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A prominent characteristic of streams draining catchments in West Dapto, New South Wales, are well developed macrochannels that have formed within alluvial terraces in mid-catchment zones. A detailed hydraulic modelling study using HEC-RAS, HEC-GeoRAS and Arcview GIS indicates that these macrochannels are scaled to accommodate high magnitude floods. They offer a significant degree of natural protection from flood events up to and in excess of 100 years recurrence interval, essentially by operating as 'bankfull' channels during such events. Macrochannel landforms can be clearly distinguished and mapped on fine-scale digital elevation models (DEMs) and other GIS data sources such as rectified aerial photography, offering the opportunity to integrate analyses of fluvial landforms and channel processes into hydraulic modelling studies, and ultimately, flood-risk avoidance strategies. Such an approach has the potential to improve on traditional flood risk avoidance methods that are focussed primarily on design-flood heights by enabling the interpretation of hydraulic modelling outputs in the context of fluvial landforms that exert a significant control on flood behaviour.

Keywords

Macrochannels, their, significance, for, flood, risk, minimisation, West, Dapto, South, Wales, GeoQUEST

Disciplines

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Macrochannels and their Significance for Flood-Risk Minimisation, West Dapto, New South Wales

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Abstract

A prominent characteristic of streams draining catchments in West Dapto, New South Wales, are well developed macrochannels that have formed within alluvial terraces in mid-catchment zones. A detailed hydraulic modelling study using HEC-RAS, HEC-GeoRAS and Arcview GIS indicates that these macrochannels are scaled to accommodate high magnitude floods. They offer a significant degree of natural protection from flood events up to and in excess of 100 years recurrence interval, essentially by operating as 'bankfull' channels during such events. Macrochannel landforms can be clearly distinguished and mapped on fine-scale digital elevation models (DEMs) and other GIS data sources such as rectified aerial photography, offering the opportunity to integrate analyses of fluvial landforms and channel processes into hydraulic modelling studies, and ultimately, flood-risk avoidance strategies. Such an approach has the potential to improve on traditional flood risk avoidance methods that are focussed primarily on design-flood heights by enabling the interpretation of hydraulic modelling outputs in the context of fluvial landforms that exert a significant control on flood behaviour.

Introduction

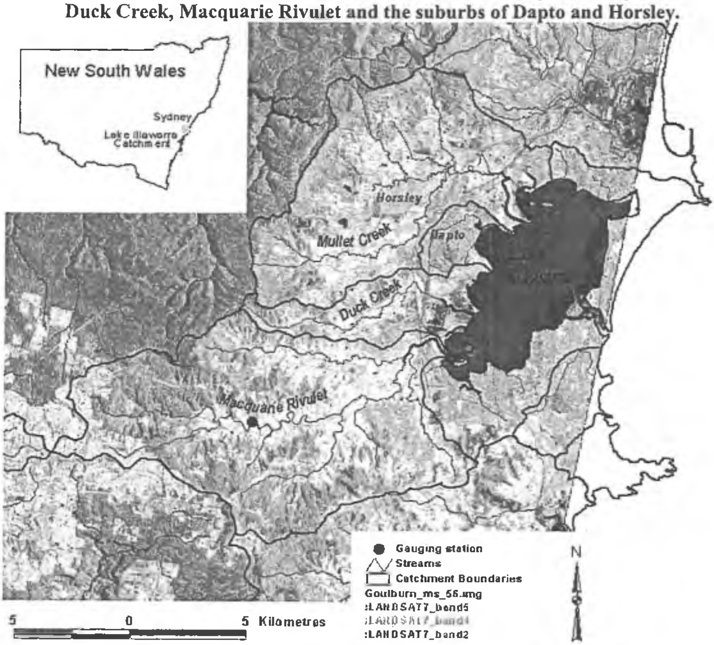
The Illawarra region of New South Wales is prone to a high frequency of intense rainfall and damaging flood events. On the basis of the spatial distribution of rainfall recurrence interval isolines, Nanson and Hean (1985) proposed that the greater Wollongong area could expect a 100 year flood event once every 20-25 years. In a summary of previous studies of historical flood events, Reinfelds and Nanson (2001) suggested that the frequency of 'flood disasters' across the greater Wollongong area was even more frequent at approximately 1 in 8 years. This remarkable hazard susceptibility for a densely populated coastal region was attributed to a combination of geographical factors which include small, steep and highly runoff-responsive catchments draining a coastal escarpment that rises to an elevation of approximately 600 m within 10 km of the sea. The most recent 'flood disaster' occurred in August 1998 when over 1000 dwellings were flooded with total damages estimated at $75 million (Reinfelds and Nanson, 2001).

