'Torrents of terror': The August 1998 storm and the magnitude, frequency and impact of major floods in the Illawarra Region of...

Article *in* Australian Geographical Studies · November 2001

Ivars Reinfelds
New South Wales Department of Primary Industries

'Torrents of Terror': the August 1998 Storm and the Magnitude, Frequency and Impact of Major Floods in the Illawarra Region of New South Wales

IVARS REINFELDS and GERALD C. NANSON, *School of Geosciences, University of Wollongong, New South Wales, Australia*

Abstract

The Illawarra Region some 80 kilometres south of Sydney is characterised by a prominent coastal escarpment that rises to 700 m within 12 km of the coast and forms a locus for frequent, high intensity rainfall events. One of the most recent recorded events occurred on 17 August 1998 with rainfall intensities at several pluviometers exceeding 120 mm hr^{-1} over a duration of one hour, with up to 249 mm falling in 3.5 hours during the main storm burst. Detailed pluviometer data indicate that the storm was non-stationary and moved down catchment producing a widespread zone of 120 mm hr^{-1} intensity rainfall over a 30 minute duration across mid-lower catchment areas after similar intensity but longer duration rainfall in catchment headwaters. Slope-area reconstructions of peak discharge indicate that small catchments on the escarpment within the zone of maximum intensity experienced close to 100% rainfall-runoff relationships, with peak discharges correlated to short duration ($<$1 hr) peak rainfall intensities. Widespread erosion occurred particularly where urban development had encroached on natural water courses. Debris/hyperconcentrated flows originating from both anthropogenic and natural sediment sources caused damage to urban areas. This paper provides an overview of the spatial and temporal characteristics of the 17 August 1998 storm, the hydrologic and geomorphic response of the streams, and the nature of damage to urban areas. It reassesses the frequency of recent high-magnitude rainfall/flood events in the region, discussing the relationships between rainfall intensities, estimates of flood magnitudes and stormwater channel capacities.

KEY WORDS *geomorphology; hydrology; rainfall intensity; hydroclimatic behaviour; flood frequency; flood hazard; hyperconcentrated flow; debris flow; culvert blockage*

Introduction

The Illawarra region on the south-eastern coast of Australia is well known as an area which experiences frequent high magnitude rainstorms and flood events (Neller, 1980; Davidson, 1981; Nanson and Hean, 1985; Weeks, 1992). For example, in February 1984 a localised storm with rainfall of 640 mm in nine hours and a peak intensity of 123 mm hr^{-1} over a one hour duration occurred in the southern Illawarra, setting new records for temperate Australia (Bureau of Meteorology, 1994). In an assessment of the magnitude, frequency and effects of that event, Nanson and Hean (1985) hypothesised that 1:100 year rainfall and flood events occur somewhere within the greater Wollongong area approximately every 25 years. The most recent such event occurred on 17 August 1998 in what is normally the driest month of the year, causing extensive damage to public infrastructure and approximately 1000 private properties (Hunt and Kofod, 2000). The insured loss for residential, commercial and industrial property amounted to A$50 million, and damage to public infrastructure and property was estimated at A$25 million (Hunt and Kofod, 2000).

'Torrents of terror, Illawarra's night of devastation' and similar headlines in a regional newspaper (*Illawarra Mercury*) occur with an historical frequency belying point estimates of recurrence intervals for high magnitude events (Davidson, 1981; Weeks, 1992). Indeed the 17 August 1998 storm, inaccurately reported in some media circles to be a one in 300 year event, was followed by a flood on 24 October 1999 that inundated approximately 50 houses, of which many had flooded only one year earlier. This research provides an overview of the characteristics and geomorphic effects of the 17 August 1998 event, the historical frequency of recent high magnitude rainfall/flood events in the Illawarra region, and a discussion of relationships between rainfall intensities, estimates of flood magnitudes and channel capacities for urban Illawarra streams.

Regional setting

Physical and climatic characteristics

The Illawarra Region lies some 80 km south of Sydney on the New South Wales (NSW) coast and is populated by about 300000 residents in the main urban areas of Wollongong and Shellharbour (Figure 1). A pronounced coastal escarpment, with an average elevation of some 400–550 m and a maximum elevation of about 700 m above sea level, forms a dramatic backdrop to the urbanised and narrow coastal plain (Figure 1). The coastal plain widens from the north where the escarpment intersects the coastline near Thirroul and attains a maximum width of about 12 km in the Lake Illawarra catchment (Figure 1).

The Illawarra escarpment produces a strong orographic rainfall gradient, with average annual rainfall varying from approximately 1100 mm at the coast to over 1600 mm at the escarpment crest. Escarpment high points and prominent spurs that extend on to the coastal plain (for example, Mt Keira, Mt Kembla, Stockyard and Saddleback Mountains — Figure 1) further influence local rainfall characteristics. Various average-annual isohyet maps indicate loci for higher rainfall of about 1800 mm per annum around these spurs (Fuller and Badans, 1980; Fuller and Mills, 1985; Pilgrim, 1998).

Catchments draining the Illawarra escarpment are small, with the largest of these, Macquarie Rivulet and Minnamurra River, having areas of less than 10 km^2 where they enter the coastal plain (Figure 1). The majority of trunk and tributary streams draining the escarpment in the more densely populated areas of Wollongong, however, have catchments less than about 2 km^2 upstream of the westward limits to residential development (Figure 1). Longitudinal profiles for trunk streams draining the escarpment are steep, falling as much as 200–300 m km^{-1} before reducing to less than 5 m km^{-1} on the adjacent plain (Nanson and Young, 1981).

Hydrological characteristics of Illawarra streams

The longest discharge records for Illawarra catchments are available for Macquarie Rivulet at Albion Park, with some 50 years of annual maximum discharge data, and Minnamurra River at Jamberoo with seven years of data. Log Pearson III analyses of annual maximum data

