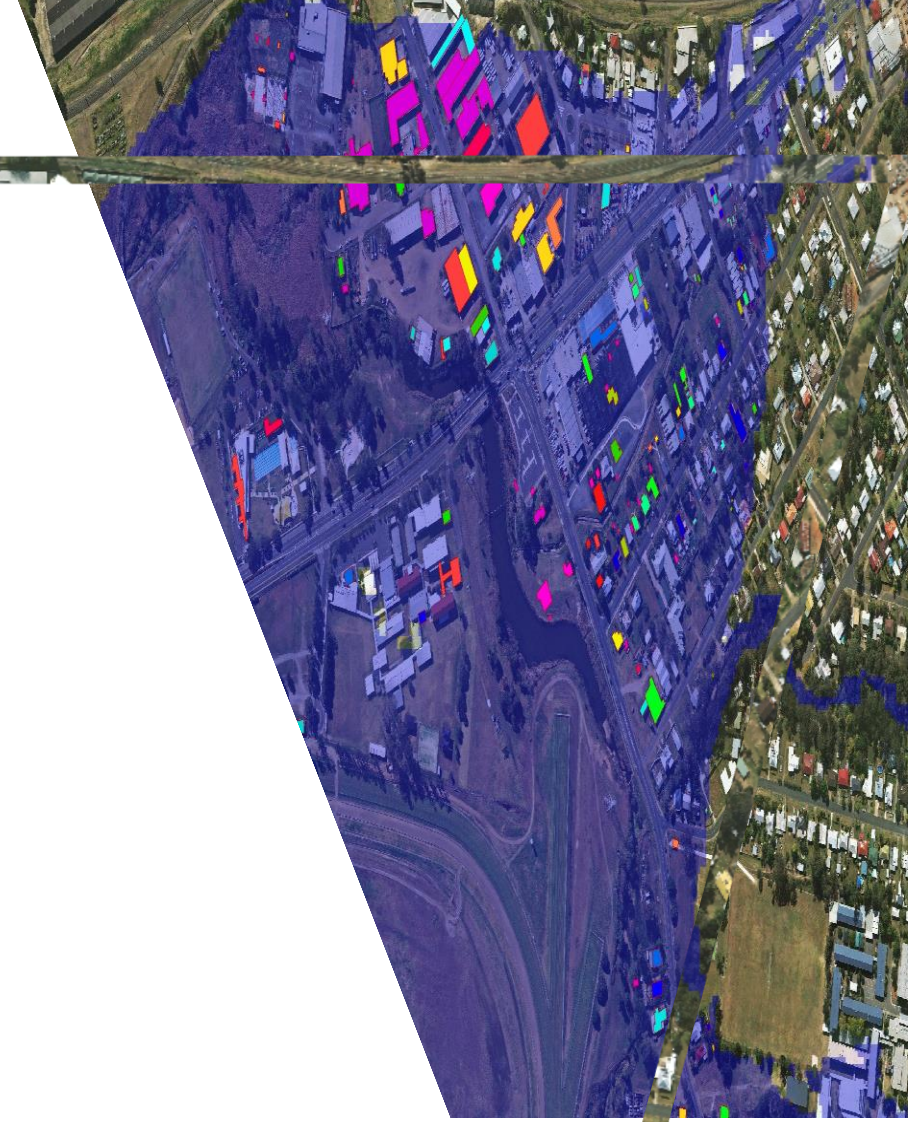

waterRIDE™

Cessnock City Council

Cessnock Citywide Flood Study

31-03-2021

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Project No: 311015-00087 – waterRIDE: Cessnock Gridflow Report

Rev	Description	Author	Review	Advisian Approval	Date
1	Draft	TML	CJD		22-5-20
2	Draft – title update	TML	CJD		27-5-20
3	Draft – model update	TML	CJD		31-3-21

Table of Contents

Appendix List

1 Introduction

Cessnock City Council approached Advisian to provide catchment wide flood mapping to supplement the existing detailed flood study modelling within their Local Government Area (LGA).

GridfFlow was the chosen approach as it provides rapid, indicative flood mapping identifying overland flow paths and flood corridors outside of the scope for most catchment wide flood study hydraulic models.

2 Methodology

2.1 Overview

GridFlow is a grid based modelling tool with the objective of rapidly determining flood extents for any return period rainfall on a gridded DEM. The GridFlow model essentially determines flow paths across the surface of the DEM by generating a flow accumulation grid which provides the upstream catchment area at any grid cell. The downstream termination points (*ocean, main river or lake*) can then be traced upstream through the grid to generate flow paths of connecting grid cells. An automated backwater analysis is then performed along the flow paths using the cell catchment area to determine flow by means of the rational method (*employing the latest AR&R parameters*), and using the DEM to generate cross-sections at variable spacings dependent on the stream size. The water surface is then generated by triangulating between adjacent cross-sections.

This backwater process proceeds up along each flow path and then sequentially along each tributary until the entire dendritic network is processed for each downstream end point. Parameters in the model can be adjusted to validate the surface against modelled or gauged flow or level data.

The GridFlow method has been shown to produce reasonable results across rivers, streams and overland areas in a fraction of the time taken for more conventional modelling methods. Typical model runs on large grids may generate many thousands of cross-sections along thousands of tributary flow paths with run times less than an hour.

A comparison of GridFlow results with 1D and 2D modelling has shown differences of around 0.3m. Larger differences occur upstream of lateral constraints which may not be captured by the automatic cross-section locations. Vertical changes in grade are automatically captured and, pre-set cross-sections can be inserted by the user to specifically capture lateral constraints that are evident in the DEM, such as bridge abutments, etc. We have found these issues to be most significant for moderately graded areas of small to medium sized streams where there is little floodplain area. This issue is less significant on the flatter coastal plains of large to very large rivers where a wide extent of the floodplain is occupied.

GridFlow modelling has been used extensively to support the insurance industry in identifying flood risks at properties Australia wide and a detailed analysis with validation against standard modelling results across the Brisbane LGA has also been performed.

A peer reviewed paper titled 'A Rapid Approach to Modelling Overland Flood Risk' was presented at the 34th IAHR World Congress held in Brisbane, June 2011 detailing the GridFlow theory and

Methodology. A copy of the paper can be found in Appendix A. The procedure has been considerably refined since this publication.

