NATURAL HAZARDS RESEARCH PLATFORM

Contest 2015

Title: Faster, efficient, flood forecasts

Leader: Dr Graeme Smart
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Title: Faster, Efficient Flood Forecasts

Programme Leader: Dr Graeme Smart

Affiliation: National Institute of Water and Atmospheric Research Ltd. (NIWA)

Peer Review: J. Walsh, R. Henderson, C. Zammit, A. Grey (NIWA), and G. Campbell (GWRC).

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Key message for media:

Conventional river-flow forecasting and high-resolution floodplain inundation models usually run too slowly to be used for real-time flood forecasting. In this “Faster Flood Forecasts” project we combined hydrologic catchment models and hydraulic floodplain models into a single package, allowing distributed rainfall inputs over both the catchment and the downstream floodplain. The resulting model can also simulate bores (“flash floods” or “walls of water”), which are missed by conventional catchment models. The model was checked by comparing model results with a Waikanae River flood measured during January 2005. In this test-case the uncalibrated model predicted a streamflow peak that was a little too large and early, but the extent of inundation was better predicted, and the computational time was fast enough to theoretically allow active inundation forecasting provided that a 24-hour storm was accurately forecast more than two days in advance. The goal now is to develop and fine-tune the model so that can simulate a 24-hour storm in *under* 24 hours, and when that it achieved the model could be run continuously for operational inundation forecasting.

Abstract:

Flooding has impacts on multiple economic sectors as well as causing human and community losses. This research concerns speeding up of flood inundation forecasting to allow warning for the timing and severity of impending flood events. A combined hydrologic (catchment) and hydrodynamic (floodplain) model is developed as a single package (FFF model), allowing distributed rainfall inputs over the Waikanae River catchment and onto the downstream floodplain and town. The FFF model run time is faster than previous, individual component models, but typically takes two days to run a 24-hour storm inundation simulation when computed on an IBM Blade H cluster.

When the hydrologic function of the combined FFF model was evaluated by comparison with measured streamflow from the January 2005 flood, the (uncalibrated) model predicted a streamflow peak that was 15% too large and 50 minutes too early. For the same flood, the equivalent conventional catchment (TopNet) model, with 8 parameter calibration, predicted a streamflow peak that was 3% too large and up to 60 minutes too early (the model time-step is 1 hour). The difference in floodplain inundation was significant however, not because of the different inflow peaks but because the hydrologic catchment model did not include flooding from rainfall that fell on the Waikanae floodplain. Thus, in this application, while conservatively predicting the timing and size of the flood, the combined FFF model predicted the inundation extent better than a conventional hydrologic-hydraulic model chain.

Keywords: Floods, forecasting, inundation, hazard, runoff.

Introduction / Background:

Operational flood forecasting systems currently use hydrologic models to predict river flows (Cattoën et al, 2016; Pagano, 2013; Wetterhall et al., 2013) and the river flows are then used in hydrodynamic models to predict floodplain inundation (Smart, 2016). Flood inundation forecasting thus comprises three steps: atmospheric (rainfall) modelling; hydrologic (catchment outflow) modelling; and hydrodynamic (floodplain inundation) modelling. Each type of model has been refined over the years to give higher resolution and more accurate data for better prediction of floods. However, the combined run-time of the sequence of three computer models is usually too long (several days) to be useful for realistically and accurately forecasting the extent of an impending flood. Furthermore, chain linking of models makes the process of real-time assimilation of updated input data and feedback/forward of interdependent results more problematic.

This research stems from hydrodynamic modelling undertaken by NIWA in Fiji, and by EQC in New Zealand for evaluating the increase in flood vulnerability following the Christchurch earthquakes. In both cases it was necessary to input rainfall directly onto the floodplain to reproduce observed flooding. i.e., the floodplain also acted as a catchment. This innovation, allowing distributed water sources (and sinks) across the topography of a floodplain, rather than have it overflow from river channels, is termed "rain-on-grid" modelling. The rain-on-grid facility is now available in several commercial hydrodynamic flood modelling packages. An additional innovation recently introduced by NIWA is "adaptive grid" hydrodynamic modelling, which decreases model run time by allowing the size of individual computational grid cells to vary during the course of a flood. Such a model may use 2m x 2m computational cells at a location where water starts to spill over a road berm and then switch to 16m x 16m computational cell at the same location when the berm is deeply submerged by floodwaters.

This research now investigates combining the hydrologic and hydrodynamic models of the forecasting chain. It achieves this by extending hydrodynamic models to include all catchments which feed the floodplain of interest. Adaptive computational cells are proposed to embrace both large catchments at a coarse scale and small individual channels at a fine scale. Effective rainfall (precipitation less evaporation and infiltration) can be distributed across the modelled catchments and floodplain in the manner predicted by an atmospheric model (weather forecast). The advantages of this approach are that rainfall may vary with time and location so that, for an extreme example, a storm may move down a catchment and across a floodplain as a growing flood moves in the same direction. A further advantage is that many of the complex parameters of comprehensive hydrologic catchment models become insignificant under the heavy rainfall conditions that lead to dangerous floods and do not need to be included (e.g., evaporation and infiltration).

The research was undertaken on a representative New Zealand location that had rainfall and runoff measurements, as well as a digital elevation model floodplain and catchment, using an open source, adaptable grid, shallow-water equation solver (Basilisk) to model the selected floodplain and catchment area. Algorithms were investigated to represent catchment topography and flow within computational cell sizes ranging over two orders of magnitude (from square metres in the valley bottom streams, to thousands of square metres on catchment hillslopes). Model runs were made using recorded storm rainfall to simulate river flows, and the results compared with measured catchment outflows. The performance of selected algorithms was evaluated, as was the accuracy and sensitivity to catchment parameters. Finally, the combined hydrologic-hydraulic, catchment/ floodplain model was evaluated in terms of potential forecasting improvements compared to conventionally linked hydrologic and hydrodynamic models.

Benefits to New Zealand

Flooding is New Zealand's most costly natural hazard (Te Ara, 2013). It has economic impacts on the agriculture, horticulture, transport and energy sectors, as well as causing human and community losses. Techniques to avoid or mitigate flood losses involve moving people, buildings and infrastructure away from the floods or moving the floods away from the human and economic assets.

This project worked to improve flood inundation forecasting, which gives warning of the timing and severity of impending flood events. Such warning saves lives by assisting CDEM in planning evacuations, and saves economic losses by providing information for temporary flood protection measures and enabling transportable assets to be moved out of harm's way (in both urban and rural areas). When linked to long-range rainfall forecasts (e.g., NIWA's EcoConnect), the proposed methodology should lead to flood inundation warnings several days in advance, long enough for mitigation actions to be taken.

In addition, the bulk of New Zealand's electricity is generated from hydro storage schemes. Maximising hydropower generation requires minimising spilled floodwater. With more accurate knowledge of impending flood inflows, it will be possible to reduce reservoir storage through pre-flood generation, allowing reservoirs to recharge during the ensuing floods. Where catchments have reservoirs, therefore, the proposed approach can include attenuation of flood peaks by reservoir storage to reduce downstream inundation.

The research presents a simpler, potentially faster, accurate, flood inundation prediction technique to help reduce flood-induced losses across New Zealand. This helps fulfil the call in the Ministry for the Environment's *Flood Risk Review, National Infrastructure Plan* (2011) for "the ability to mitigate economic, social and environmental impacts of future hazards through the application of reliable planning and forecast information".

