

# **A Flood (hazard) Mapping Framework Covering All of the A.C.T. Using Radar Rainfall**

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## **ABSTRACT:**

Although flood mapping is currently tightly linked to the flood study and flood risk management process, is there a better more efficient and dynamic way to ensure not only up to date flood maps but other benefits not provided through the current process? A National Disaster Resilience Program (NDRP) funded project currently underway is providing a new methodology through the creation of a framework hosted on the largest and fastest computer in Australia. Further, traditionally accurate flood modeling is reliant on a well validated hydrologic model balanced with hydraulic models capable of representing realistic flood flows as a result of rainfall over the catchment. However nearly all calibration/validation models of real recorded events are reliant on usually extremely sparse recorded rainfall data from representative rain gauges. However for several years now radar data has been available but is scarcely used. The development of a (X,Y,t) spatial grid format in the ANUGA model allows grid rainfall time series to be used as input. Hence the application of RADAR rainfall directly to the 3D terrain is now feasible.

Finally it is clear that to produce accurate flood modelling results all models are not equivalent. The various types of models include: 1D, 2D, 3D, FE, FD, FV, VOF, SPH. What does this all mean and currently which approach is most efficient, accurate and robust? Currently the quasi standard is 2D modelling however 3D is sneaking up just around the corner. But at a catchment scale FV is still the winner for now.

This paper discusses various aspects of setting up the Flood Mapping Framework for the ACT, flood modelling software development, the application of RADAR rainfall in establishing greater accuracy in flood modelling and what and why open source is attractive.

## **Why a framework?:**

The National Computational Infrastructure (NCI) contains the 'Raijin' computer containing ~57,500 cores, 160TB of RAM and 10 peta-bytes of storage and is thought to be the 27<sup>th</sup> fastest computer in the world. It also now hosts the "ACT flood mapping framework", which is capable of modelling floods over all catchments that leads to flood flows in the ACT.

This paper provides extensive discussion on the methodology of the "Framework", the benefits and the motivation.

## **Introduction**

In Australia the process under which most flood studies and floodplain management outcomes are funded and managed is something that usually takes years to complete and usually costs well in excess of \$100,000 per catchment. Currently in the Australian Capital Territory (ACT) only a small portion of contributing catchments and flood affected areas have been modeled and mapped, and much of what has been done is dated. A current National Disaster Resilience Program (NDRP) funded project aims to rectify this situation by the creation of an innovative, efficient and cost effective framework for flood mapping. The framework is reliant on the computational capabilities of the ANUGA model (Nielsen Roberts), the fact that it is open source, and some of its most recent inclusions, such as the ability to apply RADAR rainfall to models. This in combination with the recent development and availability of a “Calibrated RADAR Rainfall” product from the Australian Bureau of Meteorology (BOM) makes the establishment of such a framework a sensible approach.

### ***What is a Framework?***

In this context, a “Framework” is a structured approach whereby complex computationally intensive tasks can be reproduced consistently and efficiently. Other researchers have also described ideas relating to frameworks for at least 10 years (Bates et al 2004), (Weichel et al 2007). Indeed there is somewhat of a ongoing or renewed interest in this concept (Lant 2011), (Winsemius et al 2013), (Sampson et al 2014) from various aspects including the insurance industry.

The concept to develop a “Framework” rather than simply a model or a report (such as a flood study) is driven by the desire to enable a method by which flood mapping can be produced, reproduced and updated at will as necessary. It is clear that we are facing an uncertain climatic future, hence it is equally clear that flood modeling completed with climate information today will need to be revisited when that climate data changes. Note, similarly, major changes to the terrain, such as the construction of a major highway, may require an update to flood mapping, for which the framework can be utilized.

### **Why use the ANUGA model?**

The birth of the ANUGA (Nielsen, Roberts, Gray, McPherson, Hitchman, 2005) model came out of an identified lack of robust 2D modeling platforms capable of modeling extreme flow behavior such as that which occurs when a tsunami strikes dry land. The extreme behavior seen in the many Tsunami videos on YouTube and even the extreme flow behavior of some of the footage of the 2011 Queensland flood is not able to be modeled by all flood modeling platforms. However it is possible to model and recreate such behavior in the ANUGA model as it was specifically designed to do so.

Japan Tsunami:

<http://www.youtube.com/watch?v=GpuLIrUYsl>

<http://www.youtube.com/watch?v=noq8FYvRqgs>  
<http://www.youtube.com/watch?v=5-zfCBCq-8I>

QLD Flood:

<http://www.youtube.com/watch?v=GuYkKir3LF4>  
<http://www.youtube.com/watch?v=6O5RsQF3-IM>  
<http://www.youtube.com/watch?v=bSILibxCOWg>

Although those images and video captured is shocking, it is important to realize the nature of flood water and the need for models to have the ability to properly represent it.

ANUGA is a conservative Finite Volume Discontinuous Shallow Water Wave solver on a flexibly sized triangular mesh.

### ***What's it matter? Finite Difference, Finite Volume, it's all the same isn't it?***

The very short answer is no, it's not the same!

It is critical to determine the most suitable mathematics that may be needed to properly describe the behavior of real events. Excessive smoothing or inability to conserve volume will lead to instability and inaccuracies that will shadow the real underlying flow behaviour. Real flood events contain innumerable regime changes (Sub-Super Critical flow) spatially and temporally. The inability to identify these may result in inaccuracies or instability elsewhere in the model.

As professionals involved in the flood modeling process it is critically important to have some understanding of the tools being used and to determine their suitability. This requires some superficial knowledge of the underlying complex mathematics and why different approaches have the ability to produce different results.

### *THE MATHEMATICS OF RESOLVING THE MOTION OF FLOOD WATER:*

The Navier-Stokes equations are known as the full equations of fluid motion. Depth integration of these equations leads to the Shallow Water Wave equations (SWW), which implies that the vertical velocity of the fluid is small compared to the horizontal velocity. The shallow water wave equations are derived from two basic conservation laws, conservation of mass, and conservation of momentum (or Newton's second law).