We note that GridFlow surfaces should be considered as indicative only and are not recommended for settings strict planning constraints such as minimum floor levels.

2.2 Model Inputs

The following DEM's were provided and processed into a singular 5m resolution grid framework:

- Singleton- 2011
- Maitland - 2012
- Wollombi - 2012
- Morisset - 2014
- Gosford West – 2016

This base grid was truncated to encapsulate the Cessnock City Council LGA and was supplemented by SRTM data where no data was provided. The provided DEM's required some manual modifications where anomalous data was present, these areas were also updated using available SRTM data.

For channel bathymetry, the provided flood study model datasets were used to define the watercourse topography where available.

GridFlow initially generates a hydrologically compliant DEM by running a pit removal process and generating a cleaned DEM and a flow accumulation grid. The model was then run for the 20, 50, 100 and Extreme ARI events using the pit removed DEM, the flow accumulation grid, IFD curves (extracted from the BoM), and Cy values from AR&R 1987 (See Table 1).

Table 1 GridFlow Input Cy Values

x year ARI	Cy Value
20	0.448
50	0.519
100	0.583
Extreme	0.900

The below GridFlow specific paramaters were used in final model outputs:

- Minimum Catchment Area = 2.00 Hectare
- Minimum Flow = 1.00 m^3/s
- Mannings 'n' = 0.06
- Flow Correction Factor = 3.1

Some screenshot examples of the GridFlow approach:

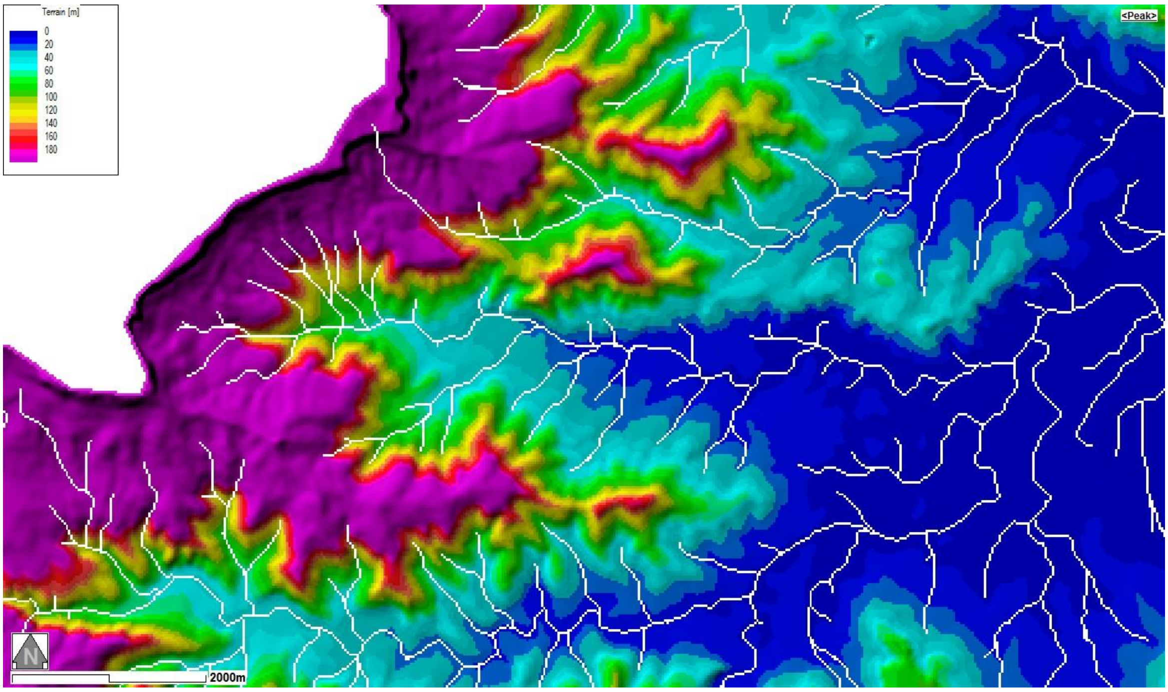

Fig 1. Identification of flowpaths across DEM.

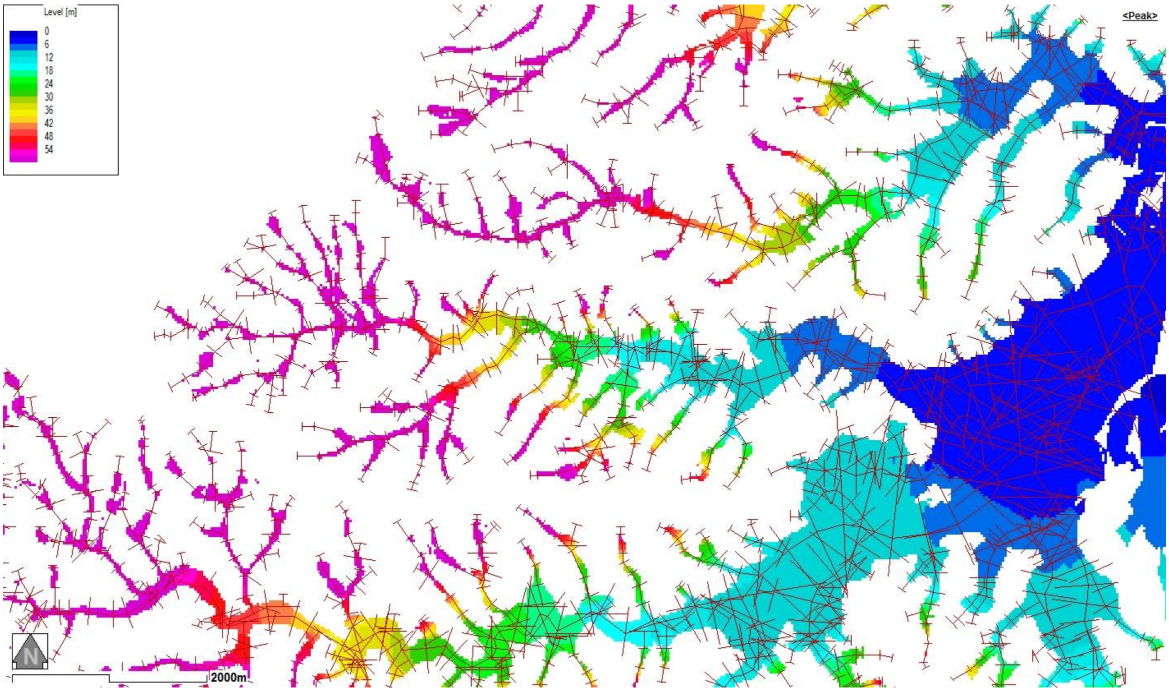

Fig 2. Water Level Surface and Cross Sections Used in the Hydraulic Calculations.