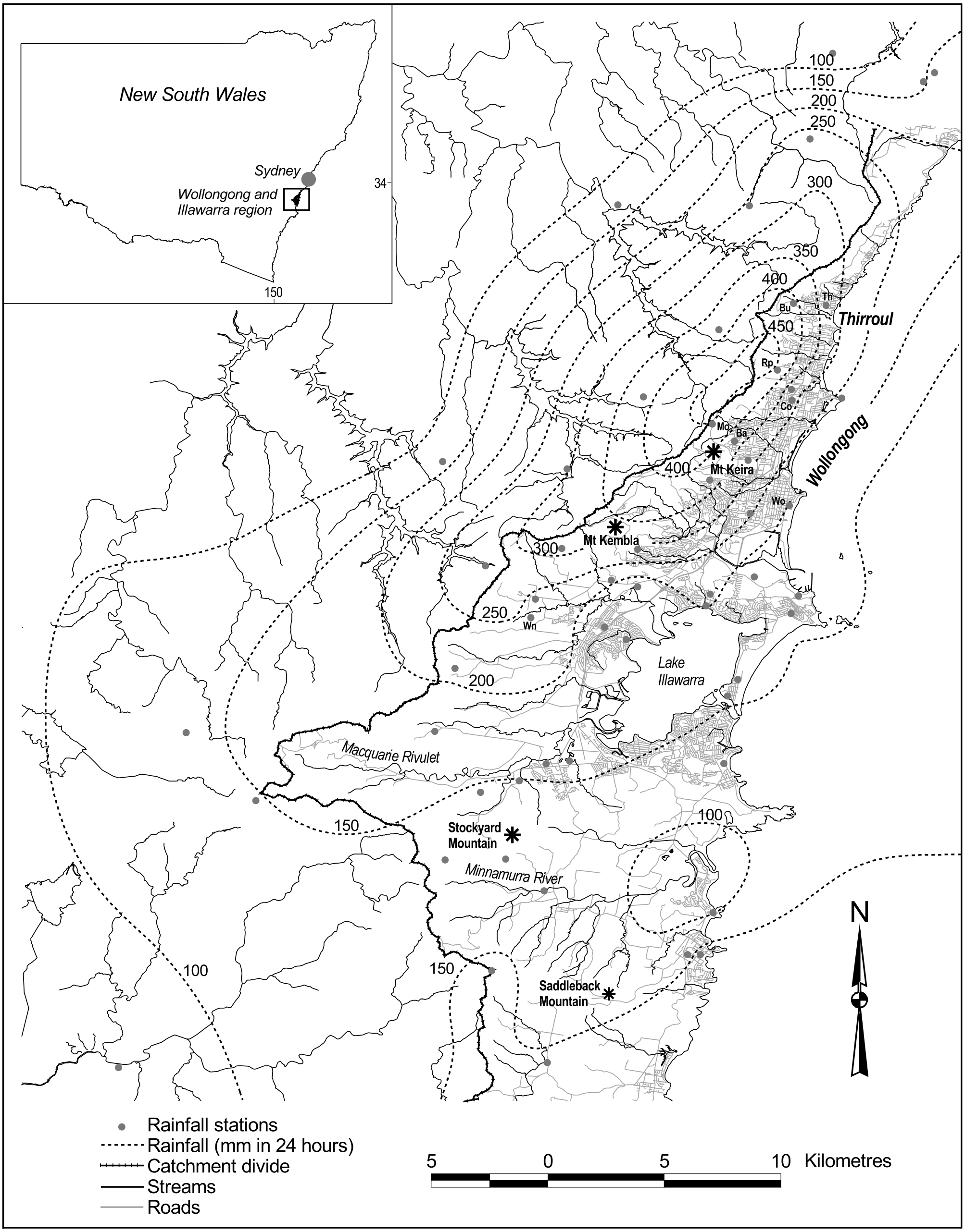

Figure 1 Map of the Illawarra Region showing the 24 rainfall distribution for the 17 August 1998 storm event. Two letter codes denote pluviometer locations: Bu — Bulli; Th — Thirroul; Rp — Rixons Pass; Co — Corrimal; Mo — Mount Ousley Road; Ba — Balgownie; Wo — Wollongong; Wn — Wongawilli.

Table I Log-Pearson III estimates of discharge in m^3s^{-1} and runoff (mm hr^{-1}) from annual maximum discharge data for Macquarie Rivulet at Albion Park (1949–1998) and Minnamurra River at Jamberoo (1971–1980), NSW, Australia. Note that discharge figures are higher for Minnamurra River because of the considerably shorter record set within a period of higher than average flood activity. ARI — annual recurrence interval.

	Discharge in $m^3s^{-1}km^2$ and (runoff in mm hr^{-1}) for ARI 1.01 to ARI 100							
ARI	1.01	1.1	2	5	10	20	50	100
Macquarie Rivulet	0.012 (0.04)	0.16 (0.58)	1.77 (6.4)	5.86 (21.1)	9.78 (35.2)	14.16 (51.0)	20.32 (73.2)	25.10 (90.4)
Minnamurra River	0.52 (1.9)	1.58 (5.7)	4.93 (17.7)	10.42 (37.5)	15.39 (55.4)	21.35 (76.9)	30.52 (109.9)	38.83 (139.8)

from 1948 to 1998 for Macquarie Rivulet at Albion Park suggest that floods of 20 and 50 years recurrence interval produce unit area discharges of about 14.2 m^3s^{-1} km^{-2} and 20.3 m^3 s^{-1} km^{-2}, respectively, for a catchment 35 km^2 in size (Table I). Although there is a paucity of gauging data available for Illawarra streams in urban areas, almost all of which have catchments much smaller than 35 km^2, the Macquarie Rivulet data clearly indicate that catchments which originate on the escarpment generate very high discharges per unit area (Table I).

The rapid increase in annual maximum flood discharge plotted against recurrence intervals (Table I) produces a very steep flood frequency curve for Macquarie Rivulet (Neller, 1980). 'Catastrophic' events, defined by Erskine and Warner (1999) as events 10 times the magnitude of the mean annual flood, thus occur with a relatively high frequency of about 25 years. The flash flood magnitude index for Macquarie Rivulet determined as the standard deviation of the $\log_{10}$ of the annual maximum flood series is 0.729, placing Macquarie Rivulet within the high range of values reported for eastern Australia (Erskine and Livingstone, 1999).

Rainfall characteristics and estimates of flood magnitude for the 17 August 1998 storm

Rainfall characteristics

Steady rain fell throughout the Wollongong region from 0900 onwards on Monday 17 August 1998, with minor peaks in intensity of 30 mm hr^{-1} to 70 mm hr^{-1} over 30 minutes duration occurring at most pluviometers between 1230 and 1330 and again between 1500 and 1600 (Figure 2). Both of these early rainfall peaks produced overbank flows in several streams of the coastal plain, but there are no notes of above-floor flooding in State Emergency Services emergency telephone records for these times. The heaviest rainfall occurred between 1700 and 2030 when 249 mm of rain were recorded at the Mt Ousley Road pluviometer, with 237 mm falling at Balgownie and 217 mm at Bulli (Figure 2). It should be noted that prior to the main burst of the 17 August storm, the Wollongong area had received up to 400 mm of rain over the previous 47 hours (Evans and Bewick, 1998). The heaviest 24 hour totals occurred along the crest of the Wollongong escarpment between Bulli Pass in the north and Mt Ousley Road to the south (Figure 1).

