ARR BLOCKAGE: NUMERICAL IMPLEMENTATION AND THREE CASE STUDIES

Paul Ollett[1] Bill Syme[2]
[1]HYDRA*LINC* Pty Ltd, Gold Coast, Queensland
[2]BMT WBM Pty Ltd, Brisbane, Queensland

ABSTRACT

Comprehensive guidance on the blockage of hydraulic structures, especially culvert entrances, has always been sparse. Recently guidance on the blockage of hydraulic structures has now been provided to the industry for comment through the Australian Rainfall and Runoff (ARR) Book 6 Chapter 6 (second draft) and associated Revision Project 11 Stage 1 and Stage 2 research reports. The ARR Revision Project 11 Stage 1 report and Stage 3 Blockage Guidelines offers an energy based method for calculation of blockage discharge, which differs significantly in its approach to 'hydraulics' from conventional industry practice. The effect of this additional methodology on flood and stormwater studies is largely unknown. The ARR guidance also produces blockage factors that are both Annual Exceedance Probability (AEP) dependant, and location dependent within a catchment, and are therefore difficult to implement in flood hydraulic packages. In this paper the ARR blockage approach is implemented in the TUFLOW software, whereby blockage scenarios based on differing AEPs and catchment land-uses may be easily managed via the Event Management functionality. The ARR blockage energy approach is compared with conventional industry blockage calculations to examine how the methods differ in theory. Finally, the ARR blockage method is compared with conventional practice using three flood models. Two of the models are large creek models from the Brisbane local government area. The third model is of a recent large subdivision application where the impacts on lot yield are important.

Key words: Australian Rainfall and Runoff, ARR, blockage, culvert, energy loss, flood, hydraulics, matrix, modelling.

1 INTRODUCTION

Australia's national guideline on flood estimation, Australian Rainfall & Runoff (ARR), is about to be updated. The new ARR was 'officially released' as a partially completed document in 2015 (Ball, 2015), with finalisation of the remaining chapters due later this year 2016. The ARR 2015 review early on identified knowledge gaps in the industry, and undertook a series of Revision Projects to help fill these gaps. Revision Project 11 Blockage of Hydraulic Structures has been undertaken in a series of stages:

- **Project 11 Stage 1** Final Report November 2009 (Weeks, et. al., 2009);
- **Project 11 Stage 2** Final Report, February 2013 (Weeks, et. al., 2013);
- **Project 11 Stage 3** Blockage Guidelines – Draft for Discussion, February 2014 (Weeks, 2014);
- **ARR 2015 Book 6 Chapter 6** Blockage of Hydraulic Structures – Draft for Industry Comment, November 2015 (Weeks and Rigby, 2015).

A review of these reports was undertaken to determine what requirements may be needed from the point of view of incorporating the new guidance into stormwater and floodplain flood simulation, in applications where 2-dimensional flood routing technology is commonly employed.

It should be noted that the following paper does not attempt to provide guidance on the assessment of debris quantities or the management of debris which are also included in the ARR reports, but only the application of the guidance directly to flood simulation.

2 ARR BLOCKAGE OVERVIEW

The purpose of this section is to identify where flood software enhancements are warranted to facilitate implementation of the new ARR guidelines.

2.1 Location of Structure and Risk Dependence

Weeks and Rigby (2015) provide guidance for assessment of debris availability, mobility, and transportability with the aim to assess debris potential. All of these factors are heavily dependent on the nature of the catchment's land use, and position of the structure within the catchment and stream network. Therefore each structure may be subject to one of nine debris potential categories (Weeks and Rigby, 2015, Table 6.6.4).

Also discussed is a risk based assessment of blockages, where sensitivity analysis is recommended in order to identify areas where consequences due to various blockage scenarios are high. Sensitivity tests are recommended for an “all clear” to assess potential for increased downstream flooding, and the case for $2xB_{DES}$ (upper limit 100%) to assess increased flooding upstream.

Monte Carlo or stochastic modelling of debris blockage is discussed along with its benefits, however the approach is limited by our current lack of knowledge on distributions of blockage values.