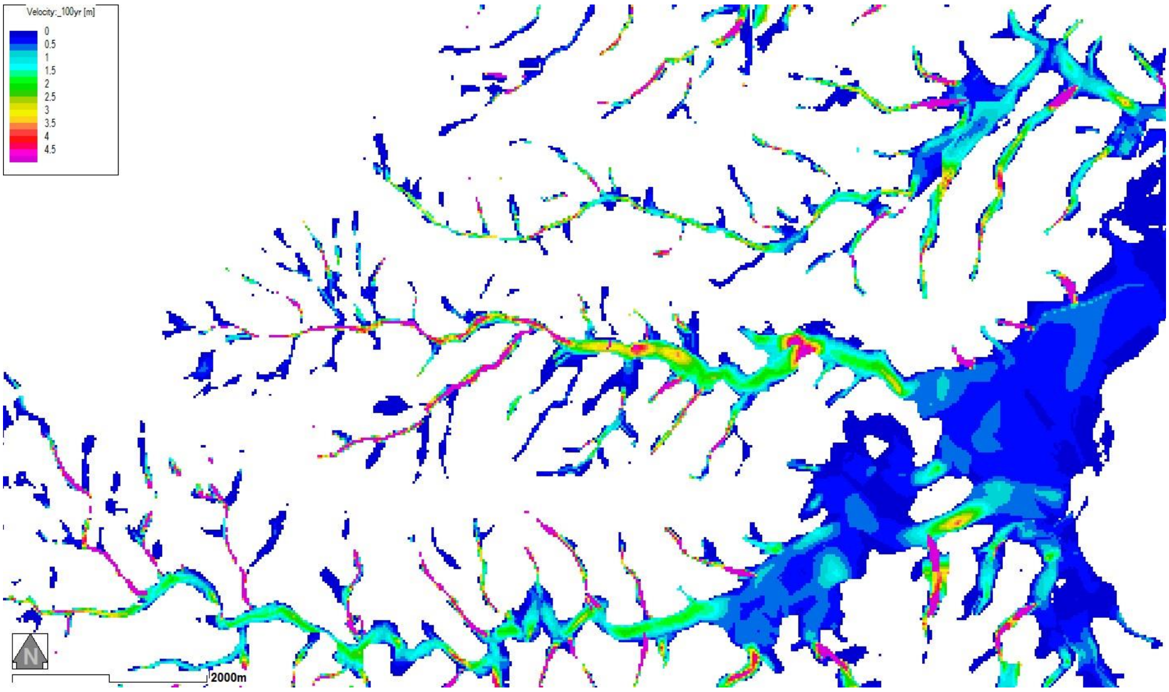

Fig. 3 Velocity surface.

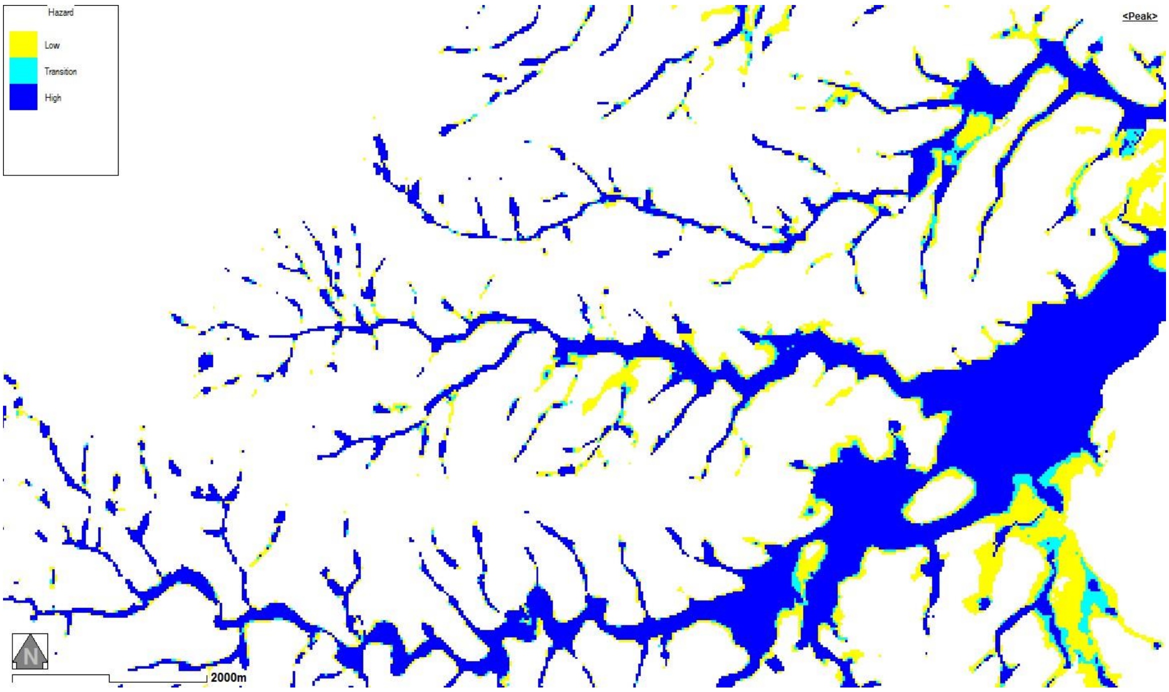

Fig 4. Flood Hazard (VxD) Surface (in this case, using NSW Floodplain Development Manual Categories)

2.3 Model Validation

The GridFlow model results were validated using the provided flood study model result datasets. Generally, the GridFlow results were found to be consistent with each of the flood studies based on overlaid flood extents. This was verified by spot checking flood levels at various locations in each catchment where flood model results were available which were well within acceptable tolerances.

2.4 Flood Planning Definitions

The GridFlow outputs were processed to determine various flood planning area definitions upon request. For Flood Planning Levels (FPL), the 100 year ARI surface was re-calculated to increase the level by 0.5m and re-mapped onto the DEM with updated flood extents.

