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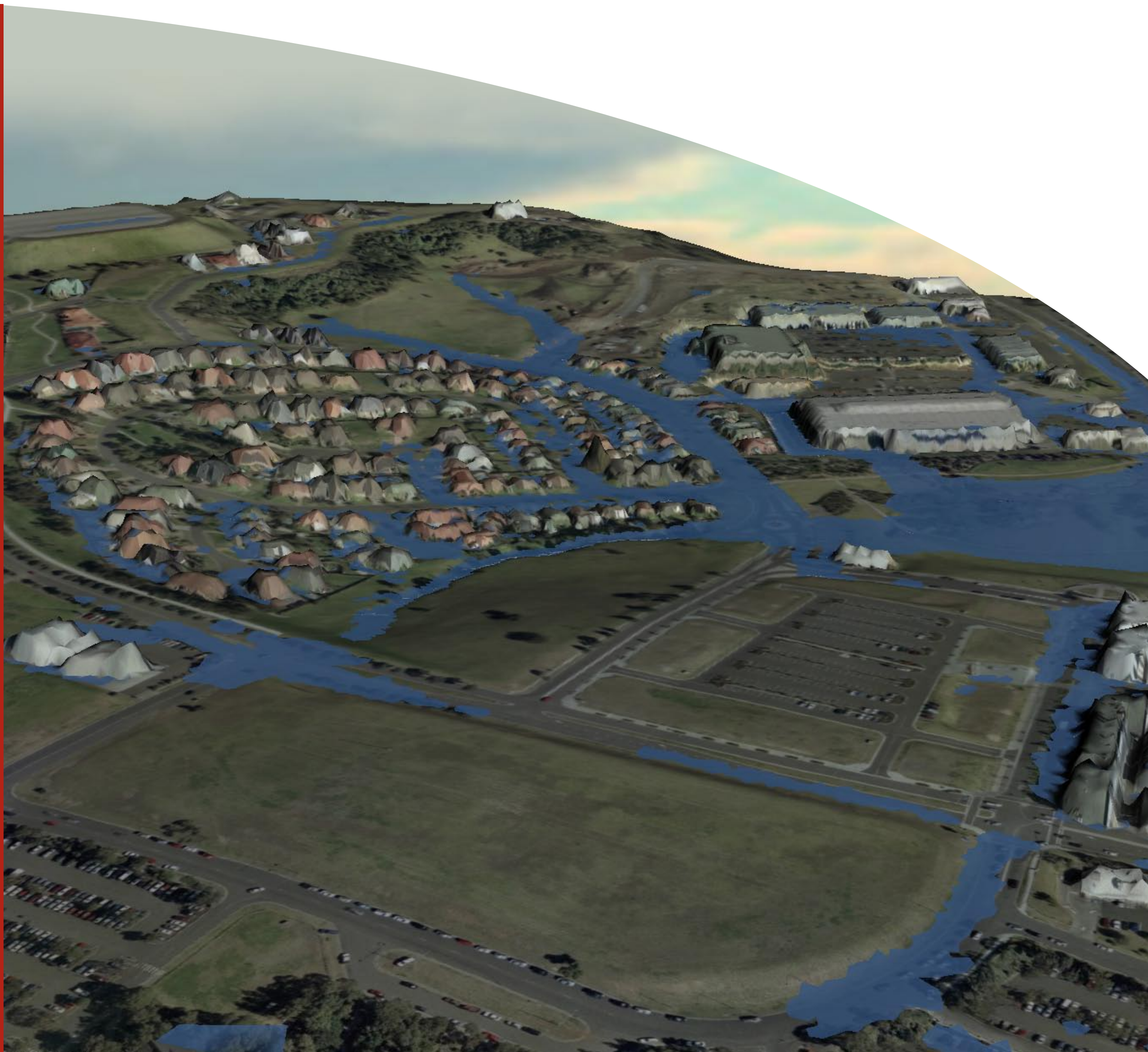

APPLYING GEOSCIENCE TO AUSTRALIA'S MOST IMPORTANT CHALLENGES

Investing in the development of an open source two-dimensional flood modelling capability

GEOSCIENCE AUSTRALIA
RECORD 2009/36

by

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Photo on front cover
Flooding of an urban area, modelled using ANUGA
Photo courtesy: Shellharbour City Council/Rudy Van Drie

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Executive Summary

Floods are Australia's most expensive natural hazard with annual average damages estimated at $377 million. Modelling flood hazard and potential flood impact is therefore an important first step in reducing the cost of floods to the community. The availability of a rigorously tested free software modelling tool for flooding would assist in meeting this objective. ANUGA is a collaborative effort of Geoscience Australia and the Australian National University and has gained increasing interest as an open source two-dimensional flood model. The development of ANUGA for flood modelling purposes has been guided and furthered through close consultation with a number of local government and consulting engineers.

