ANUGA: - Identifying Real Hazard by Direct Hydrology in 2D Hydraulic Model and the role of roughness

ANUGA : identifier les risques réels par la modélisation hydraulique 2 D et le rôle de la rugosité

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RÉSUMÉ

En décembre 2006, le gouvernement fédéral australien a publié, par le biais de Geoscience Australia (GA), un solveur d'équations 2D pour vagues de hauts fonds, logiciel appelé ANUGA et développé conjointement par GA et l'Université Nationale d'Australie (ANU). Bien que le développement de ce logiciel visait spécifiquement la modélisation d'un tsunami frappant une bande côtière, avec une forte puissance de calcul des chocs et de gestion de l'interface zone humide/zone sèche, le modèle a été étendu aux inondations fluviales et urbaines. Les tentatives d'application directe de la pluviométrie dans le domaine de calcul 2D avec d'autres modèles à matrice fixe a produit des résultats moins satisfaisants. Toutefois, l'approche triangulaire non structurée du logiciel ANUGA n'a pas été entravée par les mêmes problèmes que ceux identifiés avec les autres modèles. Le modèle ANUGA est comparé au modèle hydrologique WBNM et au modèle 1D Hec-Ras. De plus, une meilleure approche d'identification des dangers est discutée. Toutefois, l'identification d'une éventuelle approche (soldée par un échec) consistant à augmenter artificiellement les paramètres de grossièreté pour prendre en compte la zone urbaine, et l'impact de cette approche qui masque la véritable étendue du danger constitue un autre artéfact. Le présent article donne les résultats des travaux de recherche et d'investigation entrepris dans ces domaines.

MOTS CLÉS

2D, hydrodynamique, hydrologie, hydraulique, non structuré, triangulaire, matrice, modèle, imprécision, danger, impacts

ABSTRACT

In December 2006 the Australian Federal Government through Geoscience Australia (GA) released a 2-Dimesnional Shallow Water Wave (SWW) equation solver. The software has been jointly developed by GA and the Australian National University (ANU). The software is called ANUGA. Although development of this software was specifically to target modelling a tsunami striking the coast line with robust shock capturing and handling of the wet/dry interface, the model has been extended to river and urban flooding. The application of rainfall directly onto the 2-Dimensional computational domain has been attempted with other fixed grid models with less than optimum outcomes. However ANUGA's unstructured triangular grid approach appears to not be hampered by the same problems identified with other models. The ANUGA model is compared to the hydrologic model WBNM and the 1D Hec-Ras model. In addition a better approach to identifying hazard is discussed. Yet another artefact has been the identification of the possible ill-fated approach of artificially increasing roughness parameters to account for urban terrain and the impact of this approach in disguising the real extent of hazard. This paper reports of findings of research and investigations undertaken in these areas.

KEYWORDS

Two, dimensional, hydrodynamic, Hydrology, hydraulics, unstructured, triangular, grid, model, roughness, hazard, impacts

1 INTRODUCTION

The use of 2-dimensional hydrodynamic flow models has generally been restricted to hydraulic analysis only. Determination of flood levels resulting from storm events has generally still been reliant on the use of hydrologic models in conjunction with these 2D flow models. However this paper will show that a relative new model that is freely available can replicate hydrologic response accurately. In addition the role of exaggerated roughness values to account for urban obstacles is questioned, as an invalid approach when identifying hazard.

2 IDENTIFYING HAZARD

The identification of hazard is a primary task in the process of developing a flood study. This process provides the ability to identify those areas within the flood plain where there is a heightened level of risk. Further the ability to observe the level of hazard at each time step (through animation for example) provides a highly beneficial platform to identify impacts on evacuation routes during flood events of various magnitudes.

2.1 How is Hazard Defined

Howells et al (2004) provide a good overview of the evolution of the development of hazard definition around the world. Most practitioners have opted for a momentum based description based on Velocity x Depth. A typical example being that as described in the Australian, NSW 2005 Flood plain Development Manual. http://www.environment.nsw.gov.au/floodplains/manual.htm

Figures L1 & L2 in the above document shows the approach adopted by the 2005 NSW Flood Plain Development Manual. VanDrie (2008) shows that although these two graphs appear next to one another, in regard to defining hazard they barely relate to one another through the parametric terms of Velocity and Depth.

2.2 Other (Better?) Hazard Definitions

Trieste (1988) provided an alternate definition through a series of graphs. Although the development of the curves defined is not well described, the importance may be abstracted by simply identifying the shape of these curves in the graphs. Clearly the curves are not defined using only VxD. VanDrie (2008) explores this further and provides a single relationship that mimics characteristics of the shape of the Trieste curves and when applied to the results of a 2-dimensional hydrodynamic analysis provides a much greater range of values from which to differentiate hazard with.

