THE EVOLUTION OF BLOCKAGE POLICY IN WOLLONGONG – 18 YEARS ON FROM THE 1998 FLOOD

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Introduction

Blockage of bridges, culverts and other stormwater conduits is a key consideration for Wollongong City Council (Council, or WCC) in fulfilling its floodplain management responsibilities. WCC established a blockage policy in 2002, primarily in response to major flooding that occurred in the LGA in August 1998 and October 1999. The policy is implemented as part of Council's Development Control Plan (DCP).

In 2015, WCC engaged an independent team of consultants to review the blockage policy. The scope of the review was to:

- Undertake a comprehensive investigation of available historical records of blockage in the Wollongong area;
- Review the existing blockage policy implemented in the Wollongong DCP;
- Undertake detailed probabilistic modelling analysis of the available data;
- If appropriate, recommend an alternative policy based on robust technical analysis, and in line with best practice for design flood estimation, to the extent allowed by the data.

There are several contributing factors why blockage is a major focus of floodplain management policy in Wollongong. The Illawarra escarpment causes orographic effects leading to relatively high extreme rainfall intensities. The LGA contains multiple parallel catchments running from the escarpment to the coast, and development has primarily occurred in the flatter lower parts of the catchment, leading to a relatively high proportion of flood prone land. Most of the upper catchment areas are forested, so there is a relatively high availability of debris. Furthermore, there are several major arterial roads and railway lines along the coast, aligned perpendicular to the flow direction in the majority of catchments. This results in a relatively high number of major bridge and culvert structures with high embankments crossing the floodplain, in close proximity to developed areas. Finally, much of the development throughout the 20th century occurred over, or in close proximity to, the natural creeks, leading to significant sections being replaced by pipe. Flood risk in these locations is therefore relatively sensitive to blockage.

Guidelines arising from the Australian Rainfall and Runoff Revision Project 11 (Weeks, 2013) provide a generic approach to allow blockage to be estimated for any location in Australia. However the guidelines recommended that if there is any recorded history of blockage for a particular location, this history should be taken into account in the relevant hydraulic analysis. The guidelines also state that "inclusion of blockage in Monte Carlo analysis would be valuable in the consideration of uncertainly for flood assessment."

The primary focus of this paper is to describe the probabilistic analysis undertaken for the review. The aim of the analysis was to estimate "probability neutral" blockage factors for design flood modelling – that is, the blockage factor that could be included in numerical models which would produce a flood level equivalent to the design rainfall being used.

Conceptualisation of blockage

The definition of "blockage," and its quantification and measurement, is not straightforward. When talking about the inside of a pipe or culvert, there are two main approaches to describe the amount of blockage:

- Visual blockage – the amount of blockage estimated from personal observations or photos, by estimating the size of the obstruction as a percentage of the total flow area. Unfortunately, this method provides relatively little insight into the effect of the blockage on flood behaviour. A dramatic looking "blockage" may have almost no influence on flood levels if the debris is highly porous, and the flow velocity is relatively low. Vegetation growing in front of a culvert can be knocked flat and provide little hindrance during a flood. Another common example is that post-flood photos often show a debris mat which would have floated during the flood then subsided into the waterway, and does not accurately reflect the blockage at the peak.
- Hydraulic blockage – more complex to quantify, this is based on the impact that blockage has on flood peak levels during a flood. Large flood-producing storms are relatively rare, and in flash flood environments it is extremely difficult to get qualified personnel to the site of flooding to take measurements, particularly at the peak of the event. As well, there are large variations from one event to another. Even if qualified personnel are present, there are usually more pressing concerns like assisting with protection of people and property from flood risk and damage.

Kramer et al (2016) investigated effects of blockage in a physical hydraulic model, and provided a definition of hydraulic blockage based on differences in the upstream water level for the blocked case compared to the unblocked case. While this definition is valid under the principles of hydraulic theory, it is very hard to implement in practice because it is impossible to re-produce the same flow conditions to measure the unblocked case. This definition also cannot be easily specified as an at-site parameter in a hydraulic model. Iterative modelling would be required to converge on the specified blockage factor. More attention in this area is required to reach a consensus on defining and implementing blockage in design flood estimation.

For the purposes of this paper and the analysis presented, hydraulic blockage is defined as the reduction in total effective flow area through the structure at a given combination of inlet and outlet water level, compared to the unblocked case.

Challenges for predicting and managing blockage risk

It is inherently difficult to include consideration of culvert blockage as part of a floodplain management framework. This difficulty arises for several reasons:

- The degree of blockage in a culvert and its effect on surrounding water levels is almost impossible to measure for short duration flash-flood events, due to the difficulty in getting qualified personnel and appropriate equipment on-site during the flood event;
- There are a lot of random factors that determine whether blockage occurs, and how severe it is, in any given flood event;
- The physical flow behaviour and turbulence around culvert inlets is complex, and blockage introduces additional complexities that can be different to represent in computer models;
- In some locations, peak flood levels can change dramatically (e.g. several metres) depending on the blockage assumption, and there can be "high-regret" consequences if the risk of blockage is not considered.

Due to the above factors, there is generally a lack of high quality data to quantify the historical effect of blockage on floodplains, particularly in urban areas. The uncertainty surrounding blockage makes it difficult to implement effective policies for its consideration.

