are represented by circular channels sized according to Rotorua Lakes Council (RLC) stormwater asset GIS online database [3].

Subcatchments and routing branches

Model subcatchments were delineated manually by inspecting the following spatial information: BOPRC's digital elevation model (DEM) based on the 2011 LiDAR aerial survey; Aerial photography of streets, buildings, and stream channels; RLC's stormwater network; BOPRC's surface flow-path layer (digitally created from the DEM). The 1:50,000 scale topomap was also useful at gross scale.

Judgement was necessary to resolve apparent conflicts between the DEM, the digitally created flow-path layer, and the stormwater network. In some cases the flow-path layer appears to track contrary to the general ground surface topography due to minor surface features such as footpaths and small street-gutters aligned off-contour. In some cases the piped network flows in directions different from the surface topography. When resolving such conflicts the following two considerations were core: That the model should generate appropriate boundary conditions at locations suitable for a comprehensive hydraulic model, which in turn would solve the conflict explicitly; and that the scale of the flow response was matched to the surface features - e.g. small road-side gutters would likely be over-whelmed by large design-scale discharges, which would largely follow the gross land-form. When having to choose between the flow direction of the piped network and that of the gross landform, the model's flow direction was selected after considering the size of pipe-work against the size of the contributing catchment and the relative slope of the ground surface.

The resulting subcatchment delineation and routing network (branches and nodes) are shown in Figure 1 and Figure 2 below. An ArcMap workspace and the key GIS shapefiles have been stored alongside the model on BOPRC network drives to provide access to model location details.

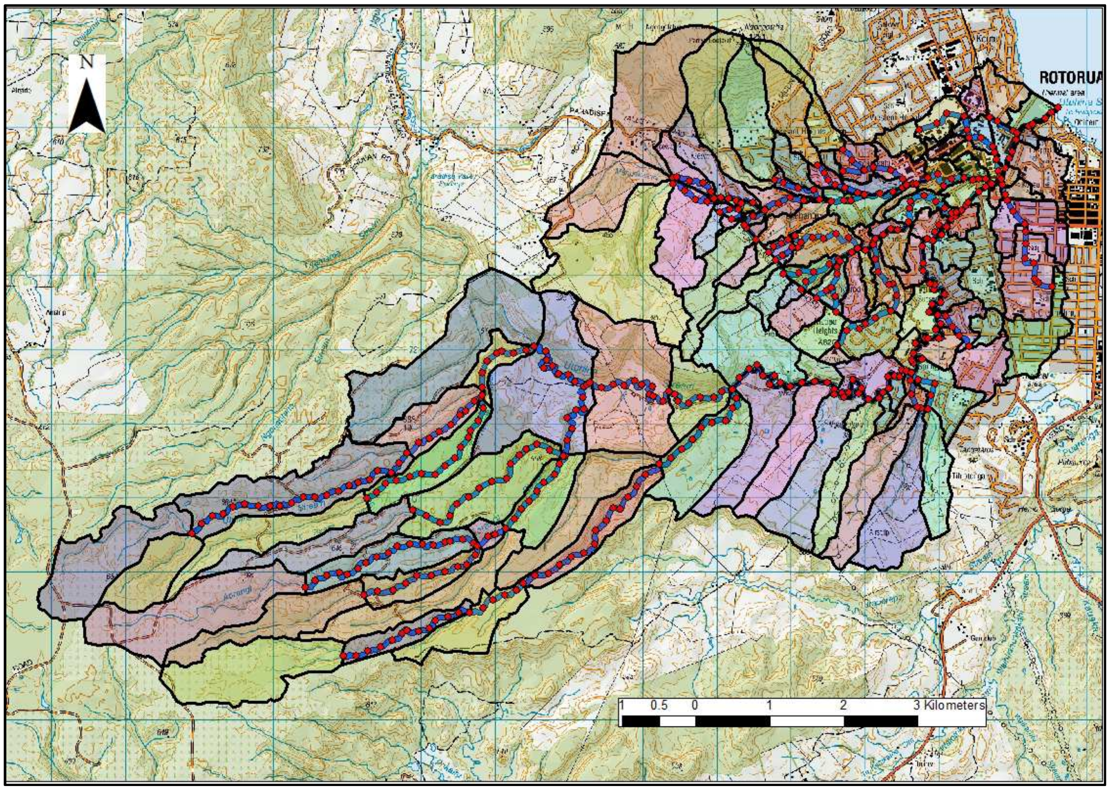

Figure 1: Map of subcatchments, routing branches and routing nodes - catchment scale

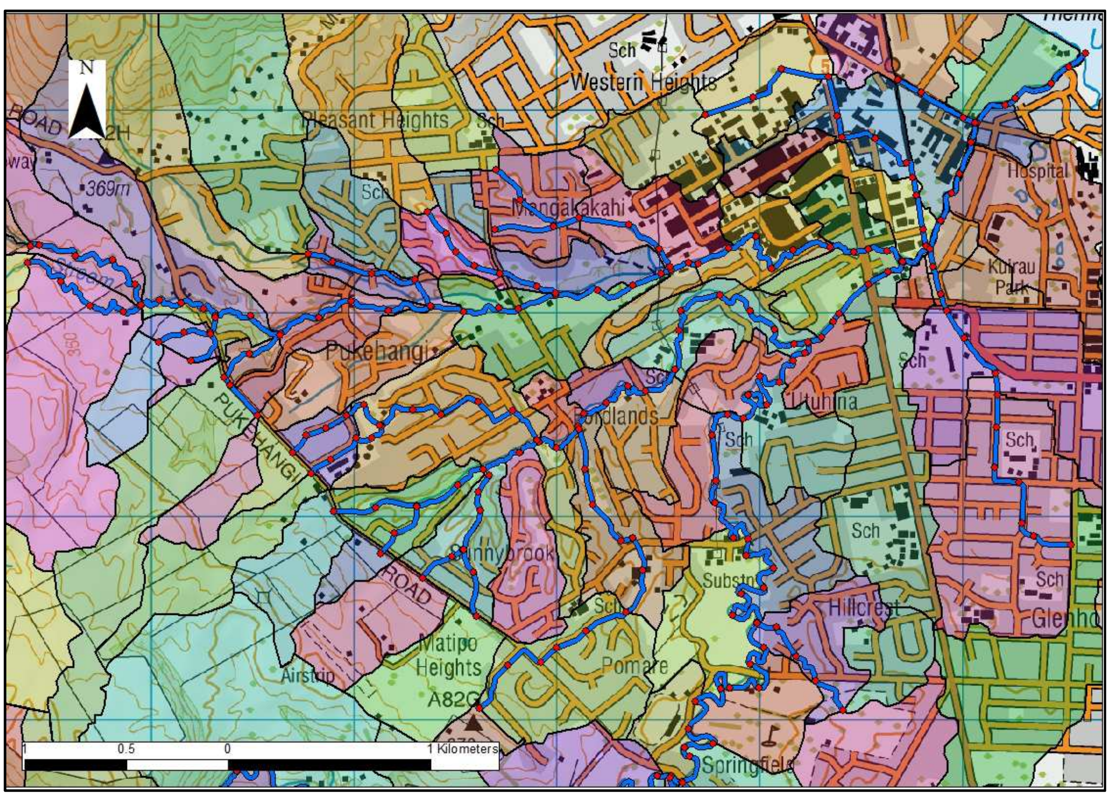

Figure 2: Map of subcatchments, routing branches and routing nodes - urban area

Pukehangi Road plan change

One potential application of the hydrological model is to generate boundary conditions for detailed stormwater system modelling at a proposed residential development area near Pukehangi Road. The intention is that a catchment-wide hydrological design model and a stream network hydraulic model (by/for BOPRC) will provide a comprehensive basis for detailed stormwater studies of sub-parts of the stormwater system. The plan change area polygon (red polygon in Figure 3 below) was provided by Rotorua Lakes Council (RLC). Model routing nodes and subcatchments in this location have been configured to integrate with stormwater modelling by/for RLC and stream network modelling by BOPRC.

