ASSESSMENT OF SEA LEVEL RISE AND CLIMATE CHANGE IMPACTS USING ANUGA

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Abstract:

With the unprecedented onset of climate change, and resulting sea level rise and increased rainfall intensity, comes the ever increasing need to model those impacts, and then re-model as the knowledge base changes. Currently there is inadequate capacity to provide the level of modeling required to arm authorities with the required knowledge to alert the community of hazard and risk associated with the uncertainties of climate change. What is needed is a considerable boost in building capacity to undertake the modeling of these impacts.

In 2002 the then Australian Federal Government set several mandates, one of which was to “Build Capacity”, for the identification of hazards and management of risk. Details are documented in the 2002 Federal Budget and the 2002 COAG review.

The Boxing Day tsunami brought into focus the need to identify hazard associated with these events. This was the trigger that led to the development of ANUGA into a tsunami assessment tool. In December 2006 Geoscience Australia released the ANUGA software as FOSS (Free and Open Source Software). ANUGA has the ability to accurately model, Ocean impacts including wave and tsunami, and riverine flooding. Since climate change will impact both of these, this model is seen having the potential to be the tool necessary to assess climate change impacts properly.

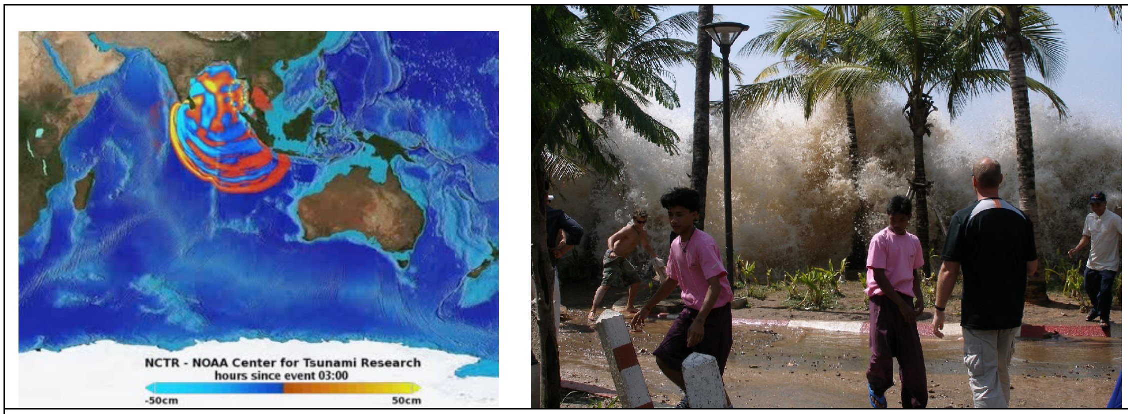

Fig. 1. – The 2004 Boxing Day Tsunami, Trigger For The ANUGA Model

1.0 Background:

The Ocean has an impact on the full range of flood (inundation) emergency management scenarios, from beach erosion under wave attack and extremes such as tsunami to storm surge associated with storm events which have a considerable impact on flooding in the lower portions of catchments as the catchment flows struggle to leave the catchment entrance needing to build sufficient momentum to overcome the raised Ocean level. It is clear that what ever the cause, any projected rise in Ocean level will adversely impact the full range of inundation events.

Call it what you will:- “Climate Change”, “Global Warming”, or a more fundamentally correct description “ Atmospheric Energizing”; what is clear is that more than likely storm events will be more energized, more violent, more extreme and likely more frequent. It is well known and documented that human activities produce enormous amounts of heat that not only raise temperatures but also significantly increase rainfall intensity (Barry and Chorley 1968). St Louis, London and Bombay have all had measured increases in rainfall (up to 30%) due to the energizing effect. What was once a phenomenon at a local scale (cities) is now occurring on a global scale (climate change). This outcome will lead to more extreme rainfall intensities and storm volumes, and more extreme winds leading to larger waves and higher storm surges. This will result in more frequent and extreme inundation events in rivers and along coastlines that will cause havoc to human activities and infrastructure.

Although without radical changes to current human activity, there is nothing humanity can do to alleviate the impact; there are things that can be done to ensure humanity can prepare itself by better understanding and predicting the extent of the impact. The focus of this paper is the recent provision of a FREE and OPEN SOURCE 2D-Hydrodynamic Finite Volume shallow water wave equation solver called ANUGA:- and how its application to modeling highlights its ability to easily add or adapt code to specifically account for “Climate Change Impacts”.