The basic conservation laws are integral equations, of the form:

- the rate of change of the conserved quantity in an arbitrary region is equal to the flux of conserved material through the boundary of the region (plus some pressure force terms integrated over the region or the boundary of the region in the case of the conservation of momentum law).

The integral formulation is a little inconvenient as it means that we have an infinite number of equations to solve (one for each conceivable region). But the solutions to

these integral conservation laws can deal with resolving extremely complex flow such as moving bores and hydraulic jumps.

- The finite volume method (FVM) approximates these integral conservation laws by choosing a finite number of regions, the finite “volumes”, which cover the area of interest.
- The finite volume method updates the amount of mass and momentum in each of the finite volumes, by integrating the pressures and fluxes across the edges of each of the volumes. An important part of the method is determining the flux across the interfaces between the volumes. This comes down to approximating the fluxes across an interface separating two constant states, as found for instance in a dam break problem.
- This type of problem; to solve the 1-d shallow water wave equation, with initial condition given by two constant states separated at the origin, is known as a Riemann problem. This problem has an analytic solution, but the solution is quite complicated, and more importantly, numerically expensive.
- Generally finite volume methods applied to conservation laws use approximate Riemann solvers, which are faster to calculate and also incorporate some averaging which stabilises the calculation.

In the case of ANUGA, the regions used are triangles, so as to allow the mesh to be flexibly sized to concentrate in regions of interest (shore line, valley floors), and the approximate Riemann solver is that presented in Kurganov et al., which is a well tested efficient solver based on averaging the exact solution over a small test region around the jump in the initial conditions.

This combination of FVM and efficient approximate Riemann solver, produces a method which ensures conservation of both mass and momentum, is built to deal with solutions with large jumps in the conserved quantities (bore, dam break and hydraulic jumps), and can deal with supercritical flows as part of its design.

If we are in situations where these challenges are not occurring, i.e. when the solutions of our equations are very smooth, then we can use the fundamental theorem of calculus to transform the integral equations into an equivalent system of differential equations.

These are the shallow water wave equations that are usually presented. As long as these differential equations are written in conservation form, we can actually think of them as a short hand notation for the original integral equations.

Once we have a set of differential equations, it is natural to use finite differences to approximate the derivatives and form a discrete set of finite difference equations, for the values of approximate solution at a set of grid points (as opposed to the average values within a volume for the FVM). This produces a finite difference method (FDM).

As long as the solutions are smooth, we expect the approximation obtained by the finite difference method to be close to the approximation obtained by the finite volume method, which should be close to the actual solution of the underlying conservation integral equations. Interestingly, if the solution of the integral equations is not smooth (as in the classical dam break problem involving a rarefaction wave and a shock) then the solution obtained by the finite difference method can converge to a solution with a different shock speed.

So why use the Finite volume Method applied to the conservation form of the Shallow water wave equations?

The conservation form of the equations are based on the underlying physical conservation laws. They allow us to solve problems in which large jumps in the mass and momentum occur, such as bores, dam breaks and hydraulic jumps. The use of the Riemann solvers automatically deals with the problem of determining the direction in which information needs to flow, which in turn allows the method to deal with subcritical and supercritical flows naturally.

The FVM method allows us to easily use unstructured meshes to concentrate our efforts in regions of interest.

If we use a FDM based on the conservation form of the equations, then we need to build finite difference operators which deal with the flow characteristics, i.e. upwind solvers. While this is possible, it turns out to be quite similar to the processes of developing a good approximate Riemann solver for the FVM.

If the FDM is applied to a non-conservation form of the equations (say in terms of depth and velocity) then the danger is that the method will produce the incorrect shock speeds in dam break problems. It should be noted that MIKE-21 (Abbot 1979), SOBEK, SWASH (Stelling 1984) and TUFLOW (Syme 1991) all discuss the use of this approach.

Generally though, the FDM assumes that the solutions are smooth, and so in non-smooth cases, such as dam breaks or bores, the assumption that a finite difference method is a good approximation breaks down and results in serious instability in the model.

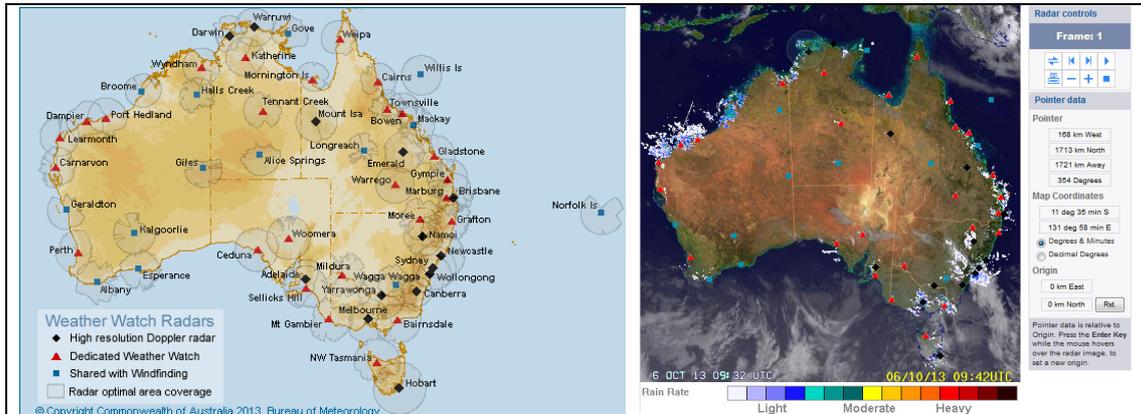
Hence it can be seen that there are considerable advantages in applying a FVM solution in order to resolve the behavior of flood water.

## **RADAR RAINFALL.... Any Benefits?**

Since its very first application in the flood space (rather than tsunami) ANUGA appeared very stable and able to replicate catchment hydrology correctly (Van Drie et al 2012). The ability to apply rainfall directly to the terrain was immediately seen as beneficial, by removing the dependent step of external hydrologic modeling.