The parameters provided used to generate Floodway, Flood Storage and Flood Fringe regions are presented in Figure 5.

- Floodway is defined as areas where:
  - the velocity multiplied by depth (V x D) > 0.25 m^2/s, **AND** peak velocity > 0.25 m/s, **OR**
  - peak velocity > 1.0 m/s

  The remainder of the floodplain is either Flood Storage or Flood Fringe;
- Flood Storage comprises areas outside the floodway where peak depth > 0.2 m; and
- Flood Fringe comprises areas outside the Floodway where peak depth < 0.2 m.

Fig 5. Flood Planning Region Definitions

3 Model Outputs

The model generates a catchment area surface and water level and velocity surfaces for each ARI selected (using waterRIDE™, this then leads to VxD and Hazard). The water level surfaces are checked for hydraulic consistency (rarer floods higher and wider than lesser floods) and adjusted as required. These issues can arise in steeper upper catchment areas where critical depth is forced at a cross-section for one ARI but not others.

The surfaces were provided as waterRIDE™ grids containing water level, depth, velocity, VxD and Hazard (H1-H6) data. Cross-section GIS files with hydraulic parameters attributes are provided as MapInfo file format.

Flood extents and hazard regions (H1-H6) for each ARI were provided as ESRI Shape files.

The Flood Planning Level (FPL) surface was provided as a waterRIDE™ grid as well as an associated flood extent ESRI Shape file.

Floodway, Flood Storage and Flood Fringe regions were also provided as ESRI Shape Files.

Appendix A Peer reviewed GridFlow publication

A Rapid Approach to Modelling Overland Flood Risk

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Abstract: *Australian insurers have commenced offering flood insurance based on a mainstream flood risk database. However, the potential risks related to overland flooding in urban areas are not adequately identified. An empirical grid based model has been developed to provide a rapid assessment of potential overland flood extents from design rainfall intensities. The approach employs a flow accumulation analysis of digital elevation data identifying overland and mainstream flowpaths and their upstream catchment area. The rational method and AUSIFD are used to obtain design rainfall intensities and catchment concentration times, and thus allow design flows to be determined. The water surface, which is obtained by simply applying Manning's equation to a cross-section and bed slope along each flowpath, is intersected with the DEM to map the potential flood extents. A comparison with hydrodynamically modelled data and sensitivity checks of the empirical parameters has shown good agreement across a number of flood frequencies.*

Keywords*: flood surface, modelling, flood risk, insurance*

1. INTRODUCTION

The apparent growing number of natural disasters around the world over the last decade, coupled with the increasing awareness of potential climate change effects has highlighted the concern of the re-insurance industry as to whether home policy insurance premiums are adequately covering the risk or that exclusions are being adequately expressed.

The insurance industry in Australia has recently been increasing its offerings in flood related insurance products and significant effort has been applied in quantifying the insurance risk for mainstream flooding where flood studies have been undertaken. The core of this effort has been undertaken for the Insurance Council of Australia in the creation of the National Flood Insurance Database.

The focus is now spreading to overland flooding where there is a growing imperative to quantify the risk from all categories of runoff and flooding capable of affecting properties and an insurer's policy portfolio.

The ever growing data store of LiDAR terrain data has facilitated analyses in this area with the availability of detailed digital elevation models (*DEMs*). An analytical methodology has been conceived to provide a reasonable representation of various flood surfaces, suitable for insurance purposes, by processing a raster or gridded DEM without the need for time consuming and costly traditional hydraulic modelling.

2. CONCEPT

The concept involves the identification of flowpaths across a gridded DEM with typically a 5 m cell size, the determination of water levels along these flowpaths, and finally identifying the extent of the inundated area. The result is a raster GIS surface which may be used to provide a reasonable assessment of the overland flood risk potential for a portfolio of insurance policies.

Whilst the concept is simple, application of the methodology involves a sequence of analytical steps which fortunately lends itself to computer processing.

The sequence can be summarized as follows:

i. Create a conforming DEM with watershed flowpath continuity to either the edge of the grid or to internal sinks such as lakes and swamps. This process is commonly referred to as pit removal and can be undertaken in most GIS applications.

ii. Run a flow accumulation model on the conforming DEM to identify flowpaths and incomplete catchments.

iii. Run a combined hydrology and hydraulic analysis to determine water levels along the flowpaths.

iv. Convert the flowpath water levels into a seamless water surface, and map the surface to the DEM to identify the inundation extents.

3. FLOW ACCUMULATION

The flow accumulation model is akin to dropping a marble on every cell of the DEM grid and incrementing a counter at each cell a marble rolls over. The well known ‘D8’ method is used to identify the lowest of the surrounding 8 cells into which the marble will roll. Once completed, the cell count essentially identifies the upstream catchment area for every cell on the grid, and a threshold can be applied to establish the commencement of overland flowpaths, Figure 1 & Figure 2.