Fig. 2. Tsunami approaching Coffs Harbour

Fig. 3. At 400 Seconds (Note Reflective Waves)

2.0 INCREASED RAINFALL INTENSITY and VOLUME:

Climate Change; Global Warming; are symptoms of the root cause:- more energy in a denser atmosphere, leading to a much more energized atmosphere, which by definition must become more extreme. This results in more frequent and intense rainfall events with greater volumes of water than ever before.

This will result in more extreme flooding conditions. (Similarly cold snaps and extreme wind events are likely to be worse. Whether droughts will become more extreme is still up for debate, as again by definition more energy in a global weather system will lead more frequent extreme changes rather than prolonged conditions.

Currently the Australian Industry Standard for determining rainfall intensities for design purposes (Australian Rainfall and Runoff Volume 2) is under review. There is little doubt that the resulting design intensities will be increased over those used in 1987. Thus there will be increased pressure to update the design rainfall data more frequently than has been done to date (23 years). It is likely that rainfall intensities will need to be updated every 10 years or so, and include a methodology to adopt increased intensities for the interim periods.

At every point when rainfall intensities for design purposes have been updated there will be a need to re-run flood model to update current flood studies, as well as complete flood studies for areas not previously modeled. In order to update every flood model in the country there needs to be a considerable increase in capacity to undertake this modeling.

Where can this additional capacity building for flood modeling occur?

3.0 Increased Wave Activity:

Similarly the resulting increases in energy (atmospheric energizing) {climate change} will lead to much higher winds sustained for longer periods of time, resulting in higher waves and greater wave setup on the coastline. These conditions will lead to more sustained and severe ocean inundation and wave attack of the coastline, estuaries and lower reaches of rivers. Raised ocean levels in conjunction with increased rainfall intensities will result in more widespread river break out and inundation. Further all of these impacts will result in more extreme erosion of these environs.

Current methodologies are extremely limiting in their ability to identify the hazard, and even the erosion potential.

4.0 Storm Surge:

In addition to wave climate and wave setup, more extreme low pressure cells will result in greater storm surge. This in addition to wave related activity will further increase inundation levels from ocean sources and the need to accurately determine the extent of impact and re-assess as necessary. This requires extensively greater capacity to model the impacts and hence the need to consider areas within which this capacity can be built.

5.0 Scour and Erosion:

It is clear that with more extreme conditions in the Ocean and more rainfall, issues such as beach erosion and the resulting scour or river entrances (and uncontrolled break out over dune systems) will become significantly more important to account for and predict.

6.0 Current Methodologies:

Traditional approaches to determining coastal hazard have focused on parametric equation driven methods such as S-Beach. For a time in Australia this was the favoured model with extensive funds being directed toward its further development. At the same time others like Trembanis et al (1998) and Pilkey (1994) both have severely criticised the S-Beach model for quite some time yet it is still heavily utilised, and Refer: http://www.jstor.org/pss/4300011

In light of the fact that there a few openly available alternatives, this criticism may be some what misdirected. However it clearly identifies the need to explore utilizing more fundamentally sound approaches.

The only other popular methodology relies on utilising historic air pictures to attempt to use past behaviour to predict future trends. This methodology is not at all related to underlying measurable and predictable parameters such as velocity, or focusing of energy. Very few current methodologies utilise predicted wave behaviour based on hydrodynamic analysis capturing waves and shocks. Further again very few link erosion to the resulting velocity pressure and energy fields. It is noted that currently the US army is working on a replacement for S-Beach called X-Beach, which is an unstructured grid finite volume, shallow water wave solver with an erosion routine.

In addition, increased rainfall intensities and rainfall volume will result in higher flood levels in rivers. Traditional approaches require the increased rainfall to be applied to catchment hydrologic models. The resulting predicted hydrographs are then used in 2D-Hydrodynamic models that predict the resulting flood behaviour including peak flood levels and ability to identify hazard. This is the most common approach, although several researchers have attempted to use rainfall directly on 2D computational domains. Some with success: (O'brien); some with less success (Clark 2008). Direct rainfall on the 2D computational grid is by far the most efficient methodology as only surface roughness parameters and rainfall losses are available for adjustment. The alternate method requires adjustment of parameters in the hydrologic model as well as adjustment of parameters in the hydraulic model. This at times can easily lead modelers down the path of multiple re-runs to fine tune parameters.