One of the key recommendations of the review was to implement a data collection procedure for implementation immediately after future major flood events in Wollongong. The intent is to obtain additional comprehensive data relating specifically to blockage of culverts and bridges in the area. This data may be used for future review and refinement of the blockage policy for modelling flood behaviour and managing flood risk. Improvements in the availability and cost of remote sensing equipment such as cameras and gauges may lead to improvements in collection of blockage data in the future.

Data

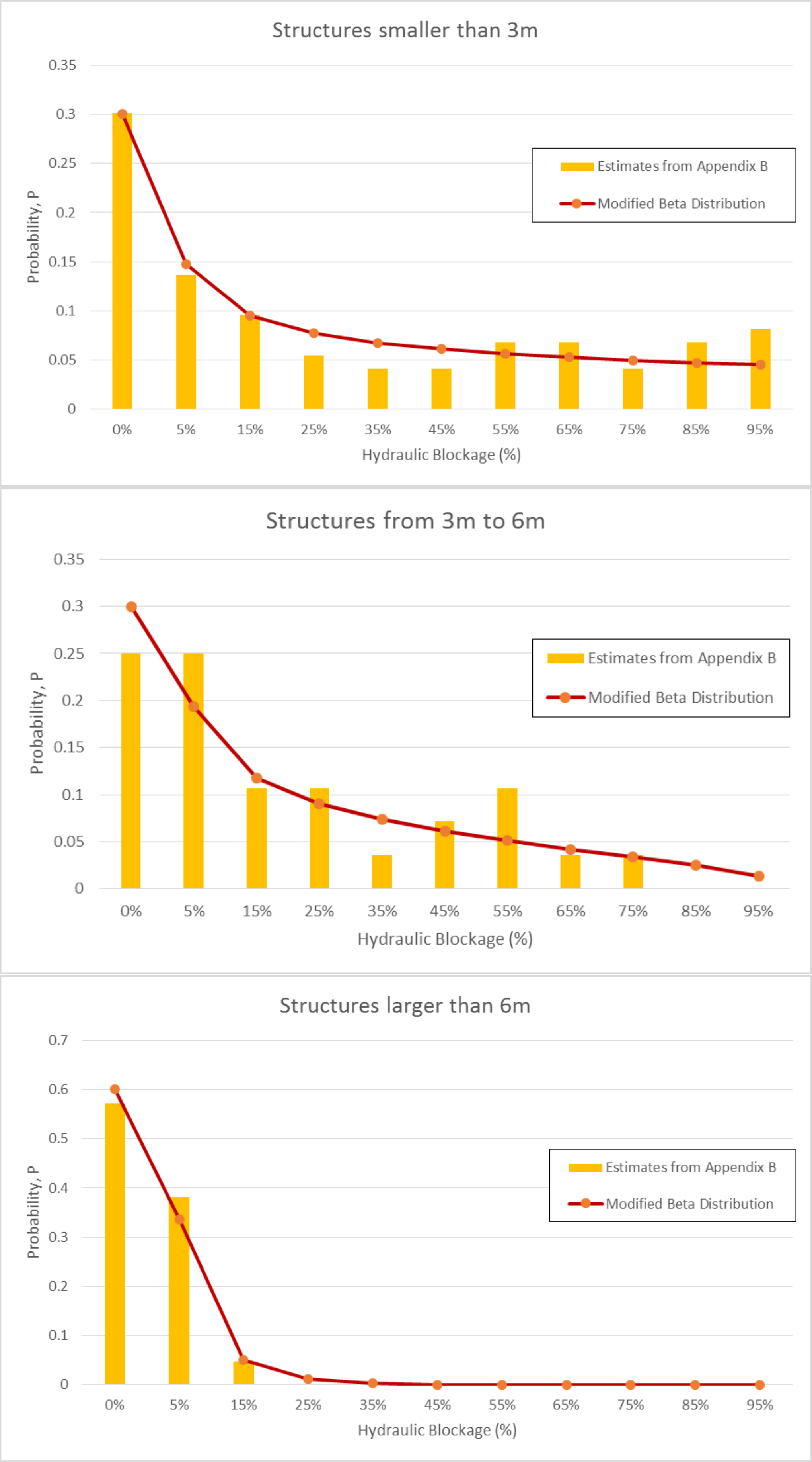
The authors developed a database of historical flood photographs related to culvert or bridge blockage in Wollongong. The database contains over 130 hydraulic blockage estimates from photographs for a range of locations and events, although primarily from the August 1998 storm. The blockage estimates are based on the visual information available from the photographs, and therefore have a high level of uncertainty since post-flood visual blockage and hydraulic blockage during the event can differ significantly. However the framework developed provides a robust methodology for future refinements of policy blockage factors, if new blockage data is obtained.

An example of the photographs available, one of the more severe instances of blockage in the record, is shown in Figure 1.

Figure 1: Blockage at Lemrac Avenue culvert in August 1998

This database was classified in structures of different sizes, and was used to estimate a probability distribution for the blockage likely to occur at a hydraulic structure of a given size. The fitted distributions are shown in Figure 2.

Figure 2: Fitted blockage distributions for various structure opening sizes



It is important that any analysis of historical data includes sites where no blockage was observed, not just the problematic sites. The number of “no blockages” has similar if not more influence than the relatively small number of sites that did block to some degree.

Methodology

The purpose of the analysis was to estimate the “probability-neutral blockage” – the blockage factor that when combined with the 1% AEP rainfall, will produce the 1% AEP flood level at a given location. This blockage will vary for different sites depending on a range of factors. The modelling methodology incorporates thousands of these potential combinations at each site to estimate the probability-neutral blockage.