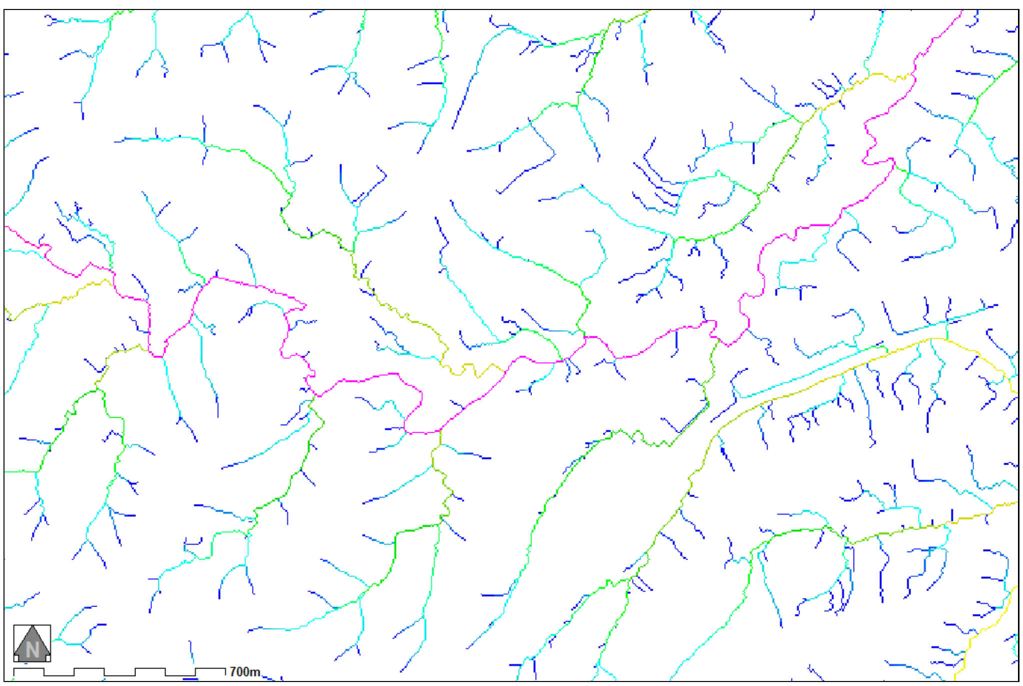

Figure 1 - Flow accumulation lines with a 5000 sq.m sub-catchment threshold

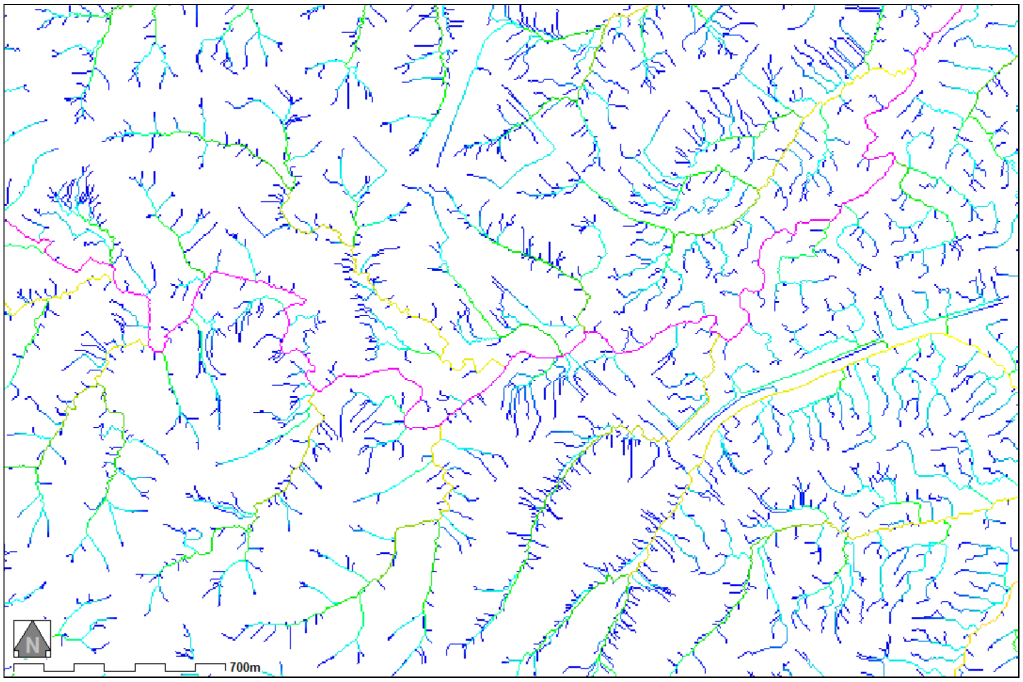

Figure 2 - Flow accumulation lines with a 1250 m^2 sub-catchment threshold

The effectiveness of the flow accumulation model is necessarily limited to DEM grids that cover entire sub-catchments for the overland flow areas of interest. To highlight this limitation on any grid, an incomplete flowpath grid is created simultaneously to identify flowpaths that would have originated outside of the grid. Cells along the grid edge and adjacent to undefined or background cells, with a flow direction into the grid are deemed to constitute an incomplete catchment, and all resulting downstream cells are likewise tagged as incomplete.

The need for pre-processing of the DEM with a pit removal algorithm is essential to avoid flowpaths becoming hung by local DEM depressions in mid catchment.

4. FLOW ANALYSIS

The flow accumulation grid identifies the contributing catchment for every flowpath cell, and the objective of the flow analysis is simply to convert the upstream catchment area into a flow and water level for a number of annual recurrence intervals (*ARI*) for all grid cells along a flowpath. The basis for the analysis is the extraction of a cross-section from the DEM through any selected cell in a flowpath, and the application of Manning's equation to determine the relevant hydraulic characteristics.

The flow passing through a cross-section can be readily determined using the rational method with regional coefficients for Australia (*AR&R 1987/1999*) and associated IFD curves (*AusIFD 2005*) for a duration equivalent to the time of concentration for the upstream sub-catchment.

The conversion of a flow to a water level evolved through a number of approaches with increasing sophistication. The initial approach employed Manning's equation with an appropriate slope and roughness value. Since the approach is regional in scope, it is not practical to apply local variations to roughness and instead a conservative default value was applied across all flowpaths on a DEM. To address the need for a slope, a normal depth calculation is used where the flowpath is traced upstream and downstream a number of cells to obtain a local bed slope.

This localized normal depth method ignores backwater effects and the continuity of the energy grade line, and whilst initial trials generated a reasonable outcome for small flowpaths with sub-catchment areas less than 50 ha, large channels in downstream reaches where bed gradients are flatter and there are numerous small adjoining flowpaths, presented spurious results.

The next refinement applied a systemic backwater analysis along the major flowpaths up to a 25 ha catchment limit.

Candidate flowpaths can be readily identified from the flow accumulation grid as cells with sufficient upstream catchment area, either on the boundary of the grid, on, in the case of an internal sink (*lake or swamp*), a terminal cell with no downstream connection. Each candidate flowpath can then be traced upstream and cross-sections extracted from the DEM normal to the flowpath at regular intervals. A Simple backwater profile balancing the EGL between adjacent cross-sections (*similar approach to HEC-2*) is progressively applied as each successive cross-section is identified. The backwater profile is started at the downstream end with either a normal depth calculation for a water level or a minimum set level to accommodate ocean or estuary levels. The backwater profile continues upstream until the low area threshold is reached.

Initial trials were undertaken with various cross-section intervals. Short intervals capture more detail in the water surface profile but succumb to cross-section alignment issues around bends in meandering reaches, whereas long intervals better capture the valley alignment but sacrifice detail.