It is further noted that the Finite Volume approach appears more robust and accurate than either the Finite Difference or Finite Element approach (Valiani etal).

7.0 The ANUGA Approach:

In December 2006 The Australian National University and Geoscience Australia released to the public a Free (and open source) 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. The model has been validated against the 1993 tsunami on Okushiri Island off Japan. Further validations against hi resolution wave tank tests at the University of Queensland (Baldock 2006) confirm the accuracy and robustness of the finite volume implementation in ANUGA for handing wet/dry and sub/supercritical flow transitions.

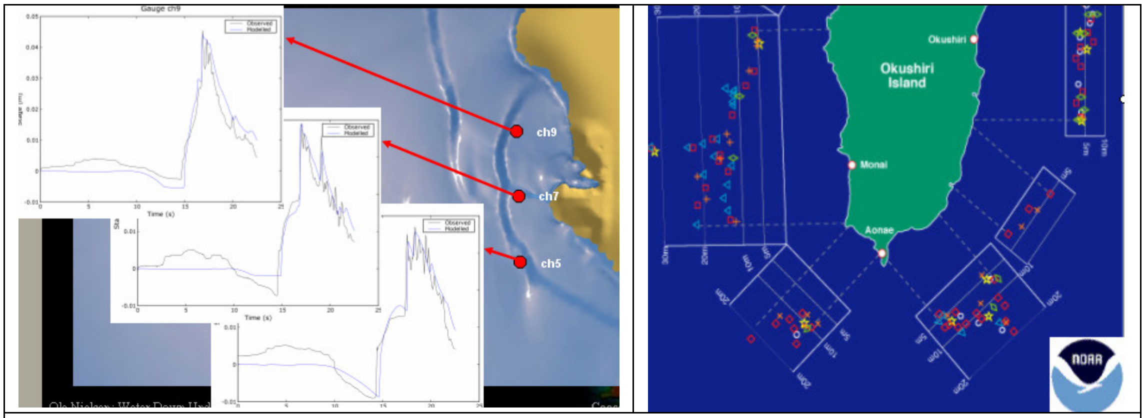

Figure 4. ANUGA:-Validated against Okushiri Tsunami run up

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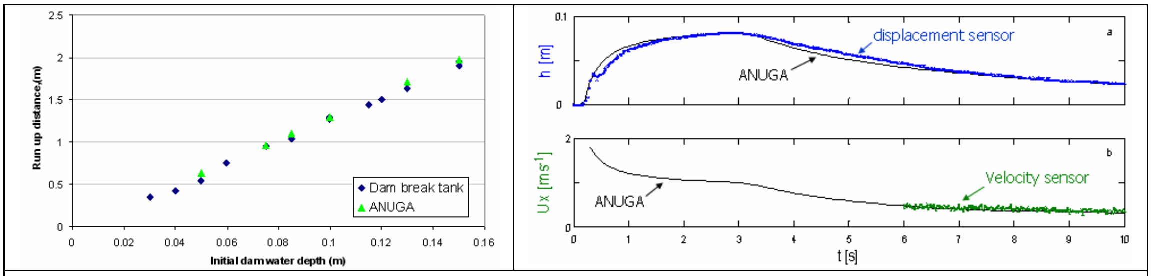

Figure 5. Wave Tank Validation of ANUGA by Baldock etal.

This being the case the model is therefore well adapted to providing a robust modeling solution to all forms general fluid flow based on the Shallow Water Wave Equation. Therefore it is capable of modeling, 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 (refer examples below). The original code is then able to be 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. 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 (X, Y), are determined. The size of the triangles may be varied within the mesh to allow greater resolution in regions of particular interest. An example may be the inclusion of bridge piers in models that include bridge crossings on flood plains.

Figure 6. Model of bridge crossing

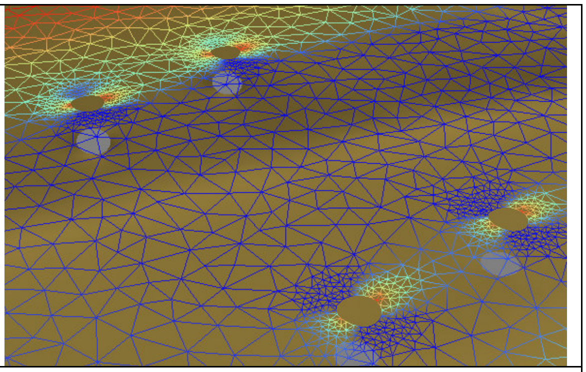

Figure 7. Refinement of the mesh allows the inclusion of the piers

ANUGA has the ability to model the impact of rainfall directly on the 2D-computational domain and/or to model inflow hydrographs derived by a hydrologic model such as WBNM (Boyd 1999, 2007) or as required a combination of both.