Research, Science and Technology (RS&T) Benefits to New Zealand

Contrary to many overseas flooding situations, New Zealand short and steep rivers mean that much of a rising flood's behaviour is determined in the hill and mountain catchments. This research develops our capability to model such areas.

Presently, catchment models used in New Zealand (e.g., Mike SHE from Europe, RORB from Australia or TopNet) are intricate, with several calibration factors. They represent many facets of hydrologic processes, but they only crudely model water flows in catchment gullies, streams and river channels. This hybrid model places less emphasis on catchment processes that are not highly significant during severe rainfall events, and places more emphasis on correctly modelling the runoff of overland water into gullies, streams and channels from mini-catchments and floodplains. The new method is compared with a TopNet rainfall-runoff model in order to ascertain whether accuracy and precision are retained.

Another RS&T benefit is that inundation modelling of the downstream river floodplain has been sped-up. For the evaluation flood, this part of the model will run *faster* than real time, indicating that real-time inundation forecasting is already feasible.

Development of capability

Early mid-career scientists undertook much of the research for this project.

Impact Statement Achievement

- **Research Aim 1.1.** Build an adaptable-gridsize, two-dimensional hydrodynamic model covering river catchments and calibrate using measured data.

Research Aim achieved? Yes.

Milestone 1: *Confirm a suitable study area* (by 31 December 2015). After consideration of existing catchment models, catchment locations with suitable LiDAR cover, catchments with suitable rain gauges and flow gauging stations, areas where flood forecasting would benefit a downstream community, and after consultation with regional authorities, the Waikanae River catchment and downstream town were selected as the study area. It included consultation with LINZ and GWRC.

Milestone 2: *Develop a 2-dimensional adaptive grid hydrodynamic model for the catchment* (By 30 June 2016). Topography and roughness grids were developed for the Waikanae River catchments at 4.5 m horizontal resolution. With these grids, a Basilisk, depth-averaged, adaptive quadtree, hydrodynamic model of a 340 km^2 area was developed (FFF model). The model was not calibrated.

Milestone 3: *Evaluate the hydrodynamic catchment model to determine the accuracy and sensitivity of outflows to catchment parameters* (by 30 June 2016). The 5 January 2005 (1/70 AEP) observed storm rainfall was used to evaluate the FFF model. Model predictions of flow in the Waikanae River beside the Water Treatment Plant were compared with the streamflow recorded at that recording station during the flood. The accuracy and sensitivity of outflows depended on the degree to which the computational grid was resolved, the numerical algorithms within the computational model, the distribution of rainfall on the catchment and the roughness of the terrain. The aerial and temporal distribution of the January 2005 rainfall across the catchments was simulated by interpolating from records at 3 rain gauges. Model run-time was most sensitive to the dynamic grid adaptation methodology that was used. Different adaptation algorithms were tested to optimise the trade-off between accuracy of predictions and model run-time.

- **Research Aim 1.2.** Extend the hydrodynamic catchment model to include floodplain topography. Evaluate the combined hydrologic/hydraulic, catchment/floodplain model in terms of measured improvements in accuracy and computation time compared to the conventional but protracted process of linking hydrologic and hydrodynamic models.

Research Aim achieved? Yes.

Milestone 4: *Extend the hydrodynamic model to include floodplain topography* (by 31 December 2016). The current model covers the entire Waikanae catchment and floodplain. Run time is faster than previous, individual component models, but typically takes two days or more to run a 24 hour rainfall-inundation simulation when computed on an IBM Blade H cluster. Methods for speeding up run time continue to be investigated in a follow-on project (see “List of End Users” below). Algorithm optimisation allowed the floodplain part of the model to run faster than real time. The model has also been used in a LINZ evaluation of the effect of LiDAR resolution on flood inundation.

- **Research Aim 1.3.** Present research results via a scientific paper and talks at e.g., NZ hydrologic society, IPENZ Rivers Group, NZ Regional Council River Managers’ Group.

Research Aim achieved? In progress (as discussed with the Platform in emails of 30 March 2017).

Milestone 5: *Produce a scientific report, suitable for submission to a peer reviewed journal in the event of a successful outcome to the research* (by 30 June 2017). The technical report is in Annex 1, below.

Milestone 6. *Present the research findings to stakeholders*. Scheduled for presentation at the NZ Hydrologic Society annual conference in Napier on 28 November, 2017 and to the IPENZ Rivers Group at the NZFSS conference in Hamilton, 19-24 November, 2017.

List of outputs

- Prototype Waikanae hybrid catchment-floodplain model.
- Technical report.
- End-user presentation to NZ Hydrologic Society annual conference (November 2017).
- End-user presentation to IPENZ Rivers Group (November 2017).
- The research was used in a report for LINZ on the use of LIDAR.

List of end-users

- Greater Wellington Regional Council, who can use the model for flood hazard evaluation.
- LINZ, in evaluating issues concerning LiDAR resolution and flood inundation.
- National and International science communities studying inundation forecasting, e.g., in NIWA SSIF Platform research.

Conclusions & Recommendations

The research focussed on increasing the computation speed and efficiency of inundation forecasting, while accurately reproducing flood size and timing.

The research developed a very computationally demanding model that took around 400 hours (16.5 days) to process a 24-hour storm (see attached technical report). By the conclusion of the project, the best computational time achieved was 43 hours to model a 24-hour storm. While this timing would theoretically allow active inundation forecasting (provided the rainfall was forecast more than two days in advance), the ultimate goal is to achieve a model that will run faster than real time (i.e., be able to simulate a 24-hour storm in under 24 hours), which would allow the model to be run continuously for operational inundation forecasting. In terms of accuracy, when the hydrologic function of the combined FFF model was evaluated by comparison with measured streamflow from the 5 January 2015 Waikanae flood, the (uncalibrated) model predicted a streamflow peak that was 15% too large and 50 minutes too early. However, the combined FFF model better predicted the extent of flood inundation better than the conventional catchment and floodplain model chain, and inundation modelling of the downstream river floodplain was also computationally sped-up.

The project achieved its Research Aims, and demonstrated the feasibility of a new type of single-model forecasting that delivers flood inundation maps. It showed that the inundation component of the model would run faster than real time, indicating that real-time inundation forecasting is already feasible for small model areas. From this point, there is a need to seek run-time improvements through further research, which may be undertaken in NIWA SSIF Platform research.

A full description of model development and graphical results is in this report’s Technical Annex.

Acknowledgements

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Faster, efficient, flood forecasts

[*To be read in conjunction with preceding abstract, introduction etc*.]

Location

The catchment and floodplain of the Waikanae River (see Figure 1) was selected for this study because (i) the range of topography, infrastructure and vegetation cover in this region represents a microcosm of conditions found across New Zealand; (ii) a sizeable flood has been recorded in the river system; and (iii) high resolution topography could be derived from LiDAR tiles (nominal 1 point/m^2 density or better) available from Greater Wellington Regional Council and LINZ.

