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Causes and Effects of Culvert Blockage During Large Storms

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Abstract

This paper presents data collected on the blockage of culverts and bridge openings by debris during a major storm. The dominant factor in determining the degree of blockage is the size of the structure's clear opening. Culvert or bridge openings greater than about 6 m are unlikely to block, and if they do block, it is likely to be only a partial blockage. Culverts with openings less than about 6 m are prone to blockage. The data collected for this storm indicates that these culverts can experience the full range, from unblocked to completely blocked.

The consequences of culvert blockage on catchment flooding are discussed. These include increased flood levels, flow diversions out of the streams, development of unexpected overland flood flowpaths, and scouring of overtopped embankments. These possibilities need to be considered when carrying out flood studies.

Introduction

On 17th August 1998 a severe storm in the City of Wollongong caused extensive flooding, with considerable damage to property, disruption of services, and the loss of 1 life. Inspection of the flooded waterways in the days following the storm revealed that a very large number of culverts and bridges had been blocked by debris. As a result of these blockages, flood levels upstream of many road and rail crossings increased, and floodwaters were diverted out of the normal stream channels into overland flow paths, increasing the extent of flood damage.

The experience from this flood indicates that there is a high probability that culvert and bridge openings will block during large storm events. This has significant implications for urban stormwater management practice. As a result of this flood, Wollongong City Council has revised its Drainage Design Code to include the possibility of structure blockage by debris.

Immediately after the storm, Wollongong City Council carried out detailed surveys of the waterways in the flooded areas. A considerable amount of data on the blockages was able to be collected, and this has been used by Council to revise its Drainage Design Code. This paper presents a summary of the blockage data collected, and investigates the factors causing the blockages. The consequences of culvert blockage on catchment flooding are also discussed.

A literature search has revealed that there is very little quantitative data available on blockage by debris. This paper should therefore provide much useful data for planners and engineers working in this field.

Catchments Studied

The City of Wollongong lies on the east coast of Australia, 70 km south of Sydney, with a population of 200,000 people. It has a large industrial base, mainly steel making and coal mining. Most of this industry is concentrated just south of the Wollongong CBD, at Port Kembla. Residential development stretches to the north and south of the CBD. The climate is temperate. Average annual rainfall is 1100-1400 mm, occurring fairly uniformly throughout the year. There are no distinct wet and dry seasons.

The CBD and residential areas are located on a narrow coastal plain running in the north-south direction, varying from 2 to 10 km in width. This coastal plain is bounded on the west by a steep escarpment, rising to a plateau 600 m above sea level. The steep escarpment produces strong orographic effects for storms moving onshore from the ocean, resulting in very heavy rainfalls. Streams in the region run from west to east, and are short (typically 2 to 10 km). They are very steep in their upper reaches (typically 20% to 30%), reducing to quite flat in their lower reaches as they enter the Tasman Sea (typically 0.5%).

The four catchments surveyed for debris blockage are heavily forested in their upper reaches, on the steep faced escarpment. Residential development is present on the lower and middle parts of the catchments, and is mainly low to medium density. Cabbage Tree Creek has some commercial development, and Allans creek has some heavy industry, in both cases at the bottom end of these catchments (table 1).

While the streams run from west to east, all major rail and road transport links run north-south along the coastline, resulting in numerous stream crossings, requiring many culverts or bridges.

Because of the steepness and short lengths of these streams, they are sensitive to short duration, high intensity rainfalls, typically with critical durations near to 2 hours. This was a significant factor in the August 1998 storm, because the most intense 2 hour burst produced extreme rainfall intensities.

Table 1. Details of Catchments used in Debris Blockage Survey

Catchment	Area (km^2)	Stream length (km)	Developed area (%)
Hewitts Creek	4.0	2.5	60
Towradgi Creek	7.2	4.1	70
Cabbage Tree	10.3	6.0	80
Allans Creek	41.0	9.0	75

Historical Large Storms in the Illawarra Region

Heavy rainfalls are produced when intense low pressure systems lay offshore and direct moisture laden air onto the coast. Orographic effects of the steep Illawarra escarpment exacerbate this and have produced extreme rainfalls on several occasions.