2.2 AEP Dependence

ARR (Weeks and Rigby, 2015) gives specific guidance on debris potential in relation to storm AEP. Heavier rainfall events are more likely to produce and mobilise debris. Section 6.4.4.6 provides guidance which allows adjustment of AEP. For example, in the case where $W < L_{10}$, values of B_{DES}% from Table 6.6.6, substituted into Table 6.6.5, would produce adjusted blockage estimates as follows.

Table 2.1 AEP Adjusted Debris Blockage (B_{DES}%) for Case $W < L_{10}$

AEP [ARI]	Debris Potential at Structure		
	High	Medium	Low
>5% [<20yr]	50%	25%	25%
5%-0.5% [20yr-200yr]	100%	50%	25%
<0.5% [>200yr]	100%	100%	50%

2.3 Positioning of Debris at Inlet

The positioning of debris at the inlet is outlined by three blockage types (see Section 6.5.2), being ‘top down’ (accumulation at obvert), ‘bottom up’ (usually sediment deposition), and a ‘porous plug’ where debris covers the entire entrance with some porosity remaining to pass flow. Added to these types (but not included in ARR) is the potential for side blockage, especially in the case of unsubmerged flow, and a general all-round perimeter type blockage.

2.4 Timing and Growth of Blockage

Section 6.5.3 and Table 6.6.9 provide guidance on the growth and timing of the fully developed blockage (B_{DES}) during the flood event, for floating and non-floating debris.

2.5 Blockage Methods

Witheridge (2009) and Weeks (2009, 2014) introduce a blockage calculation system based on whether the culvert is operating under inlet or outlet control. For outlet control a modified energy loss coefficient is applied to the culvert inlet, and for inlet control a general equation is introduced which reduces the discharge capacity of the culvert based on the blockage ratio (BR). This approach is not considered compulsory under the draft ARR blockage guidelines (Weeks and Rigby, 2015).

In addition to this, general industry practice (as observed by the author) is to implement blockage by reducing the culvert’s area by the estimated percentage blockage (B_{DES}%). This method is applied in both inlet control and outlet control cases.

These two general approaches are outlined in more detail below with comparisons made between them.

3 CULVERT HYDRAULICS

A typical culvert arrangement along with dimensions and measurement locations as referenced in this paper is shown in Figure 3.1 below. Also, a common entrance with and without blockage is shown in Figure 3.2 below. The standard equations which govern culvert discharge under inlet control and outlet control conditions are discussed as follows.

3.1 Inlet Control

Under inlet control conditions discharge becomes supercritical near the culvert entrance and is often supercritical along the barrel (Dyhouse, 2007, p.238).

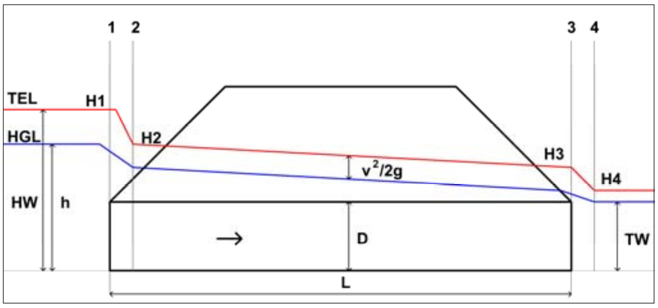


Figure 3.1 Culvert flowing full

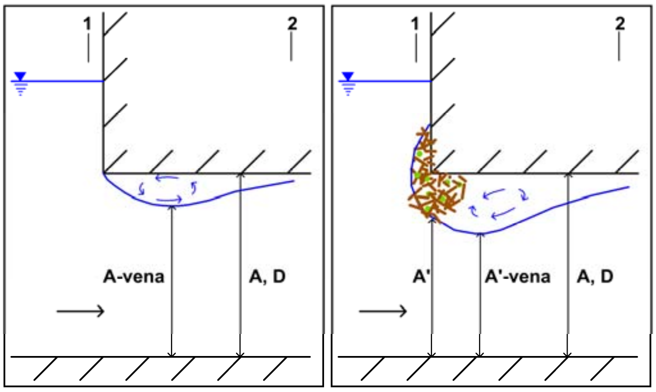


Figure 3.2a Clear culvert.   3.2b Blocked culvert.