The relationship is as follows:

HAZARD = Depth + Velocity^2 x Depth ie: $(D + V^2 xD)$ Equation 6.

Although VanDrie is not suggesting that this definition replace the current definition, the suggestion is that other more meaningful definitions be explored and compared to the approach suggested so as to easily allow practitioners to identify what the hazard number applied to an area describes in terms of the hazardous flow condition present.

From figure 2 it can be seen that this singular expression can now define the transition between Low and High Hazard. Moreover an emphasis is placed in using the range of values to more succinctly describe what that level of hazard means in a physical manner.

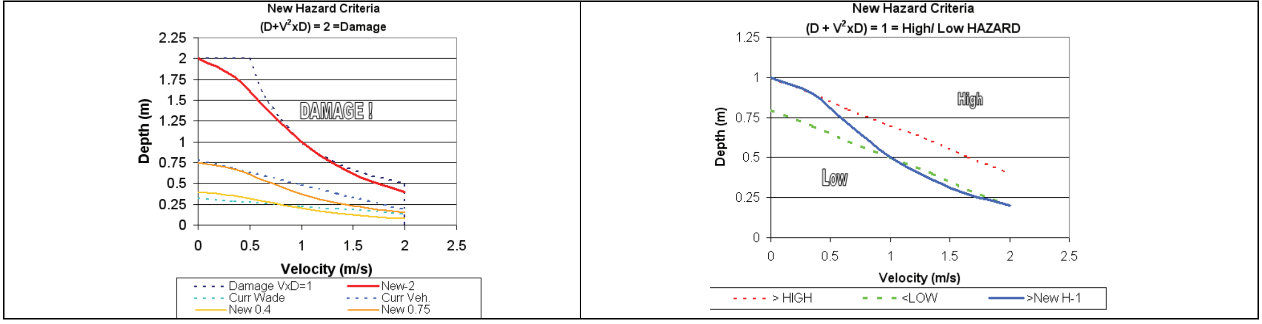


Figure 1. Comparison of NSW FDPM Hazard and New suggested approach by Van Drie (2009)

To this end it is understood that research is continuing with the utilisation of the Penrith White Water Rafting Stadium in Sydney Australia, to provide physical insight into what the range of hazard numbers looks and feels like. That is to fully define whether people can or cannot wade through the water flow presented on the rafting course. This facility can produce a flow of 14.0m3/s, and as such has the ability to produce a vast range of hazardous conditions.

2.3 REAL HAZARD

In being reliant on using only a product based purely on momentum VxD is hydraulic hazard adequately identified. Trieste and others have found that the relationship of hazard as defined only on VxD does not relate well enough to adequately differentiate the extent of HAZARD and further current methods are not logical in their application with 2D modelling techniques. The proposed approach provides higher differentiation and a simple method of application with 2D models. Being able to animate the progression of the Eq. 6 over an entire storm event provides great insight into the development of hazardous flood conditions accounting for both deep still water and shallower fast flowing water. This is seen as a more realistic approach to identifying hazard that is easily generated through the 2D methodology.

3 HYDROLOGY USING A 2-D HYDRAULIC MODEL

Historically the definition of hazard is reliant on a two step process. The first step is identifying the quantity of flow utilising a hydrologic model. A typical example being the free hydrologic model WBNM Boyd etal (1999,2007) www.uow.edu.au/eng/cme/research/wbnm.html . Typically the next step utilises a hydraulic model. In the past this may have been using the US Army's Hec-2, Hec-Ras. These are 1-Dimensional Flow models that were once the industry standard.

See: http://www.hec.usace.army.mil/software/hec-ras/hecras-download.html

However the 1-Dimensional approach has been replaced by 2-Dimensional flow models that typically solve the shallow water wave equation.

3.1 PREVIOUS ATTEMPTS

The question has been raised:- "can 2D models be used to model hydrologic response?".

A recent research paper *(Clark et al, 2008)* concluded that models such as TUFLOW and SOBEK were un able to replicate the hydrologic response when compared to well accepted hydrologic models. However both these models are fixed grid 2D models. In addition the underlying code is locked away in a black box as they are commercial codes, so it is not possible to discover why these very similar codes produce diverging results.

By contrast, ANUGA which is an Open Source unstructured grid model does not appear to share that fate. In fact many catchments have now been modelled for hydrologic response with ANUGA with impressive outcomes. This aspect is discussed in this paper.

An artefact of those catchment analyses was the observed unrealistic response displayed by ANUGA by adopting artificially raised surface roughness. This issue is also discussed in this paper.