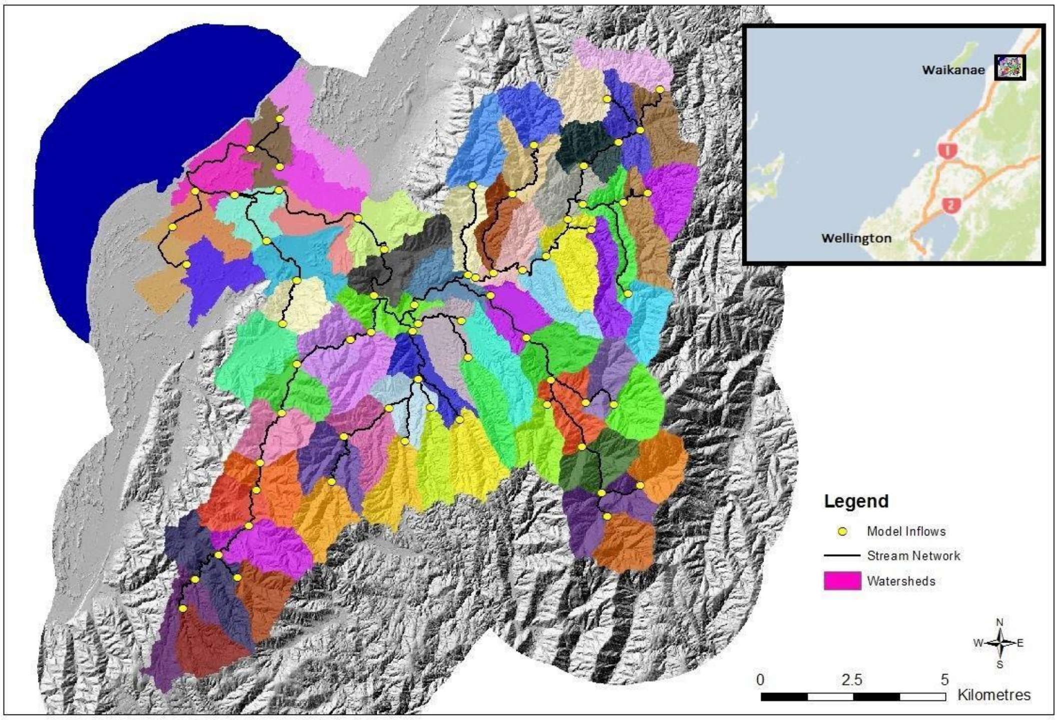

Fig. 1. Location of Waikanae River system subdivided into 67 watersheds of 2 km^2.

Hydrodynamic model

An adaptable grid Basilisk 2D hydrodynamic model was set up for the catchments and floodplains of the Waikanae River. For more information on the open source software used for solving the partial differential shallow water equations for the hydrodynamic modelling visit http://basilisk.fr/

This type of model can accurately simulate flow phenomena including bore formation (sometimes called "walls of water") which are not predicted by conventional rainfall- runoff-routing models.

LiDAR processing

LiDAR was used to provide a ground surface DEM and a surface roughness grid for the hydrodynamic model. Unrefined LiDAR was processed for the modelling grid in a series of steps.

The LiDAR point cloud data was analysed to extract surface elevation (Z) and surface roughness (Zo). The Z elevation was determined to be the lowest ground LiDAR "hit" within a specified footprint. The ground roughness was determined by an algorithm which analyses variation and absorption of returns within the local search footprint. The roughness algorithm is pre-trained for each LiDAR data

sortie using reference surfaces such as roads, gravel areas, fields, scrub, etc. (Smart, 2016). In order to correctly extract surface level and roughness there must be multiple returns from within a search footprint. Because LiDAR files are large and neighbouring LiDAR hits may be from different LiDAR flight path scans and widely separated in the data file, this roughness extraction process is computationally demanding. The roughness is assumed to not change with time and this process does not affect the run time for inundation forecasting. In the data sets there were areas with very high trees and native bush. Because flood flows pass through (not over) such roughness, forested area roughnesses were clipped to give a more realistic representation of flow through the trees rather than over the canopy (i.e. the present roughness data should not be used for atmospheric flow modelling).

The Z and Zo scattered data sets were gridded at the finest meaningful resolution, which was taken as the footprint radius used for the Z and Zo detection. These raw grids were then upscaled to a 4.5 m DEM grid size suitable for hydraulic modelling. For upscaling of roughness, the average of underlying sub-grid values is used to set the upscaled grid value. For upscaling of ground elevations, using the average underlying value smooths high and low points and does not necessarily preserve the level of natural barriers to flow such as crest elevations of stopbanks, or the drainage invert level of overland flow paths or drains. One solution is to define break lines along critical features such as stopbanks or drains and enforce pre-defined breakline elevations on the upscaled grid DEM. This is usually a manual process which can miss unexpected crest lines such as roadways, railway embankments and vegetated swales. For this modelling an upscaling algorithm (which sets the upscaled cell level to the lowest elevation at which water could spill across the underlying sub-grid cells) was used.

The LiDAR processing steps are illustrated below for a typical section of the floodplain. Fig. 2 shows surface elevation data for a sample location on the Waikanae River (the river and flood berm at Jim Cooke Memorial Park, 1km downstream of SH1). Fig. 3 shows the model DEM (gridded elevation data) and Fig. 4 shows the model roughness grid.

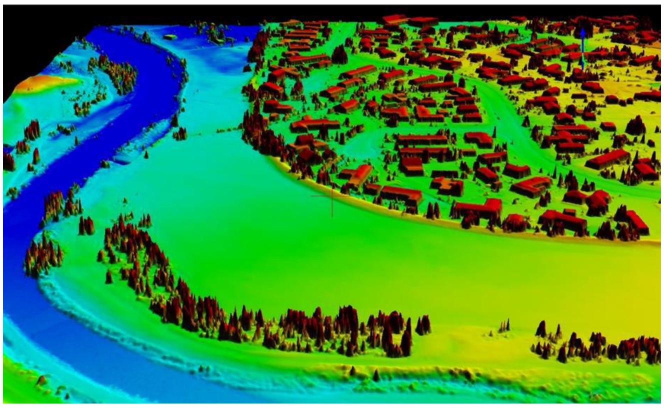

Fig. 2. LiDAR surface elevations at Waikanae, indicated by a colour scale ranging from dark blue (low) to dark red (high).

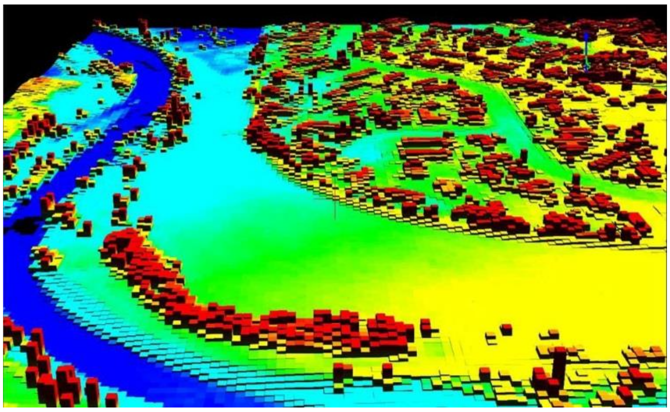

Fig. 3. Part of the DEM for the FFF model-surface elevations represented by 4.5m grid squares (with the same colour scale).