The underlying code in ANUGA was specifically developed to model a water reservoir bursting (Dam Break) on a hill in an urban environment and as such it has the ability to model:

- Fast Waves traveling down a hill
- Wave front traveling over dry land
- Shock waves resulting from obstacles (houses) being struck by dam break flood wave
- Multiple time varying transitions between sub and super critical flow.

This also therefore allows the accurate propagation of tsunami and other Ocean waves into inlets and bays for example.

8.0 Need for More Modelling:

It is difficult to plan for an incident, event or changing climate parameters if the impact is unknown. Apart from waiting for the impact to happen, the next best thing is to model the impact, in order to assess the best strategies to deal with the impact.

This can be done at present for riverine flooding by using Australian Rainfall and Runoff (1987), Bureau of Meteorology's Bulletin 53, the 1 in 100 year and Probable Maximal Floods are being modeled for most urban centres in Australia.

However it is understood that in 2008 only around 10% of the NSW had been flood mapped at a cost of around $100million (FMA Conference).
Therefore a large portion of NSW requires flood modeling based on current climate inputs. As climate parameters change the need for inundation modeling increases. Similar in the floodplains of the lower reaches of rivers, a rise in Ocean level will tend to increase the probability of uncontrolled break out. This will require a different approach to modeling to account for the formation of likely new connections to the Ocean.

In addition the likely need to link riverine flooding much closer to ocean impacts that lead to inundation event in the lower reaches of rivers changes the way in which most modeling has been undertaken to date. With these two influences it is much more likely that the occurrence of river break outs will become more prevalent. That is, with raised ocean conditions, and greater riverine flood flows, current river entrance geometries which at times are man made structures will be insufficient to pass the flood flow and result in new additional entrances forming.
A recent analysis of the Bellinger River showed that the entrance scour plays a critical role in flood events.

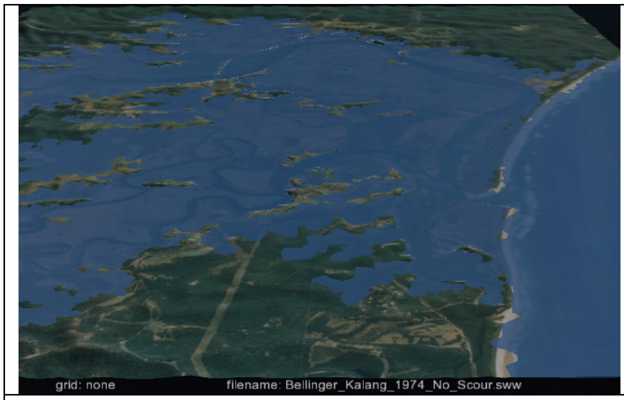

Figure 8. Bellinger River Flood Model (Entrance)

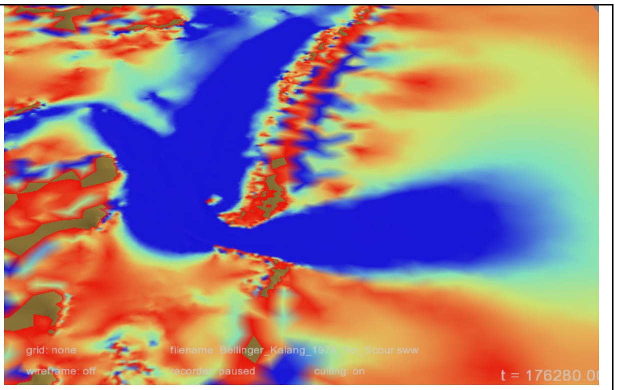

Figure 9. Momentum Plume at the Entrance

Therefore the need for much greater levels of both the extent and complexity of inundation modeling is inevitable.

In addition to needing to know the extent and location of inundation from various types of Ocean driven events, the plausible extent of damage, and vulnerability of various types of structures is equally critically important.