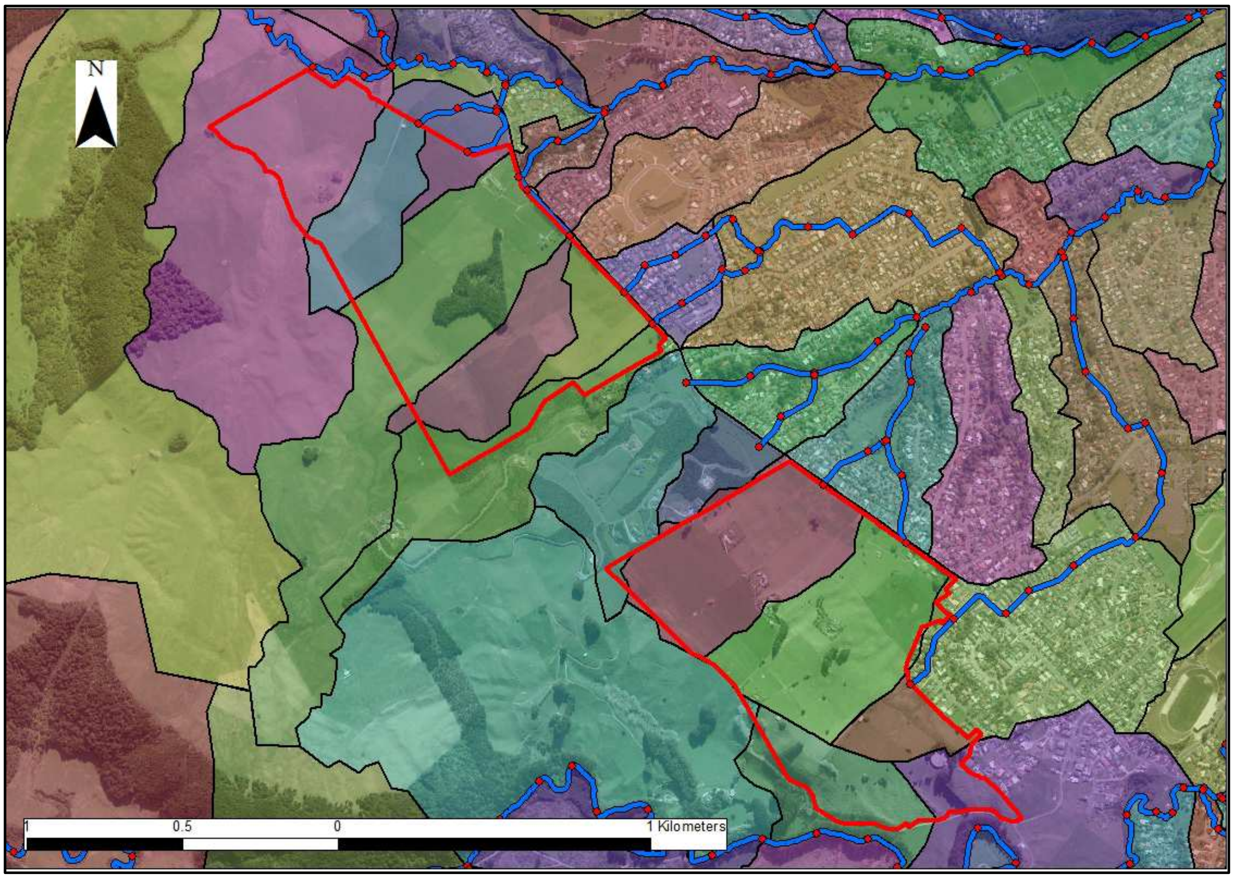

Figure 3: Map of model layout in relation to the proposed plan change area near Pukehangi Road.

Soils, land-covers, Urban land-use

The soil type information used for this modelling is from the BOPRC GIS database, which in this catchment is based on work by Rijkse [4]. Land cover information is from Landcare Research NZ LTD (Landcare)'s LCDB4.1 spatial database accessed via BOPRC's GIS.

In keeping with previous BOPRC NLR models the Utuhina model is calibrated by fitting characteristic parameters to soil types and land-cover classes. Soil parameters control rainfall loss rates and affect subcatchment internal routing by contributing to determination of the proportional reservoir coefficient K. Land cover classes also contribute to the determination of the K coefficient:

$$K = A \times B \times L^{0.33} \times S^{-0.33}$$

Where A is the soil routing parameter, and B is the land cover routing parameter. L is the length of the subcatchment's dominant internal flow path in km. S is the average slope of this flow-path.

Where possible, soil character is kept consistent across models. The Utuhina model has four soils in common with the Lower Kaituna hydrological model, which was calibrated in 2014, however these soils only cover a small proportion of the Utuhina catchment. Figure 4 maps the model's soil types and Table 1 shows the model parameters for the soil types. The dominant soil in the upper catchment is Mamaku Loamy Sand (Code: M). The lower Utuhina catchment (within the Rotorua caldera) is mainly Ngakuru Sandy Loam (Na). The Ngongotaha soils (No, NoH) cover much of the remainder between these two main areas.

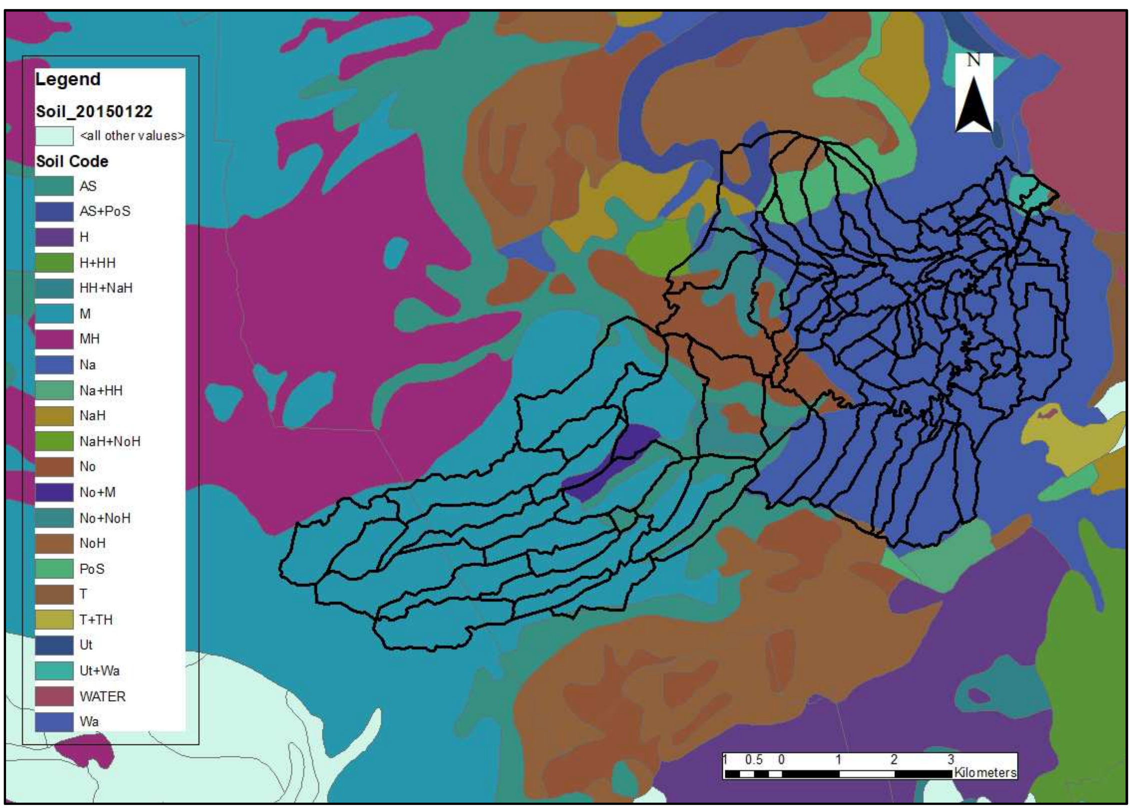

Figure 4: Map of soils used for modelling the Utuhina Stream catchment. Model subcatchments are shown as black polygons.

Table 1: Soil types and the model parameters assigned

SOIL_CODE	SOIL_NAME	Soil routing Parameter	f1	fsa	Rsa
AS	Arahiwi steepland soils	9	0.40	0.60	50
AS+PoS	Arahiwi steepland soils + Pohaturoa steepland soils	9	0.40	0.60	50
M	Mamaku loamy sand	18	0.14	0.30	70
MH	Mamaku hill soils	18	0.14	0.30	70
Na	Ngakuru sandy loam	18	0.14	0.30	70
Na+HH	Ngakuru sandy loam + Haparangi hill soils	18	0.14	0.30	70
NaH	Ngakuru hill soils	18	0.14	0.30	70
NaH+NoH	Ngakuru hill soils + Ngongotaha hill soils	18	0.14	0.30	70
No	Ngongotaha loamy sand	18	0.14	0.30	70
No+M	Ngongotaha loamy sand + Mamaku loamy sand	18	0.14	0.30	70
No+NoH	Ngongotaha loamy sand + Ngongotaha hill soils	18	0.14	0.30	70
NoH	Ngongotaha hill soils	18	0.14	0.30	70
PoS	Pohaturoa steepland soils	18	0.14	0.30	70
T	Tikitere sand	18	0.14	0.30	70
Ut+Wa	Utuhina peaty loam + Waiowhiro sand	5	0.40	0.60	50
Wa	Waiowhiro sand	9	0.40	0.60	50

Rain-loss rates for low-permeability urban land-cover classes (LCDB Class 1: "Built up Area"; and Class 5: "Transport Infrastructure") were applied proportionally on an area basis. Initial and "saturated" loss rates for these land-cover classed areas were selected to (reasonably) approximate the curve-number (CN) method used by RLC and WSP OPUS in their "Catchment 14" modelling [5]. WSP OPUS used a range of CN values specific to urban land-use sub-classes that are not available within LCDB4.1. A more explicit treatment of urban land covers may be applied in future studies but as a preliminary approach "initial" and "saturated" proportional runoff coefficients of 0.54 and 0.73 were selected to correspond with an SCS curve of CN=70 at 50mm and 100mm of rainfall depth respectively (no initial abstraction). CN=70 was selected based on a visual judgement that 1/4 of the urban catchment was represented by roads and (non-residential) pavement and 3/4 by residential lots. Figure 5 shows the land-cover classes for the catchment. The urban classes 1 and 5 are shown in Grey. Table 2 shows the LCDB land cover classes in the Utuhina catchment along with the coefficients used in the determination of the subcatchment internal routing proportional coefficient K.