3.2 INTRODUCING ANUGA

In December 2006 The Australian National University and Geoscience Australia released to the public a Free 2D Unstructured Grid, Finite Volume, Hydrodynamic Model. The model was a resultant of a Mandate put to GA by the Australian Federal Government to build capacity to identify and manage Hazard and Risk. This was interpreted and actioned by providing a software tool to aid in assessing the impact of tsunami. This being the case the model is therefore well adapted to providing a robust modelling solution to all forms general fluid flow based on the Shallow Water Wave Equation. Therefore it is capable of modelling, not only Ocean Inundation but also Riverine Flooding and the combination of both these.

The model was released as Free & Open Source Software (FOSS) meaning that every user has access to the computational code. This allows every user with the capability and will, to add or improve the content of the original code. The original code is then updated on the source forge web site making the enhancements available to every one.

A compact yet full description of ANUGA has been covered by others. *(Rigby and Van Drie, 2008) (Nielsen et al 2006 - 2009).* For more details, please refer to the following link. http://sourceforge.net/projects/anuga/

AnuGA uses a finite-volume method for solving the shallow water wave equations (Zoppou and Roberts, 1999). The study area is represented by a mesh of triangular cells in which water depth *h*, and horizontal momentum (*uh, vh*), are determined. The size of the triangles may be varied within the mesh to allow greater resolution in regions of particular interest

3.2.1 Catchment Hydrology

ANUGA is an amazingly robust and stable code for solving complex 2-dimensional flow such as an ability to capture details of hydraulic jumps and reflective waves as shown in figure 3. It also has functions built in that will allow spatially varying rainfall to be applied to a computational domain. Through this mechanism it has the ability to be used as a combined hydrology and hydraulic analysis tool.

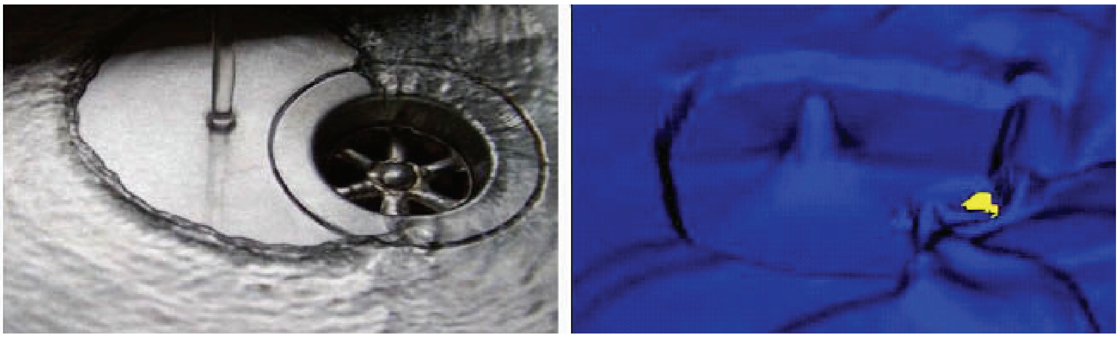


Figure 2. Example of Complex flow with hydraulic jumps and shocks (Kitchen Sink)

In order to validate ANUGA's ability to successfully replicate hydrologic response, it will be compared to a well known and accepted FREE hydrologic model called WBNM. WBNM has been validated on numerous catchments Boyd (1999,2007). The trial catchment for this exercise was a small 12.5 hectare urbanised catchment with a small centrally located park. Although there is a 900mm diameter pipe that drains the area for this exercise the assumption is that that pipe is fully blocked. The aim was to focus only on the hydrologic response. The total storage upstream of the culvert is negligible and not capable of altering the hydrologic response of the catchment. Figure 4 & 5 shows the model and the WBNM sub catchment layout.

Figure 3. Overview of the catchment

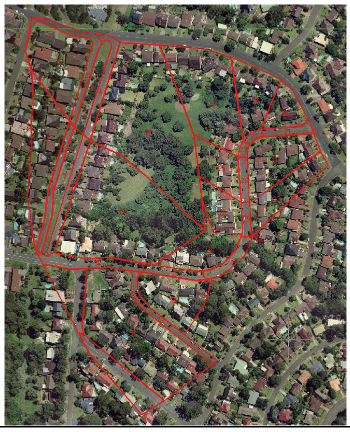


Figure 4. Setup of WBNM sub catchments

In order to validate the exercise the flow estimates have not only been compared to WBNM but also with an alternate model RAFTS through a previously adopted flood study namely the Allen's Creek Flood Study. In addition the WBNM model was provided in two forms, the initial run was setup using a single sub area. The second model was a refined 32 sub-catchment model. Further the flood profile was compared to a Hec-Ras model of the same area with impressive results.

3.2.2 ANUGA V's WBNM

ANUGA runs have been developed for the 1:5 year Average Recurrence Interval (ARI) design storm event through to the Probable Maximum Flood (PMF). The results indicate good agreement with the hydrologic models.