9.0 Determining HAZARD and Damage:

It is clear that more extreme events will result in more hazardous conditions and more damage. Currently methods to determine hazard have not evolved from the very earliest of concepts put forward some 40 years ago. Early work by Bonham (1967), Forster and Cox (1973), Gordon (1973), has not been updated. This was criticized by Cox (2004). Howells (2004) provides a good review, but no new approaches. Only Trieste (1988) and Van Drie (2008, 2010) have suggested serious alternates. This is to some extent justified by findings of Beffa (1998), Tennakoon (2004) and Pengyu (2007) specifically with the use of two dimensional flow models.
Current policy methods of identifying hazard are not keeping up with technological methods in our assessment tools. This is also the case in the determination of damage.
This was clearly identified by Dall'Osso etal. whom developed a method and prepared a report titled "A METHOD FOR ASSESSING THE VULNERABILITY OF BUILDINGS TO CATASTROPHIC (TSUNAMI) MARINE FLOODING" for the Sydney Coastal Councils Group in August 2009. However it is noted that the methodology described utilises only the static run up. The impact of the velocity of flow and resulting momentum is not accounted for in the methodology put forward.

Similarly Williams etal describe the CoFEE project (Coastal Flooding by Extreme Events) which although utilises ANUGA and accounts for momentum, this project does not have the same focus on building vulnerability, although does include aspects related to erosion potential.

These two projects clearly show that there is a growing need for hydrodynamic modeling linked to damage assessment and vulnerability.

It should be noted that ANUGA already has a “beta” damage modeling module which includes functions relating to Collapse_probabiltiy, and Damage_Cost.

The open source code in ANUGA enables any other user to build up on the code in these modules to add to the overall capability.

10.0 HOW TO PROVIDE THE MODELING REQUIRED:

Based on the performance to date, it is clear that the current approaches to providing hazard modeling and mapping will not be able to provide the relevant information in the time frame required (need it now). The current methodology is reliant to a great extent of the state authorities managing consultants on behalf of local government authorities. This has been the approach for at least 20 years. This approach is failing to provide the community with what is needed in identifying inundation hazard in a timely fashion. The resultant is that often relatively new housing developments are prone to inundation that should never have been subject to flooding.

It is clear that a considerable increase in capacity in terms of the ability to undertake inundation modeling is required. It is obvious that the Federal Government of Australia may have had that view also, when hading down a mandate to Geoscience Australia to “Build Capacity” (refer back to line 4 of ANUGA Approach above).

This being the case, now that there is the Free Software, it is necessary to produce software users. The obvious starting place for users of this Free software is Local Government, as they mostly already have the other vital requirements:-

- Access to terrain data (ALS and Contour Data)
- Access to computational Power (Council Server)

Local Government has the greatest need to identify the hazard resulting from inundation. It now has the means to undertake that task thanks to the provision of the ANUGA model.

Climate Change will only increase the need for more modeling (in addition to that needed now) and therefore obviously again highlight that local government is in a key pivotal role to undertake the required modeling.

To date Wollongong City Council and Shoalhaven City Council are utilising the ANUGA model, with Wollongong having modeled major catchments within the

City. Further currently several Councils on the Mid North Coast including Coffs Harbour, Kempsey and Port Macquarie are considering trialing the software. It is understood that Wingecarribee Shire Council is also reviewing the use of the model. It is noted that the state has warned that this may exempt these Councils from obtaining funding for models run in-house rather than by consultants.

11.0 CASE STUDY: ON APPROACH

Wollongong City Council has now been using ANUGA for nearly 3 years, and has found it invaluable for identifying problems with studies being done by consultants. Wollongong Council have been able to convince themselves that ANUGA is capable of better calibrations than that done by consulting firms. The initial calibration of the Towradgi Creek catchment shows that the ANUGA calibration far better replicates the recorded event (for almost the entire event duration) whilst the consultants calibration only matches the peak. This calibration was done at a time when ANUGA did not have bridge and culvert routines.