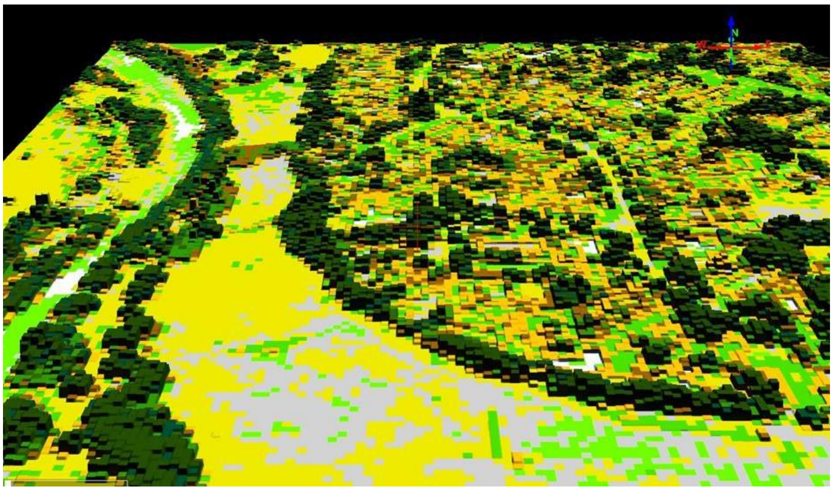

Fig. 4. Part of the FFF model roughness grid with colour scale ranging from grey (smooth) to dark green (rough).

Boundary conditions

In a conventional hydrodynamic model there are two usual types of boundary conditions: (1) Flow-vs-time inflow from upstream catchments (often a design flood or a hydrograph from a rainfall runoff model); and stage-vs-time conditions for the downstream boundary condition.

As this model incorporated all upstream catchment areas the first condition was not needed. It was used in one model run to establish the downstream flood inundation that would have been predicted with a conventional rainfall runoff hydrograph model. For all other simulations, rainfall was directly added across the catchments.

The downstream boundary condition (sea level) was determined by the recorded tidal levels that occurred during the 5 January 2005 evaluation flood.

The same topography, roughness and tidal boundary conditions were used in all model variants. Typical model-predicted inundation results for the Jim Cooke Memorial Park sample location are shown are shown in Fig. 5.

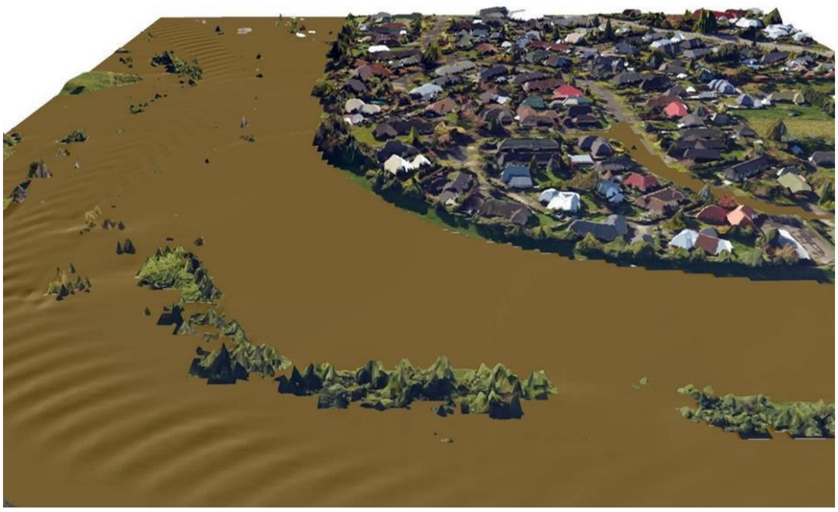

Fig. 5. Modelled water levels in the Waikanae River at Jim Cooke Memorial Park at a flow of around 300 m^3/s. This model has not been calibrated.

Evaluation flood

On 5 January 2005, a significant (1/70 AEP) flood event occurred. Floodwaters got in behind recently completed flood protection works and about 20 houses were evacuated on the south side of the

Waikanae floodplain at Otaihanga. In the Waikanae River headwaters (at the top of Akatarawa Hill Road) 124mm of rain fell in 12 hours to 6am, with peak intensity of 74mm in a 3-hour period. At 2.30 am the Waikanae River peaked at 380 m^3/s at the Water Treatment Plant recording station above State Highway 1. This was the largest flow recorded at this site since records began in 1975. Records of the rainfall (hyetograph) that produced this flood were used in two different models to simulate (hindcast) the flood. Resulting model predictions of flow in the Waikanae River beside the Water Treatment Plant were compared with the streamflow recorded at that recording station.

Conventional hydrologic modelling approach

A TopNet rainfall runoff model was implemented for the Waikanae River catchment in order to compare conventional flow forecasting results with results from the catchment-wide FFF model. TopNet has two major components; a basin module and a kinematic wave channel routing algorithm. TopNet model equations and information requirements are given by Clark et al. (2008) and McMillan et al. (2013). Spatial information in TopNet is provided by national datasets on catchment topography (a 30 m digital elevation model), physical characteristics from Land Cover Database version 3, (Land Resource Inventory, Newsome et al., 2000) and hydrological properties from the River Environment Classification hydrological network version 2, (Snelder et al., 2010). The surface water catchment hydrological model subdivided the Waikanae catchment basin into 293 sub-catchments. Topnet has 8 calibration parameters. The method for deriving TopNet initial parameter estimates from GIS data sources in New Zealand is given by Clark et al. (2008). The parameters were adjusted through evaluation of hourly streamflow and flow duration curves (observed and predicted). The calibration period was 1 September 2004 to 15 January 2015.

This period was chosen to provide the model with enough time to achieve correct soil moisture and groundwater levels by the time of the 5 January 2005 evaluation flood. The calibration period included the evaluation flood. The calibrated TopNet model was run using measured rainfall records, to give a hindcast of the 5 January 2005 flood. The output from the TopNet model is a simulated hydrograph of the evaluation flood, predicted at the location of the Waikanae Treatment Plant gauging station.

FFF model approach

The FFF hydrodynamic model was applied to the catchment area of the Waikanae River system as well as (a conventional application) to the floodplain further downstream. Various model options were investigated as described below.

The FFF model assumes that no rainfall is lost (i.e. all rainfall runs off or is stored in the catchment). In reality, the fraction of catchment rainfall that reaches the outlet of a catchment can be highly variable depending particularly on how wet the catchment is at the time of a storm. The 3-day average runoff to rainfall ratio is shown in Fig. 6 for 274 station-events recorded in the vicinity of the Waikanae catchment. For 3-day windows, on average only one third of the storm rainfall runs off. As an approximate upper limit, 85% of storm rainfall runs off within 3 days (left graph). Fig. 6 (right graph) shows that the higher volumes of runoff coincide with higher runoff to rainfall ratios.

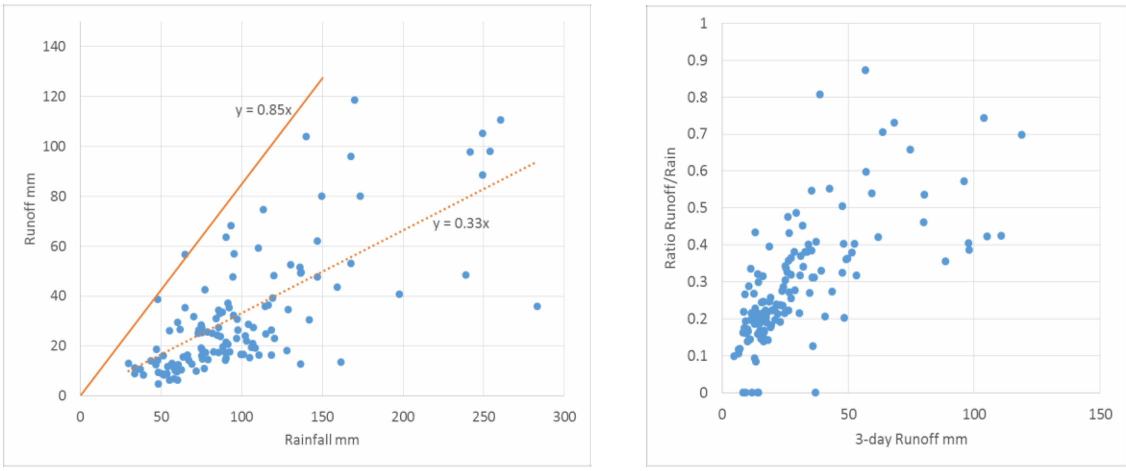

Fig. 6. Ratio of runoff to rainfall over 3 day windows for 275 station-events recorded close to the Waikanae catchment.