Table 1 – WBNM, ANUGA and RAFTS Peak Flows (m^3/s) at upstream side of culvert

Model	**1 in 1year ARI**	**1 in 2year ARI**	**1 in 5year ARI**	**1 in 10year ARI**	**1 in 20year ARI**	**1 in 50year ARI**	**1 in 100year ARI**	**PMF**
	(m^3/s)	**(m^3/s)**	**(m^3/s)**	**(m^3/s)**	**(m^3/s)**	**(m^3/s)**	**(m^3/s)**	**(m^3/s)**
RAFTS*	n/a	n/a	6.0	7.0	8.0	10.0	11.0	17.0
WBNM 1	2.7	3.7	5.1	6.0	7.1	8.1	9.3	19.4
WBNM 32	2.7	3.6	5.1	5.9	7.1	8.1	9.2	16.1
ANUGA	n/a	n/a	4.8	5.7	6.9	7.8	9.2	25.7

*peak flows (no hydrographs) from Allan's Creek Flood Study

3.3 Comparison of Hydrograph Shape

Further by comparing the resulting hydrographs from the hydrologic model to those developed by the ANUGA model it can be seen that ANUGA is capable of emulating the hydrologic response of the catchment correctly. The shape of the hydrograph, the timing of the peak and overall storm volume are all comparable. In fact it may be the case that ANUGA produces a more realistic outcome as shown by the initial delay in flow at the start of the event. Figures 6, 7 and 8 provide details of the hydrograph comparisons.

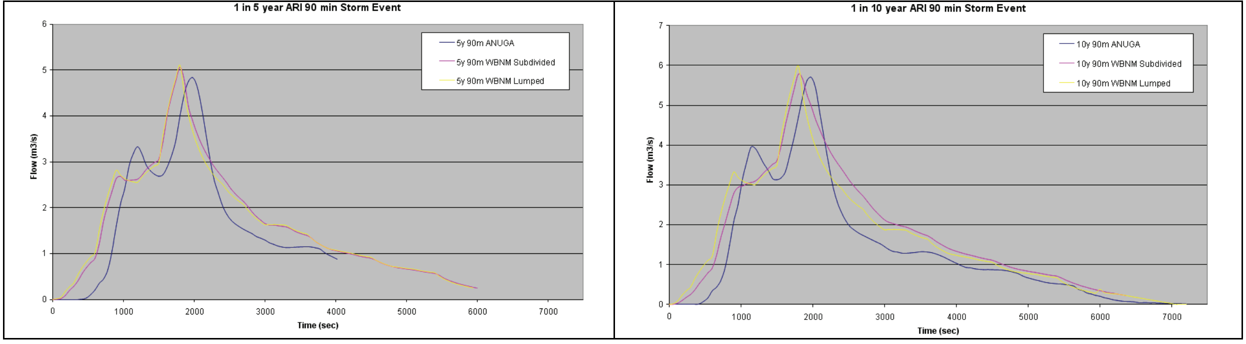


Figure 5. showing 5yr and 10 yr ARI hydrographs compared

Worthy of a mention is the fact that WBNM2007 reproduces almost identical hydrographs with (1) a single lumped sub area or with (2) a refined 32 sub catchment model.

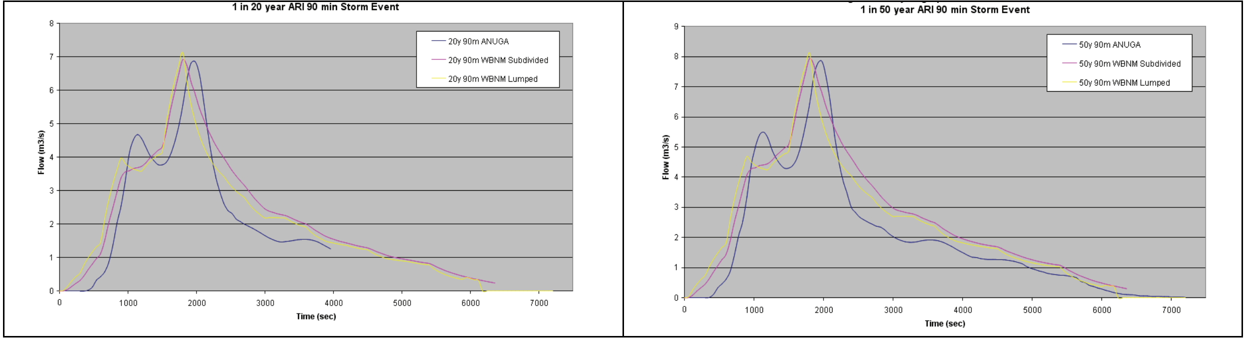


Figure 6. showing 20yr and 50 yr ARI hydrographs compared

The consistent reproduction of the WBNM2007 results for the full range of storm events by ANUGA is in stark contrast to the findings of Clark et al using 2 fixed grid models.