This paper highlights case studies where ANUGA has been used for both hydrological and hydraulic modelling. This paper also makes two broad recommendations. The first recommendation is for further model validation against historical flood events. Additional model comparison is also needed, particularly against other two-dimensional models. ANUGA should also be validated against a suite of hydraulic tests to provide confidence in ANUGA's ability to be used as a general purpose hydraulic model.

The second broad recommendation is that the ANUGA software is further developed to make it comparable with other two-dimensional flood models. Priorities for this development include the ability to model structures (culverts, pipes and bridges), the addition of a kinematic viscosity term and the inclusion of discharge as an inflow boundary condition. The ability to incorporate variable bed elevation in models, account for water storage in buildings and consider spatially and depth varying Manning's friction 'n' are also important. The development of a graphical (geographical information systems) user interface would make ANUGA more accessible.

1. Background

Floods are the most expensive natural disaster in Australia, with the average annual cost of flooding from 1967 to 2005 estimated at $377 million[1]. Flooding and riverine processes can result in additional impacts such as erosion and deposition, however, the economic and environmental cost of such impacts is likely to be highly underestimated because of the difficulties in accounting for costs. Floods in Australia are predominately caused by heavy rainfall, with La Nina years experiencing more floods on average than El Nino years. Flooding in Australia generally falls into two broad categories, flash floods and riverine floods. Managing the risk posed by these floods on our communities is the responsibility of the Australian states and territories (hereafter referred to collectively as the Jurisdictions). Determining the area affected by floods through detailed inundation modelling is however generally undertaken at a local government level.

Local government often employs consultants to undertake flood studies. These studies typically use proprietary software which is too expensive for many councils and some consultants to obtain. The availability of appropriate open source software capable of modelling floods would enable local government to not only access the underlying software itself but to retain and adapt the models developed in-house as appropriate (e.g. to assess the impact of a proposed property development on water levels and flow direction).

With the loss of flood expertise in many councils and push towards contract management rather than in-house model development, not every local government has the inclination or expertise to competently develop and/or run a flood model. However, even where a council itself has no expertise in the open source software, a consultant with the expertise could be brought in to either develop a model, or to modify a model developed by another consultant, if the software and the files for the model were both retained by a council.

Such a situation would provide a higher degree of ownership and accountability by the local government, a situation much more difficult to obtain when proprietary software is used. Even among councils where the cost of obtaining such models is not prohibitive, the availability of a rigorously tested free software modelling tool would enable the release of resources for other priorities such as the collection of high resolution survey data needed for assessing flood risk.

Open source software also provides greater flexibility. Access to the underlying source code enables experienced users to adapt the code for their own projects. It can also result in more rapid software development, with users worldwide able to contribute and direct the codes development. A clear well defined process and stringent testing of new code can however be used to ensure that the core code remains robust. Further information on the organisational benefits of open source software, including reliability, stability, auditability, cost, flexibility and freedom, support and accountability may be found for example from http://open-source.gbdirect.co.uk/migration/benefit.html or http://opensource.org/.

The Australian Government through Geoscience Australia (GA) has collaborated with the Australian National University (ANU) to develop and validate an inundation modelling software tool called ANUGA. ANUGA is Free and Open Source Software (FOSS). The mathematical model behind

[1] Bureau of Infrastructure, Transport and Regional Economics (BITRE) analysis of the Emergency Management Australia database, Table 30, p. 44 in BITRE, 2008. About Australia's Regions, Department of Infrastructure, Transport, Regional Development and Local Government, Australian Government, Canberra.

ANUGA is suitable for modelling complex flows in shallow water involving hydraulic jumps (shock waves), rapidly changing flow regimes and flows into dry beds. The study area in an ANUGA model is represented by an unstructured triangular mesh. Further general information on ANUGA may be obtained from the ANUGA user manual freely available from http://datamining.anu.edu.au/anuga and the ANUGA software may be downloaded from http://sourceforge.net/projects/anuga.