The storm studied in this paper occurred in August 1998. Just over one year later, in October 1999, another storm flooded 50 of the houses that had been damaged in the 1998 flood. Other large storms occurred in June 1952, October 1959, November 1961, March 1974, and March 1975, October 1983 and April 1988.

A storm on 18th February 1984 centred on the town of Dapto, 5 km south west of the CBD, produced record rainfalls, which exceeded the historical extreme rainfalls by up to 29% (Shepherd and Colquhoun, 1985). Figure 1 shows rainfall recorded at the Wongawilli gauge. The highest 24-hour rainfall in this storm was 796 mm. This storm led to revision of the Australian Probable Maximum Precipitation procedure for short duration storms (Australian Bureau of Meteorology, 1994)

August 1998 Storm

From 13 to 17 August 1998, a low pressure system in the northern Tasman sea, and a high pressure system to its south, combined to direct moist unstable air onto the mid coast of NSW. This, combined with an upper air trough and the orographic effect of the escarpment, produced very heavy rainfall. The highest rainfall recorded over the 5 days was 745 mm. At Mount Ousley, high on the escarpment, 445 mm was recorded over a 24-hour period, with 180 mm falling in the most intense 2 hour burst within this time (Evans and Bewick, 1999). Figure 2 shows rainfall mass curves for 2 stations located near the top of the escarpment.

Comparison with design rainfall Intensity-Frequency-Duration data (Institution of Engineers Australia, 1998) gives Average Recurrence Intervals ARIs exceeding 100 years for durations between 30 minutes and 6 hours at some locations. These high ARIs occurred at locations high on the escarpment. It should be noted that ARIs were less than this in the lower parts of the catchments, lying between 20 and 50 year ARI near the coast. Figure 3 shows rainfall intensity-duration data for the August 1998 storm and the February 1984 storm superimposed on design rainfall Intensity-Frequency-Duration data for the City of Wollongong . This figure is indicative only, because design IFD curves would be higher for locations on the upper escarpment, and lower for points on the lower catchments.

The most intense 2 hour burst occurred between 5 pm and 8 pm on 17 August. Approximately 375 mm of rain had fallen in the 4 days prior to this, so the catchment was completely saturated. Additionally, very heavy rain fell during the day of the 17th, so that by 5 pm, streams were already running full when the intense burst began.

The combination of a very high rainfall intensity occurring over the 2 hour critical duration of the catchments, with a saturated catchment, and streams already running full, led to very severe flooding. All rail and road links were cut, leaving the city isolated for several days. A large proportion of the culverts and bridges were blocked by debris, diverting floodwaters from their normal stream channels into ill-defined overland flow paths through the residential and commercial areas of the catchments. In several cases, floodwaters diverted by the blocked culverts flowed overland for considerable distances before entering adjacent streams.

The geography of the region, comprising a narrow coastal strip running north-south, intersected by many streams running west-east, caused difficulties for emergency services. When conditions were at their most extreme, this landscape created dozens of isolated communities cut off from each other by flooded roads, and only people directly beside an emergency services facility could be assisted (Opper, 1999).

Some 1000 houses were severely affected and more than 3500 insurance claims were made. Private property losses were estimated at AUD$50 M and public infrastructure damage at AUD$25 (Reinfelds and Nanson, 2001). In the aftermath of the flood, long battles for compensation ensued between residents, claiming damage from rainwater, and insurance companies, claiming that damage was caused by rising floodwaters in defined watercourses. Ultimately, 88% of claims were determined to be due to damage by rainwater and paid. The remaining 12% were deemed to be flooding and payment was declined. Political agitation later led to ex-gratia payments, without admission of legal liability, for many of the remaining claims (Cooper, 1999).