R.J. Morrison, S. Quin and E.A. Bryant (Editors) (2005). Planning for Natural Hazards – How Can We Mitigate the Impacts? GeoQuEST Research Centre, University of Wollongong.

The solution to flood risk for many hydraulic engineers is considered a standard engineering task in which a design discharge is selected and an appropriate water surface level calculated. Major landform modifications and flood control structures are then employed to modify flood levels up to a specific design level (Plate, 2002). However this 'control' of high magnitude flood events can lead to the destruction of natural cycles for aquatic and riparian ecosystems and the loss of the natural geomorphology of streams (Hickey and Salas, 1995). In addition, the success of engineering structures, landform modifications and engineering designs are never assured (Plate, 2002). Streams are dynamic systems and assumptions on which the original engineering designs are based can change over 50-100 year time scales in such a way as to affect their ongoing design performance (Reinfelds and Nanson, 2004). This can be particularly hazardous for areas where high magnitude floods are frequent occurrences. In the Wollongong area, there are numerous examples of older engineering designs that facilitated encroachment on streams, which in hindsight, have turned out to be inadequate in providing an appropriate level of flood risk protection (Reinfelds and Nanson, 2001; Older, 2001; Peterson, 2002).

There are some 10,000-20,000 new dwellings planned for development over the coming decade for the Lake Illawarra catchment (Reinfelds and Nanson, 2004), a figure that will double to triple the size of the existing urban footprint within the catchment (Figure 1).

Figure 1: Location map based on November 2002 Landsat image showing Mullet Creek, Duck Creek, Macquarie Rivulet and the suburbs of Dapto and Horsley.



The Lake Illawarra catchment includes a number of significant streams subject to one of the largest historical flood events to have occurred in the Illawarra region; the February 1984 flood event (Nanson and Hean, 1985). A detailed set of aerial photography (1:8000 scale) commissioned to record the effects of the 1984 event on stream channels were not fully utilised by earlier studies (Nanson and Hean, 1985; PWD, 1985; Webb McKeown, 1997; Grootemaat, 2000) but can potentially provide a significant benefit to land use planning for flood hazard avoidance in that area. This detailed set of aerial photography and the availability of high resolution digital elevation models (DEM's) and other Geographic Information System (GIS) data sets, together with the recent integration of Arcview GIS and HEC-RAS hydraulic modelling software, provides an opportunity to undertake an integrated and detailed GIS based assessment of interactions between fluvial landforms and flood hydraulics. The aim of this paper, therefore, is to:

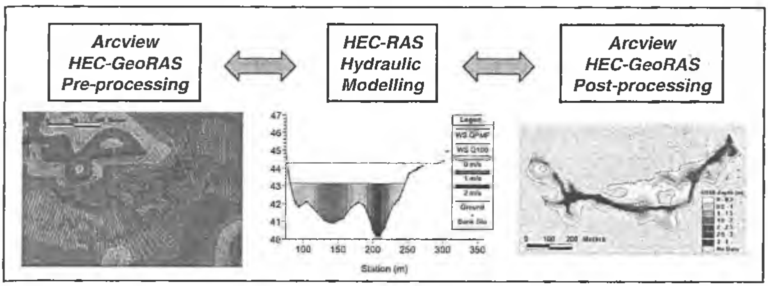
i. improve our understanding of fluvial systems in the West Dapto area, particularly the hydraulic operation of stream channels and their floodplain systems; and
ii. to discuss the benefits of integrated GIS based assessments of fluvial landforms and flood hydraulics for improving flood risk avoidance strategies and environmental outcomes for urbanising streams.

Methods

Arcview, HEC-GeoRAS and HEC-RAS hydraulic modelling

There are three major components to developing a hydraulic model using the integrated combination of Arcview, HEC-GeosRAS and HEC-RAS (Brunner, 2002a). First, pre-processing of digital terrain models is undertaken in Arcview using the HEC-GeoRAS pre-processing functions (Figure 2). Second, a hydraulic model is developed using standard HEC-RAS procedures from the HEC-GeoRAS pre-processed data (Figure 2). Third, floodplain wetted area polygons, velocity grids and depth grids are generated from HEC-RAS model outputs using the HEC-GeoRAS post-processing functions in Arcview and then integrated with other GIS data sets for analysis and presentation (Figure 2).