Detailed pluviometer data indicate that the timing and duration of maximum rainfall intensity were not synchronous between closely spaced pluviometers. Rainfall intensities peaked between 1900 and 1930 at the Bulli Pass, Rixons Pass and Mt Ousley Road pluviometers, and between 1930 and 2000 at the Thirroul, Russell Vale, Corrimal and Balgownie instruments (Figure 2). Mapping of 30 minute rainfall intensities (in mm hr^{-1}) clearly demonstrates that the zone of maximum intensity for the

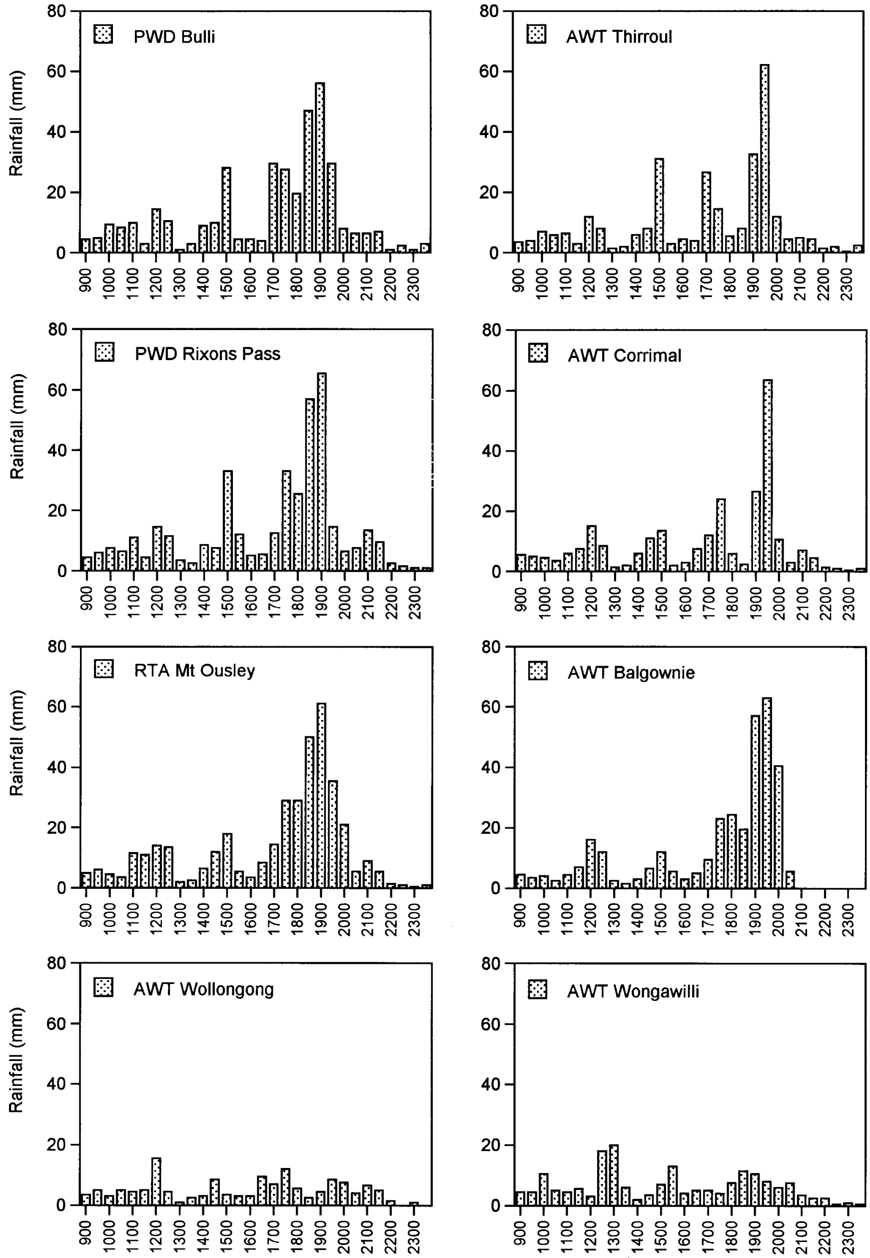

Figure 2 Histograms of 30 minute rainfall totals for 8 pluviometers in the Illawarra region from 0900 to 2400 on 17 August 1998. Note the spatial variability in rainfall over short distances (see Figure 1 for pluviometer locations) and temporal variability in the timing of maximum storm intensity.

storm spread from north to south along the escarpment from Bulli Pass to Mt Ousley Road between 1830–1900 and 1900–1930 (Figure 3a, b). Between 1900 and 2000, the zone of maximum intensity moved eastward away from the escarpment in a predominantly down-catchment direction between Thirroul and Balgownie (Figure 3b, c). By 2000–2030, thirty minute rainfall intensities across much of the urban area had declined to less than 60 mm hr^{-1} with the exception of a lingering area of moderate intensity (60–80 mm hr^{-1}) around the Balgownie pluviometer (Figure 3d).

The implications of the non-stationary behaviour depicted in Figure 3 are that 30 minute duration rainfall intensities of 120 mm hr^{-1} occurred across extensive mid and lower catchment areas of Cabbage Tree, Towradgi, Collins, Woodlands and Hewitts Creeks some 30–60 minutes after rainfall peaked in catchment headwaters (Figure 3). This type of down-catchment movement of high intensity rainfall over small, saturated catchments with short response times is clearly a storm characteristic conducive to producing larger than expected peak discharges in mid-lower catchment areas. Recent hydrologic modelling for Towradgi Creek catchment using August 1998 pluviometer data yielded peak flood discharges in lower catchment areas approximately 10% higher than achieved by 1 in 100 year design events following *Australian Rainfall and Runoff* guidelines (Bewsher Consulting, 2001). Grootemaat (2000) demonstrated that down-catchment movement of high intensity rainfall was also a characteristic of the February 1984 and October 1999 events. Such storm behaviour clearly presents an important challenge to future hydrologic modelling and design flood estimation for the Illawarra.

Evans and Bewick (1998) assessed average recurrence intervals for rainfall intensities over various durations. They determined that maximum five to six minute intensities ranged between two and 10 years recurrence interval, with one station (Thirroul) registering a 10–20 year recurrence interval. Rainfall intensities over a 30 minute duration were generally of 20–50 years recurrence interval, increasing to 50–100 years recurrence interval over one and two hour durations. Rainfall recurrence intervals do not necessarily translate into similar runoff or flood recurrence intervals as determined by simple analyses of critical rainfall duration, particularly given small, saturated catchments with short response times subject to non-stationary storm behaviour. In a review of the 17 August 1998 event, Pilgrim (1999) suggested a maximum recurrence probability of about 30 years for the floods resulting from the 17 August 1998 event. It is interesting that Pilgrim's recurrence probability estimate is similar to that suggested by Nanson and Hean (1985) from an assessment of the spatial extent of recurrence interval isolines for the February 1984 event.

Flood discharge

Peak flood discharge was estimated using the slope area method at one site on Cabbage Tree Creek in the escarpment foothills with a catchment area of 1.7 km^2 within the zone of maximum intensity of the storm. Two closely spaced cross-sections and bedslopes were surveyed in a straight channel reach characterised by a trapezoidal channel set between a high alluvial surface and a vegetated colluvial slope. The maximum flood level could be identified clearly from trashlines and disturbance to groundcover vegetation on the colluvial slope, with the surveyed cross-sections indicating that the alluvial surface was inundated by approximately 20 cm. This overbank flow across the 10 m wide alluvial surface is not included in the peak discharge estimates given in Table II, lending a degree of conservatism to the estimates.