Comparison with flood damage costs at other locations in Australia indicated that damages in the Wollongong region, relative to the number of properties flooded, were significantly higher than in other locations. This is attributed to the high velocities in the steep streams in Wollongong (Rigby and Silveri, 2001).

The storm caused some 190 landslips in the steep talus slopes of the escarpment. A particularly dramatic consequence was the failure of coal waste dump located on the escarpment, with coal waste and slag washed down the streams and through overland flow paths into residential areas (Reinfelds and Nanson, 2001). This flow of water and solids caused some residential lots to be buried to a depth of 1 metre.

Data Collected in August 1998 Storm

On the day after the storm, while emergency teams were restoring services and clearing debris from creeks and properties, engineers from Wollongong City Council walked the creeks, taking photographs and noting the extent of damage. A selection of these photographs is included in the appendix. In the weeks after the storm, engineering consultants were engaged to survey four of the creeks in more detail, concentrating on the blockage of culverts and bridges by debris.

For 3 of the 4 catchments, essentially all culverts and bridges on all tributary streams were surveyed. For Cabbage Tree creek, all culverts along 2 of the tributary streams were surveyed. For each culvert, the following data were collected:

- Type of material blocking opening
- Land use upstream of the culvert
- Degree of blockage
- Size and type of culvert
- Stream slope upstream of the culvert
- Location of culvert on the catchment
- Catchment area draining to the culvert
- Distance to the next upstream culvert
- Whether next upstream culvert was blocked
- Total number of culverts upstream

Culverts were circular pipe or rectangular box in cross section. Pipe culvert diameters ranged from 0.75 to 2.75 m, and box culvert widths from 1.05 to 3.6 m. The number of cells at each location ranged from 1 to 6, except for major stream crossings at freeways and railway lines, which had up to 10 culverts. Bridges were generally in trapezoidal cross section channels and clear spans exceeded 5.5 m in all cases. Table 2 summarises the culverts and bridges surveyed.

Table 2. Details of Culverts and Bridges Surveyed

Catchment	Total number of culverts	Culverts surveyed	Total number of bridges	Bridges surveyed
Hewitts Creek	20	20	7	7
Towradgi Creek	30	26	8	8
Cabbage Tree Creek	20	5	4	4
Allans Creek	76	76	16	16

Causes of Blockage

Modes of blockage

Four modes of blockage were identified:

- Progressive build up of sediment, scoured from upstream bed and banks, in the barrel of the culvert. This blockage typically developed from the bottom up, and in cases of partial blockage, only the lower part of the culvert was affected.

- Initial blockage by large items of floating vegetation, such as trees or parts of trees. This material then provides support for smaller vegetation, such as shrubs and grasses. Vegetation debris came from collapsing banks or adjacent overbank areas, and typically blocked the culvert from the top down.

- More abrupt blockage by urban materials, including refuse, building materials, fences and sheds, which are swept into streams by overland flows and by streams breaking their banks.

- Less common circumstances where a large item, such as a motor vehicle or shipping container suddenly and totally blocks the culvert opening. Larger items such as the shipping container are even able to block the larger openings of bridges.

Blockage by sediment typically occurs both in the culvert entrance and along the barrel of the culvert, whereas the other three blockage modes typically block the entrance only.

Type of blockage material and land use

Blockage material was classified as *Sediment*, ranging from fine sand to boulders; *Vegetation*, ranging from long grass to shrubs and trees; and *Urban debris*, including all artefacts of human use – fences, timber, shopping trolleys, car tyres, and so on. Land use upstream of the culvert was classified as rural (generally in the upper parts of the catchments); urban (in the middle and lower parts); and mixed (where there was a mix of rural and urban).

The major source of sediment was from massive scouring in the steeper reaches of streams, which was then deposited in the middle and lower reaches. Collapsing banks contributed large quantities of vegetation as well as sediment. In the developed areas, considerable amounts of urban material were mobilised by streams breaking their banks, and from overland flow paths, which developed as the blocked culverts, diverted water from their normal stream paths.