Figure 2: Relationships between HEC-GeoRAS, HEC-RAS and Arcview showing TIN model with cross-section layout in Arcview HEC-GeoRAS, modelled water surface profiles at a cross-section in HEC-RAS and example of grid output of inundation depth for 100 year ARI event in Arcview HEC-GeoRAS.



HEC-GeoRAS preprocessing for HEC-RAS

A Triangulated Irregular Network (TIN) data set with a z-value (elevation) tolerance of 0.10 m covering Mullet Creek catchment was generated from the Land and Property Information (LPI) 5 m cell size Digital Elevation Model (DEM) using standard Arcview 3D Analyst procedures. The LPI 5 m cell size DEM from which the TIN model was created is based on 1970s two metre contour mapping. The TIN model generated from the LPI DEM had node and triangle densities of 5789 and 11577 per km^2. A total of 317 cross-sections over a 6.5 km stream length with an average downstream spacing of approximately 20 m were used to extract geometric data from the TIN model for import into HEC-RAS (Figure 3). The hydraulic model was divided at Cleveland Road so the bridge, which is not represented in the TIN model, could be excluded from the analysis (Figure 3).

Figure 3: Hydraulic model layout showing placement of 317 cross-section along 6.5 km of Mullet Creek used to extract geometric data from a TIN model for importing into HEC-RAS.

Manning's n values of 0.05, 0.10 and 0.15 were modelled to assess hydraulic behaviour under current (pasture dominated floodplains and channels with relatively little riparian vegetation n=0.05), past (pre-European rainforest dominated floodplain and channel n=0.10) and possible future floodplain and channel conditions (dense regenerating riparian vegetation and/or weed invasion due to reduced grazing pressure n=0.15). A Manning's n of 0.15 represents a high to maximum for channels with very weedy reaches, deep pools or floodways, with heavy stands of timber and brush and a normal value for floodplains with dense willows in summer (Arcement and Schneider, 1989; Brunner, 2002b, his Table 3.1, p. 3-13), and thus represents a possible 'worst case' scenario.

HEC-RAS hydraulic modelling

HEC-RAS is a free software program designed to perform one dimensional hydraulic analysis for steady and unsteady flow simulations (Brunner, 2002b). The program automatically uploads geometrical data (flow paths, cross-sections etc) embedded within an import file from HEC-GeoRAS pre-processing undertaken in Arcview GIS (Figure 2). Once the geometric data has been uploaded, standard procedures detailed in the HEC-RAS User Manual (Brunner, 2002a) are used to add further details to the geometric data (e.g. Manning's n values, ineffective flow areas, tributary junctions etc). In this study, all models were run in mixed flow regime mode to enable modelling of super and sub-critical flow zones, with the upstream boundary condition set to critical depth and the downstream boundary condition set to normal depth. Slope inputs for the normal depth boundary conditions were determined from 2 m contour data.

Once the hydraulic simulations have been performed and reviewed, a HEC-RAS export file is generated for import back into Arcview GIS through the HEC-GeoRAS extension. The HEC-RAS export file contains data enabling generation of detailed grid maps of inundation depth and velocity and polygons of inundation extent for each of the steady flow simulations (Figure 2).

Estimation of design discharges for HEC-RAS modelling

Design discharges for 10, 20, 50 and 100 year Average Recurrence Interval (ARI) events were determined by the Probabilistic Rational Method (PRM) as outlined in Australian Rainfall and Runoff (Pilgram, 1998). Maximum flood (Q_{max}) discharges were calculated according to the equation

$$Q_{max} = 139.71 * A^{-0.3236} \quad \text{(Equation 1)}$$

where Qmax has units of ($m^3s^{-1}km^{-2}$) and A is catchment area (km^2).

This equation was created by Reinfelds and Nanson (2004) by sub-settting catchment areas 2-1000 km^2 and fitting a least squares trendline to a data set of world maximum recorded rainfall runoff floods compiled by Costa (1987). Discharge estimates from this equation are commensurate with PMF estimates in published Wollongong area flood studies for streams draining the Illawarra escarpment (Bewsher Consulting, 2001; Wollongong City Council, 2002;).