The industry standard (traditional) two step approach is an obvious source of introducing errors, or the need to balance two different types of errors, that are capable of cancelling out the appearance of the error. {Which can be extremely problematic.} Therefore direct rainfall 2D modeling is seen as one of the only ways forward in improving flood modeling. Further the need to accurately replicate spatial distribution makes the availability of a calibrated RADAR rainfall product from the Bureau of Meteorology also potentially very beneficial.

It is clear that most real storm events are poorly captured by the sparse network of rain gauges in most catchments. This makes it almost impossible to produce well calibrated flood models. Currently only a portion of the nation is covered by RADAR.



**Australian RADAR coverage and composite national image from BOM website**

However most of the larger population centres are covered by RADAR hence it is likely that the majority of flood affected properties and infrastructure can be modelled using RADAR derived rainfall. The calibrated RADAR rainfall uses “Raw Reflectivity” from the radars, in combination with rain gauge data, and other climatic data such as wind speed and direction to produce an on ground calibrated rainfall time history over the area of coverage of the radar. The data is made up of 360 x 1 degree radials that radiate out a 2km spacing covering +/- 128km. (Seed et al 2007) provide a description of the data, and also describe the process of calibrating the radar data.

A procedure for estimating radar rainfall in real time consists of three main steps:

- 1) the measurement of reflectivity and removal of known sources of errors,
- 2) the conversion of the reflectivity to a rainfall rate (Z–R conversion), and
- 3) the adjustment of the mean field bias as assessed using a rain gauge network.

Generally the calibrated radar rainfall data is available as either 30 minute, 10 minute or 6 minute time slices.



**Example from Australian Radar (Reflectivity Index)**

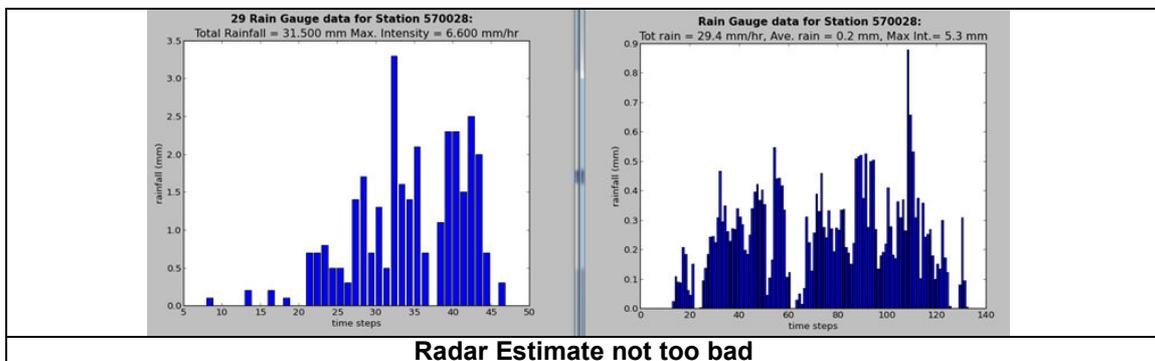
Further details about this form of rainfall data can be found on the BOM web site:  
[http://www.bom.gov.au/australia/radar/about/calculating\\_rainfall\\_accumulations.shtml](http://www.bom.gov.au/australia/radar/about/calculating_rainfall_accumulations.shtml)  
[http://www.bom.gov.au/australia/radar/about/radar\\_images\\_intro.shtml](http://www.bom.gov.au/australia/radar/about/radar_images_intro.shtml)  
[http://www.bom.gov.au/australia/radar/about/using\\_radar\\_images.shtml](http://www.bom.gov.au/australia/radar/about/using_radar_images.shtml)

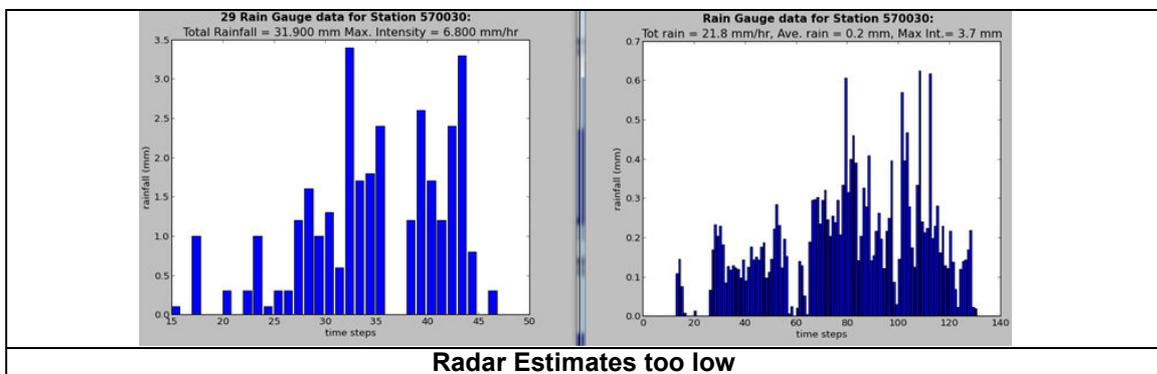
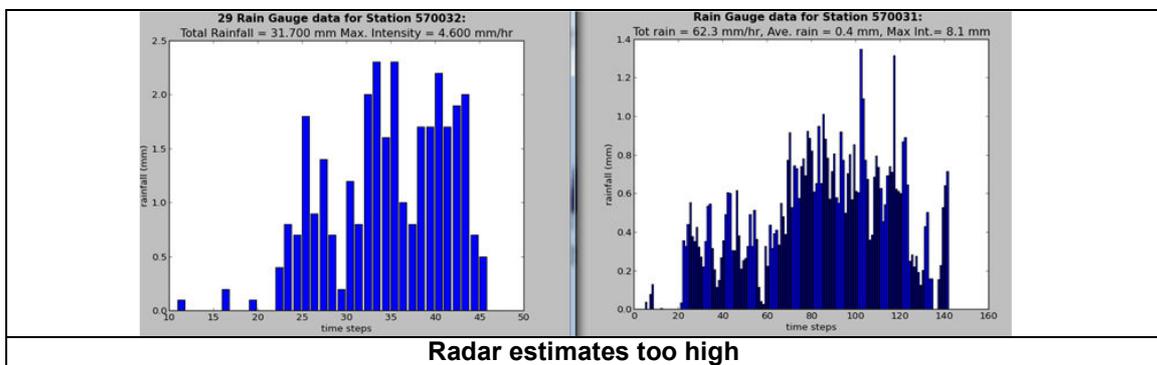
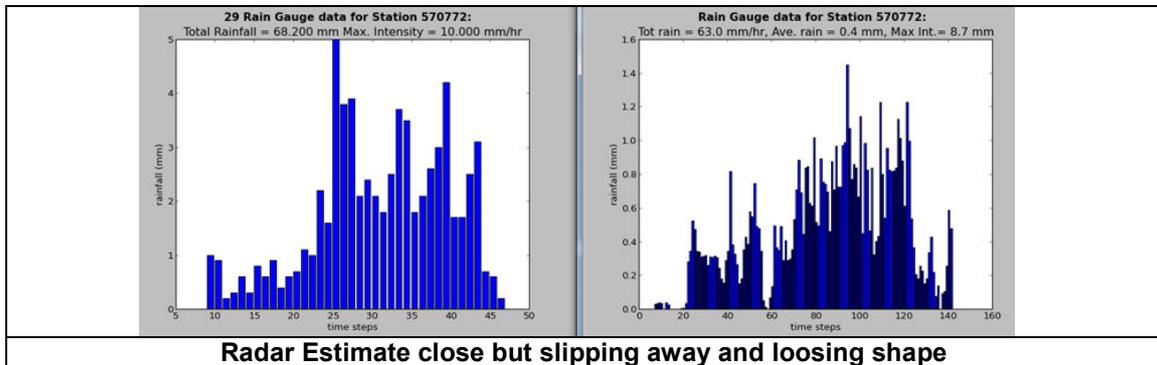
### Comparing RADAR to Rain Gauge Data