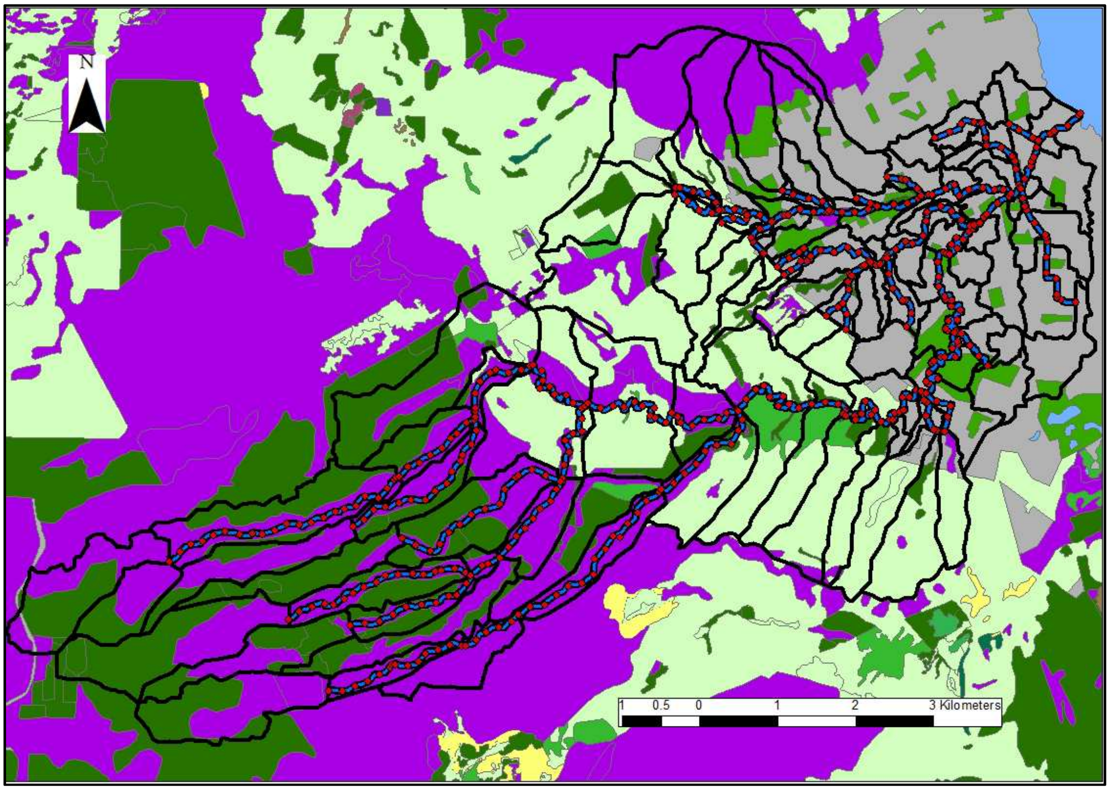

Figure 5: Map of land cover classes from Landcare Research NZ Ltd's LCDB 4.1. Urban low-permeability classes 1 and 5 are shown as grey. Indigenous forest is purple. Exotic forest is dark green. Pasture is light green. The green polygons in the urban area are parkland.

Table 2: Land cover classes, names, and routing parameters

LCDB CLASS	LCDB NAME	Land cover routing parameter
1	Built-up Area	0.01
2	Urban Parkland/ Open Space	0.05
5	Transport Infrastructure	0.01
20	Lake and Pond	0
40	High Producing Exotic Grassland	0.25
41	Low Producing Grassland	0.25
52	Manuka and or Kanuka	0.5
54	Broadleaved Indigenous Hardwoods	0.7
64	Forest Harvested	0.5
68	Deciduous Hardwoods	0.7
69	Indigenous Forest	0.7
71	Other Exotic Forest	0.5

Rain gauges, Radar rain, Forecast rain application

When run in flood forecasting mode, rain inputs to the model are applied in the following order of preference based on data availability at each time-step: Rain-radar gridded data; Rain-gauge data; MetService forecast rainfall. Calibration runs are the same except that forecast rainfall is not required. When run in design mode, synthetic rain inputs are applied.

Radar data

Rain radar data is currently supplied as hourly rain depths on a 250m grid. As part of its processing at MetService a "correction" is applied based on rain gauge observations. Due to time constraints in MetService's delivery sequence it is beneficial for BOPRC to repeat this process as further gauge data becomes available. Details can be found in [6].

In this model, radar rain depths are interpolated linearly within each hour to determine rain intensities over each modelled time step. Rain is attributed on a subcatchment-area-averaged basis. Radar data is treated as point data and is applied to a subcatchment if the point falls within that subcatchment. Some very small subcatchments - such as the main channel between stopbanks - do not contain a radar point. For these, the nearest radar point to the subcatchment's centroid is applied.

The radar data from 2011 was supplied on a 1km grid. For analysing the January 2011 flood the nearest radar point to each subcatchment centroid was applied.

There is a band of poor radar observation that crosses the mid-catchment about in line with the edge of the Rotorua caldera. This is caused by a high peak (732m) at the northern end of the band, in line with the radar tower (near Mamaku). This would cause the observed rain depths in those locations to be less than actual during the calibration event modelling. The data from within this band was disregarded from the analysis. Subcatchment rainfalls were derived from the remaining radar observation points. In one subcatchment this reduced observations by 80%.

This treatment of the band of reduced radar observations is also applied to the flood forecasting modelling. For the model calibration (verification) of the January 2011 event, data was applied as delivered.

Rain gauge data

Rain gauge data is applied specific to each subcatchment. Of the telemetered rain gauges available on BOPRC's Hydrotel system, the six nearest gauges to each subcatchment centroid are used to estimate the rainfall at that subcatchment by spatial interpolation on an inverse-distance-squared weighting for each time-step. If one of the nominated gauges is un-available at that time (e.g. the new gauge at Relph Road is not available for the calibration events) then the interpolation is carried out with the remaining gauges. Rain gauge data is used in this way only if radar data is unavailable for that time step. During flood forecasting it is not unusual for several hours of radar data to remain undelivered over a multi-day storm. In the three calibration events, any hours of radar data that was un-available were replaced with rain gauge data using this method. Figure 6 below shows the rain gauges used in this study along with a portion of the radar grid and the forecast rainfall grid.

Forecast rainfall data

Gridded forecast rainfall data is available from both NZ MetService and NIWA. At this time BOPRC's flood forecasting system makes use of three sets of output from MetService's NZLAM weather predicting model. The datasets are hourly predicted rain accumulations on an 8km grid (Figure 6). This data is applied to the model specific to each subcatchment by spatial interpolation on an inverse-distance-square weighting basis of the four nearest cardinal grid points (NE, NW, SE, SW) to the subcatchment's centroid.

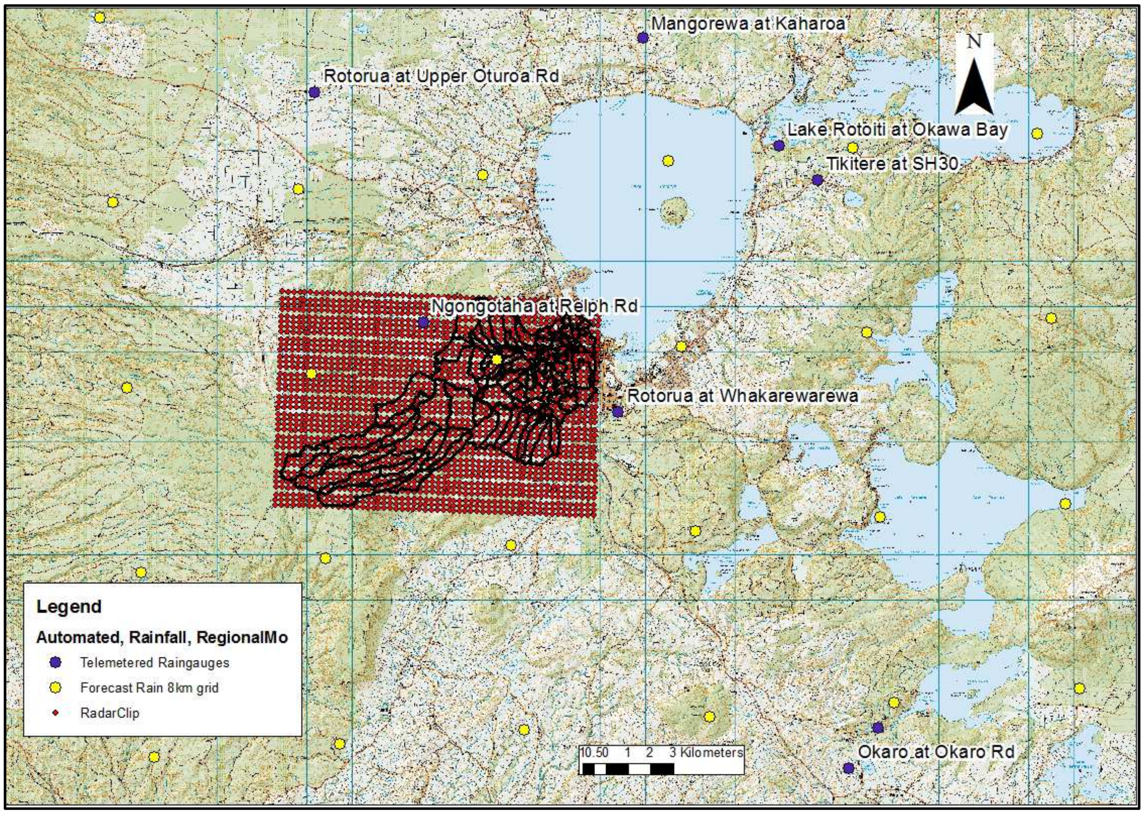

Figure 6: Rain data sources. Showing a clipped area of rain radar points (red points); forecast rainfall model output point locations (yellow points); automated telemetered raingauges used for this study (dark blue points). The Utuhina model subcatchments are shown as black polygons. The Ngongotaha raingauge is recently installed and was not available for any of the calibration events studied.