Vegetation was present in almost all blockages (85%), usually in combination with other blockage material. Most blockages consisted of mixes of the different material types, *vegetation* and *urban material* (70%) was the most common, followed by a mix of *vegetation and sediment* (15%). Blockage by a single material (*vegetation, sediment*, or *urban material*) was not common, occurring in approximately 5% of blockages for each material.

Urban material tended to block the culvert opening suddenly, allowing little water to pass through the blockage. *Vegetation* tended to build up over time, slowly decreasing the flow of water, until most of the culvert capacity was lost. *Vegetation* tended to block the top of the culvert opening. *Sediment* tended to block from the bottom up, reducing the capacity rather than completely blocking the culvert.

All land use types, rural, mixed and urban, washed off *vegetation* (and to a lesser extent *sediment*). The only significant difference between urban and the other land uses was, of course, blockage by *urban material.* Of those culverts in urban or mixed land use areas, 80% included *urban material* in the blockage.

Degree of blockage

Tables 3, 4 and 5 show the degree of blockage occurring in the culverts and bridges on all four catchments. Blockage data were available at 81 locations. Degree of blockage is the percentage of opening area which was blocked by debris, thus 0% blockage refers to an unblocked culvert, while 100% refers to a fully blocked culvert. Degree of blockage was assessed by visual inspection of the culverts. Clearly, there is some subjectivity in assessing the degree of blockage. Never the less, tables 3, 4 and 5 should give useful information on the extent and likelihood of blockage.

Because culverts were generally smaller than bridge openings, they were more likely to block, and more likely to block fully. The larger sizes of bridge openings meant that they were less likely to block, and a significant proportion (44%) remained essentially unblocked throughout the event. Some bridges (28%) were almost completely blocked, but note that these had smaller openings, generally less than 6 m.

Table 3. Degree of Blockage – culverts and bridges combined (81 structures)

Degree of Blockage %	Percent of structures
0 – 10	15
11 - 40	15
41 - 60	3
61 - 90	16
91 - 100	51

Table 4. Degree of Blockage – culverts only (63 structures)

Degree of Blockage %	Percent of structures
0 - 10	5
11 - 40	14
41 - 60	2
61 - 90	21
91 - 100	58

Table 5. Degree of Blockage – bridges only (18 structures)

Degree of Blockage %	Percent of structures
0 - 10	44
11 - 40	17
41 - 60	5
61 - 90	6
91 - 100	28

Effect of opening size

Figure 4 shows the degree of blockage plotted against opening size. For circular pipe culverts, opening size was taken as the pipe diameter. For rectangular box culverts and bridge openings, the diagonal dimension was used for opening size. All bridge openings were greater than 4.2 m, while all culvert openings were 4.7 m or less.

No structure with an opening of 6 m or larger was fully blocked. Structures of this size or larger experienced only a small degree of blockage (maximum 20%, average 10% degree of blockage).

Structures with openings less than 6 m experienced the full range of blockage, from completely unblocked to fully blocked. The degree of blockage however tended to be high, 58% were fully blocked and only 5 % completely unblocked.

Factors affecting culvert blockage

Figure 4 indicates that the likelihood and degree of blockage will be low for culvert openings greater than about 6 m. For culvert openings less than 6 m, the likelihood of blockage is high. For example, almost 60% of these culverts will be more than 90% blocked, and the average degree of blockage is close to 80%.

Although the average degree of blockage of these smaller culverts is high, figure 4 shows that blockage covers the full range from 0 to 100%. This suggests the possibility that other factors have some role in determining blockage. Relations between the degree of blockage and the factors listed earlier (material type, land use, stream slope, contributing catchment area, number of culverts upstream, and blockage of upstream culverts) were investigated.