Catchment areas for discharge estimation were determined to the nearest hectare from a flow accumulation grid developed using standard Arcview Spatial Analyst procedures. Design rainfall intensities were determined from Bureau of Meteorology rainfall Intensity Frequency Duration (IFD) diagrams presented by Evans and Bewick (2001) for pluviometers located on the Illawarra Escarpment.

Reality check on design discharge estimates

Table 1 provides design discharge estimates for six locations along Mullet Creek covering catchment areas of 1.95 km^2 to 24.8 km^2. Reinfelds and Nanson (2001) calculated flood frequency statistics for Macquarie Rivulet from a 50 year annual maximum flood record (the longest annual maximum flood record available for the Illawarra region). For the Macquarie Rivulet gauge which has a catchment area of 35 km^2, their 100 year ARI Log Pearson III flood frequency estimate returned a unit area discharge of 25.1 $m^3s^{-1}km^2$. This unit area discharge is similar to the 100 year ARI unit area discharge of 26.3 $m^3s^{-1}km^2$ at a catchment area of 24.8 km^2 for this study, thus lending confidence to the reliability of the discharge estimates used in this study.

HEC-GeoRAS post-processing for HEC-RAS

When HEC-RAS modelling simulations were complete, an export file containing detailed grid outputs of depth, velocity and flood extent was then read back into Arcview for post processing. Standard procedures outlined in the HEC-GeoRAS user manual (Brunner, 2002a) were used to extract grids of flood depth, velocity and inundation extent for each of the modelling runs encompassing different Manning's n assumptions and various flow rates (Figure 2).

Table 1: 100 year ARI design discharge estimates (peak discharge and discharge per unit area), catchment areas and time of concentration for a subset of flow change locations along Mullet Creek.

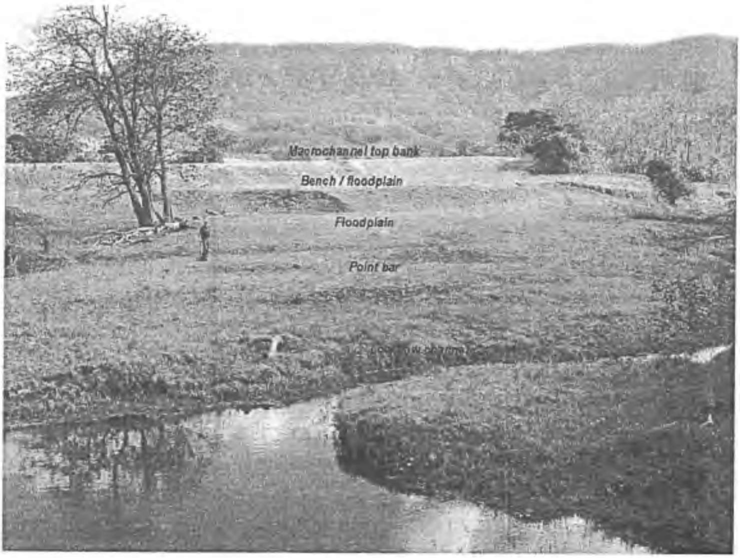
Description	HEC-RAS Reach / River Station	Catchment Area (km^2)	Tc (Hours)	Discharge (m^3s^{-1})	Unit area discharge ($m^3s^{-1}km^2$)
Top of Reach 1	1/10361	1.95	0.98	84.5	43.3
Top of Reach 2	2/9359	7.9	1.67	262.2	33.2
Top of Reach 3	3/8416	10.1	1.83	318.0	31.5
Top of Reach 4	4/5839	15.2	2.14	447.0	29.4
Top of Reach 6	6/4438	17.5	2.25	490.3	28.0
Top of Reach 7	7/1138	24.8	2.57	652.6	26.3

Results and Discussion

Hydraulic operation of Mullet Creek channel and floodplain systems

A striking feature of the Mullet Creek channel and floodplain system are the prominent macrochannels that traverse the central catchment zone downstream of the base of the Illawarra escarpment at approximately 50 m AHD (Australian Height Datum) to an elevation of approximately 10 m AHD. These macrochannels take the form of a 50-300 m wide trench cut into Pleistocene terraces. Within this trench sits a 'low flow' channel approximately 10 m wide which typically has a capacity of approximately the 2 year ARI flood or less (Nanson and Young, 1981; Grootemaat, 2000) and suite of fluvial landforms including bars, benches and floodplains at several levels representing a range of formative flows (Figure 4). Macrochannels are evident along several Illawarra streams but are especially prominent along the major streams draining to Lake Illawarra north of Macquarie Rivulet where they can be clearly distinguished and mapped on fine resolution slope maps derived from DEMs (Reinfelds and Nanson, 2004). They are not unique to Illawarra streams as similar landforms have been described by for Wollombi Brook, NSW (Erskine and Livingstone, 1999), the Narmada River, India (Gupta et al., 1999) and the Sabie River, South Africa (Heritage et al., 1999).