The probabilistic modelling assessment was completed for 20 locations. These locations were chosen to give a representative sample for a range of different catchments, structure sizes, land use, catchment slope, position within the catchment, and other factors. As a pre-requisite for modelling of a certain structure, the following information was required:

- Design flow to the structure for a range of events (preferably over a range of events from 50% AEP up to the PMF) under unblocked conditions;
- Results for water level upstream of the structure, flow through the structure, and the flow split over the deck/embankment if applicable for these full range of events;
- Details of the structure geometry to classify the structure and apply the relevant blockage distribution from Section **Error! Reference source not found.**.

The probabilistic modelling was undertaken using spreadsheet software, using relationships for flow and water level at each structure extracted from dynamic 1D and 2D hydraulic models of the relevant catchments.

The methodology for a given site was as follows:

a) Extract information about the culvert/bridge from the relevant hydraulic model, prepared for each catchment in the Wollongong LGA as part of the NSW Flood Program. The information includes the culvert size, invert levels, and overtopping level.
b) Extract the relationship between upstream water level, flow through the culvert and overtopping flow for the unblocked case. Again these results were obtained from the hydrologic and hydraulic models for the relevant catchment flood study.
c) Extract the design flow for the full range of AEP, and interpolate/extrapolate if required to determine the flow for more intermediate and more frequent events
d) Generate 1,000 different “storm” events by randomly sampling:
    i. total peak flow from step c) and
    ii. blockage from the appropriate distribution for the culvert size

   Note this sampling is done in a stratified fashion (Nathan and Weinmann, 2013), so that there are an equal number of events with flow of around 1% AEP as there are for around 50% AEP. The stratification was undertaken for 50 different AEP “bins,” with 20 randomly sampled blockages per bin, to give a total of 1,000 events
e) Use the randomly sampled blockage, e.g. 40%, to adjust the flow table through the culvert compared to the unblocked situation, based on a flow area reduction.
f) Determine the upstream water level corresponding to the adjusted culvert flow and overtopping flow (as determined from the relationship extracted from the hydraulic model).
g) For each AEP bin, add up the number of exceedances of a given flood level, multiply by the appropriate rainfall AEP, sum across the full range of AEP bins, and normalise to create the blockage adjusted AEP for that flood level.

h) Repeat the calculation across a range of flood levels to create a table of flood level probability (AEP), which accounts for probability of both rainfall and blockage.

The results were validated against selected runs of the hydraulic model from the relevant catchment flood study, to check that the interpolation procedure worked correctly. For example, test combinations of flow and blockage (e.g. 2% AEP flow with 40% blockage) were input to the relevant catchment-wide hydraulic model for each site and compared to the results from the spreadsheet. In general, the spreadsheet replicated the results well (to within 0.1 m or 0.2 m).

Results

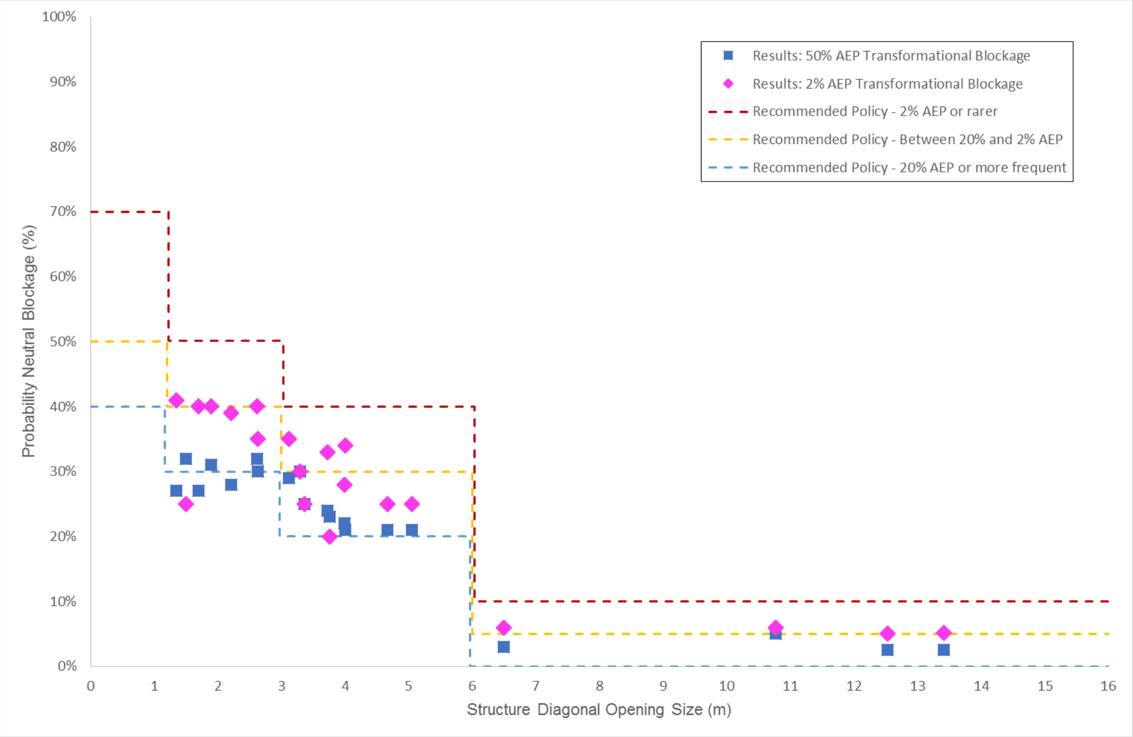
A summary of the probability-neutral blockage results for the 2% AEP and 50% AEP for all 20 sites is shown in Table 1.