The discharge capacity of the culvert is dependent on conditions at the inlet. A large amount of guidance is available for the many different types of culverts operating under inlet control, for example, Dyhouse (2007, p.245-7) and Henderson (1966, p.263). The TUFLOW software used for this paper utilises the inlet control equations in Henderson (Syme, 2016, *pers. comm.*). For unsubmerged flow where H/D < 1.2

$$Q = \frac{2}{3} C_B BH \sqrt{\frac{2}{3} gH} \quad \text{(Eq. 3.1)}$$

And for submerged flow where H/D > 1.2

$$Q = C_h BD \sqrt{2g(H - C_h D)} \quad \text{(Eq. 3.2)}$$

3.2 Outlet Control

Under outlet control conditions flow is subcritical along the culvert and the Energy Equation (or also called the Bernoulli Equation) is universally applied. The discharge capacity of the culvert is dependent on conditions at the outlet. The Energy Equation starts with an energy level at Station 4, and adds energy losses to this along the culvert to form the Total Energy Line (TEL), to determine the headwater level at Station 1 (Figure 3.1). The different types of energy losses comprise an inlet contraction loss between Stations 1-2, friction loss between Stations 2-3, and outlet expansion loss between Stations 3-4.

The energy level at a station is computed by

$$H = h + \frac{v^2}{2g} \quad \text{(Eq. 3.3)}$$

and the energy levels at stations 1 and 4 are related by

$$H_1 = H_4 + \text{losses} \quad \text{(Eq. 3.4)}$$

where losses comprise an inlet contraction loss (Eq.3.5), friction loss (Eq.3.6) and outlet expansion loss (Eq.3.7a,b).

$$\Delta H_{1-2} = k_e \frac{v_2^2}{2g} \quad \text{(Eq. 3.5)}$$

$$\Delta H_{2-3} = v_{2-3}^2 \frac{n^2 L}{R^{4/3}} \quad \text{(Eq. 3.6)}$$

$$\Delta H_{3-4} = k_o \frac{(v_3 - v_4)^2}{2g} \quad \text{(Eq. 3.7}a\text{)}$$

$$\Delta H_{3-4} = k_o \frac{v_3^2 - v_4^2}{2g} \quad \text{(Eq. 3.7b)}$$

Two outlet expansion loss equations are available in the literature, both being discussed in Henderson (1966, p.237). If the outlet velocity is assumed to be zero (as is commonly the case in engineering manuals), then the two equations become equivalent.

Different equations are available to calculate friction loss, with the one adopted above being the Manning's Equation, with ΔH_{2-3} being the vertical component of the friction slope.

Finally it is worth noting that the inlet contraction energy loss does not occur due to the flow contraction, but actually occurs due to flow expansion (and associated turbulence) downstream of the vena contracta as A_{vena} expands to A. This applies to both partially blocked and clear entrances.

3.3 Blockage Hydraulics

Two approaches are generally available when undertaking blockage analysis. The first approach is to reduce the area (A) of the culvert to the area of residual free space (A') once blockage is applied. This method is the only approach available to inlet control conditions, and is referred to as the Reduced Area Method (RAM).

For culverts which are blocked under inlet control, Witheridge (2009) and Weeks (2009, 2014) apply a basic equation which may be used to approximate the reduction in discharge capacity

$$BF = BR^{5/4} \quad \text{(Eq. 3.8)}$$

This empirical equation was derived from inlet control charts to determine the effects of variations in inlet area. As Henderson's (1966) inlet control Eq. 3.1 and 3.2 directly calculate culvert discharge capacity, Eq. 3.8 was not required.

Under outlet control conditions, two methods are available, the RAM as discussed, and also the Energy

Loss Method (ELM). The ELM is derived by Witheridge (2009), using Miller (1990, p.364)

$$k_e = \left(1 - \frac{A_{vena}}{A}\right)^2 \left(\frac{A}{A_{vena}}\right)^2 \quad (Eq. 3.9)$$

to modify k_e by incorporating the geometry of the blockage, so that Eq 3.5 above becomes

$$\Delta H'_{1-2} = k'_e \frac{V_2^2}{2g} \quad (Eq. 3.10)$$

where

$$k'_e = \left(\frac{1 + \sqrt{k_e}}{BR} - 1\right)^2 \quad (Eq. 3.11)$$

Where no blockage exists, then BR (or A'/A) (see Figure 3.2) becomes unity and Eq. 3.11 reduces to k_e. For nominal values of k_e, Table 3.1 gives the computed values of k'_e.