Design storm rainfall

A rainstorm generator is integrated into the model for use in running design simulations. The storm is of the "fully nested" type with depth-duration-probability relationships calculated at each subcatchment centroid from NIWA's HIRDS v4 spatially varying coefficients. Figure 7 below shows nested rainfall intensity, and cumulative rainfall hyetographs for a selected subcatchment.

The generator simulates a single band of rain of varying intensity that tracks across the catchment on user-specified bearing and rate of travel. The storm intensifies over a user-specified location. This storm mobility function allows the user to test the effect of storms that can travel in the same direction as the dominant river branch. Figure 8 shows Utuhina model input hyetographs (cumulative) for a selected design storm scenario.

The tool applies an allowance for the influence of climate-change-induced atmospheric warming on rainfall intensity in accordance with NIWA's August 2018 guidance [7]. The user specifies the degrees of average ambient temperature warming.

Each rainfall increment at each nominated point location (subcatchment centroids) within the storm is factored to remain consistent with NIWA's area-reduction factors (ARF) according to storm-area and storm component duration. The area is determined by the point’s distance from the storm's nominated "epicentre". Thus a concentrically circular plan-form is assumed for the shape of the storm's relative rainfall delivery. Figure 9 shows the reduction factor applied to each subcatchment for a selected duration component (1 hour) of a 1% AEP design storm.

The nesting function can be skewed: the user specifies the proportion of rain that falls before and after the central time of highest intensity. In this way storms can be tested where the most intense band of rain falls towards the end of the storm.

The design storm duration is currently limited to 3 days. This can readily be increased but at this time the NIWA HIRDS guidance is not extended to storms greater than 1% AEP and 3 days length.

It should be stressed that design-storm methods should not be relied on as the sole method of determining a flow hydrograph for design purposes. This tool should be used in conjunction with other methods: river-gauge statistics where available; or other design estimation methods when working in un-gauged catchments. If necessary, precipitation outputs from the design-storm generator can be scaled to generate hydrographs in line with a specified peak-flow magnitude determined by careful application of a broad range of methods.

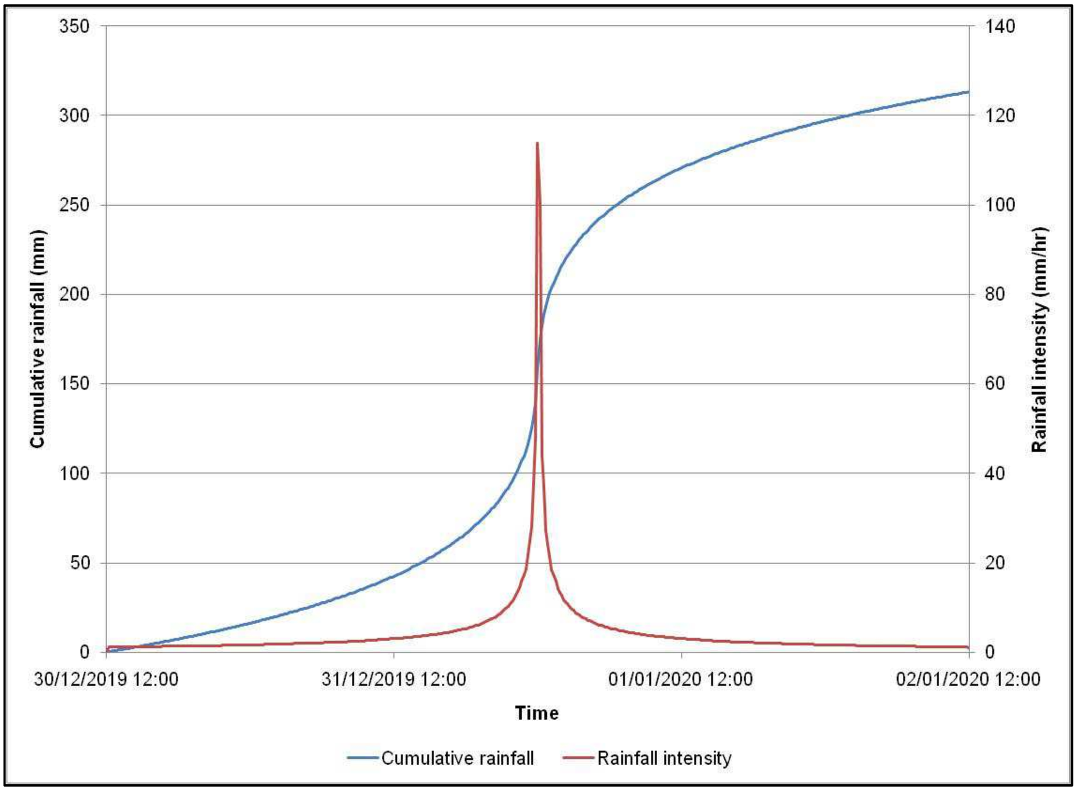

Figure 7: Typical design rainfall hyetographs; for selected subcatchment Utuhina_19450 for a 1% AEP, Zero climate warming scenario, design storm centred 140 metres north east of this subcatchment's centroid.

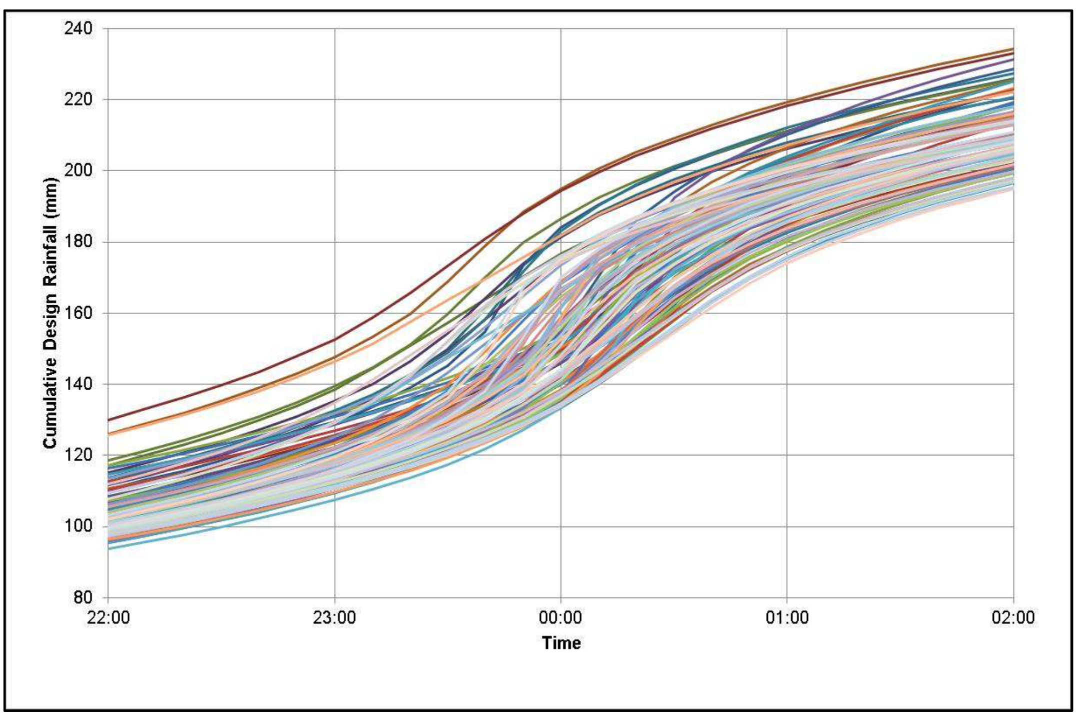

Figure 8: Illustration of design rainstorm. Showing a selected part of a 1% AEP storm centred as shown in the following figure, travelling north at 2 m/s. Each line is the cumulative rainfall depth for one of 122 Utuhina subcatchments.

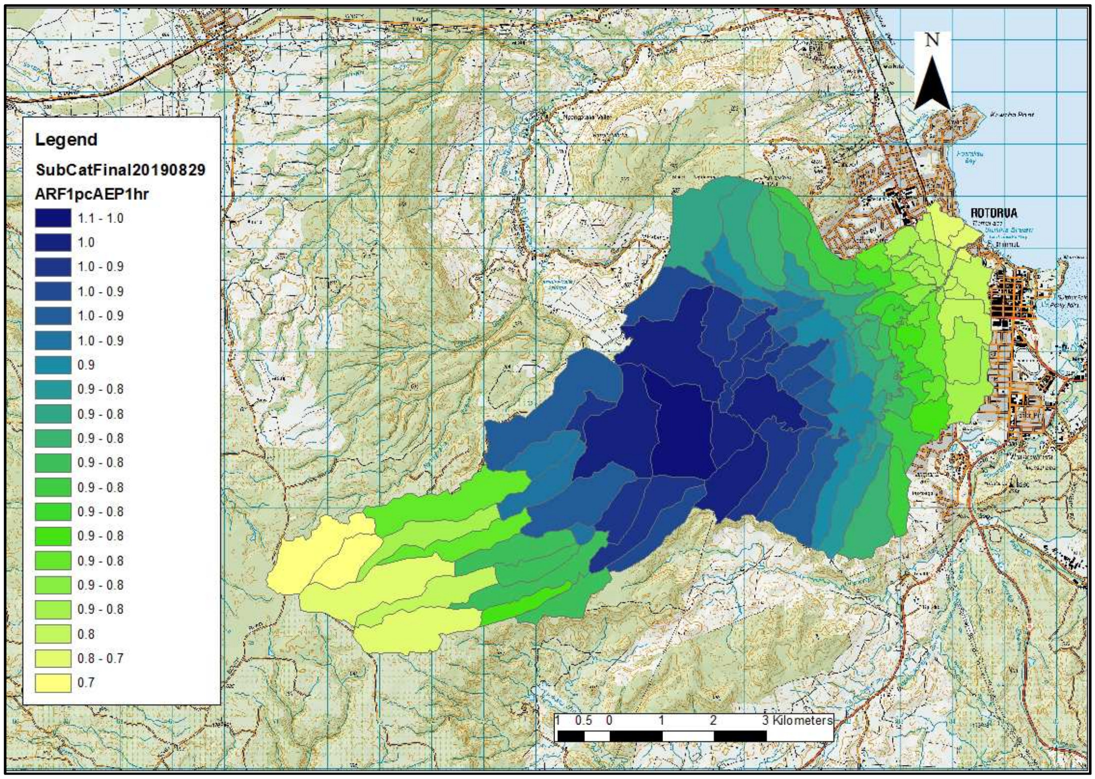

Figure 9: Storm spatial pattern. Showing the applied spatial pattern factor (based on NIWA's Area Reduction Factors) for the 1 hour duration component of a selected synthetically generated 1% AEP rainstorm.