ANUGA has been used by a number of Jurisdictions to model the impact of tsunamis on coastal communities. More recently, several local government and consulting engineers in NSW have demonstrated ANUGA's potential to be used as a tool for modelling riverine floods and flash flooding and have praised its capabilities as a robust, flexible and extensive flow model based on sound physical principles[2]. Further development and validation of ANUGA for two-dimensional flood modelling will provide the Jurisdictions and local government with an extremely stable, reliable and flexible open source two-dimensional tool for modelling flooding. Such a tool can then be used to support the development of systematic and rigorous disaster risk assessments, recommended by the Council of Australian Government's (COAG) review of natural disasters[3].

The remainder of this paper is divided into three sections. The first section highlights where ANUGA has been used to model flood hazard and discusses whether these results were validated against observed data and/or were compared against the results from previous models. The next section outlines high priority areas of development for ANUGA specific to modelling flooding. These priorities were identified through consultation with users and stakeholders at a workshop held in September 2008 at Geoscience Australia[4] and ranked through subsequent discussions. The final section discusses the recommendations made for the further development and application of ANUGA and summarises future plans.

2. Introduction and application of ANUGA to flood modelling

2.1. INTRODUCTION TO FLOOD MODELLING

Flood studies typically involve two key components; hydrological modelling followed by hydraulic modelling. Hydrologic models are used to simulate the complexities involved with rain falling on a catchment, including modelling potential losses (e.g. evaporation, infiltration), delays and paths of the rainfall. Hydrographs are produced which may be used as inputs to a hydraulic model. Hydraulic models simulate flow in channels and over the floodplain, producing information on water levels and velocities. Typically, rainfall-runoff models such as WBMN[5] or RORB[6] are used to undertake the hydrological modelling, while hydraulic models such as the one-dimensional model HEC-RAS[7] or

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[2] Rigby, E.H. & Van Drie, R., 2008. ANUGA – A new free and open source hydrodynamic model. Water Down Under 2008, 31st Hydrology and Water Resources Symposium and 4th International Conference on Water Resources and Environmental Research, April 2008, Adelaide.
[3] COAG, 2004. Natural Disasters in Australia. Reforming Mitigation, Relief and Recovery Arrangements. A report to the Council of Australian Governments by a high level officials' group, August 2002, Department of Transport and Regional Services, Canberra.
[4] For further information on the workshop including workshop objectives, the agenda and presentations go to http://datamining.anu.edu.au/anuga/wiki/SecondAnugaMeeting.
[5] Watershed Boundary Network Model (WBNM), developed by Boyd, Rigby and Van Drie, Australia.
[6] Developed by Monash University in collaboration with Sinclair Knight Merz, Australia.
[7] Hydrologic Engineering Centers River Analysis System (HEC-RAS), developed by the US Army Corps of Engineers.

quasi two-dimensional models such as MIKE 11[8] are used to simulate closed conduit flow (e.g. through pipes or culverts) and open channel flow (e.g. through creeks or open storm water drains). Other models are fully two-dimensional such as MIKE 21[9], TUFLOW[10], River2D[11] and Fst2dh[12]. The Manly Hydraulics Laboratory[13] provides an excellent background to flood modelling.

2.2. APPLICATION OF ANUGA TO FLOOD MODELLING

A summary of case studies where ANUGA models have been developed and the results compared against the results modelled with the aid of another software tool (e.g. WBMN, TUFLOW) is provided in Table 1.

Table 1: Case studies in NSW where ANUGA has been compared against other flood models.

SCALE	ANUGA STUDY	STUDY AUTHOR	COUNCIL AREA	MODEL COMPARISON
LOCALISED	Jacaranda[14]	Wollongong	Wollongong	WBMN, HEC-RAS
	Bong Bong[15]	Wollongong	Wollongong	WBMN
	Cheddar[16]	Balance	Eurobodalla	WBMN, River 2D
	Northcliff[17]	Balance	Wollongong	WBMN
SMALL	Kallaroo[18]	Balance	Shoalhaven	River 2D
	Hooka[19]	Wollongong	Wollongong	WBMN
MEDIUM	JJ Kelly[20]	Wollongong	Wollongong	WBMN
	Darragh[21]	Wollongong	Wollongong	MIKE 11, TUFLOW
	Eastwood[22]	Balance	Ryde	River 2D
	Macquarie Rivulet[23]	Rienco	Wollongong	WBMN, TUFLOW
LARGE	Towradgi[24]	Wollongong	Wollongong	RAFTS, MIKE 11, TUFLOW
	Mullet[25]	Wollongong	Wollongong	MIKE 11, TUFLOW