It is clear that RADAR produces a wealth of information regarding the spatial variability of rainfall. However it is important to also ensure that the final radar product is also closely replicating the rainfall recorded at the gauges. That is, that error has not crept in to the calibrating process. To date analysis undertaken to compare rain gauge data to data extracted from the RADAR data at the gauge site, is limited and showing mixed results. It should be noted that to date the extent of analysis is limited to a single radar (Captain's Flat {ACT}) and a single event. The following table shows the comparison of the total daily rainfall volume and maximum rainfall intensity from Gauge and Radar. For total volume 8.3% of gauge locations are within the 90 percentile whilst 54.2% are within the 50 percentile. Similarly for maximum rainfall intensity 8.3% are in the 90 percentile and 58.3 in the 50 percentile.

Max I	Radar T	Radar Mx	Percentile of Data : 90		Percentile of Data : 50		MAXIMUM RAINFALL INTENSITY					
			Diff T	% Diff T	TOTAL RAINFALL VOLUME		Diff Mx	%Diff Mx	90Perct	50Perct		
6.8	19.9	2.9	-36.1	0.355357	Too Low	Too Low	-1	-0.35536	-3.9	0.426471	Too Low	Too Low
6	75.9	10.9	48.3	2.75	Too High	Too High	1	2.75	4.9	1.816667	Too High	Too High
6	37.3	6.3	4.8	1.147692	Too High	Not Bad	1	1.147692	0.3	1.05	Not Bad	Not Bad
6.6	29.4	5.3	-2.1	0.933333	Not Bad	Not Bad	0	0	-1.3	0.80303	Too Low	Not Bad
6.8	21.8	3.7	-10.1	0.683386	Too Low	Not Bad	-1	-0.68339	-3.1	0.544118	Too Low	Not Bad
4.6	62.3	8.1	30.6	1.9653	Too High	Too High	1	1.9653	3.5	1.76087	Too High	Too High
5.2	61.7	7.7	27.9	1.825444	Too High	Too High	1	1.825444	2.5	1.480769	Too High	Not Bad
19.8	64.6	7.9	20.9	1.478261	Too High	Not Bad	1	1.478261	-11.9	0.39899	Too Low	Too Low
5	63	7.8	33.3	2.121212	Too High	Too High	1	2.121212	2.8	1.56	Too High	Too High
7.8	66.2	10.2	11.4	1.208029	Too High	Not Bad	1	1.208029	2.4	1.307692	Too High	Not Bad
10	63	8.7	-5.2	0.923754	Not Bad	Not Bad	0	0	-1.3	0.87	Too Low	Not Bad
6.4	68.5	7.7	17.2	1.335283	Too High	Not Bad	1	1.335283	1.3	1.203125	Too High	Not Bad
9.4	27	3.3	-24.3	0.526316	Too Low	Not Bad	-1	-0.52632	-6.1	0.351064	Too Low	Too Low
6.8	30.3	9.9	-15.5	0.661572	Too Low	Not Bad	-1	-0.66157	3.1	1.455882	Too High	Not Bad
4.8	21	4.4	-8.9	0.702341	Too Low	Not Bad	-1	-0.70234	-0.4	0.916667	Not Bad	Not Bad
8.4	30.5	4.7	-24	0.559633	Too Low	Not Bad	-1	-0.55963	-3.7	0.559524	Too Low	Not Bad
10.6	20.6	2.5	-44.5	0.316436	Too Low	Too Low	-1	-0.31644	-8.1	0.235849	Too Low	Too Low
7.2	20.8	3.7	-36	0.366197	Too Low	Too Low	-1	-0.3662	-3.5	0.513889	Too Low	Not Bad
8	32	5.1	-21.5	0.598131	Too Low	Not Bad	-1	-0.59813	-2.9	0.6375	Too Low	Not Bad
6.8	26.4	4	-24.4	0.519685	Too Low	Not Bad	-1	-0.51969	-2.8	0.588235	Too Low	Not Bad
7.2	21.1	3.2	-36.6	0.365685	Too Low	Too Low	-1	-0.36568	-4	0.444444	Too Low	Too Low
8	16.3	2.9	-33.7	0.326	Too Low	Too Low	-1	-0.326	-5.1	0.3625	Too Low	Too Low
12.8	26.9	4.9	-64.5	0.294311	Too Low	Too Low	-1	-0.29431	-7.9	0.382813	Too Low	Too Low
7.6	22	4.5	-37.4	0.37037	Too Low	Too Low	-1	-0.37037	-3.1	0.592105	Too Low	Not Bad

Examples of typical gauge comparison results follow:





It is quite clear that RADAR rainfall has the potential to vastly improve the description of Spatial distribution of rainfall. However, until it can be shown that it is consistently capable of reproducing the rainfall recorded at rain gauges, it is likely that this format will remain experimental only.