Clark found that “when TUFLOW was run with a 5 metre grid, the model became unstable and crashed. Although the model ran stably when the timestep interval was reduced from 1 to 0.5 second…”

Further Clark states that, “Both 2D models are sensitive to changes to the DEM computational grid cell size. There is a trend in the SOBEK results for the peak flow rate to decrease as grid cell size increases. The trend for TUFLOW is the opposite, with the exception of the 100 metre grid cell size results, the peak flow rate tends to increase as grid cell size increases. Despite the differences in trends, estimates from both models appear to converge to the WBNM estimates as grid cell size decreases. The volume of rainfall excess discharged from the catchment is also highly affected by adjustments to this parameter.”

It appears that ANUGA does not have these tendencies with model grid size down to 0.1m2 running stably. The case study model has triangles down to 0.1m2 and a total of 60,000 triangles.

A very concerning result reported by Clark is concerning the TUFLOW results, it was found that: “results indicate that TUFLOW estimates are highly sensitive to adjustments to the timestep parameter. When run with a 2 second timestep, 34% more rainfall drains from the catchment than was actually applied as rainfall excess, this is indicative of mass errors occurring. When run with a 0.5 second timestep, the recession limb of the hydrograph stops attenuating after approximately 4 hours to become a constant flow rate of 55m3/s, longer run times at this timestep could potentially lead to the generation of mass”. Again ANUGA is not impacted by any issue related to mass balance or time steps. The time step is computed internally and the FINITE VOLUME methodology ensures mass balance is maintained correctly.

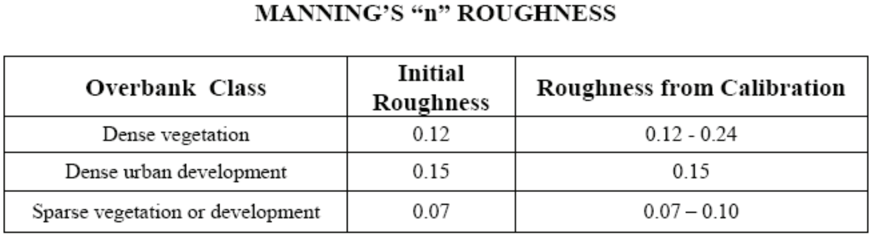
Yet another concern raised by the Clark paper is the trend due to the impact of varying the roughness. SOBEK reportedly varied in discharge by 23% and TUFLOW by 32% by doubling roughness from 0.04 to 0.08. This is certainly not the finding using ANUGA.

4 ROLE OF ROUGHNESS

In pipe hydraulics the role of the Roughness parameter (Manning-Strickler, Darcy-Weisbach) is applied to account for the impact of the internal surface roughness on the ability of the pipe to convey the flow. It is also applied as a roughness height to attempt to indicate the extent to which the surface roughness impacts the boundary layer. Similarly in open channel and overland surface flow roughness is almost universally accounted for using Manning’s roughness. Chow (1959), French (1986) and many others provide descriptive texts with images to aid in identifying roughness on floodplains. Smart (2004) provides details of the variation in the impact of roughness with increasing depth on the floodplain, and suggests an improved formulation for flow resistance.

4.1 Surface Roughness in Urban Areas

Clearly our urban landscapes are quite unnatural from many perspectives. This includes from the perspective of flowing water. The fact that in many cases there are isolated fully enclosed pockets of land surrounded by either buildings or fences, results in a strong impediment to flow. In order to account for this modellers have been using an approach whereby the roughness values are artificially increased. Generally Manning’s values of up to 0.15 had been recommended by the US Army in using Hec-Ras. Although a variety of values can be sighted in any number of flood studies that have been completed. Roughness values as high as N=20.0 have been utilised in some studies apparently to account for the lag.

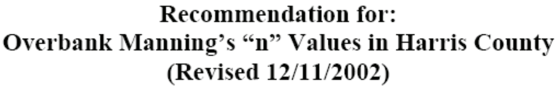


MANNING’S “n” ROUGHNESS

Overbank Class	Initial Roughness	Roughness from Calibration
Dense vegetation	0.12	0.12 - 0.24
Dense urban development	0.15	0.15
Sparse vegetation or development	0.07	0.07 – 0.10

Table 2: Typical Mannings values applied in Hec-Ras from “CLEAR CREEK GENERAL REEVALUATION REPORT HYDROLOGIC ANALYSIS WITHOUT PROJECT CONDITIONS

However Harris County in the US, published a guideline in 2002 where values of 0.99 and 99 were used and recommended for use with Hec-Ras.