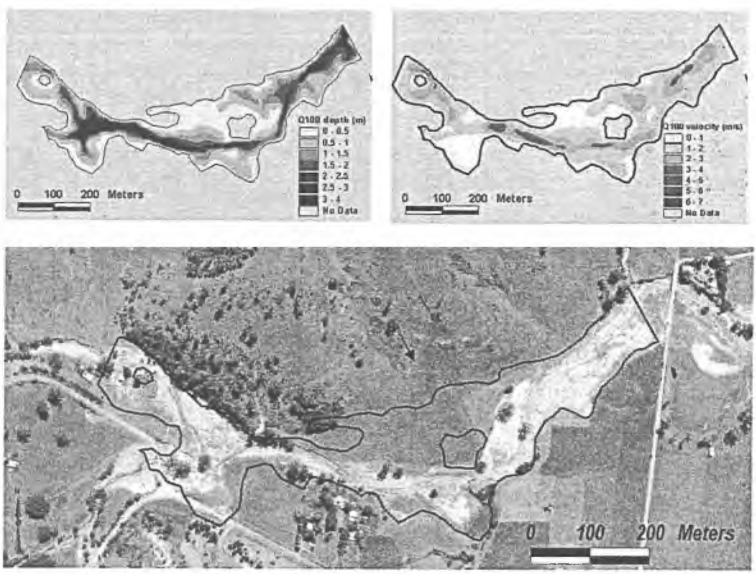
Figure 4. Macrochannel, bench, floodplain, point bar and low flow channel landforms. View of Mullet Ck upstream toward Illawarra escarpment.



The TIN model generated from the LPI DEM for the hydraulic modelling component of this study was compared by Roper (2004) to a TIN model generated from more recent photogrammetric data specifically commissioned for a flood study. This comparison found that the TIN model based on the LPI data provided an excellent representation of topographic features at a scale commensurate with that required for hydraulic modelling of high magnitude floods (Roper, 2004). Both large-scale landscape features such as macrochannel banklines, and smaller scale features such as the 'low flow' channel described above, were well depicted within the LPI TIN model and are clearly apparent on fine resolution DEM slope grids (Reinfelds and Nanson, 2004). This reliable topographic representation enabled generation of detailed and realistic grid outputs of velocity distribution and flow depth in HEC-GeoRAS that compared well with patterns of flood scour and deposition apparent on the February 1984 post-flood aerial photography (Figure 5).