Rainfall Input

3 climate stations are located within the boundaries of the Waikanae catchment (Table 1). The precipitation at these sites was used to drive the calibration and validation of the hydrological (TopNet) model and to provide input for the evaluation flood. Aerial distribution of precipitation within the models was determined by interpolation between the rain gauge data using the inverse distance method.

Table 1: Climate stations used for the Waikanae catchment.

Name	Tideda ID	Catchment	Elevation (masl)
Akatarawa at Warwicks	59007	Hutt	345
Waikanae at Treatment Plant	58004	Waikanae	40
Waiotauru at Kapakapanui	59104	Otaki	1020

The same temporal and aerial distribution of rainfall was used for comparison of the hydrological and FFF models. Spatially averaged rainfall was used in some FFF model variants to evaluate the effects of different grid-sizing algorithms.

FFF model options investigated

To optimise model accuracy and run time the following approaches were considered:

- Temporal and spatial rainfall injection
- Improvement of flow resistance calculation at shallow depths
- Size of computational cells
- Algorithms to govern flow within computational cells
- Sensitivity of results to catchment parameters (roughness, cell size)

Shallow injection depths

During a computational time step of e.g. 1 second, a rainfall intensity of 3.6 mm/h produces an incremental depth increase of one micron (1 x 10^{-6} m). Not only can such very shallow depths cause numerical instability in a hydrodynamic model (Yu & Duan, 2017) but the flow friction (and consequently velocity) is not correctly represented by flow resistance equations designed for turbulent channel flow (Smart, 2016). In conventional floodplain models computation is typically suspended in cells with depths less than a given threshold. This “dry cell” threshold, which is large relative to rainfall depth per computational time-step, can result in sporadic, unrealistic flow surges when large computational catchment cells reach the “dry” level threshold.

Flow resistance equation

In order to better represent flow resistance at very shallow depths, modified flow resistance equations designed for a wider range of flow depths were used. At depths similar to or lower than the ground roughness height, a linear vertical velocity profile is assumed. This not only improves model realism but also increases computational speed and stability (Smart, 2016).

Catchment rainfall injection

Rainfall injection methodology from the 3 catchment rain gauges could range from interpolated local rainfall amounts input at every model grid node, to 3 injection points at the centroid of polygons representing the assumed cover of each rain gauge.

Rainfall could be injected at every computational time step or at a fixed time interval (e.g. every 6 sec, 60 sec, 15 min etc.). The Basilisk model solver can dynamically adjust the computational cell size according to the time step, water depth and velocity.

With dynamic cell size optimisation a dilemma occurs if a model does not resolve into small cell sizes where water depth is very shallow. This is because depth will only become significant in places where the model is resolved at sufficient resolution to reveal the deeper stream channels within the topography. Thus, water will pond at an unrefined rainfall injection point until it reaches the “dry cell” threshold or spills over the crest level of the averaged neighbouring cells. Once this happens, velocity increases and the cell size will be decreased to reveal finer channels. Consequently, a mini “dam break” surge can occur which propagates downstream. The propagation of surges can be governed by flux limitation within the model code.

Options to increase depth in model computational cells were investigated by:

- injecting rainfall in bursts every few minutes or seconds (temporally coarser rain);
- injecting rainfall at more widely spaced points (spatially coarser rain);
- a combination of both; and
- refining and varying the computational algorithms within the model (dynamic cell sizing and numerical flux limitation).

Size of computational cells

Several algorithms to govern dynamic cell size adaptation were investigated but none were identified that could correctly resolve stream channels under all drying and wetting conditions. The adopted (computationally advantageous) solution was to prevent coarse levels of dynamic adaptation within the pre-defined catchment stream channel network.

Sensitivity of results to catchment parameters

The model run time and predicted outflow hydrograph were compared using different cell sizes and ground roughness options.

Results

Rainfall injection

As an initial trial, rainfall was added to every cell of the model according to the storm hyetograph using a low dry cell threshold. The model took around 400 hours (16.5 days) to process a 24 hour storm. This "rain-at every-point" approach inhibited dynamic grid adaptation, was computationally demanding and was abandoned because the slow computation speed precluded this type of approach from being used for forecasting purposes. Various options were then investigated, for example, rainfall injected every 120 seconds at points spaced every 100m.

Temporal and spatial density of direct rainfall injections

After several trials, rainfall was injected to the model every 10 seconds. Fig. 7 shows flood hydrographs at the Waikanae Water Treatment Plant recording station with 67 rainfall injection areas (yellow line) and with 294 rainfall injection points (light blue line). The 67 injection points resulted from subdividing the Waikanae catchment into 2 km^2 sub-catchments as shown on Fig. 1. The 294 rainfall injection points are taken from the TopNet rainfall-runoff model (used as a benchmark to evaluate the performance of the FFF model). As the total rainfall over the catchment is fixed, the more injection points, the lower the rainfall depth injected at each point. This results in a longer time to fill a cell up to the "dry" level at which the cell becomes computationally active (the yellow hydrograph starts to rise about 6:20am on Fig 7, whereas the blue one starts to rise an hour later). The greater number of injection points (294 versus 67) resulted in a somewhat smoother catchment outflow hydrograph.

The size of sub-catchment represented by each injection point affected the time to reach the "dry" threshold of computational cells but had little influence on peak flood flow or peak timing once a reasonable number of injection points were used.