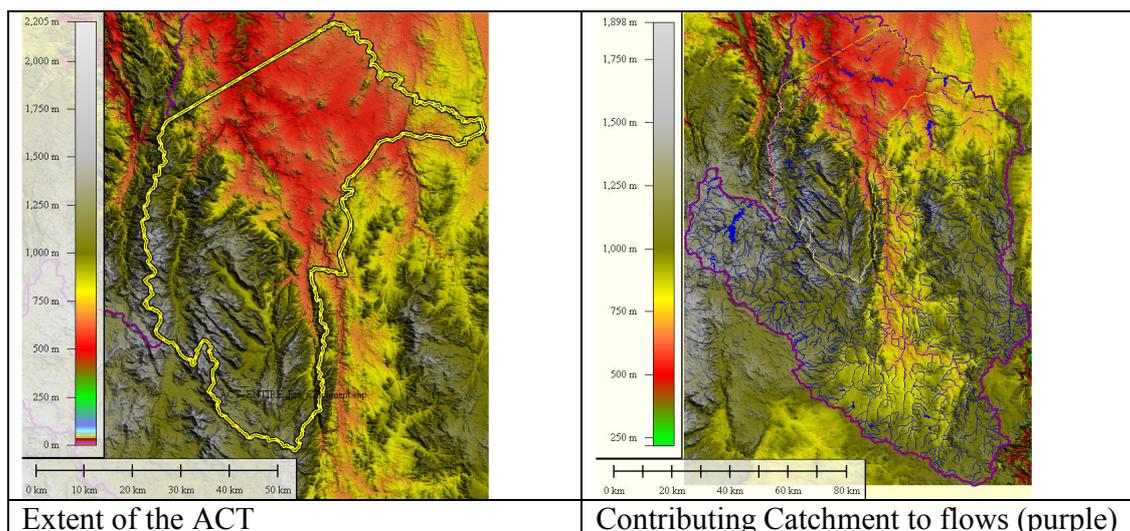
Notwithstanding this it is clear that the calibrated radar product will continue to improve making this approach not only attractive in its ease of application (in models with grid rainfall capability) but also likely much more accurate in describing the volume of rainfall falling on catchments compared to a sparse rain gauge network.

## APPLICATION OF RADAR RAINFALL: The ACT FLOOD FRAMEWORK

The ACT Flood Mapping Framework covers the entire contributing catchments that result in flood flows in the ACT. The Australian Capital Territory (ACT), covers an area of around 2358km<sup>2</sup> including around 78km<sup>2</sup> of water surfaces. Its total contributing catchments include around 9500km<sup>2</sup> of terrain. Hence to model flooding the entire area must be modeled. The Framework will house a repository for all of the required data to allow modeling of the entire catchment or portions of it as may be necessary. The data repository will hold:

<b>DATA TYPE</b>	<b>Source or Form of Data</b>	<b>Options to vary</b>
Terrain	ALS/LIDAR 30m ASTER 90m STRM Survey	Time history of terrain data will allow model to remain up to date but also able to model historic events. Terrain may be updated to reflect changes (new roads or suburbs being established).
Drainage Structures	Extracted from Roads ACT data base, or from survey. Size of openings etc.	Time Stamps
Surface Roughness	Grids or polygons of roughness	Will need to vary in time to reflect changes in land use
Water Level Data	Lake water levels	Time History of water levels for major water bodies
Design Rainfall	IFD based Data in Temporal patterns	The latest 2013 IFD or 1987 IFD can be used
Real Event Rain Gauges	Gauge Rainfall Data	The ability to use gauge data to compare to DESIGN and RADAR events
Real Event RADAR	BOM Calibrated RADAR from Captains Flat	

It is noted that the data sources will all be time stamped so that multiple version of data covering the same item or area can be stored. This will allow and ensure that when models are created to reflect a scenario the correct data is associated that was relevant at that time. For example a 1974 flood model must reflect the conditions in terrain and development at that time.