Contrary to expectations, no strong relations between these factors and culvert blockage were found. The strongest relation involved stream slope (figure 5 shows this relation for those sites which had this data), where locations with steeper stream slopes tended to have more blockage. This could be due to the greater ability of steep streams to mobilise debris, and the more mobile nature of the debris type (sediment and vegetation) in the upper parts of the catchments. However, it should be noted that the steeper slopes occur in the upper parts of the catchments where the culvert openings are smaller, which will itself lead to increased blockage. Thus the increase in blockage with slope may in part be due to the smaller opening size.

Effects of Blockage on Flooding

Consequences of blockages on flooding

Most instances of blockage occur where a stream is carried under a road or rail embankment by a culvert or a bridge opening. Blockage of the structure has four consequences for flooding in the catchment :

- Flood levels upstream of the structure will always increase
- Flood peak discharges in the channel downstream of the structure may change, due to the flood routing effect of the water stored upstream of the structure
- The increased upstream flood levels may cause some of the floodwater to be diverted out of the stream to some other part of the catchment
- Scouring of the road or rail embankment by the overtopping flows may cause it to collapse, releasing a surge of water into the downstream channel

Once a structure blocks, flood peak discharges in the downstream channel will generally decrease, although the effect may be minor in many cases, and in some cases can lead to a slight increase. When the culvert blocks, water levels upstream of the structure rise. If the embankment level does not greatly exceed the channel bed level, floodwater will flow over the embankment, which acts as a weir. The reduced throttling effect of the weir, relative to the smaller opening of the culvert, together with the small storage volumes in the upstream channel, will give only a small reduction in peak discharge. If the embankment level is considerably higher than the channel bed, upstream flood levels will rise but may not overtop the embankment. In this case downstream peak discharges can be reduced considerably. The first of these cases is the more common for the Wollongong catchments, so the predominant effect of culvert blockages is to reduce downstream peak discharges by only a small amount.

In most cases the bank elevations of the upstream channel are lower than the road or rail embankment. Thus culvert blockage will cause diversion of flows out of the channel to other points on the catchment. If the water is diverted into an adjacent stream, flood peaks in the immediately downstream channel can be significantly reduced, but at the expense of increased flooding problems in other parts of the catchments. Alternatively, the diverted floodwater may rejoin the same stream at some point lower in the catchment, increasing flood damage en-route. In both cases, there is considerable potential for damage to property from flooding in overland flowpaths particularly if such flow is unexpected.

A common occurrence in Wollongong is for blocked culverts to increase upstream flood levels sufficiently to overtop the road embankment. Jersey dividing barriers on the roadway prevent the water re-entering the stream, and floodwater is diverted along the roadway until it reaches an adjacent stream.

Flow diversions can produce dramatic changes to the flood behaviour of the catchment, many of which may be unanticipated. Because the extent of blockage is greater for the larger storms, flood flow patterns will be different for large storms than for small storms. This should be considered in flood studies of any catchment prone to stream blockages.

Implications for flood studies

The experience of this large storm has provided several lessons for engineering flood studies.

Design floods are sometimes estimated by subtracting an "average" rainfall loss from the design rainfall. This is done to allow for the possible occurrence of any value within the full range of antecedent wetness conditions when the storm occurs. The August 1998 Wollongong storm had a considerable amount of preceding rainfall before the intense 2 hour burst occurred, meaning that the catchment was saturated by this time. In Australia, almost all flood producing storms on rural catchments are of long duration (Pilgrim, 1966), so that rainfall losses in the intense burst will be close to zero. Large storms such as the August 1998 suggest that it may be appropriate to adopt lower rainfall losses when estimating design floods on rural and part urban catchments.

In Australia, design floods are estimated by selecting the critical duration rainfall burst for the catchment. For the Wollongong catchments, this is near to 2 hours. Stream flows are generally assumed to be zero at the start of the burst, and any flood detention basins are assumed to be empty. As noted above, the large amount of rainfall preceding the critical burst in August 1998, meant that the streams were running full at this time.