Recommendation for:
Overbank Manning's "n" Values in Harris County
(Revised 12/11/2002)

4.1.1 Differences in the Role of Roughness in 1D and 2D formulations

Little research has been done in identifying the differences of the impacts of applying exaggerated roughness values in 1-D formulations compared to 2-D formulations. It may be inappropriate to assume that what provides valid results in HEC-RAS will provide valid results in other software particularly if the underlying schema is applied differently. For example cross section based application of roughness versus aerially applied roughness.

Although little formal research has as yet been completed there are numerous websites filled with discussions on this topic. Eg:- http://www.cedex.es/pipermail/rivers-list/2007-May/000679.html

4.1.2 Role of Roughness in 2D Hydrologic approach

Not only does roughness provide the critical parameter to determine the resistance of the surface to flowing water, by that same mechanism from a hydrologic perspective it represents the LAG within the catchment. Traditional hydrologic lumped models provide a lag parameter. ANUGA and the approach of using a 2D model does not have a separate lag parameter the lag is a resultant of the selected surface roughness.

4.1.3 ANUGA's approach to applying Roughness

As described by Nielsen et al ANUGA describes the impact of bed friction on the momentum of the flow as shown below.

$$S_{fx} = \frac{u\eta^2\sqrt{u^2+v^2}}{h^{4/3}} \text{ and } S_{fy} = \frac{v\eta^2\sqrt{u^2+v^2}}{h^{4/3}}$$

Figure 7. Application of Manning's N in ANUGA

The equations constituting the finite-volume method are obtained by integrating the differential conservation equations over each cell of the mesh. By applying the divergence theorem Neilsen obtained for each cell an equation which describes the rate of change of the average of the conserved quantities within each cell, in terms of the fluxes across the edges of the cells and the effect of the source terms.

5 IMPACT OF INAPPROPRIATE ROUGHNESS ON HYDROLOGIC RESPONSE

So what does a Manning's Roughness of 0.99 or 99 physically mean? How can we try to determine what impact adopting such values may have on different solution schemas? It is a concern and possibly even alarming to think that some models will allow users to select parameters that have no defined meaning. As the results using ANUGA will show, when the underlying algorithm are robust the introduction of non-sensible parameters leads to non-sensible results.

5.1 ANUGA results with a variety of Roughness values

The same catchment model as described above has been re-run using a single value of roughness over the entire catchment to understand the impact of varying the roughness value on ANUGA's ability to replicate the hydrologic response. The roughness values selected were:

N = 0.0, 0.01, 0.1, 1.0, and 10.0. These were compared to the WBNM hydrograph shape.

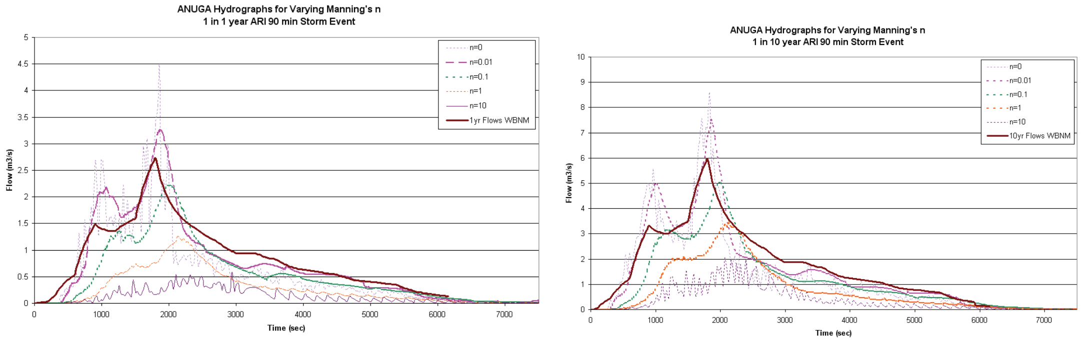


Figure 8. Comparison of ANUGA Hydrographs with Various Roughness Values 1&10 Year Events

As can be seen the results show that the predicted value from the hydrologic model lies between the ANUGA models with roughness between N=0.01 and N=0.10. It is considered that this result validates the range of expected applicable roughness values. In fact when inappropriate values of roughness such as N=0.0 and N=10.0 were selected the model results loose sensibility. There are wild fluctuations in flow. Rather than considering this to be a flaw or fault in the model, this is in fact confirming to us that there is a range of roughness that is sensible outside of which it simply should not be used. Interestingly the value of N=1.0 continues the trend of increasing catchment LAG and reducing peak flow. Recall that N=0.99 was recommended by Harris County. However their advice stated that there was little impact of applying N=0.99 or N=99.0.

It is noted that the above graph is for the 1 in 1 year design storm event. In order to ensure that the results were not impacted by the range of discharge the same exercise was undertaken for the 1 in 10 year and 1 in 100 year design storm events.