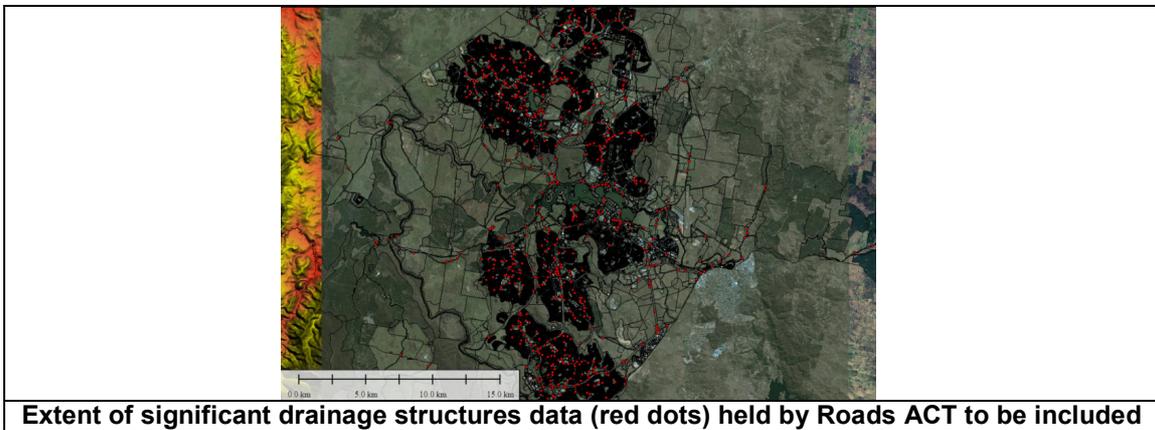


**ACT boundary 2358km<sup>2</sup> and its contributing catchment extent 9500km<sup>2</sup>**

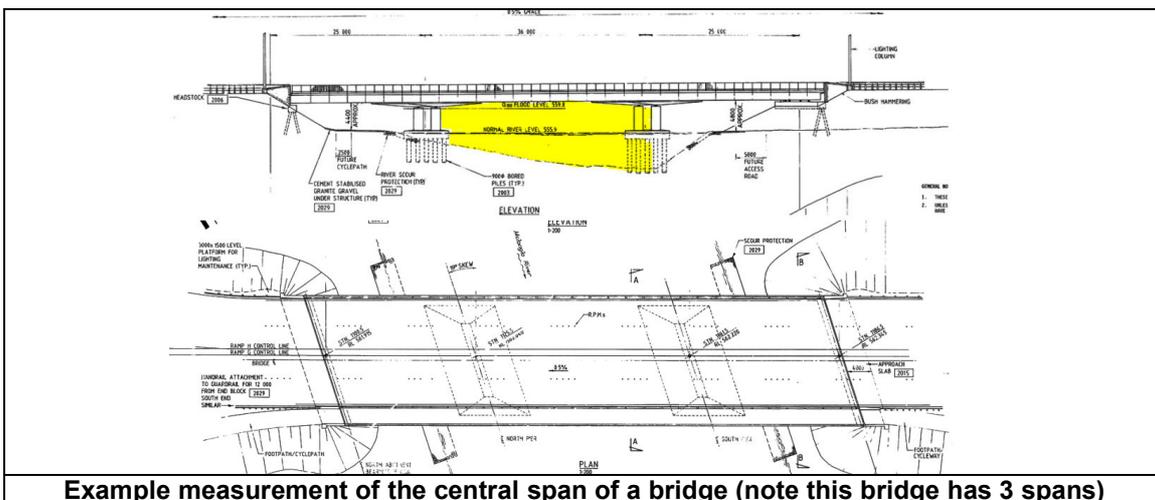
Once all the data has been assembled a scenario manager will be built that will control what files are compiled to be sent to ANUGA for analysis. In this way the Framework can be used to model historic events, current events, and even future plausible scenarios (including future development for example).

### **STATUS AND PRELIMINARY RESULTS**

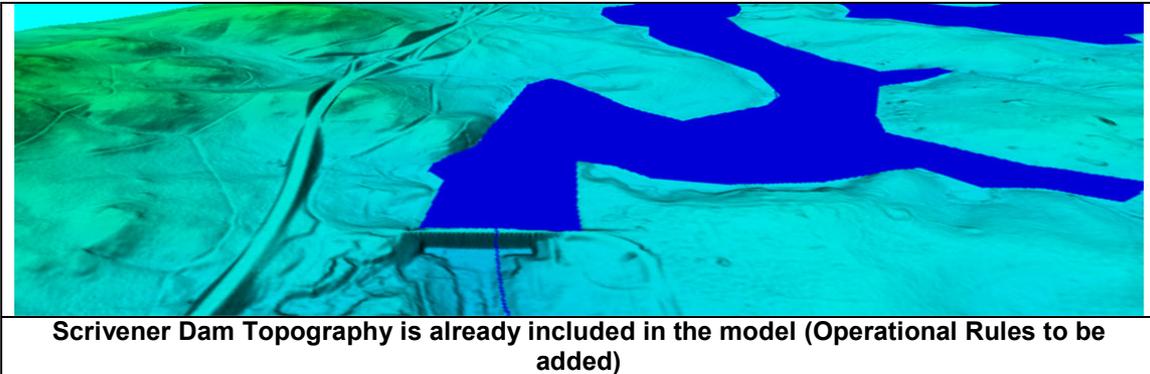
The NDRP project is a 3 year project aimed to be completed by March 2016. Currently a relatively time consuming process is being undertaken whereby Roads ACT have provided plans of all drainage structures within the ACT of which around 900 will be included in the modeling framework. The extraction of bridge and culvert dimensions from scanned plans is an extremely tedious and time consuming task.



Bridge and major culvert data can at times only be retrieved by physically measuring information from plans of the structures or the structures themselves. The latter approach to survey each structure is well beyond the scope of expenditure for this current project. Hence this project is reliant on the review of 1000's of drawing sheets.