Calibration

Calibration[1] was carried out for the April 2018 flood event. This was estimated by the rated water-level recorder at Depot Street to have peaked at 29.5 m^3/s. Figure 10 shows the storm total rainfall as observed by radar. This storm was heavy in the upper catchment with some isolated intense storm activity within the Rotorua caldera. Figure 11 shows the model response (blue) overlaid with the Depot Street Utuhina stream gauge rated flow estimate (pink). Figure 12 shows the model results at Mangakakahi gauge also on Depot Street.

The model peak discharge (Utuhina at Depot St) is 31.93 m^3/s (8.2% greater than gauge estimate) and this arrives 15 minutes before the gauge record peaks. The shape of the model result hydrograph is similar to the recorded, with a definite double peak. The model's sharp first peak is sourced within the Otamatea branch, which joins the Utuhina 700m upstream of the Depot Street gauge. This information along with the truncated appearance of the first peak of the recorded hydrograph suggests that the Otamatea discharge is impacted by capacity constraints in its channel or within its subcatchments. This was also indicated in the WSP Opus analysis of this branch [5]. It is possible that a final calibration run within a Mike11 (or similar) hydraulic model will alter this first peak of the model response.

[1] It should be recognised that calibration may be refined following detailed hydraulic modelling of the lower stream reaches - based on inflows from this hydrologic model. The routing method applied here does not resolve conveyance constrictions or the effects of ponding and "side-spilling". This stage can be viewed as preliminary calibration.

Both of these recording gauges are on Depot Street in Rotorua City. The Utuhina stream gauge is downstream of the confluence where the Mangakakahi Stream joins the Utuhina Stream. The rating record at BOPRC (the Utuhina gauge's monitoring authority) shows the rating is well supported by gaugings up to similar magnitudes as the calibration events.

The Mangakakahi stream gauge is upstream of the confluence. From inspecting Figure 12 the rated flow at Mangakakahi is not well reproduced by the model's response; however careful comparison with Figure 11 indicates that the Mangakakahi gauge is being impacted by high water levels in the Utuhina Stream at the peak of the flood. [I intend to visit the site to check this] In addition to this, the gauge's monitoring technician at NIWA indicated that the rating is not yet supported by high-stage gaugings [8]. Conclusion: the Mangakakahi Gauge is not yet reliably rated and that the wide discrepancy showing in Figure 12 does not necessarily indicate a poor model calibration.

By way of verification, the model was run with data for the March 2017 event (29.4 m^3/s), the August 2014 event (31.1 m^3/s), and the January 29 2011 event (35.3 m^3/s). Figure 13 thru Figure ***16*** below show the rainfall distributions and model results at the Utuhina Stream gauge at Depot Street. It is considered that the model reasonably reproduces the recorded flow hydrographs.

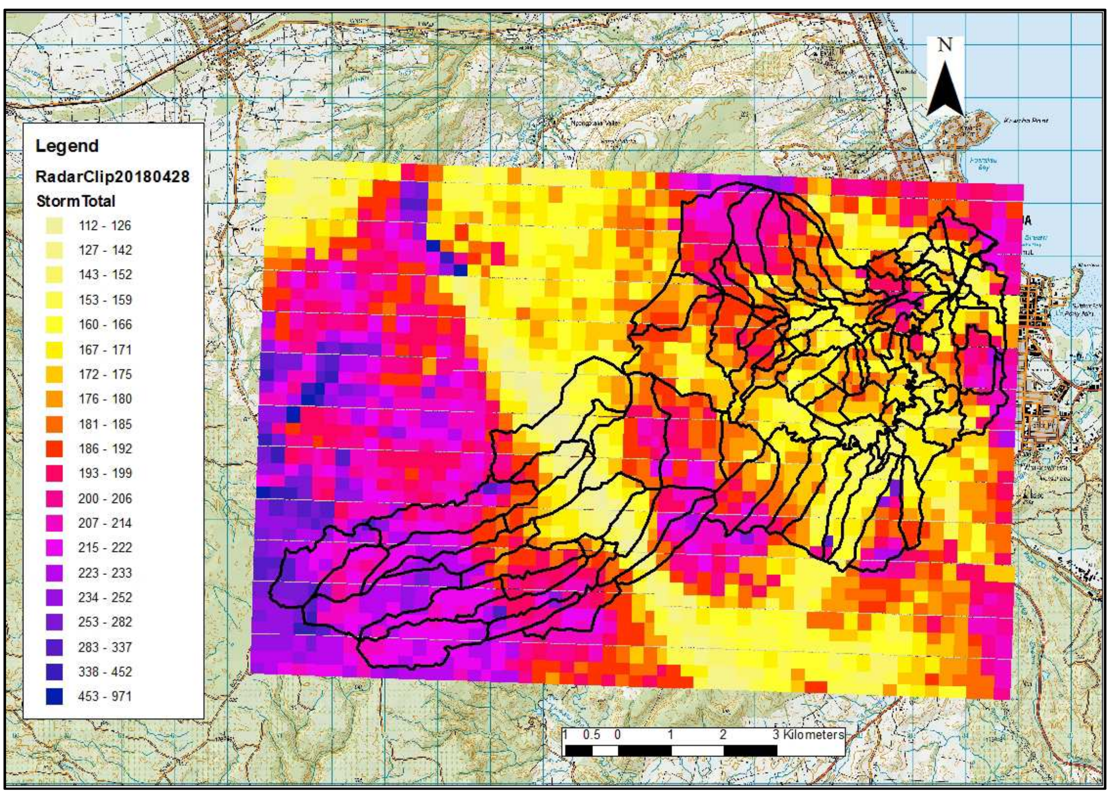

Figure 10: Storm total rainfall radar observations (mm) for April 28 - 30 2018. The bright yellow stripe across the mid-catchment is a zone of reduced observation shielded by a high ridge-line peak at its northern end.

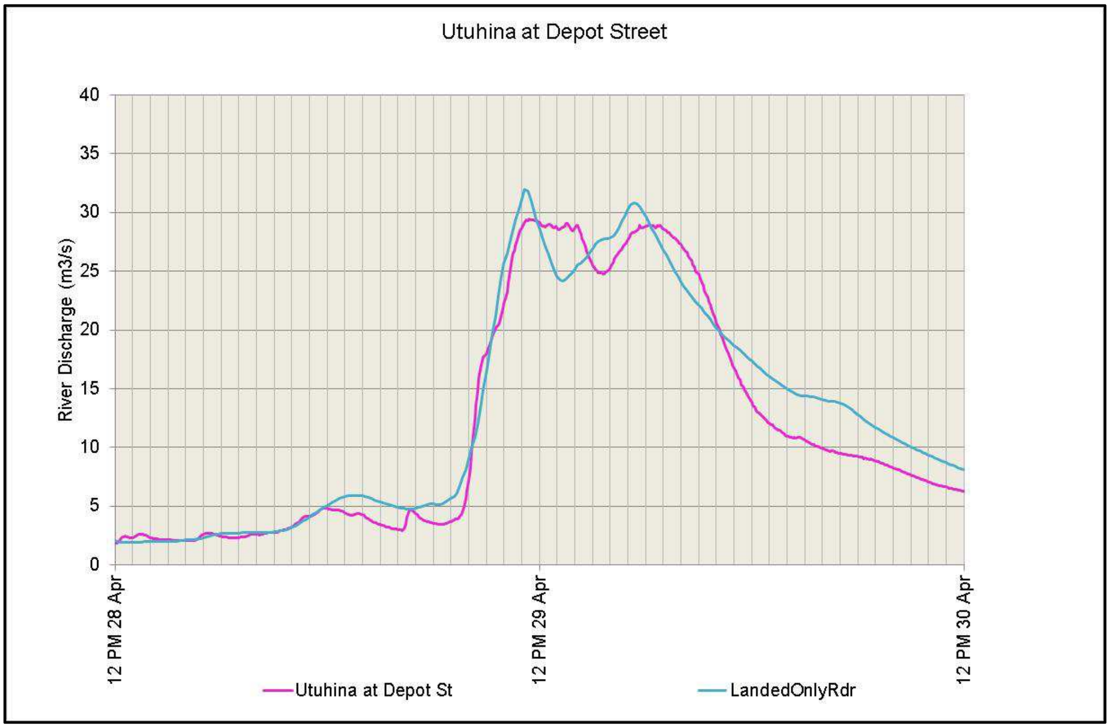

Figure 11: Model discharge results at Depot Street stream gauge on Utuhina Stream for April 29 2018 (blue line) overlaid with stream gauge rated flow hydrograph (pink line).