8 Developed by the Danish Hydraulic Institute.
9 Developed by the Danish Hydraulic Institute.
10 Developed by BMT WBM, Australia
11 Developed by the University of Alberta, Canada.
12 Developed by the United States Federal Highway Administration.
13 Manly Hydraulics Laboratory, 2006. Review and Assessment of Hydrologic/Hydraulic Flood Models. Report prepared for the New South Wales Department of Natural Resources, December 2006.
14 Wollongong City Council, 2009. 21 Jacaranda Avenue, Figtree, Wollongong.
15 Wollongong City Council, 2008. Bong Bong Road Detention Basin Study, Wollongong.
16 Balance Research & Development, 2009. Proposed Development at Cheddar Street, Moruya, Report to Eurobodalla Shire Council.
17 Balance Research & Development, 2008. Assessment of Flood Level at 318 Northcliffe Drive, Lake Heights, Project ID: 07J002.
18 Balance Research & Development, 2009. Kallaroo Road Flood Investigation, Eworal Bay, Shoalhaven City Council.
19 Wollongong City Council, in draft. Hooka Creek Catchment, Wollongong.
20 Wollongong City Council, in draft. Flood Modelling of the JJ Kelly Catchment in Wollongong City, Wollongong.
21 Wollongong City Council, in draft. Darragh Drive Flood Study, Wollongong.
22 Balance Research & Development, in draft. Model of Eastwood Central Business District related to a proposal to install a large Gross Pollutant Trap on the trunk drainage system. Report for Ryde Municipal Council.
23 Rigby, E., 2008. Macquarie Rivulet Floodplain Adjacent to Albion Park Airport, Rienco Consulting for Jordan Mealey Consulting Engineers.
24 Wollongong City Council, in draft. Towradgi Creek modelled with ANUGA, Wollongong.

The studies have been divided into four sub-categories based on scale of the area modelled. They include:

- Localised, for example, a flood study to test the impact of a proposed new development and roughly less than 1 km^2.
- Small, approximately covering an area of 1 to 20 km^2.
- Medium, approximately covering an area of 20 to 100 km^2.
- Large, approximately covering an area of 100 to 200 km^2.

The process of developing Table 1 was useful in identifying and prioritising locations for further pilot studies designed to test ANUGA's capabilities in a range of situations. For example, the process highlighted that at the time of writing, ANUGA had not yet been applied to a catchment where the hydraulic model exceeds 200 km^2. It also highlighted the need for validation of ANUGA models against historical data from at least two flood events.

The results modelled using ANUGA have been compared against both existing hydrological and hydraulic models. Direct rainfall was applied to the terrain in a number of studies and the hydrographs and/or water levels produced using the hydrological model WBNM were found to be comparable to those produced in ANUGA for a range of events at the sites in question. For example, both ANUGA and WBMN predicted the same flood levels at the downstream control (roadway culvert) at 318 Northcliffe Drive, Lake Heights, south of Wollongong, New South Wales where the impacts of flooding on a proposed unit development were being modelled[26]. In another example, a range of events were modelled in the JJ Kelly catchment in Wollongong City and hydrographs at the site which experienced flooding were compared to results modelled using WBNM, with a good resulting fit. The flood levels were then compared to two adopted flood studies in the catchment using WBMN and RAFTS[27] for the hydrology and HEC-RAS and EXTRAN[28] for the hydraulics, with similar results obtained[29].

The early results of ANUGA's performance as a hydraulic model are more mixed. Preliminary model validation for Towradgi Creek catchment in Wollongong, New South Wales, indicate a good fit with hydrograph shape and time to peak of recorded and modelled water levels at the reference location, though the volume in the ANUGA model is underestimated because of the absence of bridges in the model[30]. Results produced from an ANUGA model for Mullet Creek in Wollongong have compared very favourably to preliminary flood levels estimated by another study where the MIKE 11 and TUFLOW hydraulic models were used[31]. However, unsatisfactory results from model validation and comparison using the nearby catchment of Macquarie Rivulet have highlighted the need for further testing of ANUGA's performance against a suite of basic hydraulic tests before full confidence can be placed on its abilities as a general purpose hydraulic model[32].