Whilst this approach improved the predicted flood surface along the major flowpaths, the intersection with the smaller flowpaths defined with the initial approach, had a varied success with a number of water surface inconsistencies, especially where the main channel created a backwater on the tributary.

The final approach involved the application of the systemic backwater method across all flowpaths. This approach required the identification of the major flowpaths as previously indicated, and as each flowpath is processed, tributaries are identified and added to the list of flowpaths for subsequent processing. The backwater and tributary identification procedure is run recursively until all the branches of the starting major flowpaths have been processed.

Refinements were also applied to the location of cross-sections and to their alignment. The nominal distance between cross-sections was determined on the basis of the upstream catchment area to ensure a spacing appropriate to channel size and flow. Additional cross-sections were established at sharp changes in bed gradient to better capture local hydraulic conditions, and the alignment of a cross-section was rotated relative to the adjacent downstream cross-section, if necessary, to avoid the cross-section alignments crossing over each other.

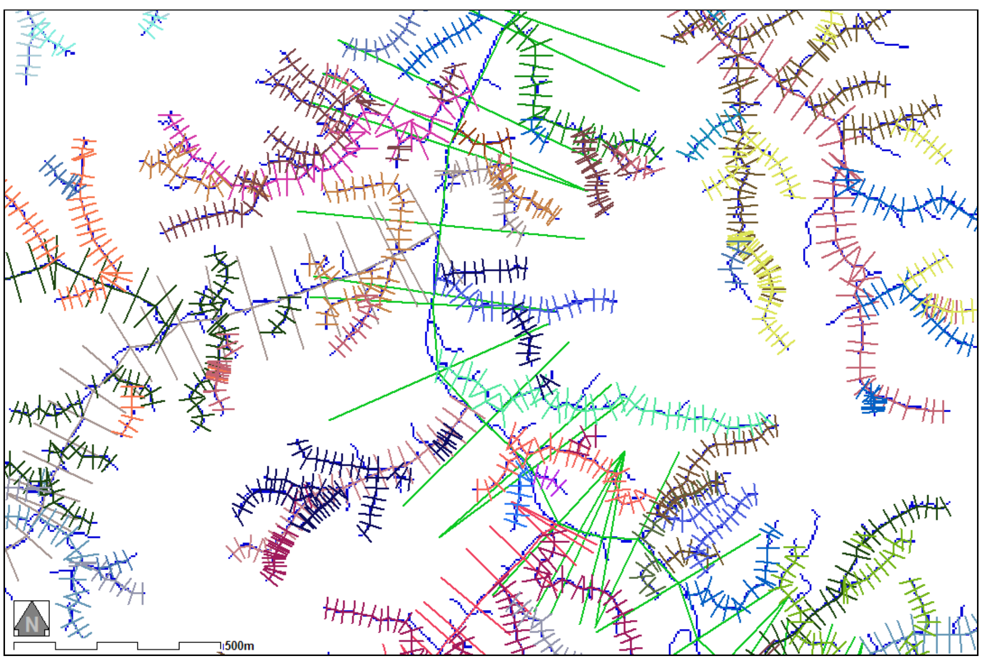

Figure 3 - Typical automated cross-section arrangement along part of main channel and tributaries

5. WATER SURFACE MAPPING

Once each cross-section is identified either through the maximum distance or at a change in bed gradient, the cross-section alignment is set normal to the flowpath centerline and extended left and right to an offset distance factored by the upstream catchment area. The offset was established to ensure adequate coverage of the floodplain. All cells between a pair of adjacent cross-sections can be assigned a water level as a linear interpolation based on the cell's perpendicular distance to each of the cross-sections. Each side of the centerline between the cross-sections is processed separately in this manner and water levels are not assigned to dry cells.

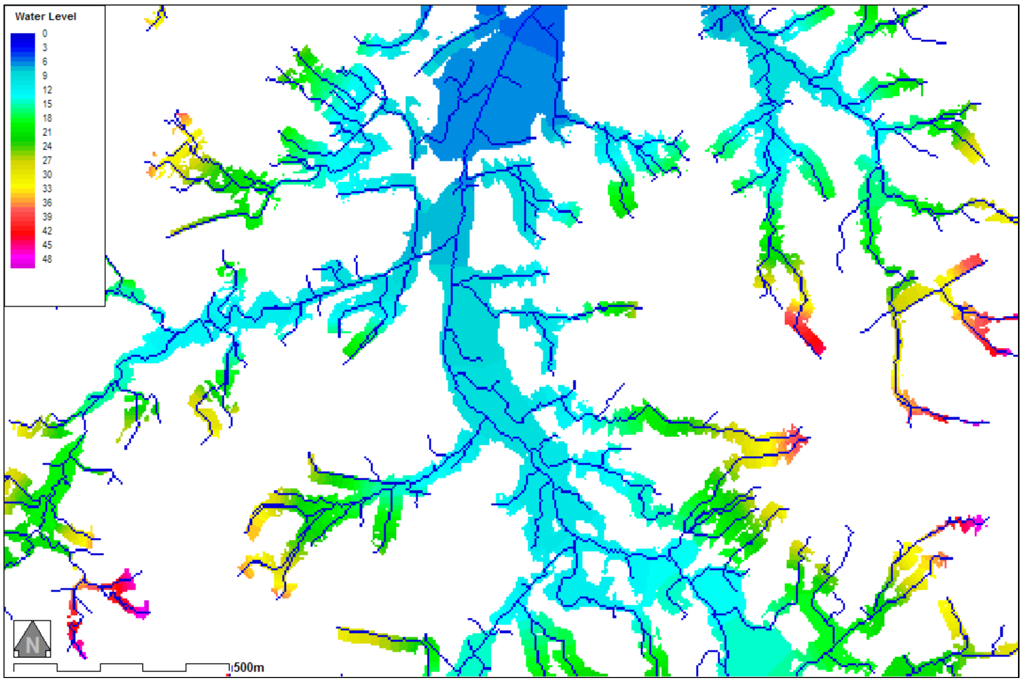

Figure 4 - Water surface superimposed with flowpaths

6. LIMITATIONS

Considering the objective is to rapidly and cost effectively quantify potential flood risk from relatively small catchment areas and not to replicate mainstream flood studies, a number of limitations have been accepted.