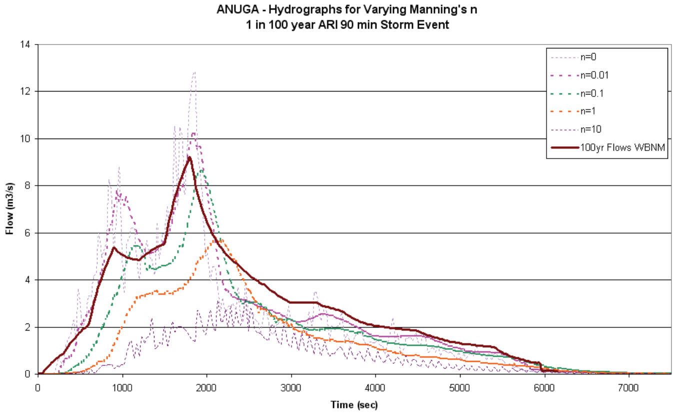


Figure 9. Comparison of ANUGA Hydrographs with Various Roughness Values 100 Year Event

6 IMPACT OF INAPPROPRIATE ROUGHNESS ON HAZARD

As was discussed in some detail by Van Drie (2008) selection of appropriate surface roughness is critical in correctly identifying and differentiating the level of hazard within a flood prone urban landscape. Not only is it critical to validate studies by the resulting flood level, but it is also critical to correctly identify hazardous (and potentially hazardous) conditions within that flood prone area.

It is clear that if modellers are reliant on hydrologic models to provide the values of flow to be used in 2-Dimensional hydrodynamic models, and then those models are utilising artificially high roughness values, the results will not be capable of correctly identifying the actual hazard that exists within the catchment. Through this process it is also possible that the calibrated hydraulic model may actually shroud the fact that the hydrologic model was implemented incorrectly. This is true regardless whether it is a 1D or 2D model.

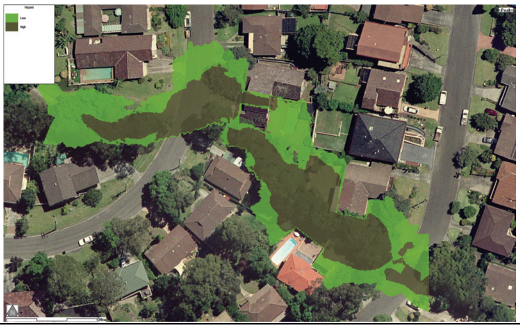


Figure 10. Provisional Hazard Map (1 in 100 Yr ARI)

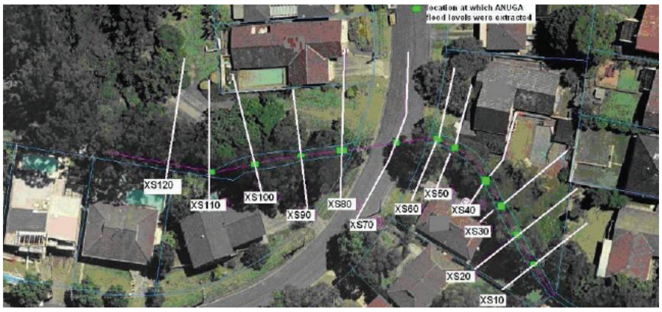


Figure 11. Hec-Ras layout for comparison

7 BETTER APPROACH

A far better approach would appear to be reliant on restricting the roughness values to a sensible range of no greater than 1.0, and to physically include the presence of obstacles in the 2-Dimensional flow model domain. The advantages of this approach have been previously discussed by VanDrie (2008). This was the outcome reported by Tennakoon (2004) and Pengyu Chen (2007). In fact Pengyu Chen concludes that the greater the number of parameters the better the tangible and intangible impacts can be assessed. Tennakoon suggest adopting a 3 parameter approaching using (a) depth of inundation, (b) duration of inundation and (c) the kinetic energy of the floodwater.

8 TESTING ON A LARGER SCALE

If ANUGA is capable of replicating the hydrologic response and identifying hazard on a small 12.5 hectare catchment, surely the approach is valid for larger catchments. Currently this approach has been applied to catchments up to 250 square kilometres and it is understood that work is currently underway to trial ANUGA on a 1080 square kilometre catchment.

8.1 Coffs Creek example, Coffs Harbour

The Coffs Creek catchment is around 2500 hectares in area. In March 2009 a significant rainfall event caused widespread flooding within the catchment. As an exercise for a Local Government Information Technology Conference an ANUGA model was setup to show case its capabilities. Six hours of rainfall around the peak of the event were applied to the entire catchment. The model was shown to consistently replicate measured flood levels throughout the catchment.