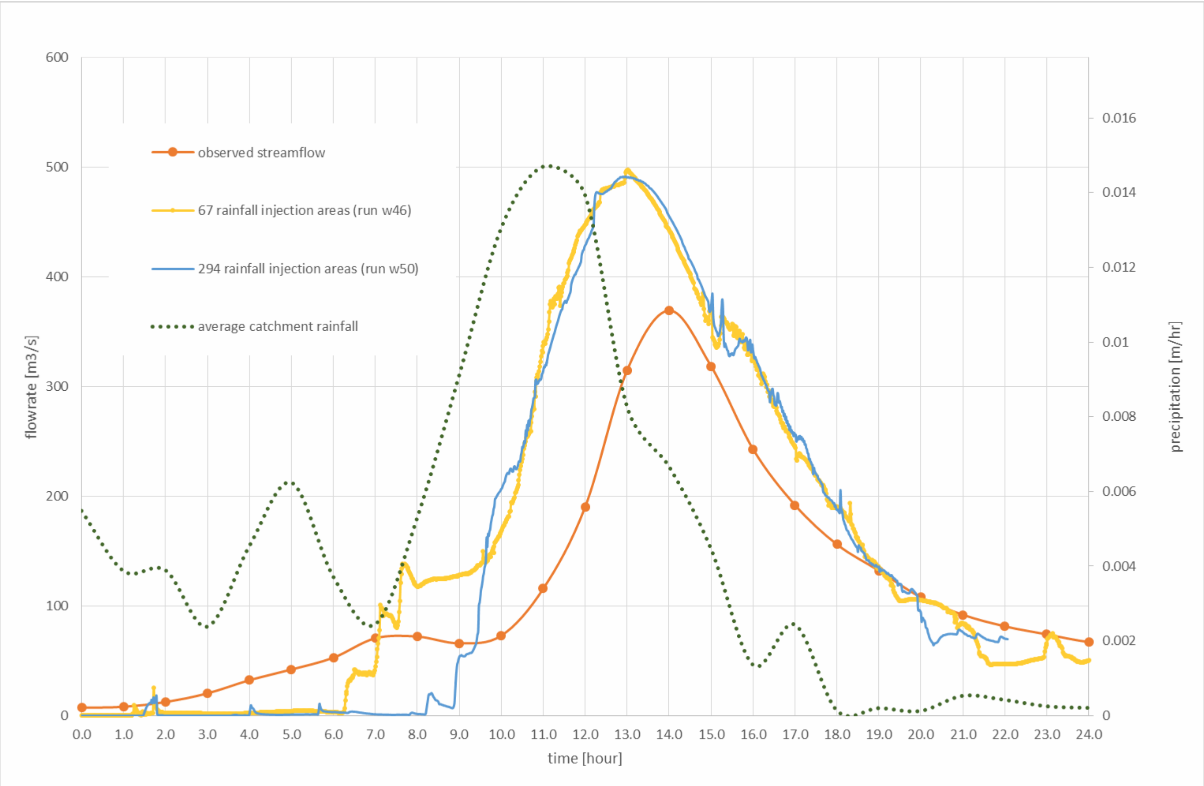

Fig. 7. Simulated river hydrographs at the at the Water Treatment station using the FFF model (with a 10mm "dry" cell level) showing the effect of density of rainfall injection with no losses.

Numerical flux limitation

Fig. 8 shows flood hydrographs at the Water Treatment Plant recording station to illustrate the effect of numerical dissipation in the model equation solver. Standard flux limitation (yellow line) captures small surges in the flow. With increased flux dissipation (blue line) the hydrograph becomes smoother but decays more rapidly.

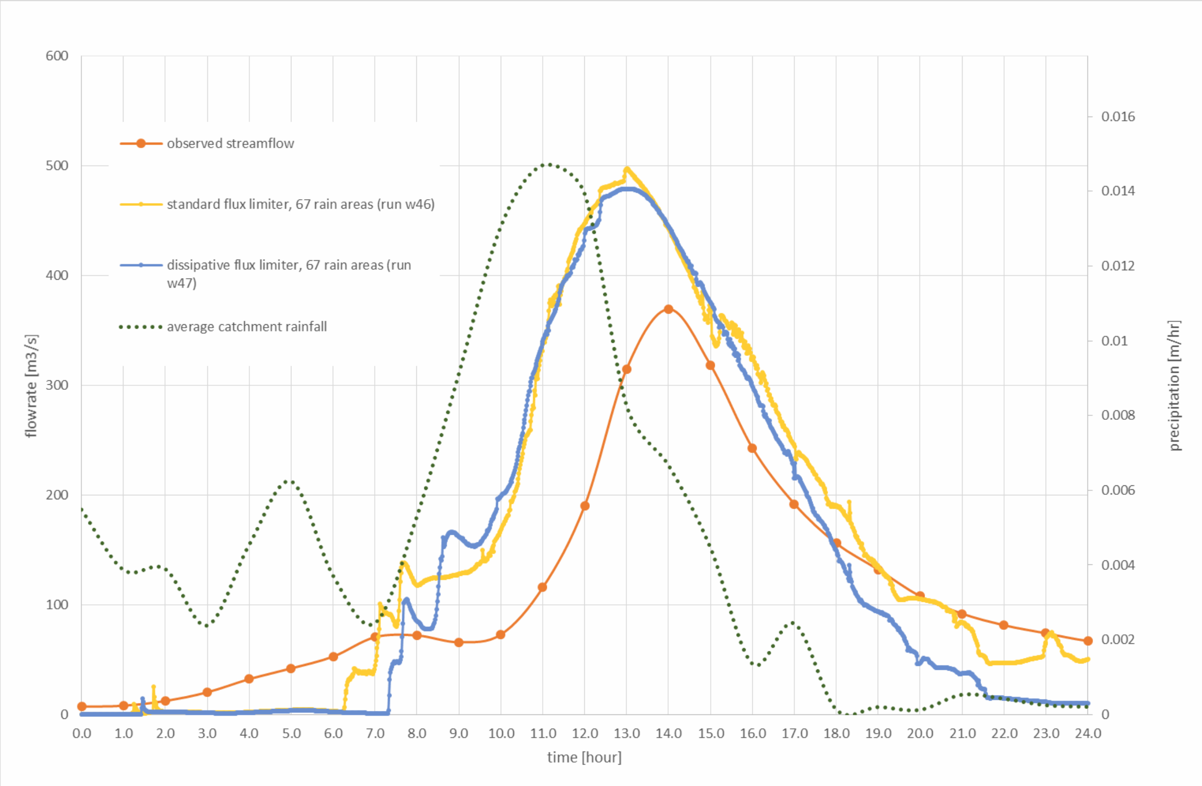

Fig. 8. Simulated river hydrographs at the at the Water Treatment station using the FFF model (with a 10mm "dry" cell level) showing the effect of flux limitation on FFF model with no losses.

Rainfall losses and comparison with Rainfall-runoff model

The FFF model has no provision for evaporation, evapotranspiration, soil moisture storage or groundwater storage. The TopNet model of the catchment, used for comparison, has 8 calibration parameters. In order to give a candid evaluation of the FFF model, no calibration of this model has been carried out so far. It is impossible that all rainfall falling on the catchment will reach the Water Treatment Plant recording station (as implied by Figures 7 and 8) and a standard, ballpark 15% rainfall loss factor (Fig. 6) is now applied at each rainfall injection point for each 10 second rainfall timestep of the model. Fig. 9 then shows comparative flood hydrographs predicted by the FFF model (with 15% rainfall losses) and by the fully calibrated rainfall-runoff TopNet model. It would be possible to generally adjust the rainfall loss ratio according to Fig. 6 and adjust the "dry" threshold and/or other variables in order to calibrate the FFF model to give a closer approximation to the observed streamflow hydrograph. However, the purpose of this research is to investigate the feasibility of rapid hydrodynamic catchment modelling and not mask any limitations due to assumptions inherent in the FFF model by "curve fitting" parameter adjustment.

In this raw state, the FFF model predicts the flood peak around 50 minutes early and overpredicts the peak by 15%. The fully calibrated TopNet model predicts the flood peak 0 - 60 minutes early (running at an hourly time step) and overpredicts the peak by about 3% (Fig. 9).