Table 1: Analysis locations and probability neutral blockage results

ID	Location	Catchment	Size	Size Class	50% AEP probability-neutral blockage	2% AEP probability-neutral blockage
C01	Lachlan St Thirroul	Hewitts	2.7m by 2m Box (x2)	Class 3	25%	25%
C02	Lawrence Hargrave Dr Thirroul	Hewitts	2.8m by 2.5m Box (x3)	Class 3	23%	20%
C03	High Street Woonona	Collins	2.15m by 1.5m Box (x3)	Class 2	32%	40%
C04	Red Ash Drive Woonona	Collins	Bridge	Class 4	5%	6%
C05	Thompson St Woonona	Collins	3m by 1.35m Box (x3)	Class 2	30%	30%
C06	Gladstone Street Bellambi	Bellambi Gully	2.5m by 0.8m Box (x3)	Class 1	30%	35%
C07	Lemrac Avenue Corrimal	Towradgi	1.5m Pipe	Class 2	32%	25%
C08	49 Meadow Street Corrimal	Towradgi	3m by 2.2m Box (x2)	Class 3	24%	33%
C09	98 Meadow St Corrimal	Towradgi	1.8m by 0.6m Box (x3)	Class 1	31%	40%
C10	Memorial Dr near Railway St	Towradgi	3m by 0.85m Box (x3)	Class 1	29%	35%
C11	Memorial Dr near Carr St	Towradgi Creek	1.2m by 1.2m Box (x3)	Class 2	27%	40%
C12	Chalmers St Balgownie	Cabbage Tree	5.4m by 3.6m Box / Bridge	Class 4	3%	6%
C13	Hopewood Crescent Fairy Meadow	Cabbage Tree	3.2m by 2.4m Box (x2)	Class 3	21%	34%
C14	Princes Hwy Bridge Fairy Meadow	Cabbage Tree	Bridge	Class 4	3%	5%
C15	Montague St Bridge Fairy Meadow	Cabbage Tree	Bridge	Class 4	3%	5%
C16	Princes Hwy near Mt Ousley Rd	Cabbage Tree	1.35m Pipe (x4)	Class 2	27%	41%
C17	67 Montague St Fairy Meadow	Cabbage Tree	1.85m by 1.2m Box (x4)	Class 2	28%	39%
C18	The Avenue Figtree	Byarong	3.65m by 2.9m Box (x5)	Class 3	21%	25%
C19	Blackman Pde near Rickard Rd	Charcoal	3.7m by 1.5m Box (x2)	Class 3	22%	28%
C20	F6 Freeway Figtree	American	3.65m by 3.5m Box (x8)	Class 3	21%	25%

This information is plotted against structure opening size on Figure 3.

Figure 3: Results - probability-neutral blockage versus structure opening size



The data points show a strong relationship of decreasing probability-neutral blockage with increasing structure size. Notably, the values are all below 50% blockage, but suggest an increasing trend for structures smaller than 1.2 m (no such structures were modelled stochastically, since in general these smaller culverts will not convey a significant proportion of the flow for the flood events of interest to the policy). These relationships were the key outcome of the probabilistic modelling assessment, and the proposed blockage factors in the recommended alternative policy were derived primarily from this information.

It can be seen that typically the 50% AEP probability-neutral blockage is lower than the 2% AEP, even though the same blockage probability was assumed for all event sizes in the analysis. That is, the analysis did not include an allowance for increasing likelihood of blockage occurring in larger events, which might be expected due to increased overbank flows and greater chance for debris mobilisation. Nonetheless, the results still indicate a lower probability-neutral blockage for lower AEP, as an inherent characteristic of most of the sites analysed. This may indicate that for smaller flood events, the increase in flood level with increasing rainfall/flow AEP is greater than the sensitivity of flood level to blockage.

Discussion at sites C07 and C11

Results for sites C07 (Lemrac Avenue) and C11 (Memorial Drive Towradgi near Carr Street) are shown on Figure 4 and Figure 5 respectively. The plots show water level against AEP. The individual data points represent the outcomes of each Monte Carlo sample. The curves show the water level for various blockage assumptions. The yellow line indicates the probability neutral flood level from the analysis, taking into variability in both rainfall and blockage.

There are notable differences in the range between the 0% and 100% blockage results at various AEPs. At C07, the range is 0.16 m for the 50% AEP event and 0.1 m for the

1% AEP event. This kind of variation could be accounted for with a typical freeboard of 0.5 m for setting residential floor levels. However at C11 the 50% AEP range is over 2 m, and 1.27 m in the 1% AEP. This is a result of the relatively high embankment height above the top of the culvert, and is probably a driver for why the culvert has a relatively large size in relation to the catchment area.

This sensitivity to blockage at C11 has a significant influence on the probability-neutral flood level (yellow line), which diverges much higher than the level produced by average blockage for AEPs rarer than 20% AEP. This is because although the probability of blockage greater than 50% is relatively low, the consequences of such blockage on the flood level are high at this location. The risks of blockage at this location are asymmetric.

At C07 on the other hand, the probability-neutral blockage tracks very closely with the level produced by the mean of the assumed blockage distribution. This is due to the relative insensitivity to blockage at this location. At C07, this is brought about by the fact that for larger flood events, the culvert only has capacity for a relatively small proportion of the total flow, and most flow will overtop the culvert regardless of whether blockage occurs.