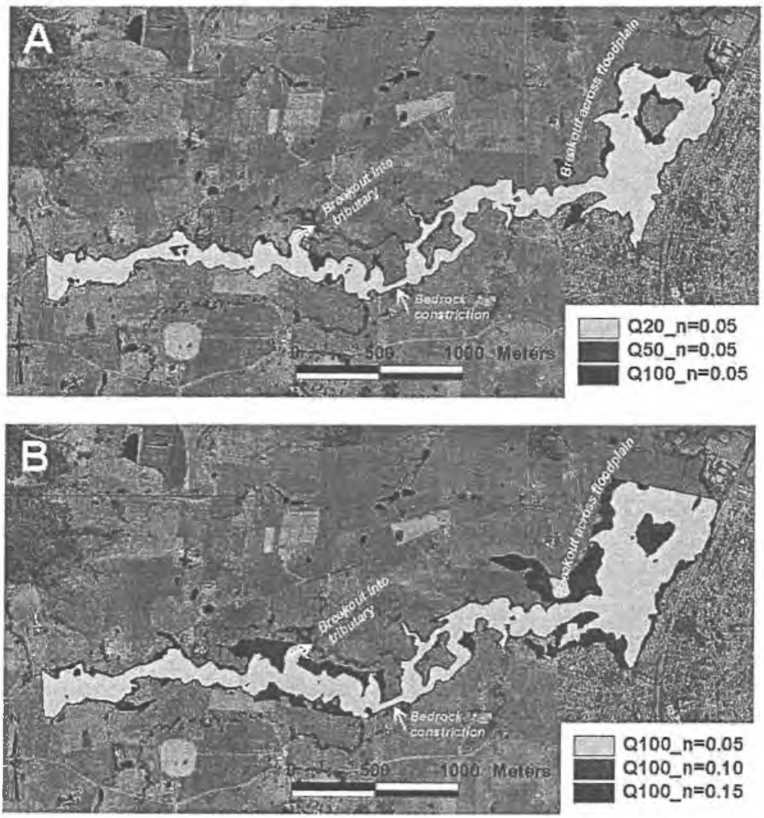
Hydraulic modelling results for a Manning's n scenario representing current channel and floodplain conditions (rural stream with extensive floodplain pasture and relatively little woody riparian and floodplain vegetation - Manning's n of 0.05), indicate that under such conditions, floods from 20-100 years ARI are almost entirely contained within well defined macrochannels (Figure 6A). This is clearly apparent by the very similar inundation extent for 20-100 year ARI modelled flows (Figure 6A). The similarity in inundation extent indicates that successively larger flows simply rise higher up the steep banks of the macrochannels. In Figure 6A, the relatively minor increases in inundation extent and breakout by floodwaters onto the terrace surface and into a left-bank tributary by 20-100 year ARI flows are attributable to backwater effects from a prominent bedrock constriction (Figure 6A). The breakout of floodwaters from the macrochannel in the most downstream part of the modelled reach (Figure 6A) is attributable to the intersection, overlapping and ultimate downstream burial by the Holocene floodplain of the Pleistocene terraces into which the macrochannel is cut.

Figure 5: HEC-GeoRAS grid outputs of depth, velocity and inundated area for design 100 year ARI event overlain over rectified post-1984 flood aerial photography.



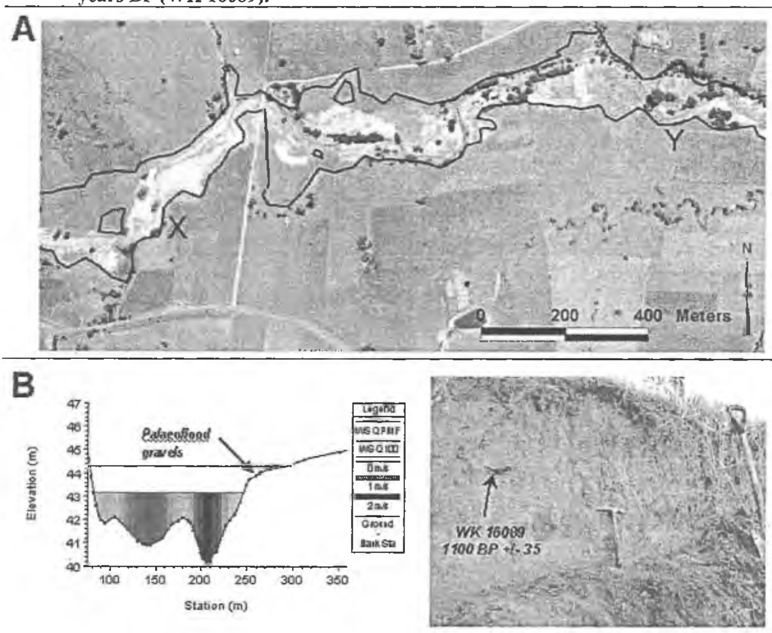
The degree to which the 100 year ARI event inundation extent is affected by differences in Manning's n assumptions is illustrated in Figure 6B. Increasing Manning's n values from 0.05 to 0.10 and thence to 0.15 clearly shows a similar pattern to Figure 6A, with widespread confinement of 100 year ARI flows to the macrochannel. The main areas of floodwater breakout under the increasing Manning's n scenarios are again confined to the backwater zone upstream of the prominent bedrock constriction and Pleistocene/Holocene landform intersection (Figure 6B). Inundation extents for the high to maximum Manning's n scenarios in Figure 6B can be regarded as somewhat conservative representations as the same high and maximum Manning's n values (0.10 and 0.15) were applied throughout the bedrock construction, thereby increasing its upstream backwater effect.