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[25] Wollongong City Council, in draft. Mullet Creek modelled with ANUGA, Wollongong.
[26] Van Drie, R. Principal Engineer, Balance Research and Development, written communication, June 2009.
[27] Developed by Willing and Partners as WP Software, Australia.
[28] A module of SWMM, developed by Camp, Dresser and McKee, University of Florida, United States.
[29] Milevksi, P. Urban Drainage Engineer. Wollongong City Council, Wollongong, written communication, June 2009.
[30] Wollongong City Council, in draft. Towradgi Creek modelled with ANUGA, Wollongong.
[31] Milevksi, P. Urban Drainage Engineer. Wollongong City Council, Wollongong, written communication, June 2009.
[32] Rigby, E. 'Director'. Rienco Consulting, Wollongong, written communication, September 2009.

3. Further development of the ANUGA software

ANUGA's development as an open source two-dimensional flood modelling capability is continually evolving. The importance of open source software in government has been recently recognised by the Australian[33] and UK governments[34]. Worldwide the use of open source software is likely to increase[35], and at an even more rapid rate in developing countries because it provides a flexible cost effective alternative to the use of propriety software.

The requirements for the further development of ANUGA as a flood modelling tool were identified during an ANUGA workshop[4] in 2008. These requirements have been prioritised (Table 2) in consultation with three key ANUGA flood modellers including Rudy Van Drie (Balance Research and Development, formerly Shellharbour City Council), Petar Milevski (Wollongong City Council) and Ted Rigby (Rienco Consulting). More information on the development required of these additional features for ANUGA is outlined below.

Table 2: Prioritised selected features required to improve the ANUGA software for modelling inundation.

FEATURE	SCALE	INTEREST	PRIORITY
Pipe network	Small to medium	Mainly urban	High
Culverts	Small to medium	Mainly urban	High
Bridges	All	Mainly urban	High
Addition of kinematic viscosity term	All	Urban/Rural	Medium-High
Inflow boundary condition	All	Urban/Rural	Medium-High
Variable bed elevation – Failure of structures	All	Mainly urban	Medium
Accounting for water storage in buildings	All	Urban	Medium
Graphical user interface	All	Urban/Rural	Medium
Spatially and depth varying 'n'	All	Urban/Rural	Medium
Variable bed elevation – Erosion and sediment transport routines user defined quantities	All	Urban/Rural	Medium-Low
Flood gates	All	Rural	Low
Pumps and storages	All	Rural	Low
Addition of a Coriolis term	All	Urban/Rural	Low

3.1. PIPE NETWORK

Underground urban stormwater drainage systems frequently carry a large portion of flow during small to moderate storm events, therefore the capacity of these systems should be considered when modelling urban flooding. In order to model the often complex piped networks that make up urban stormwater drainage systems it is necessary to also assess the inlet capacity of various configurations of street inlet pits. There are many configurations which each have their own sets of performance envelopes depending on circumstance. Two specific examples include inlets at low points or sags, or whether the inlets are on a grade.

[33] http://finance.gov.au/e-government/infrastructure/open-source-software.html.
[34] http://cabinetoffice.gov.uk/government_it/open_source.aspx.
[35] See for example the annual Northbridge survey (http://slideshare.net/bhouse/2009-nbvp-future-of-open-source-results?type=powerpoint); the results from a 2007 Australian Government review of the use of open source software in Australia (http://finance.gov.au/e-government/infrastructure/open-source-software.html) or the UK report by Peeling, N. and Satchell, J. 2001. Analysis of the Impact of Open Source Software, Report by QinetiQ commissioned by the UK Government, UK.

Long culverts such as pipe networks draining a city require more complex modelling taking time lags and flow dynamics into account. This work would require the adaptation of a one-dimensional unsteady flow model for pipes. Such a model could probably use the current architecture for injection and abstraction of water.

In complex piped drainage systems, system surcharges may lead to localised flooding in locations that otherwise would not be subjected to the extent of flow. To model these aspects accurately, a detailed assessment of the dynamic internal pressure waves is required. The one-dimensional model must interact with the surface flow two-dimensional model to get a more accurate picture of flood behaviour.

3.2. CULVERTS

Culverts play an important role in diverting stream or rainfall-runoff from covered structures such as roads or railways. Therefore, they play a major role in urban flooding, particularly when they become blocked.