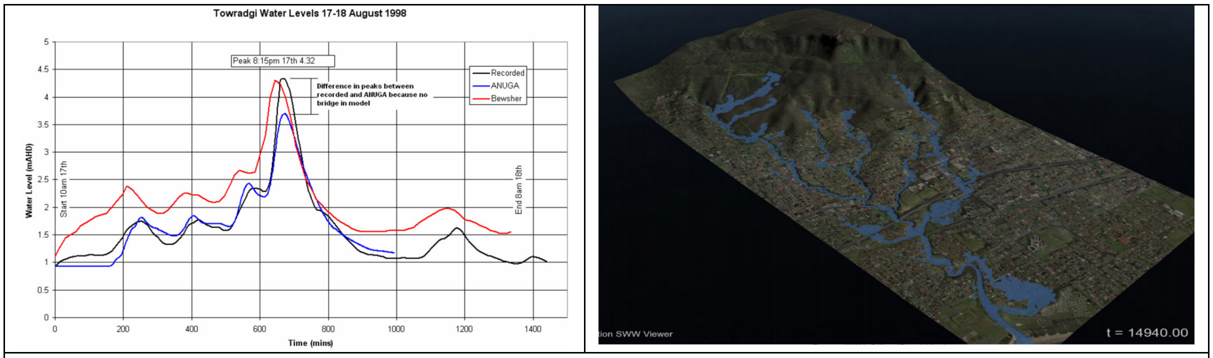

Figure 10. Comparison: ANUGA Vs Consultants calibration for Towradgi Creek Catchment

Further Wollongong City Council has used ANUGA to review a design report for the augmentation of a detention spillway with considerable consequences requiring significant redesign. The redesign was undertaken as guided by the ANUGA results.

12.0 Recent Code Adaptation (Culvert/Bridge Routines):

As mentioned the Python interface makes ANUGA readily open to adaptation to code changes. A recent example is the change from “Culvert forcing function” to “Culvert Operator.” Typically a culvert can operate under various conditions, Inlet Control, Outlet Control with or without appreciable up stream velocity. ANUGA now provides some of the most comprehensive methods of modeling bridges and culverts unlike many other models ANUGA can now accurately account for both the velocity head and momentum transfer through structures. This ensures the model accurately accounts for the momentum jet at culverts including the influence of hydraulic jumps at culvert outlets.

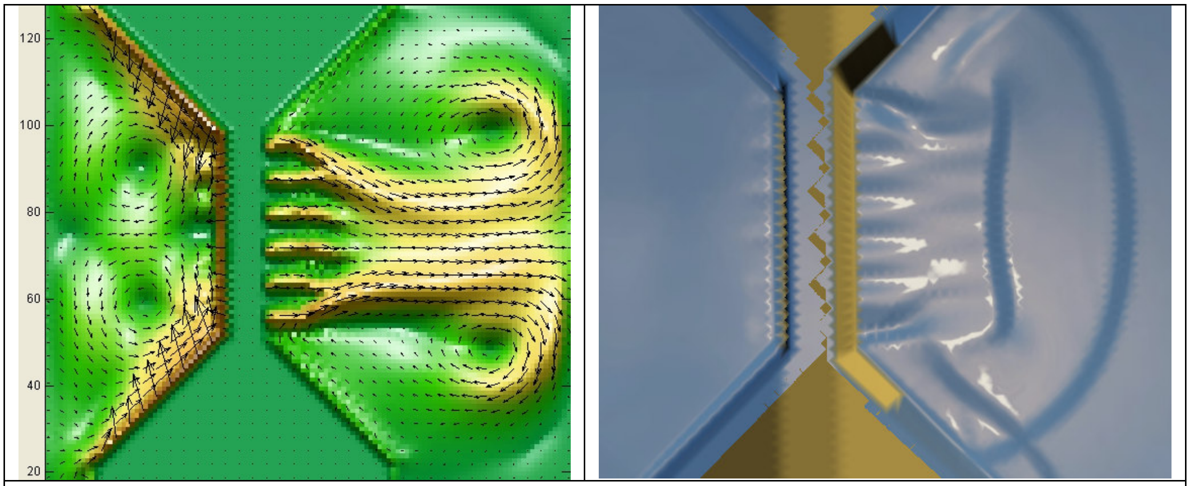

Figure 11. ANUGA plot of Momentum (VxD) and Stage (showing momentum jet and hydraulic jump at the culvert outlet of a 6 barrel culvert structure).

The Culvert routine extracts data from the model to drive the routine such as depth and velocity. In addition it calculates the internal culvert velocity which is used to assign the momentum leaving the culvert.