The primary limitation is the quality of the DEM. Aerial laser survey (*LiDAR*) is becoming increasingly prevalent with the eastern coastal strip of NSW and Queensland having recently been flown and numerous local government areas having had population centres also flown. Gridded DEMs derived from filtered ground LiDAR data are generally recognized as providing the best quality terrain definition over large areas. LiDAR's weaknesses are in areas of dense tree canopy where only sparse ground data is captured, over water bodies where no data is captured, and across grass and marsh lands where significant noise can be generated in the terrain surface. Trials were undertaken with with DEMs generated from LiDAR cloud data as well as from the more traditional DEM's derived from cartographic contour datasets. Trials were also conducted with different grid cell sizes.

The backwater approach is rigorous in so far as adequate and representative cross-sections are extracted from the DEM. Sudden changes in bed gradient along the flowpaths are readily identified and accommodated with the inclusion of additional cross-sections, however lateral constraints across the floodplain such as valley nick points and road crossings, etc are not easily identified programmatically and thus culvert and bridge backwater effects are not included in the backwater analysis.

7. VERIFICATION

Apart from the sensitivity trials described above, verification of the methodology was undertaken by comparing water surface profiles with hydrodynamic modeling results. Two sample datasets from small streams (*approximately 20 sq.km catchments*) from different rainfall and topographic regions were used in the comparison.

Table 1 - Comparison of overland flow results with hydrodynamic model results

	Max -ve Difference	Max +ve Difference	RMS Difference
Stream 1	-1.4	1.4	-0.19
Stream 2	-1.1	1.6	+0.27

The Manning's 'n' roughness trials were run on Stream 1 using values of 0.03, 0.04 & 0.05. The effect of varying the 'n' value by 0.01 was an average water level difference of 0.1 m. This is less than the RMS difference in comparing the two models, and in the context of the objective of the overland model is not considered significant. A higher 'n' value can be used if more conservative results are warranted.

As discussed above, the maximum differences relate to backwater effects at lateral constraints and are only representative of small localized areas. The root mean square differences show an acceptable comparison with much more detailed hydrodynamic modeling.