Figure 6: (A) shows confinement of floods from 20-100 years ARI within the mid-catchment macrochannel. Breakout of floodwaters into a tributary macrochannel (indicated by white arrow) occurs upstream of a prominent bedrock constriction (also indicated by white arrow). (B) shows changes in inundation extent for a 100 year ARI event under increasing Manning's n assumptions from 0.05 to 0.10 and 0.15.



Field investigations focussed on locating and characterising the sedimentological characteristics of high level flood deposits from the February 1984 and other flood events provide additional evidence as to the importance of macrochannel landforms in conveying the very large flood flows that are a characteristic of the Illawarra region. Two cut-bank exposures were found where gravel splays have been deposited along the macrochannel margins on top of the Pleistocene terraces (Figure 7A). Both deposits are composed of slightly weathered, poorly sorted gravels and sands with a maximum thickness of about 50 cm and can be traced laterally for approximately 10-30 m at the exposures (Figure 7B, c). High level flood sands deposited by the February 1984 flood event were observed at elevations about one metre lower than these gravel deposits, suggesting that a flood of substantially greater magnitude than the February 1984 event was responsible for the deposition of these high level gravels on the terrace surface.

Figure 7: (A) shows location of palaeoflood deposits identified at X and Y. (B) shows water surface cross-sections for 100 year ARI and PMF events and palaeoflood gravels atop a Pleistocene terrace at X with exposed wood fragment dated at 1100 +/- 35 years BP (WK 16089).



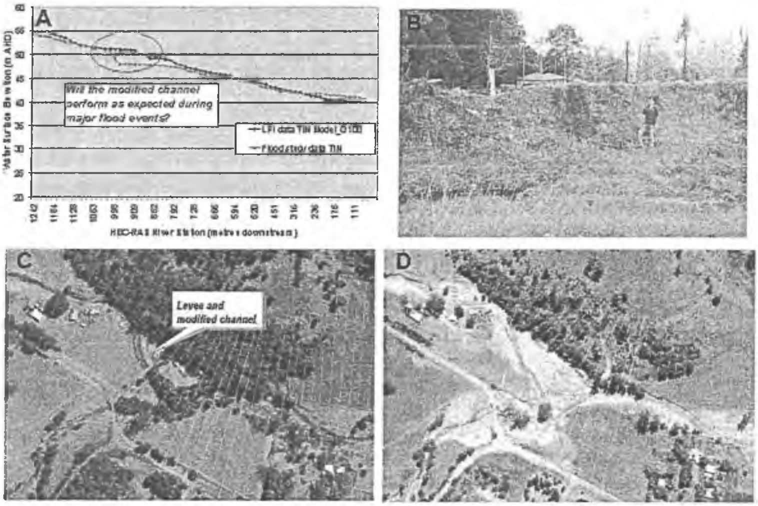
At both sites, HEC-RAS hydraulic modelling results using pre-European channel and floodplain roughness assumptions (Manning's n of 0.10) indicate that an event of about the magnitude of the PMF attains a water surface elevation sufficient to fill the macrochannel to bankfull and wash over the terrace margins at these locations. Both gravel deposits are located at the outside of bends in the macrochannel morphology (Figure 7A) and are thus in a location exposed to high velocity, turbulence and super-elevated flow conditions during extreme floods. A 20 cm long piece of wood (part of a branch), was found within one palaeoflood deposit (Figure 7B). This was dated by conventional radiocarbon at the University of Waikato at 1100 +/- 35 years BP (before present – WK 16089). The radiocarbon date together with the hydraulic modelling results and palaeoflood evidence suggests that Mullet Creek experienced an event of about the magnitude of the PMF approximately 1100 years ago.

Benefits of integrating geomorphology, GIS and hydraulic modelling for flood risk avoidance strategies and improving environmental outcomes for urbanising streams

Topographic information on ground surface elevations is the primary data source underpinning all hydraulic models. Traditionally, topographic data are captured by field survey but this is time consuming and problematic for flood studies where hundreds of cross-sections may be necessary to adequately depict the landscape. More recently, the integration of GIS with hydraulic modelling software (for example, as with the HEC-GeoRAS extension used in this study) enables use of digital terrain models, usually in the form of TIN models, in place of traditionally surveyed cross-sections. The automated generation of cross-sections from topographic TIN models in a GIS environment enables development of much more detailed one dimensional hydraulic models than possible from traditional survey approaches. The ability to generate very closely spaced cross-sections such as the 317 cross-sections over 6.5 km (an average spacing of 20 m) as used in this study negates the need to rely on interpolated cross-sections as is commonly done using more traditional HEC-RAS modelling approaches (Brunner, 2002a). For HEC-GeoRAS in particular, the ability to develop such detailed hydraulic models and to easily integrate them with other GIS data sources, such as rectified aerial photography and fine resolution DEMs, greatly simplifies the integration of hydraulic modelling results into detailed assessments of geomorphological processes during high magnitude events.