14.0 Ongoing Adaptation of the CODE (Adding Erosion Routines):

As ANUGA is written in this extremely flexible and user friendly language called "Python", it is envisaged that other users will soon add capability to the code. One obvious contender is erosion and deposition routines. ANUGA already has the ability to vary the terrain during an event simulation. Therefore it is possible to simulate the impact of erosion (or deposition). However currently there is no underlying code within the frame work that will allow this to occur based on well known available routines. However as these routines are added not only will ANUGA utilize them, ANUGA has the ability to add the necessary logic to create a hybrid of multiple methods that apply under certain conditions such as:

- 1: Meyer-Peter & Muller (1948),
- 2: Karim-Kennedy (1998),
- 3: Ackers-White (1975).
- 4: Yang (Sand),
- 5: Yang (Gravel),
- 6: Parker-Klingeman-Mclean (1982),
- 7: Van Rijn (1984a-c),
- 8: Engelund Hansen (1967).

Each of these erosion routines has a distinctive range of applicability. ANUGA could easily be adapted to allow any or all of these equations to apply based on conditions determined by the model. This would create an extremely robust flexible erosion model.

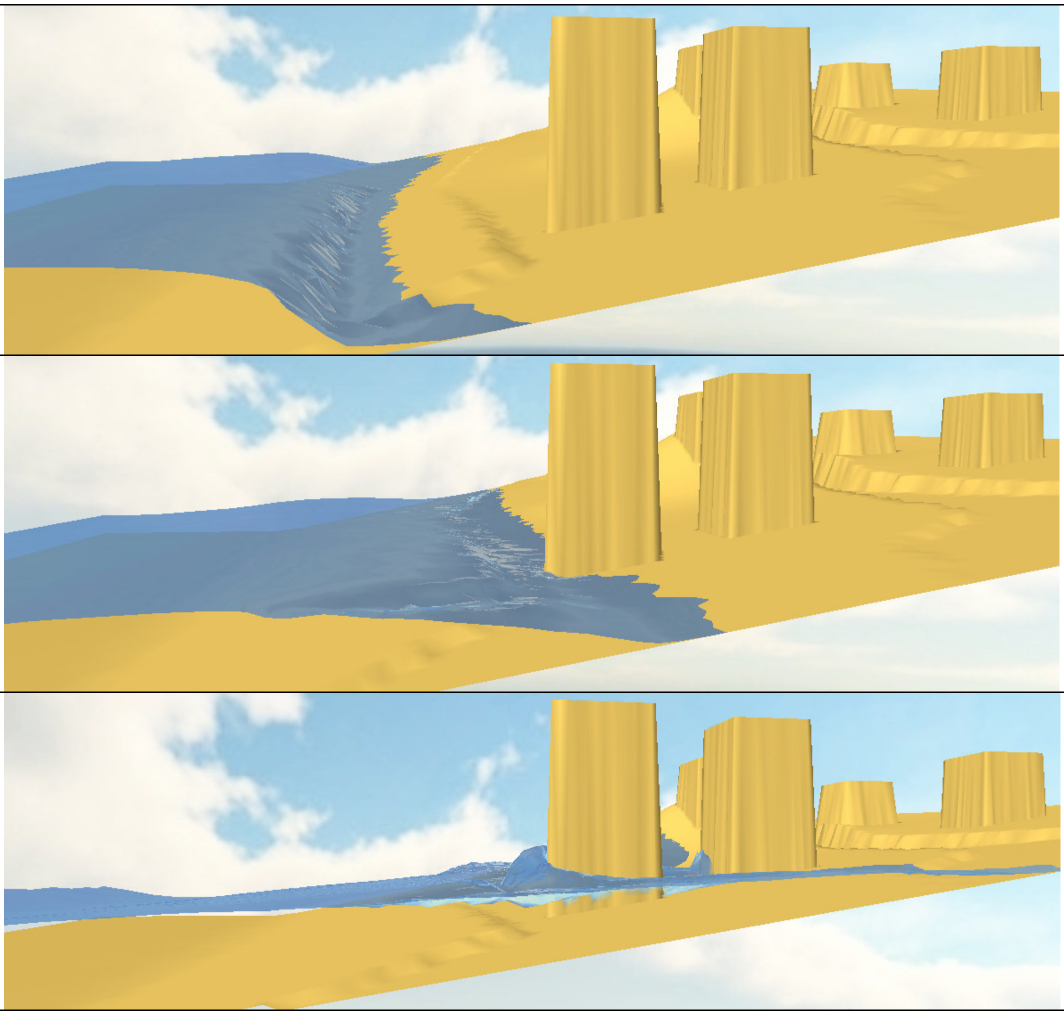

Figure 12. ANUGA example of Tsunami Striking the coast and buildings (an erosion routine would be invaluable for assessing coastal hazard.

12.0 Example Applications:

ANUGA has now been used on a very wide range of simulations from kitchen sinks to rainfall on entire complex catchments.