Comparison profiles along the two streams are shown in Figure 5 and Figure 6

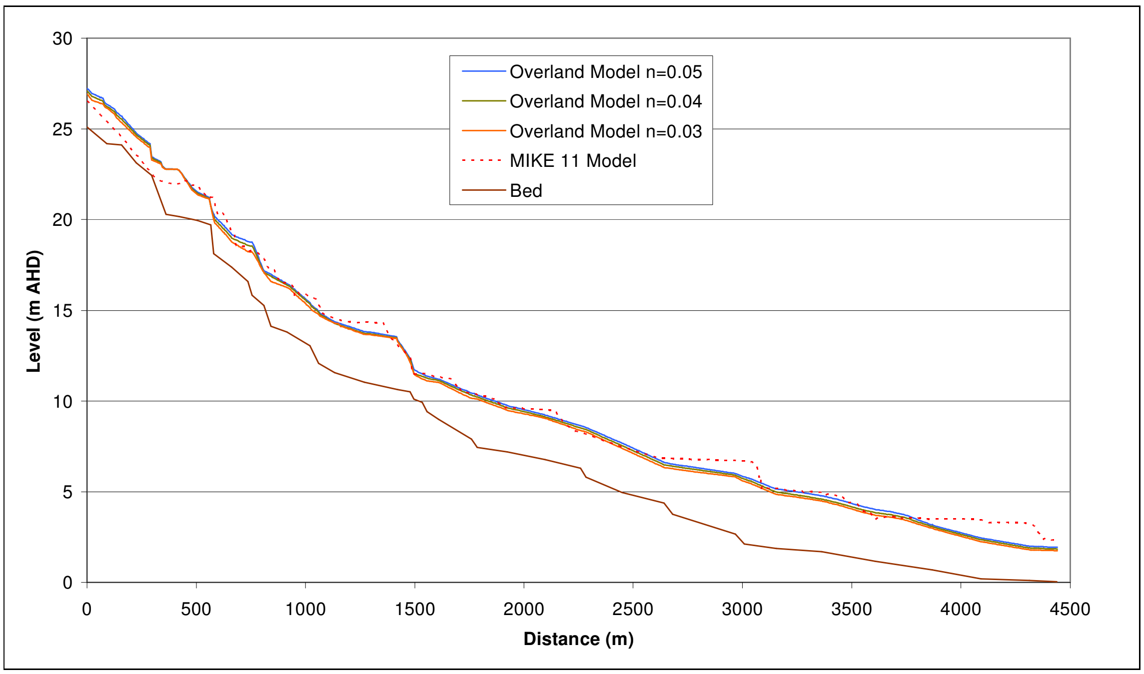

Figure 5 - Stream 1 Profile Comparison

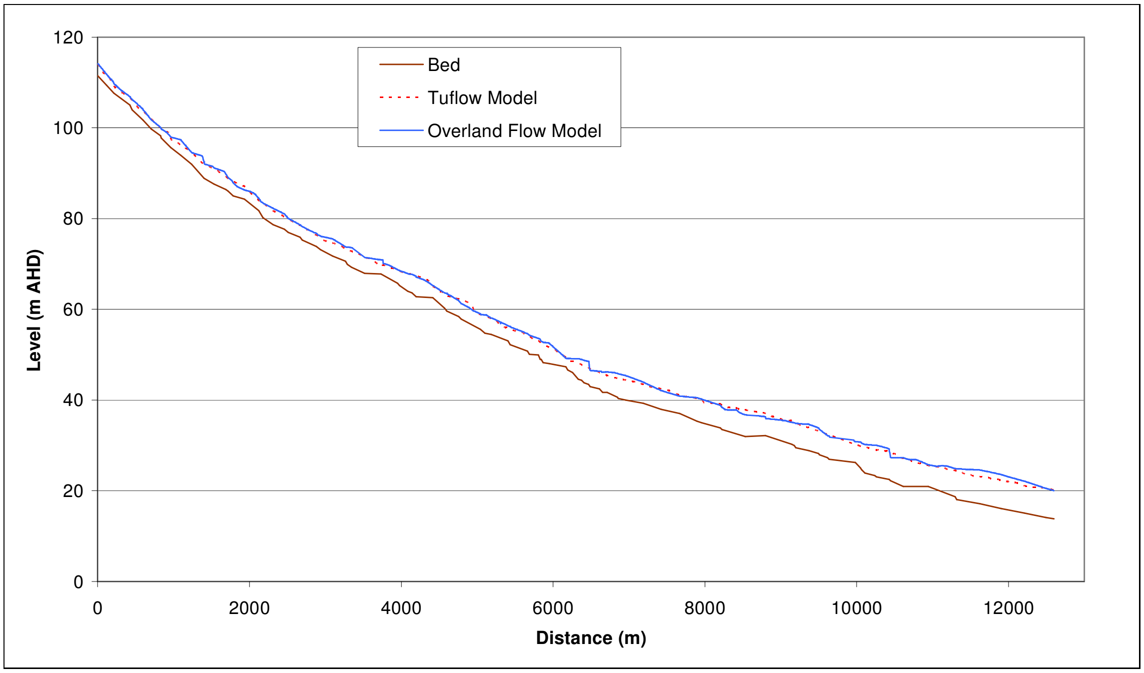

Figure 6 – Stream 2 Profile Comparison

The effect of DEM grid cell size was gauged for stream 2 by running the process for DEMs with 2 m, 5 m and 10 m grids and comparing the resulting mainstream profile with the hydrodynamic model profile, Table 2

Table 2 - DEM Grid Cell Size Comparison

	Max -ve Difference	Max +ve Difference	RMS Difference
10 m Grid	-0.72	1.71	+0.43
5 m Grid	-1.04	1.56	+0.27
2 m Grid	-1.38	1.06	+0.03

As indicated by the results in Table 2, the use of a finer grid reduces the RMS difference. Also the 2 m grid biases the results slightly lower, whereas the coarser 10 m grid biases the results slightly higher. The spatial extent of the 2 m grid water surface is more refined than the 5 m grid, but these benefits come at the cost of longer processing times, especially for pit removal and flow accumulation. A 10 m grid is considered too coarse and a 5 m grid is considered optimum.

Trials were also run with DEMs generated from digital contours. These DEMs lead to a poor definition of flowpaths in upper reaches on relatively uniform terrain areas, especially mild ridges and depressions. The problem arises with a series of small furrows, one cell wide, embedded in the DEM running normal to the slope, Figure 7. The D8 method is not capable of determining any steeper cross gradients and hence a series of ‘hanging’ parallel flowpaths are created, leading to a false expression of the flood extents.

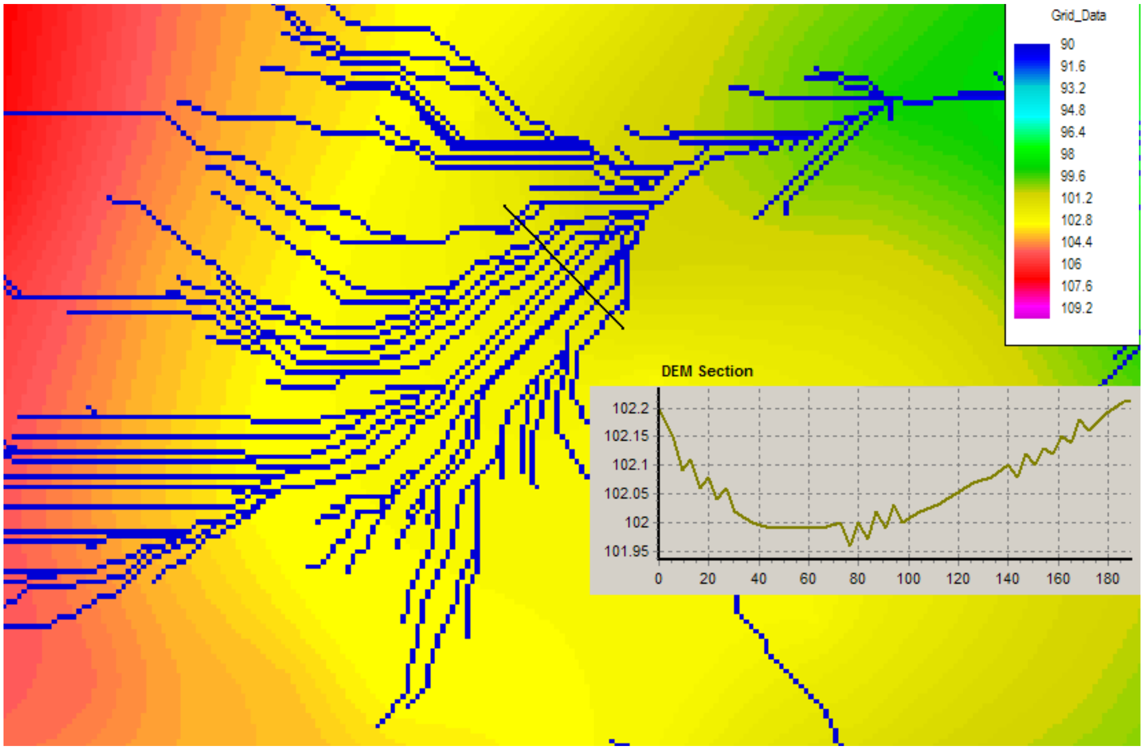

Figure 7- DEM generated from contours showing parallel flow lines in 'hanging' furrows

8. CONCLUSIONS

A rapid and easy to apply methodology aimed at identifying overland flowpaths and their resulting flood risk has been successfully developed to assist the insurance industry in quantifying their portfolio risk for flood insurance.

The concept levers the benefits of high resolution LiDAR DEMs, which, through a flow accumulation analysis identifies the dendritic flowpath network. A traditional backwater profile hydraulic analysis further provides water levels along these flowpaths which can be mapped to the DEM to generate a flood surface and flood extents.

The rigorous grid based DEM approach provides an acceptable comparison to comparable hydrodynamic model results along major flowpaths. The key benefit, apart from the cost effectiveness of the method is the definition of flood surfaces for any desired return interval across the myriad of small flowpaths and tributaries that are un-economic to model with standard hydraulic modeling techniques.

The resulting design flood surfaces provide a useful base dataset from which the insurance industry can quantify property flood risks and thus determine an adequate distribution of premiums.

9. REFERENCES

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Jenkins, GA. (2005), *AUS-IFD ver 2.01*, School of Environmental Engineering, Griffith University