In keeping with Jarrett's (1987) concerns of under-estimated Manning's coefficients for slope-area discharge reconstructions in steep mountainous streams throughout the USA, we used his equation to determine flow resistance:

$$n = 0.39S^{0.38}R^{-0.16} \qquad (1)$$

where n is Manning's coefficient, S is the energy slope (m m^{-1}) and R is hydraulic radius (m).

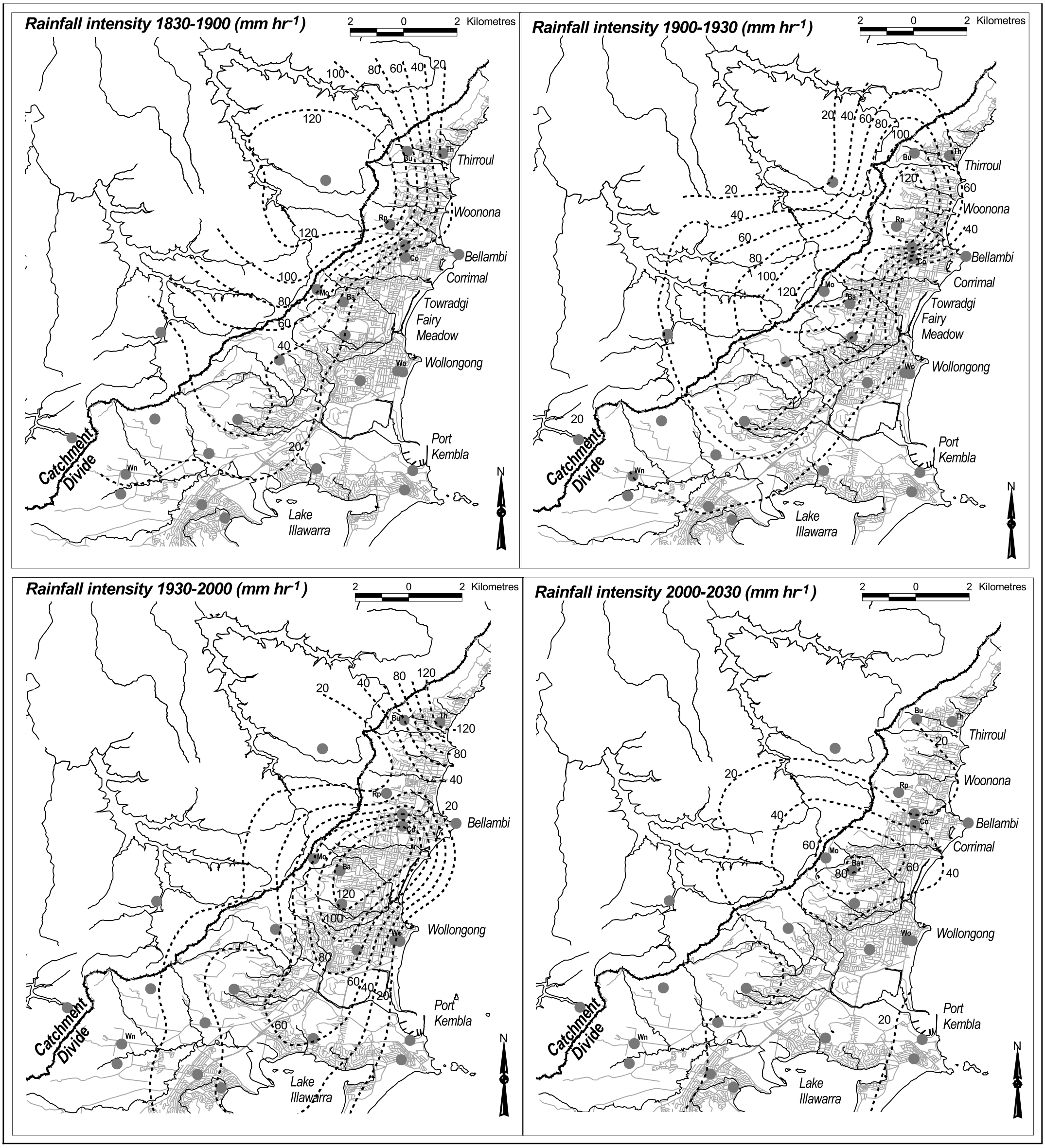

Figure 3a-d Isohyet maps of 30 minute duration rainfall intensity (mm hr^{-1}) from 1830 to 2030 hours for the 17 August 1998. Note the southeast extension/rotation of the 120 mm hr^{-1} intensity isohyet between 1830 and 1930 and the eastward movement of the 120 mm hr^{-1} isohyet near Woonona (Figure 3a, b). Between 1930 and 2000, the 120 mm hr^{-1} isohyet traversed the coastal plain in a northeast direction north of Bellambi, generating a reversal of typical escarpment to coast rainfall gradients. Two letter pluviometer codes as per Figure 1.

Table II Slope-area discharge estimation parameters for two cross-sections surveyed on Cabbage Tree Creek at a catchment area of 1.7 km^2 using techniques described by Riggs (1976) and Jarrett (1987). Mannings 'n' for cross-sections (CS) A, B and MEAN (average of cross-sections A and B) estimated from equation given by Jarrett (1987). Manning's equation used to estimate 'n' and V_{av} after discharge estimation using Riggs' (1976) formulation (equation 2 in text).

CS	A (m^2)	R (m)	D_{av}(m)	D_{max}(m)	S ($m\,m^{-1}$)	n	V_{av}($m\,s^{-1}$)	Q (m^3s^{-1})	Fr
A	24.8	1.35	1.46	2.05	0.0236	0.0895	2.10	52.0	0.55
B	23.9	1.34	1.46	2.02	0.0236	0.0895	2.09	50.0	0.55
MEAN	24.4	1.35	1.46	2.04	0.0236	0.0895	2.10	51.0	0.55
Riggs' eqn.	24.4	1.35	1.46	2.04	0.0236	0.0714	2.63	64.1	0.70

This equation provides a high Manning's coefficient (0.0895) for the selected reach (Table II), considerably greater than field estimates of about 0.06 determined by comparing site characteristics with those reported by Barnes (1967) and Hicks and Mason (1991). When combined with Manning's equation, this high roughness coefficient yields what we consider to be a low discharge estimate of 51 $m^3\,s^{-1}$ for a 1.7 km^2 catchment and a unit area discharge of 30 $m^3\,s^{-1}\,km^{-2}$ (Table II).

An alternative approach for slope-area estimation of flood magnitudes without the need for estimates of Manning's coefficient was developed by Riggs (1976). His equation is as follows:

$$\log Q = 0.191 + 1.33 \log A + 0.05 \log S - 0.056(\log S)^2 \quad (2)$$

where Q is discharge (m^3s^{-1}), A is the channel cross-sectional area (m^2) and S is the energy slope ($m\,m^{-1}$).