The current version of ANUGA has an architecture that allows a culvert routine to abstract and inject water into the ANUGA domain. Two variants exist but are still under development and have not yet been rigorously tested. One is the implementation of the United States (US) Department of Transportation's culvert equations as adapted by Dr Michael Boyd[36]. The other requires the design engineer to specify a rating curve for each culvert. The latter is not practical for large studies due to the amount of work required in setting up each culvert rating curve.

The current culvert modelling method in ANUGA is applicable only for very short culverts because it is unrealistic to assume that flow entering a long culvert will appear at the outlet of that culvert instantaneously. Therefore, a method to include a lag in the flow through the culvert is required. Many culvert flow estimating routines exist. Therefore, it is proposed that industry standard approaches be added to the ANUGA suite such as the HEC-RAS culvert models[37] and Bodhaine culvert methods[38].

3.3. BRIDGES

Modelling bridges are important where there is a substantial fall in the flood surface through the contraction or obstruction of the channel (i.e. afflux). A bridge structure is different to a culvert structure as it has internal structures that result in energy losses that influence the total afflux of the water surface through the structure. In addition bridges are always hydraulically short relative to their waterway flow width.

There are two methods of analysing the flow around bridges. The first approach is to assume the bridge acts as a culvert, with an additional energy loss applied to account for the additional internal losses. The second and more accurate approach is to model two-dimensional and open channel flows up to the bridge obvert, switching to a pressurised algorithm when the flows exceeds this level and becomes pressurised. This requires ANUGA to have the ability to switch between open channel state

[36] The generalised US Department of Transportation method is based on extensive physical model testing undertaken in the 1960's. These were developed into nomographs and later Boyd converted them to a generalised set of equations.

[37] US Army Corps of Engineers, 2008. HEC-RAS River Analysis System Hydraulic Reference Manual, Version 4.0, March 2008, Davis, CA.

[38] Bodhaine, G.L., 1968. Measurement of peak discharges at culverts by indirect methods: U.S. Geological Survey Techniques of Water-Resources Investigations, Book 3, Chapter A3, 60 pp.

and pressurised state. Above this level, flow will eventually overtop the deck, leading to a combination of pressure flow through, and weir flow over the bridge deck.

3.4. INCLUSION OF A KINEMATIC VISCOSITY TERM IN FORMULATION

Unlike the majority of two-dimensional flood models, the effects of kinematic viscosity are not considered in ANUGA. Kinematic viscosity is important in situations where turbulence may influence flow behaviour. The internal lateral shear stresses caused by turbulence or high velocity gradients impact on the flow patterns especially in forming flow separation patterns and increasing losses. By not including these impacts it is likely that the model will underestimate flood levels.

3.5. INFLOW BOUNDARY CONDITION

The inflow boundary conditions describe the physical flow conditions at the boundaries of the simulation region. Although inflow can be provided dynamically as a stage[39] height (m) at an ANUGA boundary, it is not currently possible to apply inflow directly in terms of a discharge (m^3/s) at defined upstream boundary condition locations as with most other models.

Most models use a string segment on the outer model boundary to define where flow will cross into the model domain. This requires iteratively using Manning's formula to estimate the flow depth based on flow rate, inward slope and friction at each time step. At the time of writing, hydrographs are applied as internal forcing functions essentially modelling water falling onto a small area within the domain. In order to better represent real world behaviour, ANUGA needs to provide this capability.

3.6. VARIABLE BED ELEVATION – FAILURE OF STRUCTURES

Modelling the potential failure of structures is vital on urban floodplains because of the impact not only of floodwaters on that structure, but also the resulting impact of debris on structures downstream of the failed structure.

Directly modelling the failure of structures such as dams, levees and buildings is possible by manipulating the underlying bed elevation data. While ANUGA allows for bed elevation to change dynamically during the course of a simulation, there is currently no framework for relating momentum and depth to forces that may cause buildings to fail.

3.7. ACCOUNTING FOR WATER STORAGE IN BUILDINGS

Buildings in dense urban areas can provide a significant sink for flood waters. Therefore, ignoring the ability of buildings to store floodwaters by modelling them as solid objects may overestimate flood height. Conversely, ignoring the physical presence of buildings in densely urbanised floodplains may underestimate flood height by not taking into account the effect of water displacement from these buildings.