The preceding problems are basically caused by the use of a design rainfall burst with a duration, which is critical for the catchment. One way of overcoming both problems is to use an embedded design storm, in which the critical burst is embedded within a longer duration storm (Rigby and Banningan, 1996). For example, the Wollongong catchments could use a 2 hour critical burst embedded within a 24, 48 or 72 hour storm to simulate the impact of lead-up rainfall on both storage and stream flows.

Culvert blockage leads to overtopping of embankments, and can lead to scouring and embankment failure. It is desirable to include this possibility when carrying out flood studies.

The August 1998 storm has reinforced the need to have models that are capable of modeling these effects. The flood hydrology model WBNM developed by several of the authors (Boyd et al, 1996) has been developed to model culvert blockages, flow diversions, scourable weirs, and embedded design storms.

Conclusions

A major storm in 1998 caused blockage of many culvert and bridge structures on mixed rural and urban catchments in the City of Wollongong, Australia. Data collected after the storm indicated the likelihood of blockage, and the types of material that led to these blockages.

- The major factor determining culvert blockage is the size of the clear opening. Culvert and bridge openings greater than about 6 m tend not to block, or if they do, the degree of blockage is low. Culverts with openings less than 6 m experienced the full range of blockage, from completely unblocked to fully blocked.

- No strong relations were found between the degree of culvert blockage and a range of factors, including material type, land use, stream slope, contributing catchment area, number of culverts upstream, and blockage of upstream culverts.

- The finding that blockage is essentially independent of these factors indicates that, when opening sizes are less than 6 m, there is a high risk that a culvert at any point on the catchment may block.

- The possibility of blockage can have major consequences in diverting flood flows from the normal watercourses into overland flow paths and into adjacent streams, and this should be considered in engineering flood studies.

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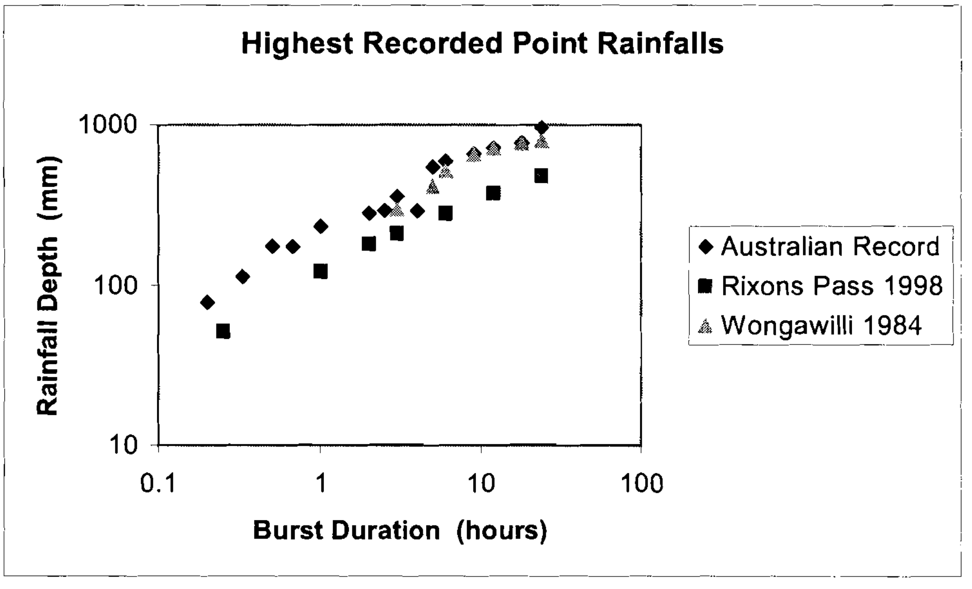