This equation provides a discharge estimate of 64.1 m^3s^{-1} or 37.7 $m^3\,s^{-1}\,km^{-2}$ when applied to the data provided in Table II. Manning's equation was used to calculate 'n' for the discharge estimate provided by Riggs' (1976) formulation for comparison with Jarrett's (1987) technique (Table II). Riggs' formulation (Equation 2) yielded an average roughness coefficient for the two cross-sections of 0.07 and is closer to our visual field estimates of 0.06. Both roughness estimates provide sub-critical flows through the reach (Table II).

It is noteworthy that the higher estimate of peak unit area discharge accords well with measured rainfall intensities at nearby pluviometers. Assuming that a 100% rainfall-runoff relationship occurred during the main burst of the August 1998 event, the higher discharge estimate of 37.7 $m^3\,s^{-1}\,km^{-2}$ equates to a rainfall intensity of 136 mm hr^{-1}. An equation in *Australian Rainfall and Runoff* (Pilgrim, 1998) for determining the time of concentration (T_c in hours) of a catchment:

$$T_c = 0.76A^{0.38} \quad (3)$$

where A is the catchment area (km^2), indicates that the time of concentration for a 1.7 km^2 catchment is about 55 minutes. The maximum rainfall intensity over 55 and 60 minutes duration at the nearby Balgownie and Mt Ousley Road pluviometers was 128.2 mm hr^{-1} and 121 mm hr^{-1}, respectively. Peak 15 and 30 minute intensities were 156 mm hr^{-1} and 158 mm hr^{-1} and 129 mm hr^{-1} and 132 mm hr^{-1}, respectively.

Given the small size, steep slopes and high rainfall intensities of Illawarra catchments, the 37.7 $m^3\,s^{-1}\,km^{-2}$ discharge estimate suggests that the times of concentration for Illawarra streams during major events may be considerably shorter than indicated by Equation 3. This situation is compensated for in application of the 'rational method' to design discharge estimation through use of runoff coefficients greater than one for events larger than 10 years recurrence interval (Pilgrim and McDermott, 1982). Assuming that a 100% rainfall-runoff situation was operating at the peak of the storm, then rainfall intensity data from the Mt Ousley and Balgownie pluviometers suggests that the time of concentration for a 1.7 km^2 catchment on the escarpment was about 30 minutes rather than the 55 minutes suggested by Equation 3.

Geomorphological effects of the 1998 storm

Debris/hyperconcentrated flows and stream channel erosion

Natural debris/hyperconcentrated flows, sometimes originating as colluvial slope failures but otherwise generated from the full mobilisation of segments of low-order alluvial streambeds, occurred in several escarpment streams. Channels that transported debris/hyperconcentrated flows exhibited typical 'U' shape scouring and deposited poorly sorted bars and fans of boulders, cobbles and mud in areas of reduced channel gradient on escarpment benches and within the escarpment footslopes. One of the more spectacular deposits of natural hyperconcentrated flow materials occurred on Hewitts Creek in Thirroul at one of the first floodplains occurring downstream along the creek. At this site of reduced channel gradient and flow expansion, the stream bed aggraded by one to three metres with poorly sorted boulders, cobbles, sand and mud deposited as a fan-like structure over 100 m in length. A bridge built across the channel contributed to the stream bed aggradation through blockage and subsequent reduction of peak flow velocities.

At least three spectacular debris/hyperconcentrated flows of primarily anthropogenic materials occurred during the storm. Of these, there is little readily available information for a hyperconcentrated flow that originated from the Bellambi Colliery in the northern suburbs of Wollongong at Woonona. It appears that one of the main coal stockpile heaps had been undercut by floodwaters and provided a massive sediment source that was subsequently deposited downstream in light industrial and residential areas. Although much of the displaced coal had been removed from the area by the time of our aerial survey, extensive deposits were still visible along Bellambi Creek and its floodplains.

Two spectacular debris/hyperconcentrated flows of anthropogenic materials were debouched from tributaries draining the north-eastern flanks of Mt Keira in Fairy Creek catchment. The Kemira Colliery, which closed in the early 1990s, has part of the above-ground facilities built on a platform of emplaced fill that straddles the headwaters of two small catchments. An extensive dump of waste coal, ash, slag and other materials also occurs below the mine site (Smith, 1999). Both the working platform of the mine and the waste material dump occur on high gradient slopes in an area of naturally unstable geology (Young, 1976), with the contact between dumped material and natural talus clearly visible in stream bank exposures.

Six large failures ranging in size from 10 to 30 metres wide across the top of the failure (but narrowing downslope), with average depths of about two metres and downslope lengths of 10–40 m, occurred on the face of the working platform of the Kemira Colliery (Figure 4a). These large failures on the downslope face of the mine's working platform formed the initial source material for debris/hyperconcentrated flows in two streams that were augmented by further large failures in the extensive dump site below the mine. The debris/hyperconcentrated flows travelled at high velocities, stripping bark from channel-margin trees, scouring channels to bedrock in steep reaches and eroding 'U-shaped' channels through accumulated sediments in the escarpment foothills. Upon reaching the first floodplains at the base of the escarpment where gradients decrease and lateral expansion becomes possible, the flows lost momentum and formed two fan-like deposits up to two metres deep, entirely filling a public reserve (Cedar Park) as well as the backyards, garages and swimming pools of numerous

Figure 4a Slope failures in anthropogenic materials on the face of the working platform of the Kemira Colliery on the flanks of Mount Keira that initiated debris/hyperconcentrated flows in two tributaries.

Figure 4b The impact of the debris/hyperconcentrated flows on residential developments at the base of the escarpment. An above ground swimming pool is buried under 1.5 m of predominantly waste coal material.

Figure 4c A bank on Byarong Creek stripped of rock protection with some 800 mm b-axis basalt boulders visible in a fresh gravel bar.

Figure 4d A collapsed concrete encroachment on a stream channel in Fairy Creek catchment leaving the adjacent dwelling less than 2 m from the banks of the stream.

homes where the natural watercourse was piped and built-over (Figure 4b). One home downstream of Cedar Park was so extensively damaged that it was subsequently demolished.

Extensive observations at Cedar Park indicated that the maximum water stage at the head of the deposit was essentially the same as the maximum elevation of bar surfaces, suggesting that the sediment fan was probably deposited at the flood peak. The implications of this observation are that the debris/hyperconcentrated flows in Keiraville buried the entrances to piped and open stormwater drainage systems at the peak of the August 1998 flood and thus may have contributed to flooding downstream by forcing floodwaters overbank at the commencement of the suburban stormwater drainage system. At one site downstream of the buried entrance to the piped drainage system, fences adjacent to an open drain inlet were bent inwards by floodwaters returning to the stormwater system rather than being bent outwards by surcharging floodwaters.