An example of the benefit of this type of approach can be seen in the upper reaches of Mullet Creek where the stream encounters rapidly reducing gradients at the base of the escarpment, a setting prone to spectacular geomorphic adjustment during high magnitude events (Nanson and Hean, 1985; Reinfelds et al., 2004; Reinfelds and Nanson, 2004). Comparison of water surface profiles for a design 100 year ARI event from hydraulic models using topographic data from before and after channel excavation and levee construction indicate that the channel modifications might lower the water surface elevation by up to 2-3 metres within this area (Figure 8A). However, the levee is constructed of an unconsolidated and poorly sorted cobble to boulder mix (Figure 8B), and in its current eroded condition, is unlikely to withstand the forces of high magnitude flows. Similarly, the in-channel modifications have focussed on the low flow channel (Figure 8C) with little regard for the natural macrochannel morphology and high sediment loads accompanying high magnitude events (Figure 8D). Given the catastrophic nature of channel response to high magnitude events in this area, the predicted water surface profiles for the modified channel should be treated with caution and limits to development should instead be determined from an integrated assessment of the hydraulic and geomorphic behaviour of the channel and floodplain systems. For the major streams draining to Lake Illawarra, the clearly defined macrochannels provide an excellent opportunity to develop accurate landuse planning boundaries from GIS based analysis of landforms and environmental constraints (DIPNR; 2004; Reinfelds and Nanson, 2004) that can be integrated with hydraulic modelling analyses of design flood levels, inundation extent, depth and velocity. Such an integrated approach offers considerable advantages over a focus on design flood heights as the primary criteria for determining limits to development around streams.

Figure 8: (A) shows modelled water surface profiles for pre and post channel modifications and a possible 2-3 metre lowering of water surface elevations during a design 100 year ARI event. (B) shows a partly eroded levee formed of unconsolidated sediment forming part of the channel modifications. (C) shows the location of the modified channel under current conditions and (D) shows the catastrophic nature of channel response in this area during high magnitude events. Pale yellow lines are cross-sections used to extract geometric data from pre and post 1984 flood TIN models for the site.



Conclusions

Stream channels in West Dapto are characterised by well defined macrochannels that traverse the central catchment zone from the base of the Illawarra escarpment at approximately 50 m AHD downstream to an elevation of approximately 10 m AHD. These macrochannels form a 50-300 m wide trench cut within Pleistocene terraces. Detailed hydraulic modelling indicates that these macrochannels essentially operate as the 'bankfull' channel during high magnitude events up to and in excess of 100 years ARI. Palaeohydrological reconstructions of exposed gravels deposited on top of the terraces along the macrochannel margins indicate that a flood event of about the magnitude of the PMF is required to wash gravels onto the terrace surface. Radiocarbon dating of a large wood fragment deposited with these gravels suggests that a PMF event occurred in Mullet Creek approximately 1100+/-35 years before present (WK 16089).

The NSW Government Floodplain Management Manual (NSW Government, 2001) recognises a hierarchy of floodplain risk management principles where flood risk mitigation represents the least preferred option in comparison to flood risk avoidance and risk minimisation through appropriate landuse planning. Hickey and Salas (1995) similarly describe non-structural control measures as being the most advantageous when dealing with flood risk. The well defined macrochannels along the trunk streams in West Dapto that are clearly apparent in fine resolution DEMs, and which exert a substantial control on flood behaviour, provide an opportunity integrate GIS based analyses of geomorphic controls on flood behaviour into land use planning assessments. Such an approach can complement the traditional reliance on design flood heights as the main consideration for limiting development around streams, and provide instead clear and accurate boundaries to development around the region's streams based on an integrated assessment of natural hydraulic, geomorphic, topographic and environmental constraints. In the West Dapto area, the macrochannels and associated terraces form an effective natural form of flood protection that largely negate the need for structural flood controls, provided that development is placed in a manner sympathetic to the natural fluvial landscape.

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