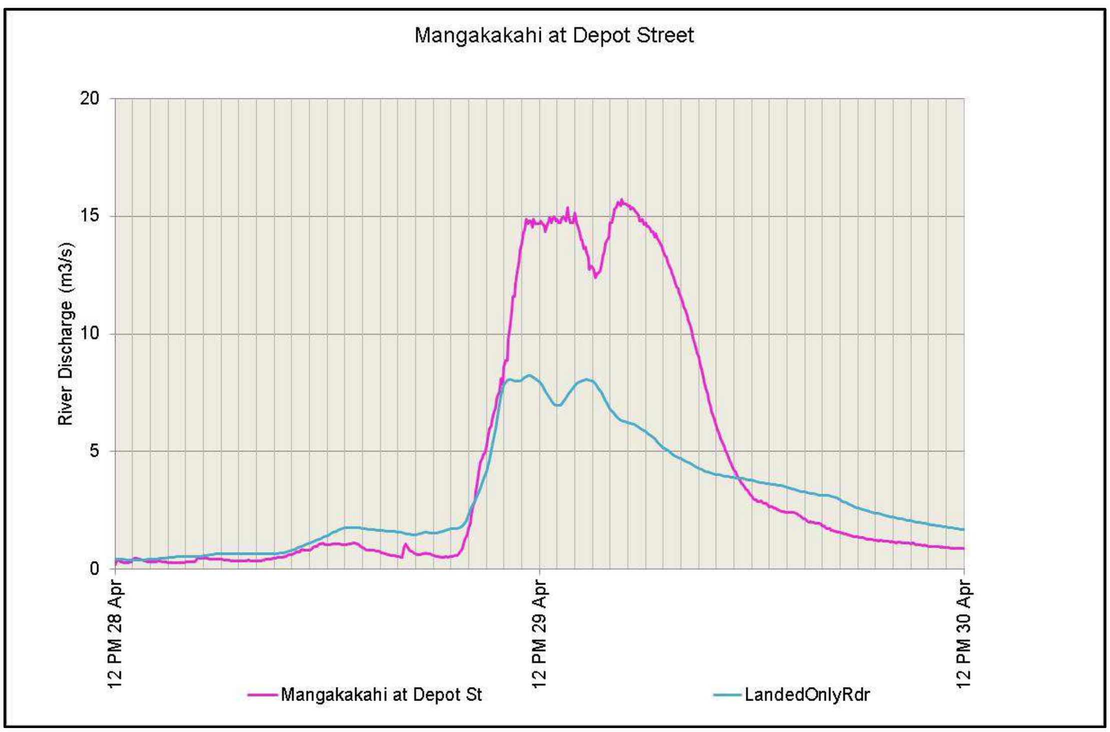

Figure 12: Model discharge results for Mangakakahi Stream at Depot Street (blue line) for April 2018 event. Rated stream gauge data is shown also (pink line). It is suspected that the stream gauge is impacted by the Utuhina confluence nearby downstream - rendering this flow rating un-reliable for calibration comparison.

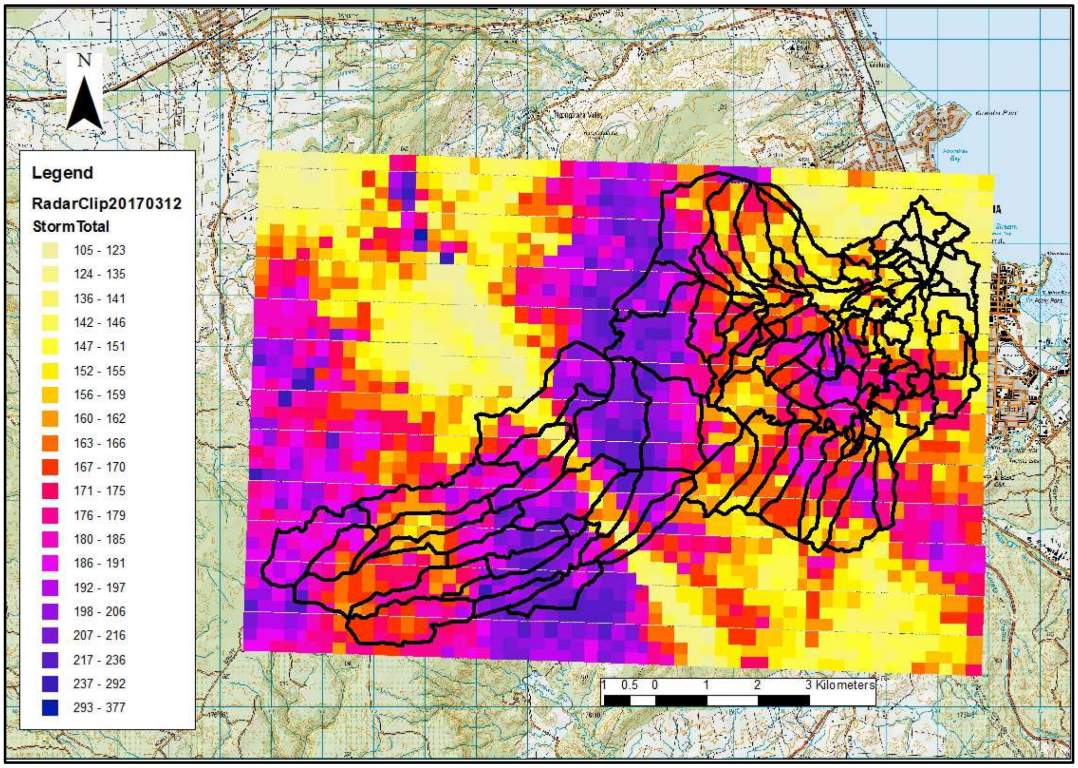

Figure 13: Storm total rainfall radar observations for March 10 - 13 2017. The bright yellow stripe across the mid-catchment is a zone of reduced observation shielded by a high ridge-line peak at its northern end.

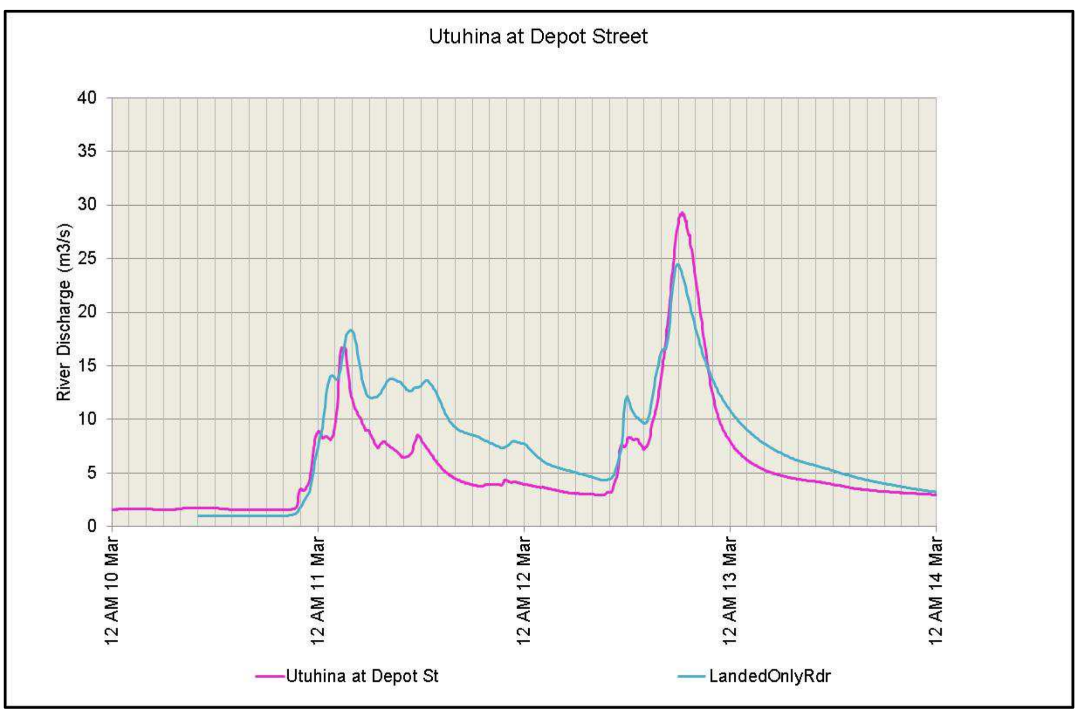

Figure 14: Model discharge results at Depot Street stream gauge on Utuhina Stream for 10-13 March 2017 (blue line) overlaid with stream gauge rated flow hydrograph (pink line).