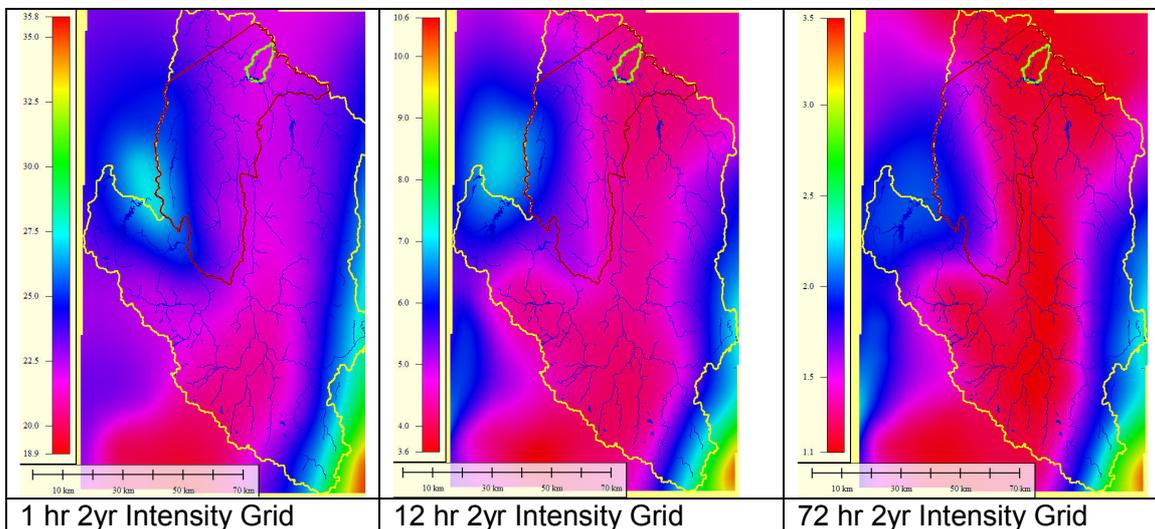


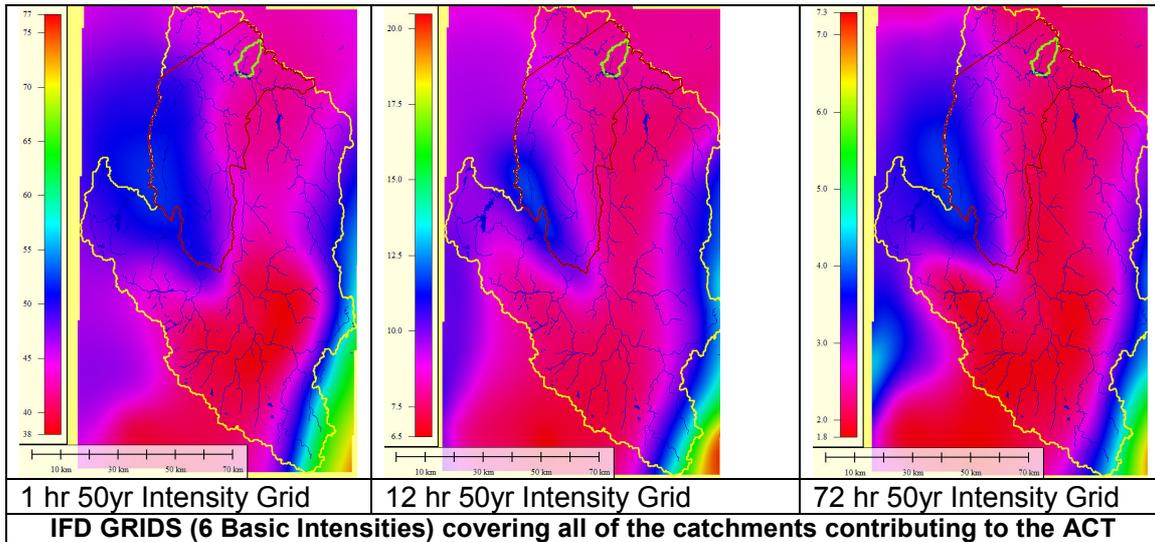
In addition to bridges and culverts other structures are also required, such as the major dams, which may have operational control rules for gates and the like. The operational rules need to be included in the model as they have the potential to significantly change the flood regime during a significant event.



Once the full complement of data is stored in a retrievable form, a series of test runs will be performed using both rain gauge data and RADAR derived rainfall data. The initial aim is to compare the two approaches, but also provide the flexibility of using gauges, as this is also necessary to utilize IFD design gauges for Design Storm Events. However it is also plausible to develop a Design IFD grid format that covers the entire catchment.

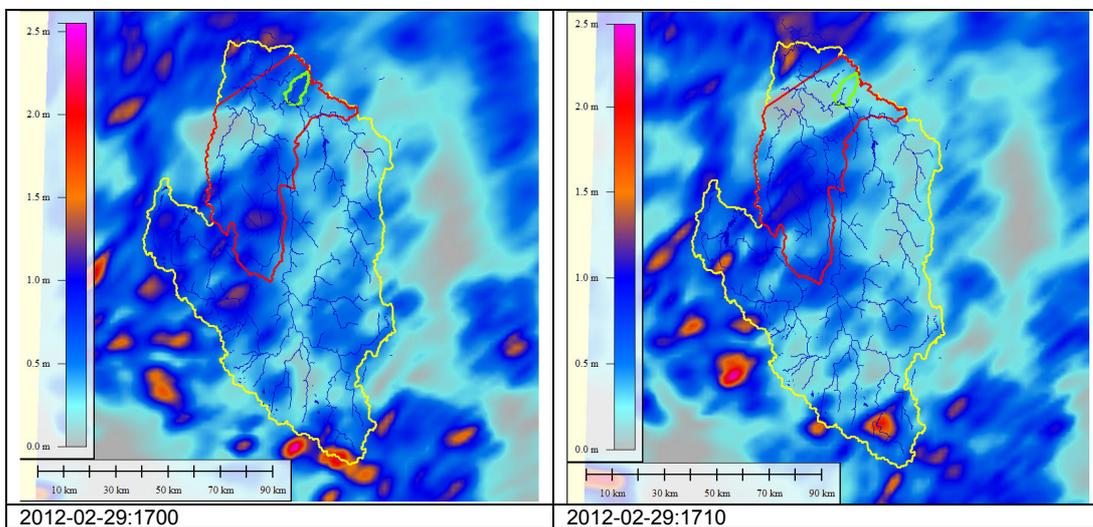
Note that in the images of grid IFD data that follows there is a noticeable band of lower intensities roughly through the centre of the catchment in a North-South direction. Further this lower band is present in all of the basic intensities.

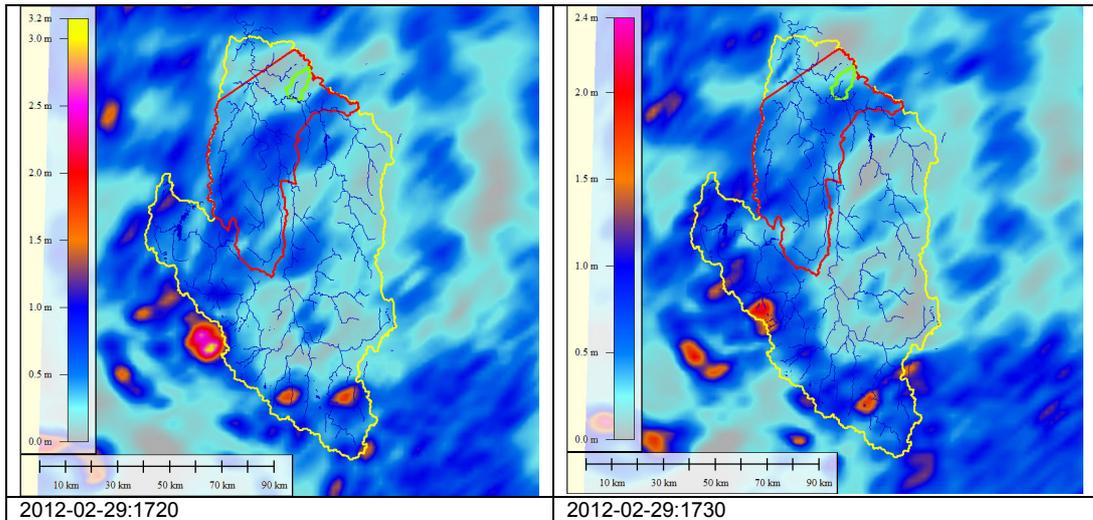




Test application of RADAR rainfall has been undertaken with relatively pleasing results.