This comparison highlights that significant variation of flow behaviour is possible as a result of blockage, depending on the local conditions. However it also introduces an important finding – the blockage for a probability-neutral flood level can be higher than the mean or median of the underlying blockage probability distribution. For example in the analysis at site C11, the following results are obtained:

- Mean of distribution (“average” blockage) – 28%
- Median of distribution (exceeded 50% of the time) – 10%
- Mode of distribution (“most likely” blockage) – 0%
- Probability-neutral blockage for 1% AEP flood level – 47%

This result arises because of the asymmetrical risks associated with higher blockage, and will generally be the case at any location where the minimum level for overtopping flows is much higher than the soffit (top) of the culvert. Of the sites investigated, this behaviour is most notable at locations C3, C8, C11, C13, C16, and C17. At other locations, the probability-neutral blockage closely tracks the mean of the assumed blockage probability distribution.

Correlation of blockage with flood magnitude

There was evidence that blockage is less of an issue for more smaller flood events, due to reduced mobilisation of debris from overbank flow. There were fewer photographs of blockage available from these events, suggesting there were less blockages to take photographs of. There have been numerous smaller floods than August 1998 in Wollongong in the last ten years, when portable digital cameras have been readily available, and to some degree it should be assumed that if there was serious and wide ranging evidence of blockage from these events there would be more photographic evidence available.

Figure 4: Probabilistic modelling results at Memorial Drive, Towradgi (near Carr St)

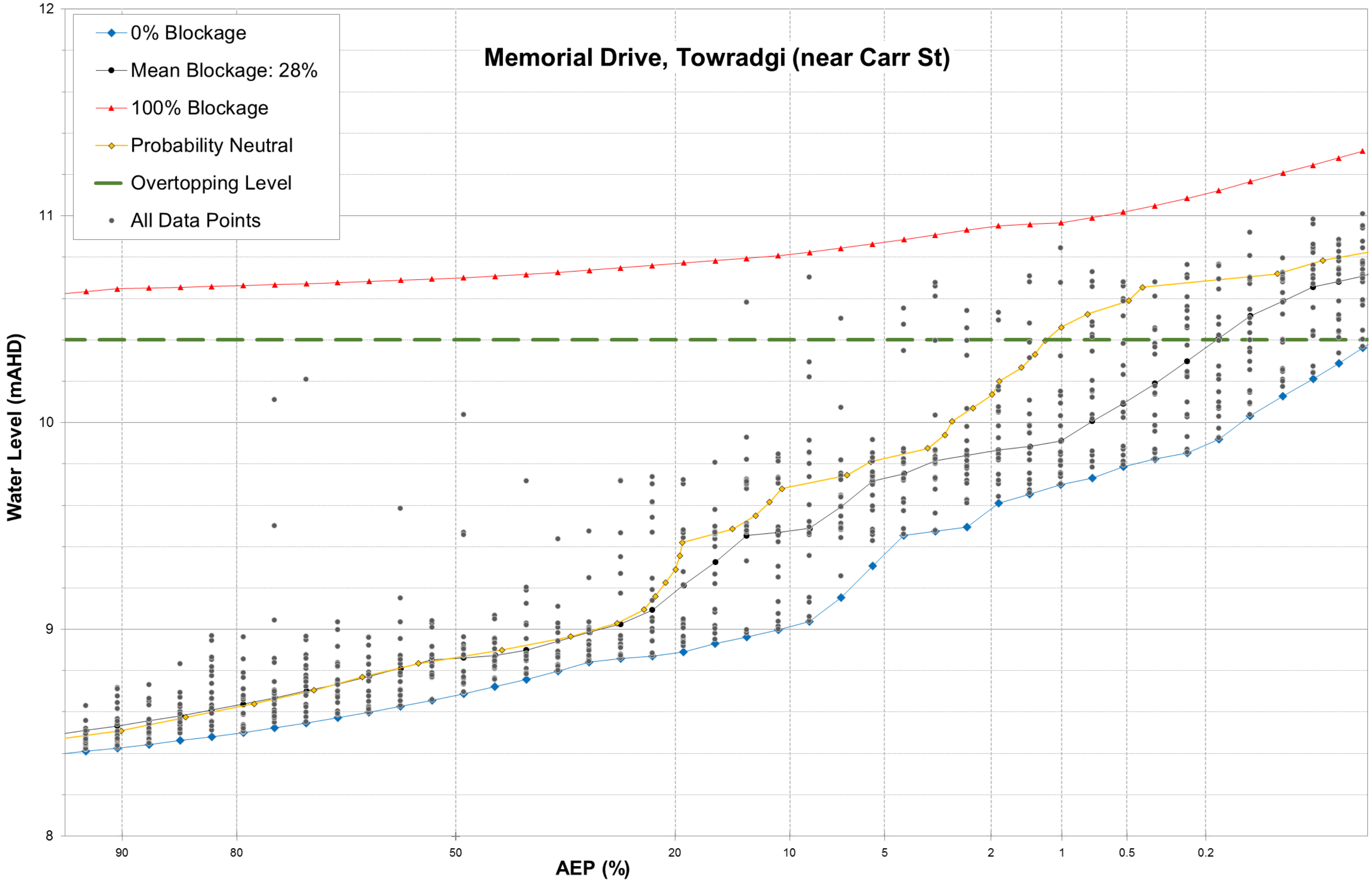
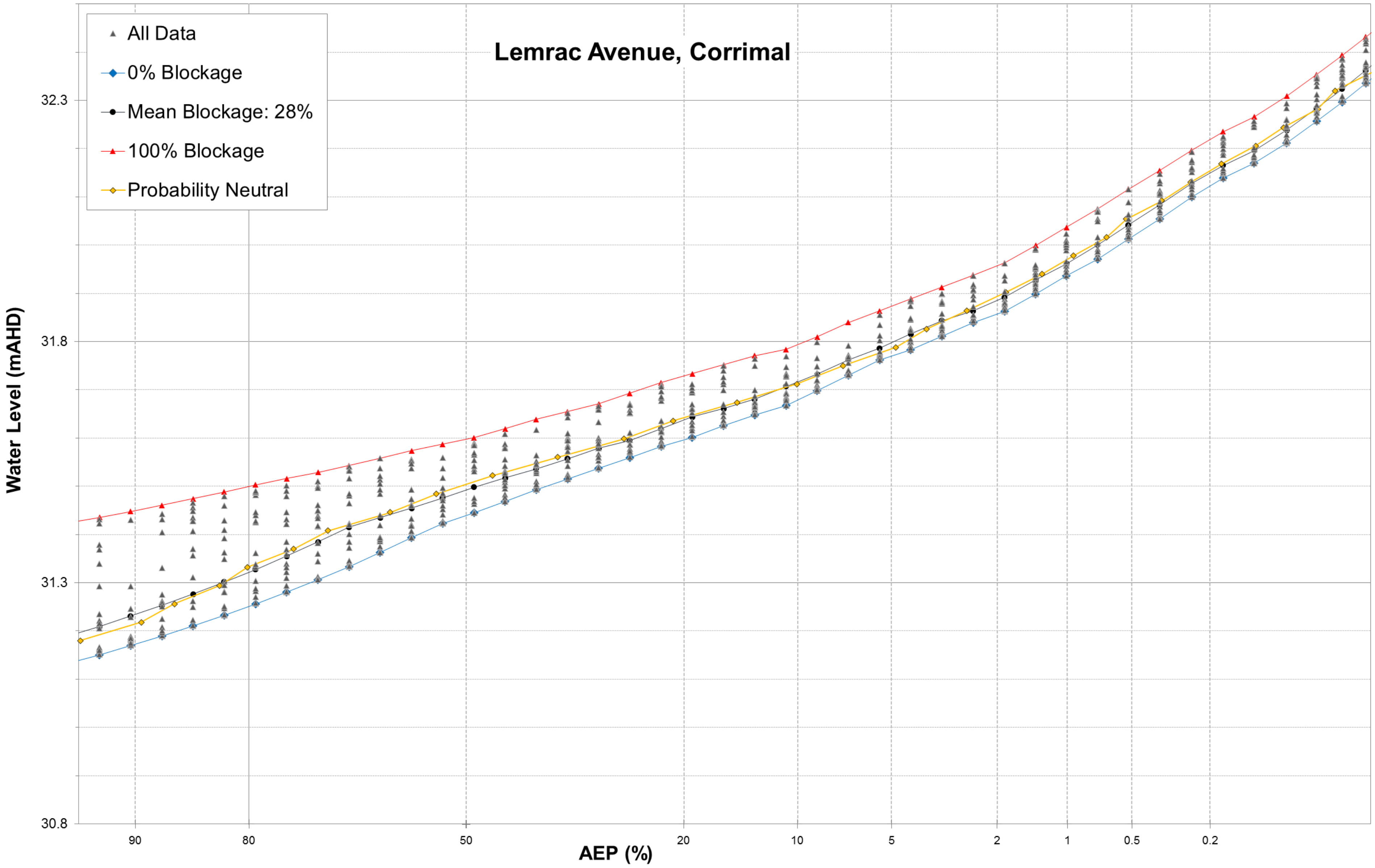