Table 3.1 Computed Values of k'_e

B_{DES}%	BR	k_e			
		0.3	**0.5**	**0.7**	**1.0**
		k'_e			
0	1.00	0.3	0.5	0.7	1.0
20	0.80	0.9	1.3	1.7	2.3
50	0.50	4.4	5.8	7.1	9.0
80	0.20	45	55	65	80
90	0.10	210	260	300	360
95	0.05	900	1100	1270	1520
100	0.00	∞	∞	∞	∞

The k'_e values for high levels of blockage (B_{DES}>50%) are very similar to other coefficients for sudden contractions, where k is related to the downstream velocity head, for example, stormwater pipeline service penetrations (DEWS, 2013, p.7-83), and valve loss coefficients (Miller, 1994, p.206).

4 SOFTWARE IMPLEMENTATION

4.1 Phased Approach

Implementation of the blockage functionality into the TUFLOW hydraulic software is to be undertaken in three to four phases.

Phase 1 (1-dimensional structures). Structure location and risk; AEP dependence; implementation of alternative 'outlet control' inlet expansion loss Eq. 3.10 and 3.11; and implement the RAM and ELM methods.
Phase 2 (2-dimensional structures). Extension of functionality to 2-dimensional structures. Also, positioning of debris at inlet using attribute flags (for example, T = top down, B = bottom up, S = sidewalls, C=circumference, P=porous). Guidance for porous blockage potentially based on grate analysis.
Phase 3. Blockage growth and timing.
Phase 4. Monte Carlo analysis as literature and guidance becomes available.

Phase 1 has been completed as part of this investigation, with Phase 2 to be implemented in the near future.

4.2 Phase 1 Overview

Structure location, Risk, AEP dependence. In order to efficiently manage a large combination of blockage scenarios, a matrix approach was adopted whereby up to 100 different classes or types of blockage can be defined (B_{DES}%) based on location within a catchment, likelihood to collect debris, all clear case, extreme blockage, and sensitivity testing (risk). For each class or type, associated blockage values may also be specified for AEP. An example matrix is provided below (see Table 4.1). Matrix scenarios may be specified for structures based on a specified default value, and an override value, or individual structure values. The ARI (used for ease of naming model files and results) is linked to the model simulation AEP, and intermediate values of ARI are interpolated.

Table 4.1 Example Blockage Matrix (B_{DES}%)

ARI	A	B	C	D	E
1	00	25	25	50	100
10	00	25	25	50	100
20	00	25	50	100	100
200	00	25	50	100	100
500	00	50	100	100	100
PMF	00	50	100	100	100

Reduced Area Method (RAM). The area of the structure is reduced by incorporating B_{DES}% in the blockage matrix into the already existing "pblockage" field used in TUFLOW for 1-dimensional culvert structures. TUFLOW currently reduces the structure width (B) for box culverts, and diameter (D) for pipe culverts to achieve the reduction in area. The RAM approach is currently applied to culverts under inlet control, and is optional under outlet control.

Energy Loss Method (ELM). The area of the structure is not modified, however the energy loss coefficient for the entrance (k_e) is increased to account for the greater flow expansion downstream of the Vena Contracta by Eq. 3.10 (see Figure 3.2a). Again, use is made of the pre-existing 1D attribute for TUFLOW structures called "form_loss", where k_e values of >1 may be applied. The same matrix is still populated by B_{DES}% and the software computes BR for Eq. 3.11. The ELM is only available under outlet control conditions.