Erosion of channel banks was particularly widespread in streams within the escarpment foothills. Some of the more spectacular examples of bank erosion occurred along Byarong Creek where basalt boulders, approximately 800 mm in diameter and emplaced as protection works around the outsides of bends, were undermined and transported for short distances downstream before being deposited in 1–1.5 m thick, poorly-sorted bars (Figure 4c). In areas where housing had encroached on streams with infilling and canalising of channel banks, undermining, outflanking and collapse of brick, concrete, rock and gabion reinforcements were common, leaving some homes perilously close to eroded streambanks (Figure 4d).

In general, channels throughout the region were scoured due to the erosion of benches and the partial retreat of banks, especially along the outsides of bends and at culvert outlets. Erosion at many locations was exacerbated by infilling of streams for urban development. Blockage of culverts and bridges affected local hydraulics, causing scour where flows re-entered streams. Upstream knickpoint migration through alluvium in streams on the coastal plain formed some of the more spectacular erosion sites as well as in escarpment streams cutting through colluvial materials. Substantial sediment and woody debris deposition was widespread over floodplains along streams within the coastal plain, and cobble-dominated sediment fans were deposited in areas of reduced channel gradient on escarpment benches and in the escarpment foothills.

Flood magnitude, frequency and stormwater channel capacities in the Illawarra region

Magnitude of 20 and 100 year floods in the Illawarra

In an earlier investigation of flood magnitudes for Illawarra streams, Boyd *et al.* (1989) noted that discharges greater than 10 years recurrence interval, as estimated by a range of modelling techniques, were up to 50% lower than indicated by flood frequency analyses of Macquarie Rivulet gauging data (Station no. 214003). The only method that produced results similar to the flood frequency analyses was the ‘rational method’ as described in the 1987 edition of *Australian Rainfall and Runoff* (Pilgrim, 1987). This discrepancy led to local debate as to the accuracy of the Macquarie Rivulet rating curve (Rigby, 1996) and hence the discharge estimates presented in Table I. Limited HEC-2 modelling of flood profiles was undertaken to resolve the issue but results appear to be inconclusive. The first HEC-2 run produced results similar to that provided by the rating curve (Rigby, 1996). A second run which included an additional estimated (not surveyed) cross-section, however, yielded considerably reduced discharges for high stage events (Rigby, 1996). To date this issue has not been resolved, despite its importance for flood estimation in the Illawarra. The upper end of the Macquarie Rivulet rating curve is still controlled by a maximum gauged flow of about $67\,m^3s^{-1}$ on 21 June 1975; a discharge equivalent to about the one in two year flood.

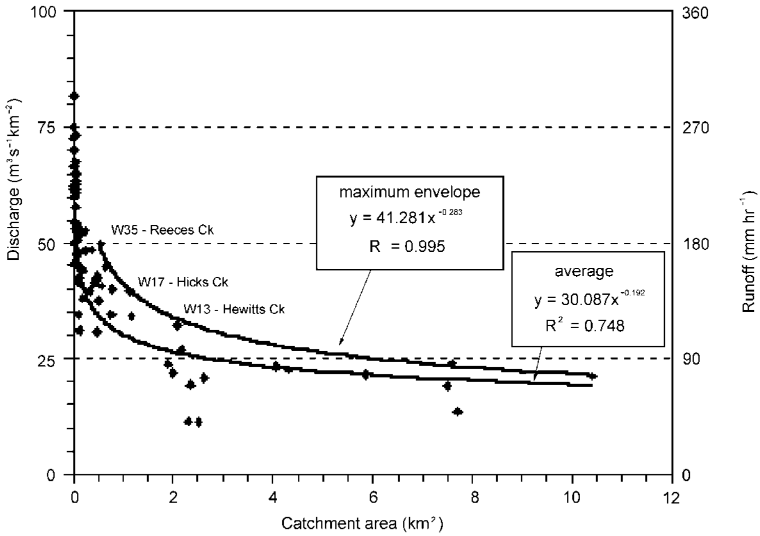

Figure 5 Maximum envelope and average power curves fitted to discharge per unit catchment area data for modelled 1 in 20 year floods in the Wollongong region. Note the exceptionally high unit area discharge values for streams defining the maximum envelope (Hicks, Hewitts and Reeces Creeks). Alphanumeric coding for high discharge streams taken from PWD (1992).

A modelling study of 1 in 20 year flood magnitudes and stormwater channel capacities for eastern Sydney, Wollongong, Shellharbour and Kiama was undertaken by the then Department of Public Works (PWD) in 1992. For the Wollongong study, PWD (1992) modelled peak flood discharges at the outlets of all catchments between Stanwell Park in the north and Fairy Creek in the south (some 60 catchments in total) using a software package RAFTS-XP, and estimated the capacity of trunk drainage systems to convey the modelled discharges. Unit area discharges calculated from data presented in the Wollongong component of the PWD (1992) study are plotted in Figure 5.

Figure 5 provides an interesting aspect to the debate about the Macquarie Rivulet gauge. A log-Pearson III estimate for a 1 in 20 year flood on Macquarie Rivulet of $14.2\,m^3s^{-1}\,km^{-2}$ for a 35 km^2 catchment (Table I) is reproduced closely ($15.2\,m^3s^{-1}\,km^{-2}$) by the formula for the 'average' power curve fitted to the entire PWD (1992) data set (formula given on Figure 5). The close agreement between two independently derived estimates lends confidence to the seemingly high unit area discharges reported in Table I. The values in Table I, however, should only be regarded as a guide to minimum unit area peak discharge estimates for Illawarra escarpment streams because unit area discharges increase exponentially with decreasing catchment area (Figure 5).

Steep, small catchment streams draining the escarpment as exemplified by Hewitts, Hicks and Reeces Creeks in Wollongong's northern suburbs, have unit area discharges substantially in excess of the 'average' curve on Figure 5. The unit area discharge relationship *as determined for the outlets of these streams*, however, can probably be regarded as representative of 1 in 20 year unit area discharges for most streams *at the base of the escarpment* in the Wollongong area. The 'maximum envelope' curve yields an equation:

$$Q_{20max} = 41.28A^{-0.283} \qquad (4)$$

where Q_{20max} is the 1 in 20 year unit area discharge in $m^3\,s^{-1}\,km^{-2}$ and A is the catchment area in km^2. The equation is applicable to catchments between $0.56\,km^2$ and $10.41\,km^2$.

Stormwater channel capacities in Wollongong

The PWD (1992) study provided a useful planning level evaluation of stormwater channel capacities for the older, established areas of the City of Wollongong. Similar to findings by Riley *et al.* (1986) of stormwater channel capacities in several Sydney suburbs, the PWD (1992) study found that approximately 44% of the 386 locations they examined were undersized to convey the modelled discharges. The August 1998 event highlighted the fact that during major flood events, blockage of culverts and bridge rails as a result of debris build-up (Figure 6a), substantially elevated flood levels and caused flow diversions between adjacent watercourses.