Figure 1 Extreme Rainfalls in Australia

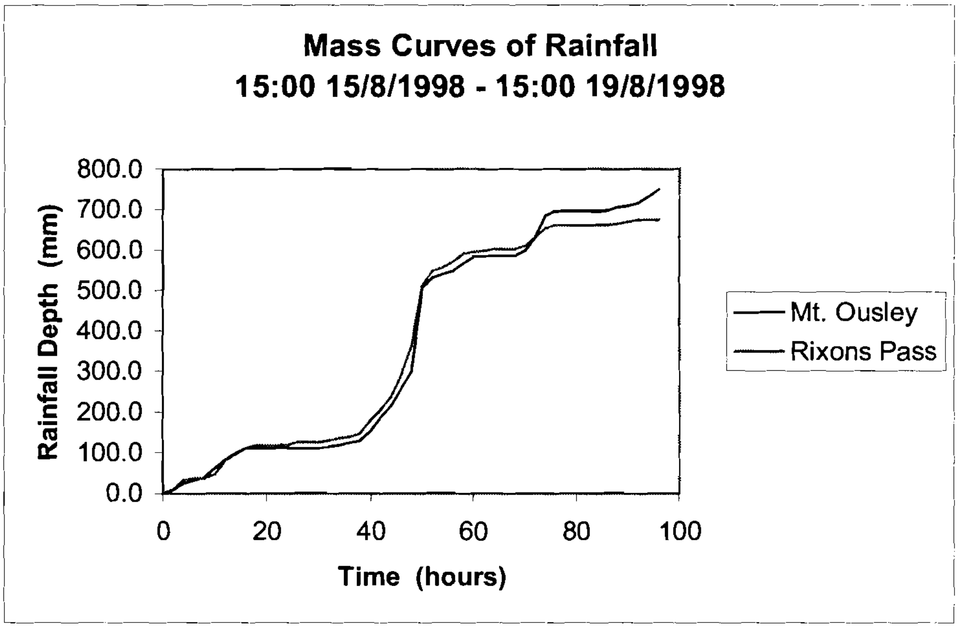

Figure 2 Rainfall Mass Curves – August 1998

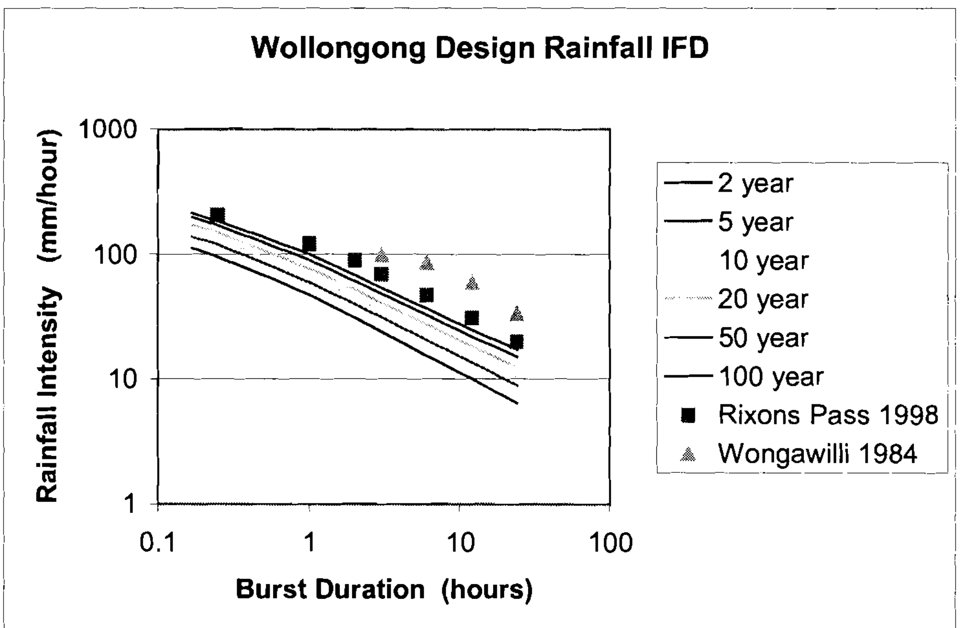

Figure 3 Wollongong Rainfall Intensity – Frequency – Duration Data