5 TESTING OF SOFTWARE AND METHODS

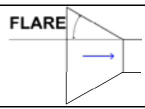
5.1 Verification of Henderson for Inlet Control

Overview. The inlet control equations documented in Henderson (1966, p.263) are not widely known, and it therefore seemed prudent to test these equations against more commonly used procedures. Potentially the most widely known inlet control system in Australia is the inlet control nomograph series re-produced by the Concrete Pipe Association of Australia (CPAA) (Aagren, 2003, p.33-34). The CPAA nomographs comprise six different inlet types (3 for pipes, 3 for boxes) whereas Henderson only distinguishes between round or square edged culverts.

Test Setup. A range of tests was undertaken to fit the Henderson equations to the CPAA nomographs by varying either C_B for an unsubmerged inlet (HW/D<1.2) or C_h (HW/D > 1.2) for a submerged inlet. A range of tests was undertaken for box culverts (D 0.6, 1.2, 1.8m for a unit width), pipe culverts (D 0.75, 1.2, 1.8m), HW/D (0.5, 1.0, 1.5, 3.0), and inlet types (1, 2, and 3). The Henderson equations were fitted to the CPAA test data using a 'Coefficient of Determination' (R^2) analysis, and the values of computed C_B and C_h were compared with the Henderson guidance to check for consistency (see Table 5.1).

Results. The results are given in Table 5.1.

Table 5.1 Inlet Control Contraction Coefficients

Inlet Type (by C_h)		C_h	R^2	C_B	R^2
CPAA Box Type 3: Extensions of sides 0°		0.57	1.00	0.86	1.00
Henderson: Edges square		0.60	-	0.90	-
CPAA Box Type 2: Wingwall flare 15° & 90°		0.63	1.00	0.88	1.00
CPAA Pipe Type 1: Square edge with headwall		0.64	1.00	0.97	1.00
CPAA Box Type 1: Wingwall flare 30° -70°		0.66	1.00	0.97	1.00
CPAA Pipe Type 3: Socket end projecting		0.72	1.00	1.00	0.88
CPAA Pipe Type 2: Socket end with headwall		0.74	1.00	1.00	0.93
Henderson: Edges round		0.80	-	1.00	-

Summary. Generally the Henderson equations and coefficients fitted well with the CPAA nomograph data. As the Henderson equations provided such a close fit, it is suspected that the two methods may have similar origins.

5.2 Verification of ELM and RAM for Outlet Control

Overview. The purpose of the ELM and RAM testing is two fold. First, the implementation of the ELM and blockage matrix in TUFLOW is tested against the equations in Section 3 to check agreement. Second, these tests undertaken comprised typical design scenarios in order to draw-out trends between the ELM and RAM approaches.

Test Setup. The test setup comprised four culverts (boxes B2.4xD1.2 and B1.2xD0.6; pipes D1.2 and D0.75), with HW/D of 1.5, 2.0 and 2.5 for the unblocked case. Measurements of discharge were made. Then blockages (B_{DES}%) of 20% and 50% were applied to all cases, keeping discharge constant and measuring the change in HW. The B_{DES} of 20% was chosen to allow readers to compare results with blockage guidance in the Queensland Urban Drainage Manual (QUDM) (DEWS, 2013, p.10-9). A culvert length of 20m was used assuming a road width of 10m, Manning's 'n' of 0.013, k_e=0.5, k_o= 1.0, v_4=0.0, and TW=D. In order to measure the maximum possible increase in headwater, a vertical 'glass wall' was assumed at the inlet headwall.

Entry Loss Coefficients. Values of k_e' calculated for the tests are given in Table 3.1. For k_e=0.5 and B_{DES}=20% & 50%, values of k_e' were 1.3 and 5.8 respectively.

Results. Results of headwater (HW) versus discharge (Q) are shown in Figures 5.2 to 5.5. The results reflect similar trends for all culverts tested, therefore specific discussion is made only in relation to the D0.7m pipe B_{DES} 50% blockage case and HW/D of 2.5. The TUFLOW software provided an almost exact match in all test cases when compared equations in Section 3. Table 5.2 gives detailed values of energy loss and energy level in relation to the measuring Stations 1 to 4 (see Figures 3.1 and 3.2a, b).

with culvert length, when in reality they are independent of friction losses.