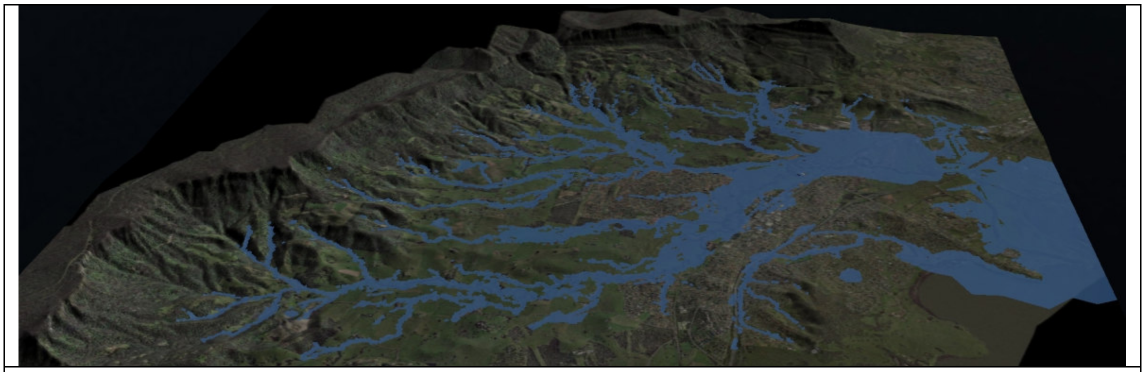

Figure 6. Complex River catchment

Geoscience Australia have used the ANUGA model to replicate the extremely rapid and forceful wave attack at Patong Beach during the Boxing Day Tsunami.

Figure 11. Patong Beach simulation of the Boxing day tsunami

Post tsunami survey and video footage have been used to validate the model. Eyewitness video footage has shown that this was one of the most extreme and forceful areas of wave attack. Refer video footage:
http://www.youtube.com/watch?v=IuUygn7BZis

ANUGA has proven itself to be robust accurate and flexible to an extremely diverse range of applications including hydrology, tsunami and detailed hydraulics.

13.0 SUMMARY:

Climate change brings with it the need to be able to rapidly assess and re-assess hazards due to inundation in River valleys and along the coast, as the unknown parameters of sea level rise and increased rainfall intensity start to solidify into a trend, it is likely that multiple re-assessments will need to occur. Current hazard modeling capacity will not be able to provide the level of modeling required. As such a new methodology is required.
This paper has identified a methodology whereby the custodians of vast amount of terrain data, also become the custodians of the models required to assess and re-assess hazard. This is seen as the most sensible, workable solution to "building capacity".

Not only is local government the custodian of data, it also has available formidable computing power in its servers, and with the release of the FREE 2D

hydrodynamic model ANUGA, access to software that is capable of providing unique insight into the level of hazard presented by climate change both in the riverine and ocean environs.
ANUGA has shown itself to be extremely robust; modelers with limited experience are capable of producing extremely high quality accurate results with limited guidance. The consequence of local government authorities not choosing to adopt undertaking climate change modeling in-house, will lead to either the modeling not being done in a timely manner, or not done at all due to prohibitive costs. The result will no doubt lead to the community not being properly informed of the extent of hazard that results from climate change impacts.

The further development of the ANUGA model is likely to include an erosion capability in the future. This is particularly true as its use grows, as due to its OPEN SOURCE nature, it is likely that additional capability will be added sooner rather than later. Figure 3 provides images of a tsunami striking a segment of coastline. With an underlying erosion routine the ANUGA model will be capable of showing the erosion impact, and possibly even damage to buildings and structures.

Erosion is seen as an even greater issue than flooding, as not only are fertile soils being washed away, but massive upland erosion, deposits vast quantities of material downstream, further restricting the lower stretches of rivers where our townships are located, thereby exacerbating the flooding problem.

14.0 RECOMMENDATIONS:

It is recommended that local government and those authorities seeking access to a methodology of rapidly assessing and re-assessing the extent and location of hazardous conditions due to inundation resulting from climate change impacts seriously consider adopting the methodology outlined in this paper using the ANUGA model.
Further it is recommended that with the uptake of the model, consideration be given to including erosion and deposition routines to the ANUGA model.
Note: It is understood there a plans to provide an online teaching forum for the both WBNM and ANUGA model, both of which are free to download and use.

15.0 Acknowledgment:

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