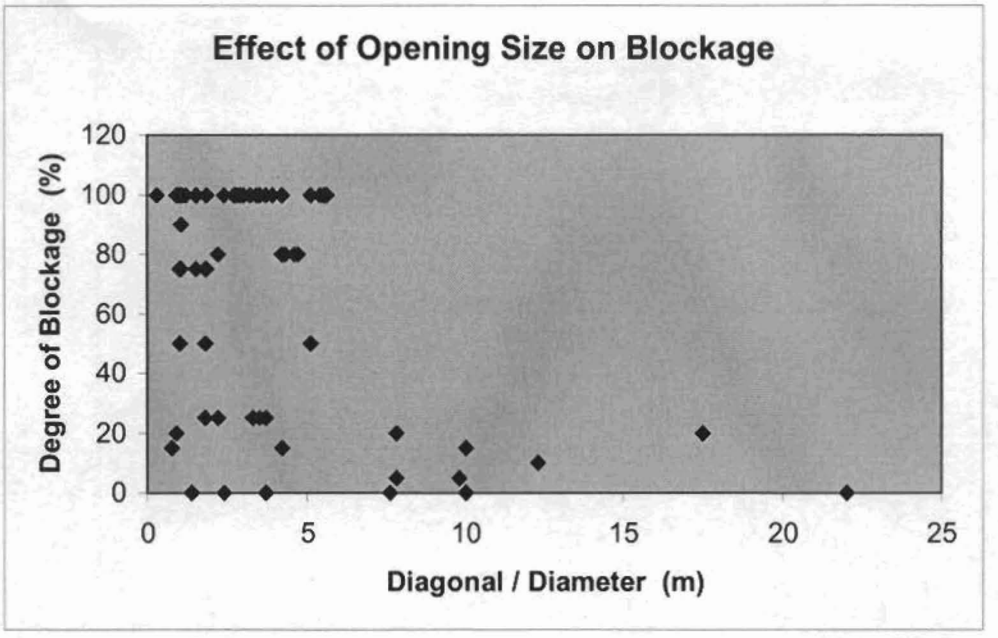

Figure 4 Degree of Blockage versus Structure Opening Size (76 locations)

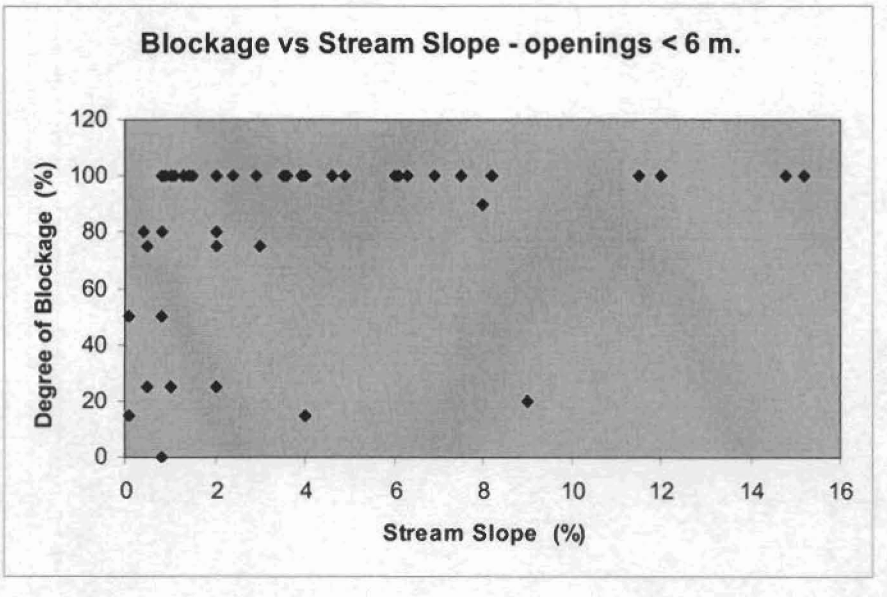

Figure 5 Degree of Blockage versus Stream Slope (58 locations)

Appendix of Photographs – August 1998 Storm in Wollongong