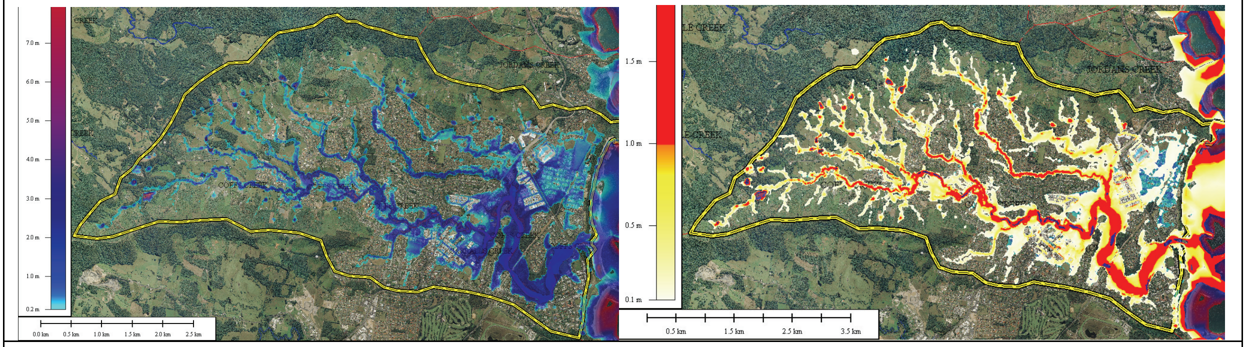


Figure 12. Typical GIS view of maximum flow depth(left) and Hazard (right) during a simulated flood event

Note that buildings have been added to the base terrain and in conjunction with the realistic roughness values this will provide the most appropriate determination of hazard.

9 CONCLUSIONS

It is concluded that the 2-D Hydrodynamic model ANUGA can replicate the hydrologic response of catchments by applying rainfall directly onto the computational domain. This is stark contrast to findings of other researchers using alternate models. In addition it is concluded that ANUGA produces realistic responses from catchments when realistic roughness values are adopted. Again in contrast the adoption of unrealistic roughness values produces un realistic results.

Finally the impact of adopting artificially high roughness values and ignoring the physical presence of obstacles (buildings) results in underestimating the severity and extent of hazard on flood prone land.

10 RECOMMENDATIONS:

It is recommended that if ANUGA is to be used to assess the hydrologic response of catchments that roughness values adopted in the model are realistic and contained within the range from 0.001 to 1.0.

In addition if analysis is aimed at identifying hazard then it is recommended that modellers include buildings and adopt realistic values of roughness.

LIST OF REFERENCES

Boyd M. J., Rigby E.H. and Van Drie R. (1999), Modelling urban catchments with WBNM2000, Institution of Engineers Australia, Water 99 Conference Brisbane July 1999.

Boyd M. J., Rigby E.H. and Van Drie R. (2007) WBNM User Manual, www.uow.edu.au/eng/cme/research/wbnm.html

Cardno Lawson and Treloar, Allan's Creek Flood Study, September 2006

Chow, "Open Channel Hydraulics", ISBN 0-07-085906-X

French, "Open Channel Hydraulics", ISBN 0-07-Y66342.4

Howells, McLuckie, Low & Avery (2004):- The Evolving Concept of "Hazard" in Flood Risk Management – can we make this work in a planning context. (44h Floodplain Management Authorities Conference Coffs Harbour 2004) pages 129 – 148

Nielsen 0, Roberts S, Gray D, McPherson A and Hitchman A (2005) Hydrodynamic modelling of coastal inundation, MODSIM 2005 International Congress on Modelling and Simulation, Modelling and Simulation Society of Australia & New Zealand, 518-523, www.mssanz.org.au/modsim05/papers/nielsen.pdf

Pengyu Chen, Flood Impact Assessment using Hydrodynamic Modelling in Bangkok,Thailand, 2007, Thesis, International Institute for Geo-Information Science and Earth Observation Enschede, The Netherlands.

Smart, An Improved Flow Resistance Formula, Pg. 259-262 River Flow 2004, ISBN 90-5809-658-0

Tennakoon, Parameterisation of 2D Hydrodynamic Models and Flood Hazard Mapping for Naga City, Philippines. (2004), Thesis, International Institute for Geo-Information Science and Earth Observation Enschede, The Netherlands.

Trieste (1988):- Downstream Hazard Classification Guidelines (US Dept. of the Interior, Bureau of Reclamation)

VanDrie, R. Simon, M. Schymitzek, I. (2008), HAZARD:- Is there a better definition? & Impact of Not accounting for buildings! Preprints of the 48th NSW Flood Plain Management Authorities Conference, Wollongong, February 26 - 29, 2008.

Zoppou, C., and S. Roberts (1999), Catastrophic collapse of water supply reservoirs in urban areas, Journal of Hydraulic Engineering, American Society of Civil Engineering, 125(7), 686–695.