Figure 5: Probabilistic modelling results at Lemrac Avenue, Corrimal



Correlation of blockage with physical catchment characteristics

As part of the data review, it became apparent that certain locations in Wollongong are more susceptible to frequent blockage than others. At 8 Lemrac Avenue for example, photographs showing significant vegetation blockage were available from three separate flood events (1998, 2011, and 2014). The culvert at this location is the first hydraulic structure placed at the bottom of a reasonably large natural catchment on the escarpment. In response to the extreme amount of debris accumulation in August 1998 (Figure 1), a debris collection structure was constructed further upstream from the culvert inlet. However despite this fence becoming completely clogged with debris in 2014, it still could not prevent major blockage of the Lemrac Avenue pipe occurring in that storm.

Furthermore, the qualitative information and photographs provided by Council maintenance personnel indicate that there are certain sites which are more prone to accumulation of silt and urban debris in the periods between large storms.

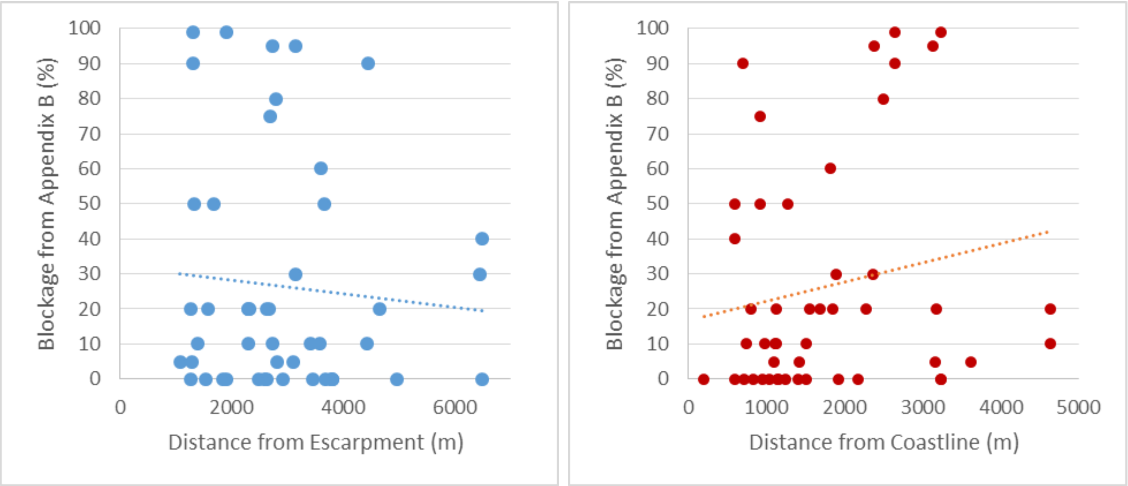
Based on these examples, it is tempting to draw a conclusion that similarly placed culverts will be similarly susceptible – that is, those culverts with mostly natural catchments immediately upstream. There are compelling logical reasons why such relationships might exist.

However, there are numerous such culverts in the Wollongong LGA, and these instances alone are not sufficient to assert that such behaviour will always occur. Given the number of similar locations, the lack of records of similar frequent blockages occurring at other locations may be evidence there is not a strong relationship. For example, other nearby catchments may have different vegetation that is sturdier, or physical features that are more likely to filter out debris from the flow so that it does not reach the culvert.

It might also be expected that predisposition to blockage might be related to the catchment slope and/or stream power. Since localised catchment slope is difficult to determine for each of the culverts in the dataset, the distance from the coast/escarpment was investigated as a proxy. Figure 6 shows blockage data plotted against the distance to the Illawarra escarpment, and the distance to the coast line.

The plots show a weak trend whereby blockage severity decreases as the culvert becomes further from the escarpment, or closer to the coast (i.e. lower blockage in flatter areas).

Figure 6: Historical blockage estimates versus distance from coast / escarpment



However there is significant uncertainty surrounding this relationship. The 95% confidence limits for the trend-line gradient include zero – that is, we cannot conclude from the available data that the trend with distance is significantly different from zero (a flat line). For example in Figure 6 the trend line gradient for the distance to the coast has a value of 0.005, with a P value of 0.2 indicating that the trend is statistically indistinguishable from zero (no trend). The upper 95% confidence limit is 0.014 and the lower 95% confidence limit is -0.04.

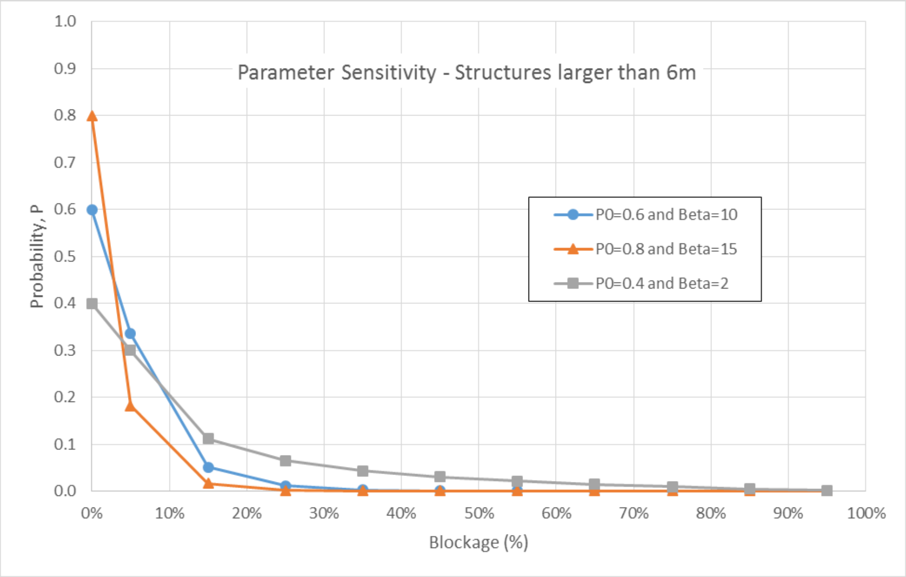
WMAwater's testing of this hypothesis therefore did not identify strong relationships that could be used for setting different blockage factors in different parts of the LGA. It was determined that while correlations of blockage severity with land-use, stream slope or other catchment characteristics may exist, there is not sufficient information currently available to quantify the correlations, or justify incorporating additional complexity into the blockage policy. This issue should be investigated further should suitable additional data become available and revisions made if required.

Sensitivity analysis of fitted blockage distributions

The blockage distribution fitted to the data is an important input to the probabilistic modelling analysis. Given the uncertainties associated with the dataset, it is therefore important to understand the sensitivity of the modelling results to variations in the assumed distribution. For each of the fitted distributions, the parameters were altered to produce distributions that would result in either higher or lower blockage likelihood, by modifying the P_0 and β parameters. The variations adopted for the sensitivity were arbitrary, and were selected in an attempt to represent possible variation in the blockage sample, in particular as a result of either more/less sites with no blockage (using the P_0 parameter) or with severe blockage (using the β parameter).