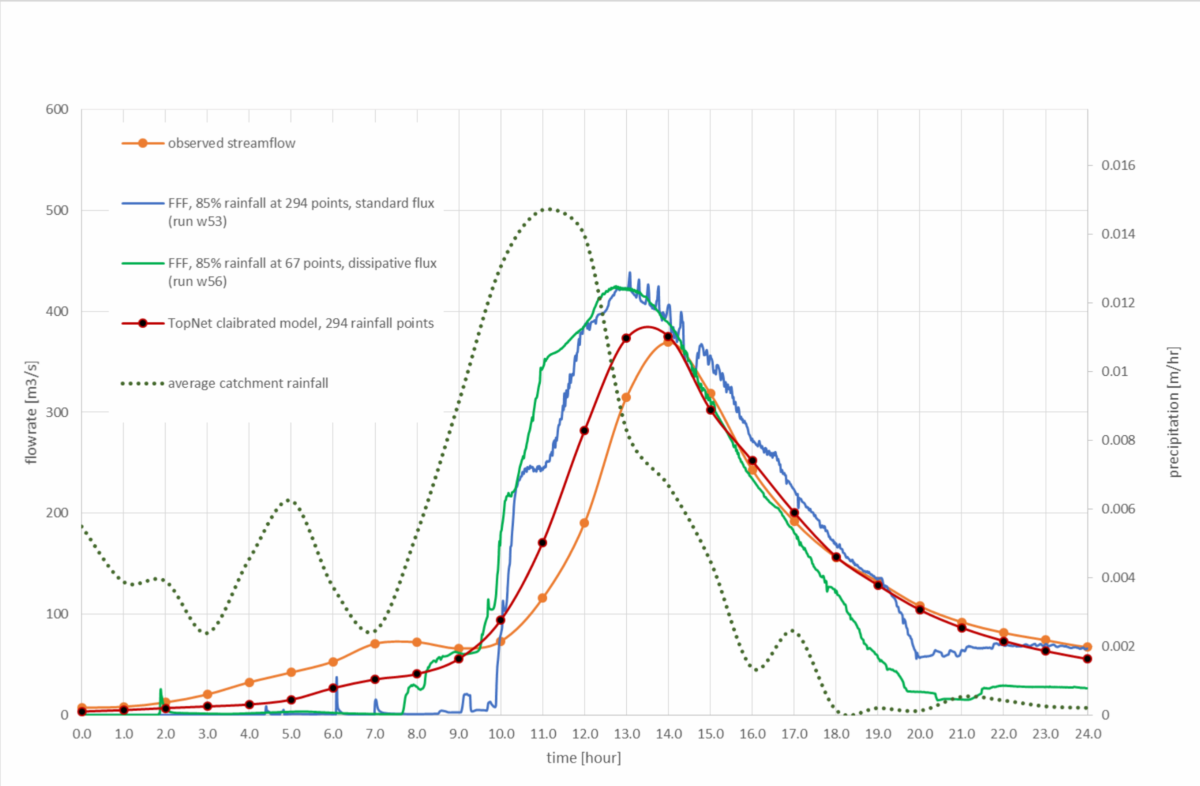

Fig. 9. Simulated and measured river hydrographs at the Water Treatment station using FFF model variants (with 85% of rainfall, different flux limitations and a 5mm "dry" level) and a fully calibrated TopNet rainfall-runoff model with hourly predictions.

Model run times

Over 60 model runs were made to investigate optimum functionality. For the 24 hour evaluation flood, the FFF run times varied from 400 hours to 43 hours when computed on an IBM Blade H cluster. The input of rainfall every 4.5m (at every node and every time step) within the 18.432 km x 18.432 km catchment and floodplain domain resulted in the most computationally demanding model (16.5 days to process the 24 hour storm). At best, the model was about twice as slow as real time (43 hours calculating floodplain inundation for a 24-hour catchment rainstorm). However, while reflecting typical operational conditions, the run time is not an ideal indicator of model efficiency because it is affected by the number of other jobs being run on the computer cluster at the same time. To compare computational requirements with different model options, the number of computational iterations was also used as a metric (typically around 400,000 for the more efficient models). Models with fewer rainfall injection points or higher flux dissipation tended to run faster.

Model inundation visualisation

Fig. 10 shows maximum depths of inundation on the Waikanae floodplain predicted by the FFF model for the January 2005 storm using the TopNet-produced flood hydrograph (red line on Fig. 9) input at the Water Treatment station. No water is shown in the catchment area as these flows are simulated within the TopNet model.

Fig. 11 shows FFF model predicted maximum depths of inundation on the Waikanae floodplain with rainfall input to streams closest to the 294 locations used in the TopNet model. The floodplain inundation is similar to that of Fig. 10 but slightly deeper due to the peak flow from the FFF model being larger than that of the TopNet catchment model.

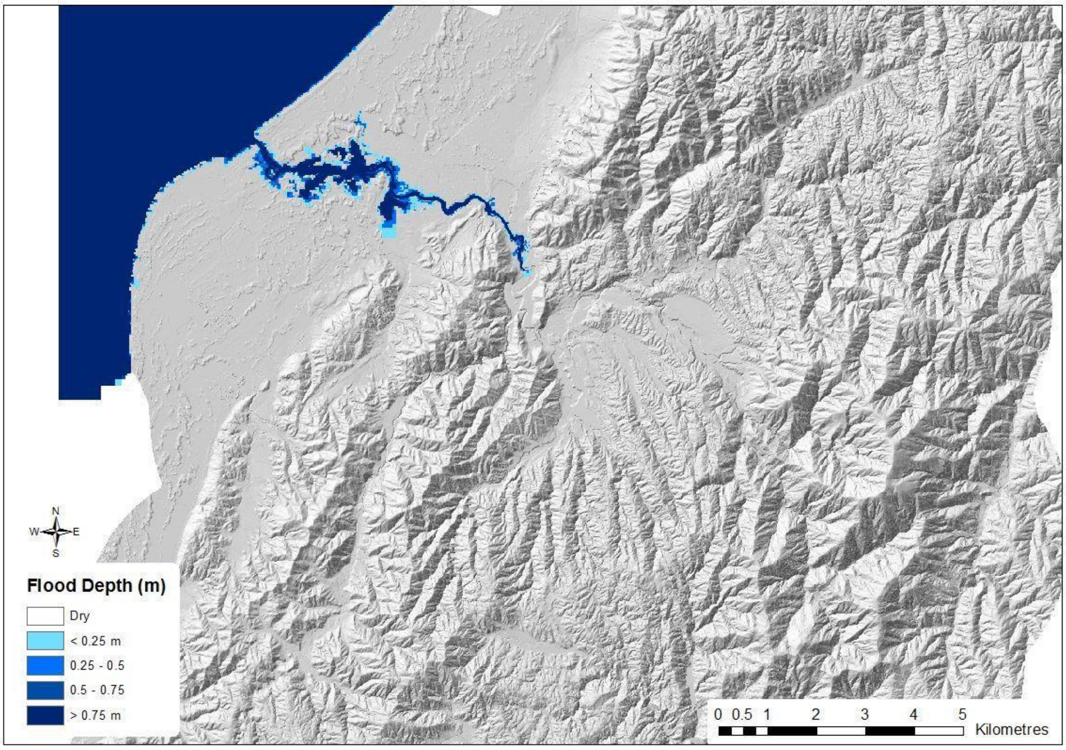

Fig. 10. Floodplain depth of maximum inundation predicted by FFF model using the TopNet model Water Treatment Station hydrograph hindcast for the January 2005 storm (run W38).