Buildings can be represented in a number of ways in ANUGA, including:

1. As part of the mesh with building boundaries represented as reflective boundary conditions. This approach amounts to buildings of infinite height and with impenetrable walls.
2. As part of the elevation model.
3. By assigning artificially high roughness values to areas occupied by buildings.

Approaches 1 and 2 assume that the buildings are solid and therefore don't take water storage into account. Approach 3 aims at balancing the water storage with flow diversion around buildings. The

[39] Stage is equivalent to 'water level' and is measured relative to a specified datum.

merits of each of these approaches are being debated and would largely depend on the purpose of the model. In order to account for water storage in buildings using approach 2, buildings could be assigned a porosity to simulate the filling and emptying of water from a building during a flood.

3.8. GRAPHICAL (GEOGRAPHICAL INFORMATION SYSTEMS) USER INTERFACE

ANUGA is currently operated through Python scripts. While this has the advantages of users being able to manipulate the code to suit their own requirements, it does make the software more difficult to use for those not experienced in using Python and/or programming. The development of a geographical information systems (GIS) based graphical front end would greatly facilitate the process of setting up the computational domain, the boundary and elevation data in ANUGA. The GIS interface would also facilitate analysis and visualisation of model output and allow the results of model diagnostics to be viewed. For example, it would enable the modeller to easily identify and remove small thin triangles which may cause instabilities in the model. It could also be used to confirm visually that boundary conditions are being applied where intended together with many other outputs typically found in the check outputs of other models. The GIS interface would also permit viewing the results in a spatial context in much more detail than is presently possible with the current application.

Work is currently underway by Rienco Consulting to permit ANUGA to read in and build a model from GIS files prepared for the TUFLOW hydraulic model. TUFLOW is the most popular two-dimensional hydraulic model in current use in Australia. By adopting the GIS structure used by TUFLOW, models built for TUFLOW can then be run by ANUGA, providing both an inexpensive check model for TUFLOW and an ability for end users (without TUFLOW) to be able to reproduce or consider the impacts of changes to previously constructed TUFLOW models.

While several options exist for the construction of such an interface, the use of Python as the language of choice for both ANUGA and the FOSS GIS product QGIS[40] makes construction of the interface in QGIS very attractive. Some early code has been developed in QGIS to explore the practicality of such an interface[41].

3.9. SPATIAL AND DEPTH VARYING 'N'

All state-of-the-art flood models recognise the substantial change in losses that occur as flow becomes shallow (relative to the local roughness height). A facility to define different areas of roughness and to temporally vary roughness with local depth as the simulation proceeds is needed for ANUGA to be a credible flood model. Initial code has been developed by Rienco Consulting and is in use but needs to be optimised for integration in ANUGA.

3.10. VARIABLE BED ELEVATION – EROSION AND SEDIMENT TRANSPORT ROUTINES

Soil erosion and sediment transport can result in damage to river banks and the deposition of tons of sediment in the lower reaches of the river system. This can lead to a loss of waterway area, which can then raise the flood level during the next flood event (e.g. during the 2009 NSW North Coast flood event).

In order for ANUGA to model erosion and sediment transport, three key components are required. These include incorporation of i) a variable bed elevation to account for the removal and deposition of matter, ii) a set of new quantities reflecting sediment concentration and density, and iii) a

[40] Begun by Gary Sherman, QGIS is also known as Quantum GIS and is open source software.
[41] See, for example, http://sourceforge.net/projects/anuga-gai.

mathematical model that relates how much sediment is going into, or out of suspension as a function of the local velocity field.

3.11. FLOOD GATES

Manual or automated gates are a significant control in many of our river systems, particularly those in rural areas. If ANUGA is to have general use in flood modelling, it will be necessary to incorporate gates into the suite of structures accommodated. This feature could, for example, be implemented by using variable bed elevation to model the gate action.

3.12. PUMPS AND STORAGES

Like flood gates, pumps and storages can be a critical control in regard to flooding in stream reaches downstream of such structures. They also need to be simulated if rural flooding is to be fully accommodated.

3.13. INCLUSION OF A CORIOLIS TERM

The inclusion of the Coriolis term is important in areas where a lot of sediment is carried in the floodwaters. This is because sediment will only deposit on the floodplain when the velocity term is reduced. The inclusion of a Coriolis term may be significant in determining the direction of subtle vortices and therefore be important for correctly describing depositional behaviour. While potentially a factor in larger and deeper embayments/lakes, this is not normally considered in shallow overland flooding where surface gradient and bed friction dominate behaviour.