The high level of damage across the Wollongong region from the 17 August 1998 event attracted considerable attention from management authorities and the insurance industry (Hunt and Kofod, 2000; Lustig and Irish, 2000). Some residences built in the 1950–80s were flooded because of peak discharge under-estimation and channel conveyance over-estimation stemming from inadequate modelling of flood hydraulics for major events with high debris loads. There are numerous examples of developments situated in floodways such as the house in Figure 6b which was inundated in August 1998 to about 1.7 m depth above floor level. In this regard it is noteworthy that older design discharge estimates based on the 'rational method' as described in the 1977 version of *Australian Rainfall and Runoff* can produce peak flow estimates that are as low as 40% of those estimated using the 1987 revision (Boyd *et al*., 1989).

Frequency of flood events in the Illawarra

Davidson (1981), PWD (1984) and Weeks (1992) provided information on the frequency of flooding under various tiered classification systems, generally of the form 'severe', 'moderate' and 'minor', based on newspaper accounts of the impacts of the floods. For the period 1945–1977, Davidson (1981) reported that 21 episodes of severe flooding occurred and that five of these events warranted classification as 'flood disasters' because of their substantial and widespread impacts on the community and 'overloading' of emergency services. PWD (1984), in their analysis of the February 1984 West Dapto event, reported that severe flooding in the Wollongong Local Government Area had occurred 17 times over a 32 year period. Weeks (1992), in her detailed analysis of newspaper accounts, reported 24 episodes of widespread flooding of residential and rural areas in 96 years from 1895 to 1991.

All three reports show a remarkable consistency in the frequency of severe flooding across the greater Wollongong area, ranging from an average recurrence interval of about 1.5–2 years (Davidson, 1981; PWD, 1984) to about four years (Weeks, 1992). The highest level of flood severity classification, Davidson's 'flood disasters', includes events that occurred in June 1952, October 1959, November 1961, March 1974 and March 1975, and since that time February 1984 and August 1998 can be added to the list. It is commonly perceived that 'flood disasters' in Wollongong are events of exceptional magnitude, perhaps having a recurrence interval of about 100 years or more. Newspaper accounts of the October 1959 event reported it as the 'worst flood for 70 years', the March 1974 event as the 'worst flooding in decades' and the March 1975 event as 'Wollongong's second flood holocaust in 12 months' (*Illawarra Mercury* quoted by Davidson, 1981 in his Appendix A). Including the February 1984 and August 1998 events, seven 'flood disasters' have occurred in 53 years from 1945 to 1998; an average frequency of about one in eight years. While the localised high intensity rainstorms that are characteristic of the Illawarra may well occur infrequently at exactly the same location, the juxtaposition of a large number of small and steep catchments

Figure 6a The Chalmers St culvert on Cabbage Tree Creek. Note the partial obstruction of the culvert and the complete blockage of a handrail by debris.

Figure 6b A dwelling built within 3 metres of a stream that was inundated to approximately 1.7 m above floor level.

with short response times upstream of a longitudinally extensive urban area combine to produce a higher regional frequency of significant events than could be expected in a less complex geographic situation. The analyses presented here, and those of Davidson (1981) and Weeks (1992), clearly demonstrate that floods which are commonly perceived to be of exceptional magnitude should be expected much more frequently across the city as a whole. They should not be seen as unusual occurrences.

Summary and conclusion

Intense storms causing extensive flooding and damage to urban and rural areas in Wollongong have occurred with an historical frequency of about one in eight years. The most recent highly damaging event occurred on 17 August 1998 when over 1000 properties were affected. Peak rainfall intensities in catchment headwaters exceeded 120 mm hr^{-1} over a 1 hour duration, and a maximum of 249 mm was recorded over 3.5 hours during the main storm burst. Prior to the main storm burst, parts of the Illawarra region had received over 400 mm rainfall in 47 hours.

Detailed pluviometer data indicate that the storm was non-stationary. Mid-catchment pluviometers recorded the down-catchment progression of an extensive zone of 120 mm hr^{-1} rainfall over a 30 minute duration after equivalent but longer duration peak rainfall intensities occurred in catchment headwaters. Such hydroclimatological behaviour may have exacerbated flood effects in mid-lower catchment areas. A recent flood study using 17 August 1998 pluviometer data modelled peak discharges in lower Towradgi Creek catchment as being approximately 10% higher than generated by a 1 in 100 year design event following *Australian Rainfall and Runoff* guidelines (Bewsher Consulting, 2001).

Slope-area reconstructions of peak discharge compared against pluviometer data indicated that small catchments draining the Illawarra escarpment within the zone of maximum intensity experienced very close to 100% rainfall-runoff relationships. A peak unit area runoff of 136 mm hr^{-1} was estimated at one site with a catchment area of 1.7 km^2; a figure corresponding well with recorded peak rainfall intensities over a 30 minute duration. These results suggest that the time of concentration for small catchments draining the escarpment may be about 45% less than indicated by the rational method in *Australian Rainfall and Runoff*, and illustrate the importance of using high runoff coefficients (such as 1.25) in the application of this technique as a check to design flood estimates.

Widespread erosion occurred along stream channels but was particularly noticeable in areas where urban development encroached on water courses and limited natural floodway extents. Two debris/hyperconcentrated flows originating in anthropogenic materials associated with a disused coal mine on the Illawarra escarpment caused damage to numerous properties within a reduced gradient depositional zone at the base of the escarpment. Locations of reduced channel gradient on escarpment benches and at the base of the escarpment are subject to significant bedload sediment deposition by hyperconcentrated/debris flows during major events. These factors need to be considered when assessing flood risks and geomorphic hazards in the Wollongong area.

Simple equations are provided in this paper that enable estimation of 'maximum' and 'average' 1 in 20 year flood discharges for the Wollongong area. While the utility of the 'average' equation may be fairly limited from a floodplain management perspective, the 'maximum' equation could be used as an alternative method to check design flow estimates for streams at the base of the escarpment. For such locations, discharge estimates for 1 in 100 year design events that provide results less than the 'maximum' 1 in 20 year equation (Equation 4) should be treated with caution.

Wollongong is a seriously flood-prone city, particularly in some of the older developed areas, and one with an increasingly detailed archive of historical flood information. The regularity with which floods cause damage to urban areas clearly suggests that urban planners and flood modellers must lean heavily toward the side of caution with regard to estimation of peak flood discharges, channel conveyance capacities and assessment of geomorphic hazards. The potential for under-estimating channel roughness in streams subject to major events characterised by high debris and sediment loads poses significant challenges to accurate estimation of design flood stages. Similarly, non-stationary storm behaviour provides additional challenges to accurate estimation of design flood discharges.

Despite the advancements in flood hydrology and risk assessment for the region after the record breaking February 1984 West Dapto event (Nanson and Hean, 1985), it is noteworthy that planning policies in place *prior* to the August 1998 event, such as modelling for 50% culvert blockages and floor levels set 0.5 metres above modelled 1 in 100 year flood levels, were still insufficient to prevent damage to some recent developments (Hunt and Kofod, 2000). Modelling of 100% culvert blockages and augmentation of design flood discharges through catchment diversions are a welcome advance in floodplain management strategies for Wollongong (Hunt and Kofod, 2000) and should provide better protection for new developments.