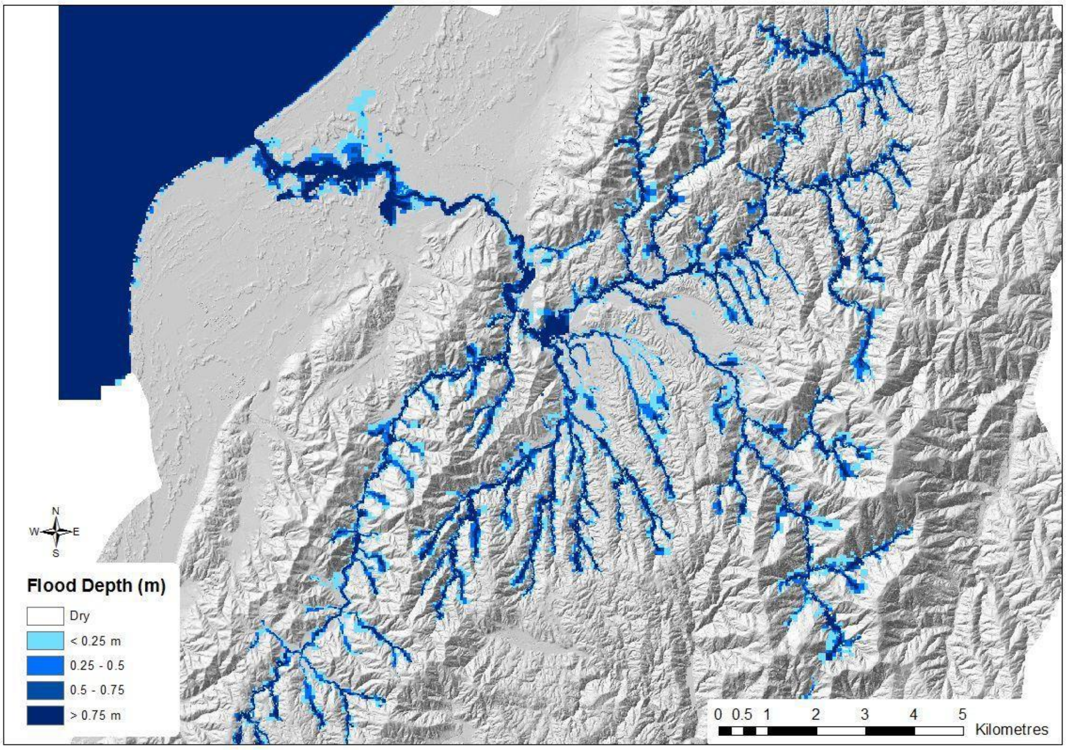

Fig. 11. Floodplain depth of maximum inundation predicted by FFF model using 294 catchment rainfall injection points (run W54).

Fig. 12 shows FFF model predicted maximum depths of inundation on the Waikanae floodplain with rainfall input at 67 injection points resulted from subdividing the Waikanae catchment into 2 km^2 sub-catchments as shown on Fig. 1. This configuration shows increased inundation on the coastal floodplain because it captures inundation from rainfall falling on this area. With fewer rainfall injection points, this model ran faster than the (catchment-only) 294 rainfall injection point models.

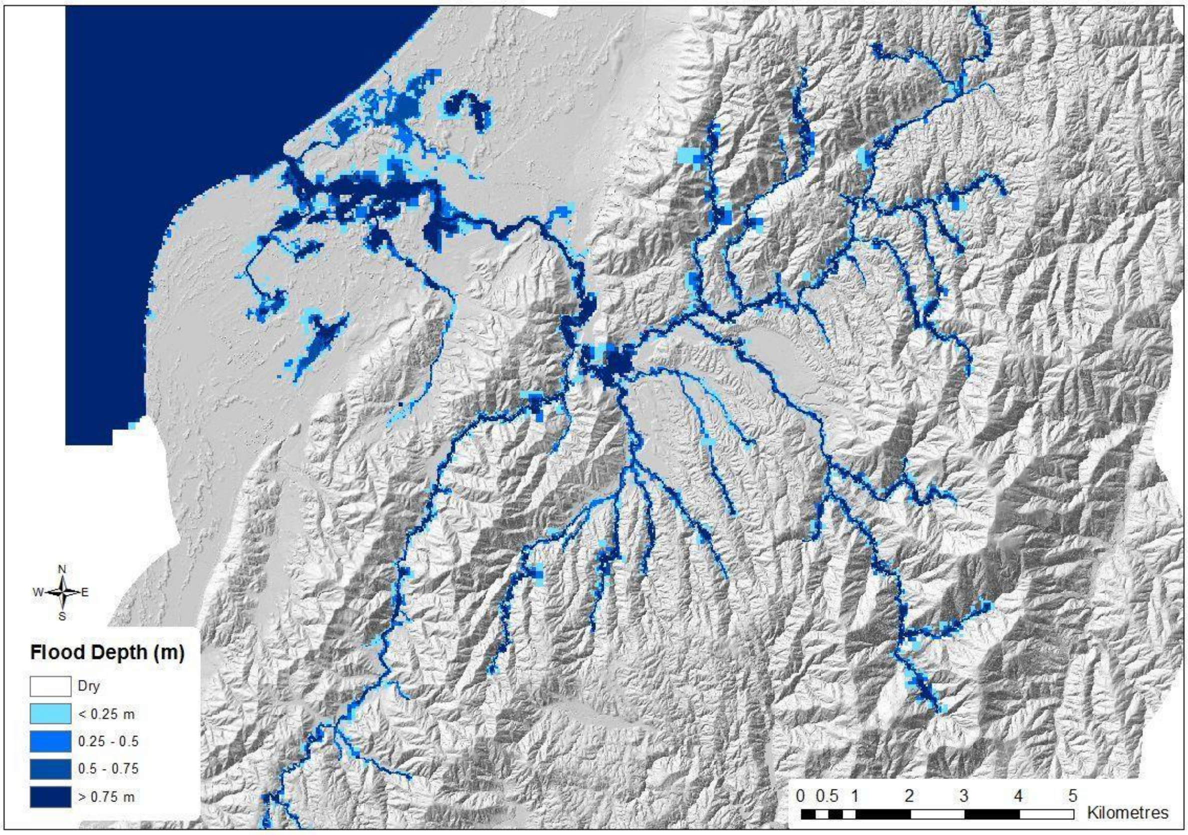

Fig. 12. Floodplain depth of maximum inundation predicted by FFF model using 67 rainfall injection points from the 2 km^2 sub-catchments shown on Fig. 1 (run W56).

Video animations of propagation of rainfall into the catchment streams and downstream to the floodplain were also produced. These will be shown at conference/workshop presentations of the research. The videos illustrate how surges can propagate downstream when there is downstream steepening and abrupt flow inputs (due to cloudbursts or coincidence of tributary inputs).

Summary and Conclusions

[*To be read in conjunction with "Conclusions & Recommendations" in the preceding, co-joined report*].

The FFF hydrodynamic model reproduces catchment integration of distributed rainfall inputs without losses. The model distributes any overbank flows across the downstream floodplains and predicts flood depths and velocities at high resolution (every 4.5 m). The model produces channel surges when there is downstream steepening and abrupt flow inputs (due to cloudbursts or coincidence of tributary inputs) and the model has the ability to reproduce bores or "walls of water". The model also simulates inundation on the floodplain caused by local rainfall. These effects are not reproduced accurately by conventional rainfall-runoff models.

The fastest computational time that was achieved was 43 hours to model a 24-hour storm. While this timing would theoretically allow active inundation forecasting provided the rainfall was forecast more than 2 days in advance, the goal is to achieve a model which will run faster than real time, i.e. under 24 hours to simulate a 24-hour storm. This would allow the model to be run continuously for operational inundation forecasting. In operational mode, it is envisaged that rainfall inputs would be interpolated from the NIWA 5km Virtual Climate Station Network. The model run time could be improved by more efficient algorithms for handling shallow flows over wide areas and/or by faster processing (GPU or HPC facilities).

The model has proven the concept of a combined catchment-floodplain hydrodynamic model and is to be used as a prototype for further research and application as an operational forecasting tool.

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