The model ran without instabilities and produced a flood surface comparable with applying rain gauge data. Sample images of the RADAR data show the extreme spatial variability compared to what would normally be expected from the application of multiple standard rain gauges. The following images show a sample of 4 x 10 minute time slices, note the isolated moving high intensity cells amongst the broader moving larger lower intensity sweep. These characteristics are also described by (Jakob & Seed 2014), highlighting that this behavior is not possible to be determined by rain gauges alone.

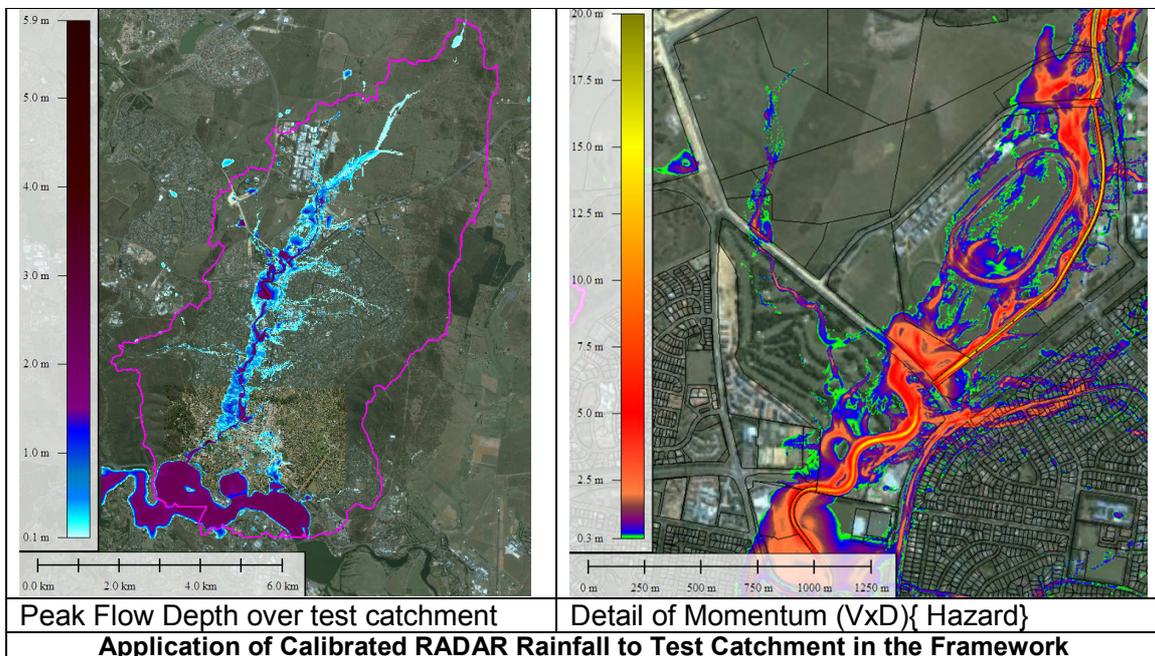




**2012 event showing 4 x 10 minute Radar time slices**

The flood behavior resulting from the radar data applied to the test catchment is unremarkable but as expected. The flood depth plot and momentum plots indicate the type of flow regime to be expected from a wide spread flood event.

Hence initial test results provide an indication that the Flood Mapping Framework is likely to deliver very good results. The fact that once set up results can be reproduced or updated at will, efficiently and very cost effectively is seen as a major benefit to the community and management authorities.



**Peak Flow Depth over test catchment**

**Detail of Momentum (VxD) Hazard**

**Application of Calibrated RADAR Rainfall to Test Catchment in the Framework**

## **CONCLUSIONS**

There are a number of distinct conclusions to draw from what has been presented in this paper:

- A Flood Mapping Framework has the potential to make the flood mapping process highly efficient and cost effective compare to the industry standard approach currently undertaken
- The application of RADAR rainfall has the potential to improve flood calibration for event modeling immensely as it provides a level of spatial distribution of the rainfall not available by any other means
- Although in its early stages of development, and at this stage plausibly questionable in its ability to reproduce rain gauge data consistently, it is clear that in time Calibrated RADAR rainfall is where the future is in flood modeling and calibration.
- The ANUGA model has several benefits over many other current models being used within the industry. The underlying mathematics being specifically designed to deal with extreme flow conditions results in a remarkably stable and robust model. The fact that it allows the application of rainfall directly over an entire catchment has obvious advantages. Finally in its ability to apply RADAR rainfall as a time series grid, provides it with an ability to account for spatial variation in rainfall that currently is not available by any other means.

## **RECOMMENDATIONS**

It is highly recommended that anyone involved in flood plain management take the time to get a good understanding of what underlying mathematics is in the models being used to produce results for them and to determine if models are actually suitable. It is also highly recommended that authorities in the flood management genre consider the potential benefits of establishing a flood modeling/mapping framework, over what has now been an entrenched industry standard approach that is both excessively costly and time consuming, with limited output and benefits. Finally it is recommended that flood modelers take a serious look at the capabilities and benefits of adopting the ANUGA model as a very serious (and accurate) modeling tool.

## **ACKNOWLEDGEMENTS**

The authors gratefully acknowledge the input and assistance of various BOM officers including Alan Seed and Kevin Cheong. We also acknowledge the assistance of Ben Evens at the National Computational Infrastructure.

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