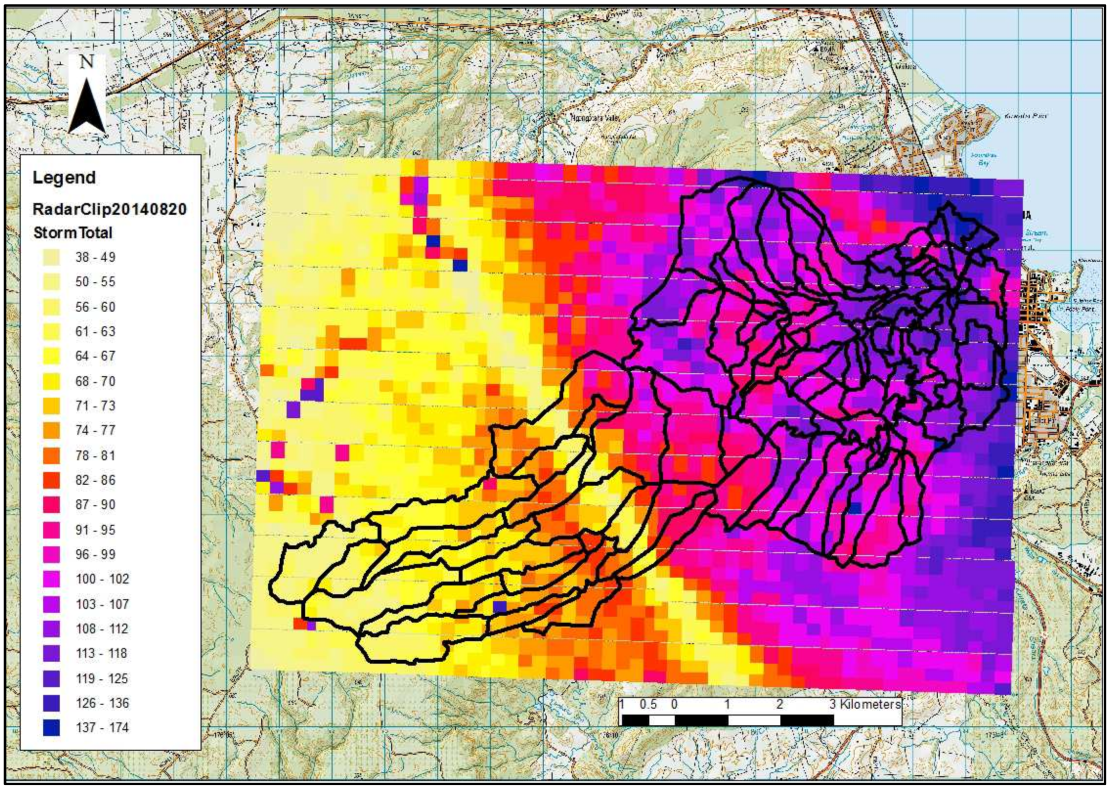

Figure 15: Storm total rainfall radar observations for August 19-21 2014.

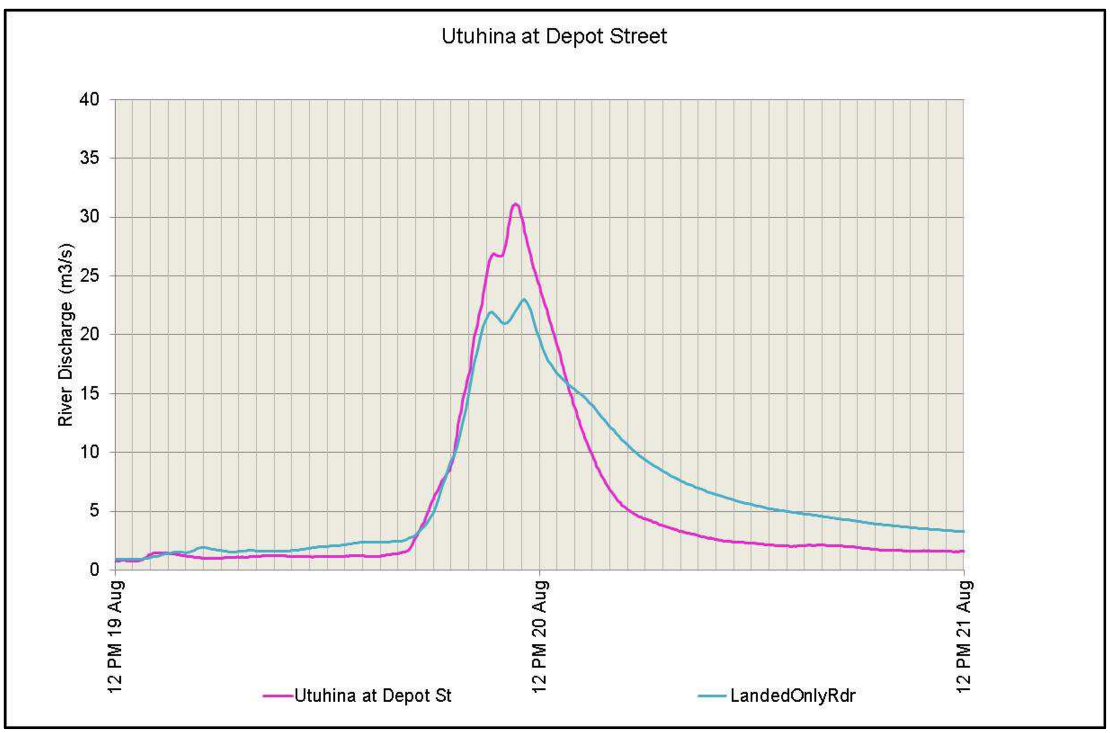

Figure 16: Model discharge results at Depot Street stream gauge on Utuhina Stream for 19-21 August 2014 (blue line) overlaid with stream gauge rated flow hydrograph (pink line).

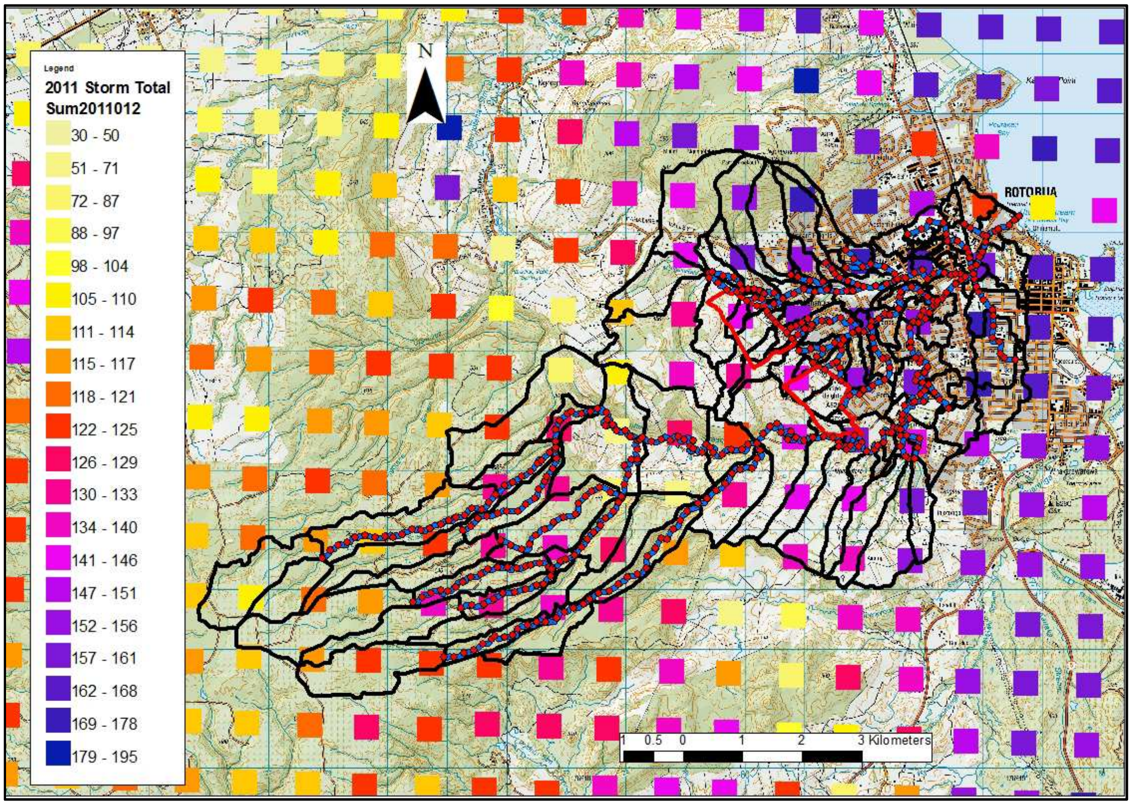

Figure 17: Storm total rainfall radar observations for January 26-29 2011.

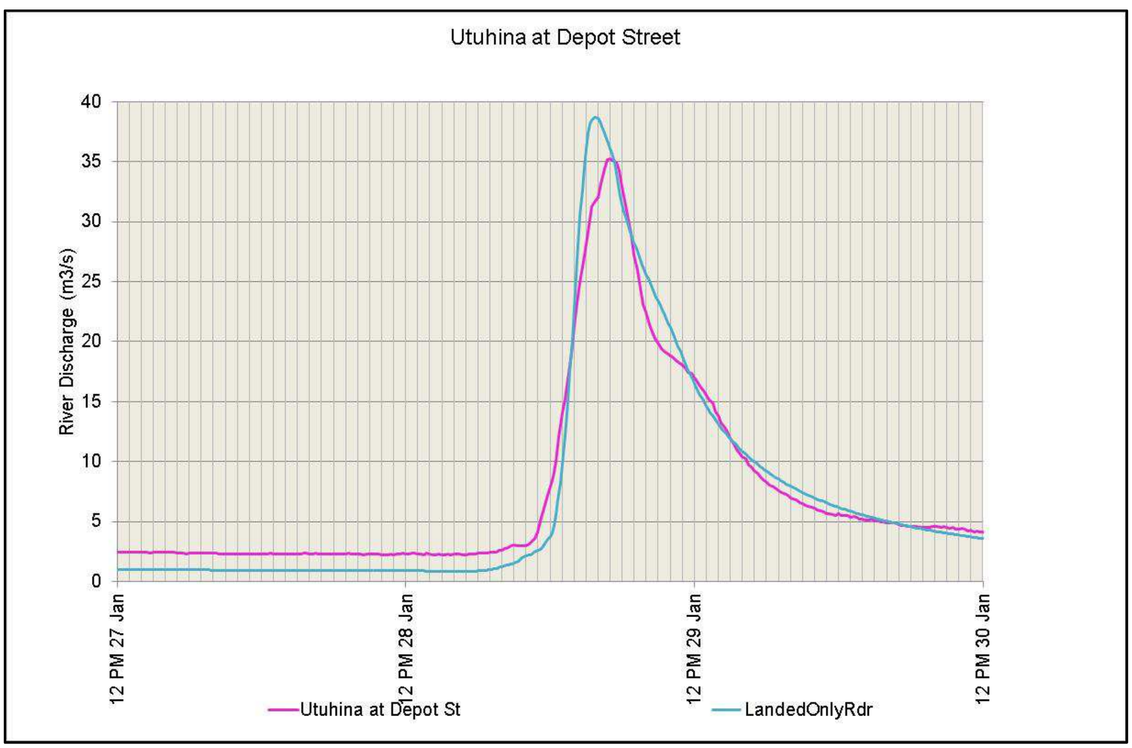

Figure 18: Model discharge results at Depot Street stream gauge on Utuhina Stream for 27-30 January 2011.