4. Recommendations

The recommendations on investing in the development of an open source two-dimensional flood modelling capability fall into two broad categories. They include:

1. Further model validation and model comparison.
2. Further development of the ANUGA software.

4.1. DISCUSSION OF THE RECOMMENDATIONS

The fundamental hydrodynamic behaviour of ANUGA has been validated against complex wave tank experiments[42] and ANUGA has been validated against field data as a tsunami inundation model[43]. However, ANUGA has yet to be rigorously validated against historical flood events.

The first broad recommendation relates to testing ANUGA's capabilities in a range of situations. ANUGA's performance should be validated against a suite of basic hydraulic tests and the results published. Such tests could include, for example, steady flow i) down a plane, ii) down a vee channel, iii) through a smooth constriction, iv) through a hydraulic jump, v) over a weir and vi) through a culvert[44]. The development of these tests of problems with known hydraulic solutions and validation of ANUGA against them; will identify any problems in the underlying code not identified

[42] Nielsen, O., Roberts, S., Gray, D., McPherson, A. and Hitchman, A. 2005. Hydrodynamic modelling of coastal inundation. MODSIM 2005 International Congress of Modelling and Simulation, Modelling and Simulation Society of Australia and New Zealand, 518-523.
[43] Jakeman, J.D., Nielsen, O., Van Putten, K., Mleczko, R., Burbidge, D., and Horspool, N. in draft. Benchmarking Tsunami Models using the December 2004 Indian Ocean Tsunami and its Impact at Patong City, Thailand.
[44] Rigby, E. 2009. 'Director', Rienco Consulting, Wollongong, written communication, September 2009.

in validation work to date and assist in finding solutions to those problems, providing increased confidence in ANUGA's ability as a general purpose hydraulic model.

Model validation against historical flood events is needed both where direct rainfall is applied to the catchment and where hydrographs are input from another rainfall-runoff model. Further model comparison is also needed, particularly against other two-dimensional flood models.

While validation and model comparison is worthwhile at all scales, it is essential for areas where no model comparison has currently been attempted. This includes catchments where the hydraulic model exceeds an area of 200 km^2, and at very localised scales, for example, around a structure such as a bridge or culvert and roughly less than 0.01 km^2.

The second broad recommendation relates to the development of additional targeted functionality to make ANUGA at least comparable to existing proprietary two-dimensional software used for modelling floods. A prioritised summary of these features is shown in Table 3.

Table 3: Prioritised features for improving the ANUGA software for flood modelling.

PRIORITY	FEATURE
High	Pipe network
	Culverts
	Bridges
Medium-high	Addition of kinematic viscosity term
	Inflow boundary condition
Medium	Variable bed elevation – Failure of structures
	Accounting for water storage in buildings
	Graphical user interface
	Spatially and depth varying 'n'
Medium-low	Variable bed elevation – Erosion and sediment transport routines user defined quantities
Low	Variable bed elevation - Flood gates
	Pumps and storages
	Addition of a Coriolis term

4.2. FUTURE PLANS

The Australian Government through Geoscience Australia has entered into a collaborative research agreement with the Australian National University to further enhance the capabilities of ANUGA, in particular through the inclusion of one-dimensional pipe flows and kinematic eddy viscosity. The agreement will also scope the upgrading of the parallel code in ANUGA to take account of flows through pipes and culverts. While ANUGA has the capability to execute on multiple processors allowing faster overall run time, the current parallel implementation cannot take culvert and pipe network models into account. The upgrading of ANUGA's parallel code will allow models that incorporate such structures to execute in parallel, reducing their run speeds. This is critical for future projects, particularly those dealing with climate change as they tend to require large computational resources. Geoscience Australia has also identified resources for validating the results produced using ANUGA with historical data and other software models for a catchment where the hydraulic model is in excess of 200 km^2.

The present and emerging ANUGA user community will continue to drive the further development of ANUGA. For example, through identifying and suggesting bug fixes, suggesting enhancements and making changes to the source code. Once rigorously tested, the changes made by the user community can be incorporated into the main code. The user community will also continue to play an instrumental role in model validation and model comparison and is driving a critical review of ANUGA's ability to replicate hydraulic solutions, with a paper on that topic scoped[45].

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[45] Rigby, E. 2009. 'Director'. Rienco Consulting, Wollongong, written communication, September 2009.