An example of the alternative distributions tested for structures with opening size greater than 6 m is shown in Figure 7.

Figure 7: Parameter sensitivity of blockage distributions



The main result of sensitivity test is the variation in the mean of the distributions. As noted from the results of the stochastic modelling, in most cases the probability-neutral blockage tracked closely with the mean blockage for many sites. These results are summarised in Table 2.

Table 2: Sensitivity analysis of fitted blockage distributions

Dataset (by diagonal opening size)	**Distribution Parameters**			**Resulting Mean Blockage**		
	Base fitted distribution	Decreased blockage likelihood	Increased blockage likelihood	Base fitted distribution	Decreased blockage likelihood	Increased blockage likelihood
Smaller than 3 m	$\alpha = 0.6$ $\beta = 1.0$ $P_0 = 0.3$	$\alpha = 0.6$ $\beta = 1.5$ $P_0 = 0.4$	$\alpha = 0.6$ $\beta = 0.5$ $P_0 = 0.2$	**28%**	**21%**	**38%**
3 m to 6 m	$\alpha = 0.6$ $\beta = 1.5$ $P_0 = 0.3$	$\alpha = 0.6$ $\beta = 3$ $P_0 = 0.4$	$\alpha = 0.6$ $\beta = 1.0$ $P_0 = 0.2$	**22%**	**11%**	**32%**
Larger than 6 m	$\alpha = 0.2$ $\beta = 10$ $P_0 = 0.6$	$\alpha = 0.2$ $\beta = 15$ $P_0 = 0.8$	$\alpha = 0.2$ $\beta = 2$ $P_0 = 0.4$	**3%**	**1%**	**11%**

There are individual sites where the sensitivity to blockage is higher than other locations. This is true for other uncertainties in the flood estimation process such as rainfall intensities, joint probability of other catchment flooding, changes in channel condition (such as vegetation growth), and future changes in climate. As with these other uncertainties, a typical way to address sites where there are high consequences associated with inaccuracy of flood estimates, is through local factors of safety (typically applied as freeboard for flood levels) for the purpose at hand.

Conclusions

Based on the outcomes of the data compilation and probabilistic modelling analysis, it was recommended that Council's blockage policy be revised. Part of the recommended policy revision was adjustments to the design blockage factors, as outlined in Table 3. The previous policy dictated blockage factors of 100% for structures smaller than 6 m (Classes 1 to 3), and 25% blockage for structures larger than 6 m (Class 4).

Table 3: Recommended design blockage factors for Wollongong

Design Flood AEP	**Bridge / Culvert Classification**				**Obstruction of Overtopping Flows**
	Class 1	**Class 2**	**Class 3**	**Class 4**	
20% AEP or more frequent	35%	25%	15%	0%	Must include appropriate representation of obstructions to flow, such as bridge decks, fences, handrails, buildings, crash/noise barriers, etc. Modelling of pervious structures such as fences and railings above the structure should assume a 50% debris blockage of the unblocked flow area through the obstruction, plus associated hydraulic energy losses.
Rarer than 20% AEP and more frequent than 2% AEP	50%	40%	30%	5%	
2% AEP or greater	70%	50%	40%	10%	

The classes are defined as follows, with some additional requirements on minimum vertical and horizontal dimensions for box culverts:

Class 1. Diagonal opening of 1.2m or smaller.

Class 2. Diagonal opening of more than 1.2m, up to 3 m.
Class 3. Diagonal opening of more than 3 m up to 6 m
Class 4. Diagonal opening greater than 6 m.

The review identified significant uncertainties relating to the blockage data collected in the aftermath of the August 1998 flood event. The modelling analysis completed as part of the review and the blockage factors developed for the revised policy are heavily reliant on re-interpretation of available photographic records from the August 1998 flooding. Additional data is required to increase confidence in the policy blockage factors. It is recommended that Council implement a comprehensive blockage data collection procedure, which can be implemented immediately following future major flood events. The procedure should be designed to:

a) Collect photographic records of culverts and bridges as soon after flooding as possible, with shots taken looking directly into the culvert barrels from both upstream and downstream, as well as other angles.
b) Survey maximum flood levels (where available, e.g. from debris marks) upstream and downstream of the culvert.
c) Collect from all culverts within a particular area, not just those where blockage is perceived to have occurred. This is vital to improve the understanding of the underlying probability of blockage occurring.
d) Utilise handheld GPS receivers to record the coordinates of photographs in the database, so that spatial analysis can be undertaken.

The blockage policy should be subject to periodic future review, particularly after any future extreme storms if additional data on blockage has been collected.

In light of the lack of experimental understanding about blockage mechanisms, further research involving physical modelling (e.g. Kramer et. al. 2016) is encouraged.

The design blockage factors identified above are not recommended for wholesale adoption in other regions, without undertaking a similar analysis using local observed blockage data. As noted in the introduction, there are a range of contributing factors which make culverts and bridges in Wollongong relatively susceptible to blockage, and which make flood levels at some locations highly sensitive to this blockage. This may not be the case in other parts of Australia.

The methodology presented in this paper is a robust method for estimating probability neutral blockage factors where data are available. The full probabilistic analysis is not required to be repeated as part of regular design flood modelling. This would be impractical as it requires consideration of thousands of different rainfall/blockage combinations to be assessed at every structure. However this analysis framework could be applied in other regions to develop similar policies, if sufficient blockage data is available.

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