Design output

As described above, the model has an integrated design storm generator that can be used to run design scenarios. Design storm modelling is an excellent method for assessing small catchments, however as the scale of the catchment increases with respect to the scale of the rainstorm the reliability is reduced. Our experience with operating design storm generators on calibrated hydrologic models of moderate-large catchments (e.g. Lower Kaituna, Rangitaiki) is that the method does not reliably reproduce peak design discharges in line with statistical analysis of stream gauge historic records. A discussion on the reasons for this is beyond the scope of this study, however design storm modelling remains useful in Utuhina in the following ways:

1. The design-storm modelling method gives a coherent and rational basis for the combining of multiple waterways, and multiple response-scales. In the Utuhina case at gross scale Mangakakahi, Otamatea, Aorangi, Upper-Utuhina streams are distinctly separate sub-catchments that all contribute to flooding along the lower Utuhina in Rotorua City. The combination of these flows in design must be carefully considered. Also at detailed scale, the method provides a coherent way to analyse a smaller sub-catchment such as a plan-change area within the context of the wider catchment. Traditionally these combinations of waterway probabilities in design has been carried out through "engineering judgement" and rules-of-thumb, which are a useful complementary method. By comparison, the design storm methods are able to address complicated multi-scale catchment responses in situations were these must be evaluated.
2. The method is useful at estimating design flows for un-gauged locations - which are often on smaller catchments, and therefore produce more reliable results anyway.
3. Because the method is explicit at the rainfall level, it provides a way to assess the impacts of climate change or land-use change on design hydrographs.
4. At present, statistically-derived estimates of design peak discharge from historical records are inherently more reliable at a stream-gauge location than design-storm modelling. These estimates can be incorporated into the method through informed modification of the design-storm inputs. The combination of these two approaches is perhaps the most usefully reliable of available design methods.

Further study of design storm scenarios at Utuhina may follow, but as a preliminary exercise a selected 1% AEP design storm was simulated in the model. It was centred near the middle of the wider catchment at 1878855 m East, 5771706 m North on the NZTM projected coordinate system (Figure 9) ; travelling on a northward bearing of 360 degrees at 2 m/s. No climate-change warming was included. It produced a model peak discharge of 64.5 m^3/s at the Utuhina Stream at Depot Street gauge location. This compares with BOPRC's most recent estimate for the 1% AEP flow of 55 m^3/s. Figure 19 below shows the model output hydrograph.

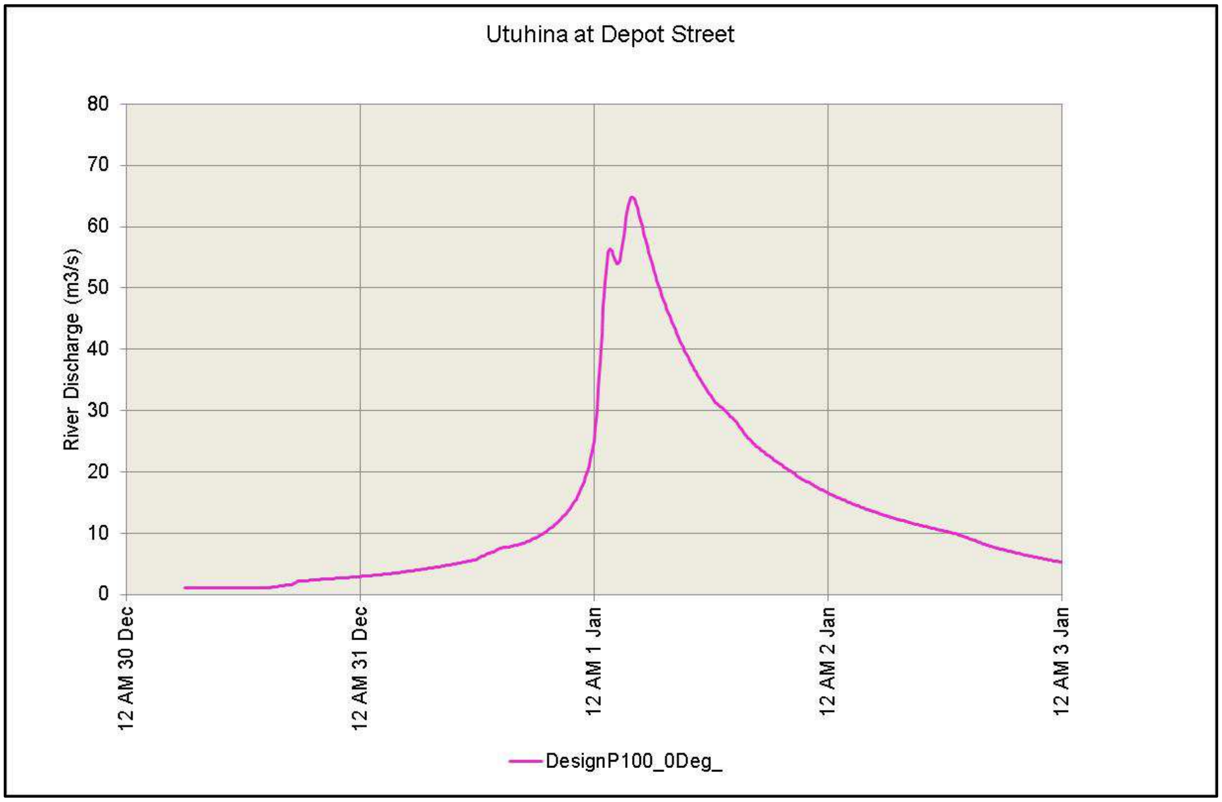

Figure 19: Design storm modelling output hydrograph for Utuhina at Depot Street from a 1% AEP nested rainstorm centred near the middle of the wider catchment.

References:

[1] BOPRC email Blackwood, P. 22 June 2017 4:04pm, *Utuhina at Lake Road & Depot Combined-20170622-Freq-1967-1996 & 2006-17 (supplied by Peter Blackwood by email on 18 September 2019)*.

[2] US Army Corps of Engineers, *Hec HMS Technical Reference Manual*, March 2000

[3] RLC online access GIS database

[4] Rijkse, W.C. 1979: *Soils of Rotorua Lakes District, North Island, New Zealand*. N.Z. Soil Survey Report 43

[5] WSP OPUS, May 2018, *Catchment 14 - Stormwater Model Build and System Performance Report*

[6] Blue Duck Design Ltd, August 2015, *BOPRC Flood Forecasting Systems - Rain Radar Processing Notes*

[7] NIWA, August 2018, High Intensity Rainfall Design System - version 4, NIWA Client Report Number 2018022CH

[8] NIWA email, 21 August 2019, *RE: Re: Mangakakahi Data*, Julie Proud, Environmental Monitoring Technician

Appendix 3: Updated table of soil response parameters for the hydrological model following calibration refinements utilising the DHI hydraulic model

Table 1: Soil types and the model parameters assigned

SOIL_CODE	SOIL_NAME	Soil routing Parameter	f1	fsa	Rsa
AS	Arahiwi steepland soils	18	0.015	0.6	50
AS+PoS	Arahiwi steepland soils + Pohaturoa steepland soils	18	0.015	0.6	50
M	Mamaku loamy sand	18	0.015	0.6	50
MH	Mamaku hill soils	18	0.015	0.6	50
Na	Ngakuru sandy loam	18	0.14	0.3	70
Na+HH	Ngakuru sandy loam + Haparangi hill soils	18	0.14	0.3	70
NaH	Ngakuru hill soils	18	0.14	0.3	70
NaH+NoH	Ngakuru hill soils + Ngongotaha hill soils	18	0.14	0.3	70
No	Ngongotaha loamy sand	18	0.14	0.3	70
No+M	Ngongotaha loamy sand + Mamaku loamy sand	18	0.14	0.3	70
No+NoH	Ngongotaha loamy sand + Ngongotaha hill soils	18	0.14	0.3	70
NoH	Ngongotaha hill soils	18	0.14	0.3	70
PoS	Pohaturoa steepland soils	18	0.14	0.3	70
T	Tikitere sand	18	0.14	0.3	70
Ut+Wa	Utuhina peaty loam + Waiowhiro sand	5	0.4	0.6	50
Wa	Waiowhiro sand	9	0.4	0.6	50