ACKNOWLEDGMENTS

We thank the NSW Department of Public Works, Australian Water Technologies, Roads and Traffic Authority, Department of Land and Water Conservation and the Bureau of Meteorology for providing data and reports. Messers. Kennedy, Wende, Butler and Cohen provided assistance in the field. Messers. Brooks, Dooley, Bucinskas, Finlayson and Rigby reviewed drafts of the manuscript and G. Grootemaat compiled the 24 hour rainfall data used in Figure 1. The interpretations in this paper remain those of the authors and do not necessarily represent the views of their employers or those who assisted with the research or reviewed drafts of the manuscript.

Correspondence: Dr Ivars Reinfelds, Water Resources Assessment Officer, Department of Land and Water Conservation, PO Box 867, Wollongong NSW 2520, Australia. E-mail: ireinfelds@dlwc.nsw.gov.au

REFERENCES

Barnes, H.H., 1967: *Roughness Characteristics of Natural Channels*. U.S. Geological Survey Professional Paper 1849.

Bewsher Consulting, 2001: *Towradgi Creek Revised Flood Study Draft Report February 2001*. Flood study prepared by Bewsher Consulting Pty Ltd for Wollongong City Council.

Boyd, M., Sivakumar M., Bertakis, E., Rigby, E.H., Downey, J., Burke, N., Ogle, A., Watts, V.M. and Clarke, G., 1989: A comparison of design flood estimation methods. In *Fifth National Local Government Conference*, Sydney, 24–29 September, 192–196.

Bureau of Meteorology, 1994: *the Estimation of Probable Maximum Precipitation in Australia: Generalised Short-duration Method*. Bulletin 53, Australian Government Publishing Service, Canberra.

Davidson, A.R., 1981: *Flooding in Wollongong 1945–1977: a Survey*. Faculty of Military Studies, Department of Geography, Duntroon Royal Military College.

Erskine, W.D. and Livingstone, E.A., 1999: In-channel benches: the role of floods in their formation and destruction on bedrock confined rivers. In Miller, A.J. and Gupta, A. (eds) *Varieties of Fluvial Form*. John Wiley and Sons, New York, Chichester, Brisbane, 445–475.

Erskine, W.D. and Warner, R., 1999: Significance of river bank erosion as a sediment source in the alternating flood regimes of south-eastern Australia. In Brown, A.G. and Quine, T.A. (eds), *Fluvial Processes and Environmental Change*. John Wiley and Sons, New York, 139–163.

Evans, J. and Bewick, B., 1998: *Wollongong Flash Flood Event, 1519 August 1998*. Bureau of Meteorology, Sydney, Australia.

Fuller, L. and Badans, R., 1980: *Wollongong's Native Trees*. Weston and Co. Publishers, Kiama, NSW Australia.

Fuller, L. and Mills, K., 1985: *Native Trees of Central Illawarra*. Weston and Co. Publishers, Kiama, NSW Australia.

Grootemaat, G, 2000: Spatial characteristics of high magnitude storms and channel response, Illawarra, NSW. Unpublished B.Sc. (Honours) thesis, School of Geosciences, University of Wollongong.

Hicks, D.M. and Mason, P.D., 1991: *Roughness Characteristics of New Zealand Rivers*. Water Resources Survey, Department of Scientific and Industrial Research Marine and Fresh Water, Wellington.

Hunt and Kofod, 2000: Wollongong floods. In *Floodplain 2000, Proceedings 2000 Floodplain Management Conference*, 9–12 May 2000, 259–264.

Jarrett, R.D., 1987: Errors in slope-area computations of peak discharges in mountain streams. *Journal of Hydrology* 96, 53–67.

Lustig, T. and Irish J., 2000: What caused the losses from the Wollongong floods of August 1998. In *Floodplain 2000, Proceedings 2000 Floodplain Management Conference*, 9–12 May 2000, 267–274.

Nanson, G.C. and Hean, D., 1985: The West Dapto Flood of February 1984: rainfall characteristics and channel changes. *Australian Geographer* 16, 249–258.
Nanson, G.C. and Young, R.W., 1981: Downstream reduction of rural channel size with contrasting urban effects in small coastal streams of southeastern Australia. *Journal of Hydrology* 52, 239–255.
Neller, R., 1980: Channel changes on the Macquarie Rivulet. *Zeitschrift fur Geomorphologie* 24, 168–179.
Pilgrim, D. (ed.), 1997: *Australian Rainfall and Runoff: a Guide to Flood Estimation*. The Institution of Engineers, Barton, Australian Capital Territory, Australia.
Pilgrim, D. (ed.), 1998: *Australian Rainfall and Runoff: a Guide to Flood Estimation*. The Institution of Engineers, Barton, Australian Capital Territory, Australia.
Pilgrim, D.H., 1999: Wollongong storm event 17 August 1998 comparison of rainfall intensities. Unpublished report for Wollongong City Council, September 1999 by D.H. Pilgrim and Associates Pty Ltd.
Pilgrim, D.H. and McDermott, G.E., 1982: Design floods for small rural catchments in eastern New South Wales. *Civil Engineering Transactions Institute of Engineers Australia* CE24, 226–234.
PWD, 1984: *Flood Event, February 1984, Wollongong Area*. NSW Department of Public Works Report No. PK 8407, Sydney, New South Wales, Australia.
PWD, 1992: *Coastal Stormwater Planning Studies — Volume II W — Wollongong Existing Drainage System*. NSW Department of Public Works Report No. DC92112, Sydney, New South Wales, Australia.
Rigby, E.H. 1996: Development of Macquarie Rivulet as a reference catchment for the Illawarra. Unpublished report for the Water Research Foundation of Australia, Illawarra Regional Committee, Stormwater Subcommittee. Forbes Rigby and Associates, Wollongong, NSW, Australia.
Riggs, H.C., 1976: A simplified slope-area method for estimating flood discharges in natural channels. *U.S Geological Survey Journal of Research* 4, 285–291.
Riley, S.R., Luscombe, G.B. and Williams, A.J., 1986: Urban stormwater design: lessons from the 8th November 1984 Sydney storm. *Australian Geographer* 17, 40–48.
Smith, J., 1999: Coal waste emplacements in the Illawarra with particular reference to the Kemira and Mt Kembla mines. Unpublished B.Env.Sci. (Honours) thesis, Department of Environmental Science, University of Wollongong.
Weeks, B., 1992: Flooding in the Illawarra: an historical perspective. Unpublished B.Sc. (Honours) thesis, School of Geosciences, University of Wollongong.
Young, A.R.M. 1976: The distribution and characteristics of debris mantled slopes in northern Wollongong. Unpublished M.Sc. Thesis, Department of Geography, University of Wollongong.