Table 5.2 Results for Pipe D0.75 and B_{DES} 50%

Method	ELM	RAM	BASE
D	0.75	0.53	0.75
A	0.44	0.22	0.44
v_{2-3}	3.23	6.46	3.23
k_e or $[k'_e]$	[5.83]	0.50	0.50
Q	1.43	1.43	1.43
ΔH (energy loss)			
ΔH_{3-4}	0.53	2.13	0.53
ΔH_{2-3}	0.33	2.09	0.33
ΔH_{1-2}	3.10	1.07	0.27
Total	3.96	5.29	1.13
H (energy level)			
H_4	0.75	0.75	0.75
H_3	1.28	2.88	1.28
H_2	1.61	4.97	1.61
H_1	4.71	6.04	1.88

The final headwater level (H_1) for the RAM is 6.04m, which is significantly higher than the ELM of 4.71m. As the RAM reduces the culvert area, velocity in the barrel correspondingly increases, leading to a higher outlet loss (ΔH_{3-4}), higher friction loss (ΔH_{2-3}) and a moderate inlet loss (ΔH_{1-2}). By contrast for the ELM the outlet and friction losses are identical to the base case (no blockage), however the inlet loss is very high which is to be expected. Figure 5.1 below illustrates these results by way of comparing total energy lines (TELs).

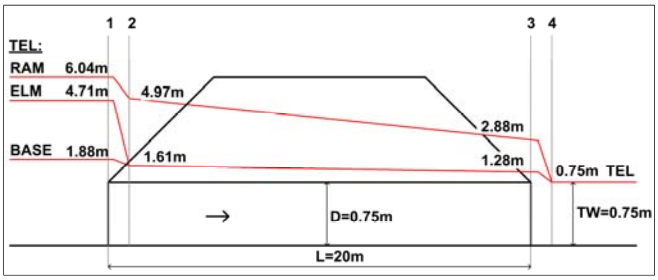


Figure 5.1 TEL Results for D0.75m B_{DES}50%

Summary. The ELM produces the same energy losses as the base case from the outlet upstream to the culvert entrance, and only then do blockage losses become apparent.

Modified entry loss coefficients k'_e due to blockage are in close agreement with similar types of arrangements in the literature, such as service penetrations of stormwater culverts, and valves.

The RAM creates highly inflated velocities in the culvert barrel, leading to exaggerated outlet and friction loses. Headwater levels using the RAM approach can change with culvert length, when in reality they are independent of friction losses.

The RAM consistently produces higher HW levels than the ELM method, and this difference grows with an increase in blockage (B_{DES}).

From Figures 5.2 to 5.5 it may be seen that for an increase in B_{DES} from 20% to 50% there is an exponential increase in headwater. This is due to the squared relationship of energy loss with velocity.

Potential outcomes with respect to civil design and flood risk assessment are discussed in Section 7 Conclusions.

6 CASE STUDY TESTS

Overview. The testing undertaken in the previous section was carried out under 'ideal' steady-state conditions. The ELM and RAM methods are further compared using three real flood models for a range of culvert configurations under fully dynamic conditions. The three flood models sourced for the comparison are:

Lota Creek (Brisbane LGA). The Lota Creek Flood Study was completed by BCC in June 2015, comprises a catchment area of 18.2 km^2, is relatively flat and low-lying, and of residential-rural and rural land-use.

Sheep Station Gully (Brisbane LGA). The Sheep Station Gully Flood Study was completed by BCC in June 2015, comprises a catchment area of 6.6 km^2, is relatively steep and elevated, and of mostly residential and rural-residential land use.

Lowood (Somerset LGA). Finally the Lowood Flood Study was completed as part of a Development Application in October 2015 and has a total catchment area of 3 km^2. The site is steep with land use being rural. The area of the subdivision is approximately 34 ha.

Three culverts were selected for testing in each of the Lota Creek and Sheep Station Gully Flood Studies. The selection criteria were to consider a range of culvert sizes, and to ensure that culvert blockage at one culvert would not alter results at other culverts upstream or downstream. For the Lowood Flood Study, only the main outlet culvert which forms the subdivisions detention and controls development levels was selected. Details of the selected culverts are given in Table 6.1 below.

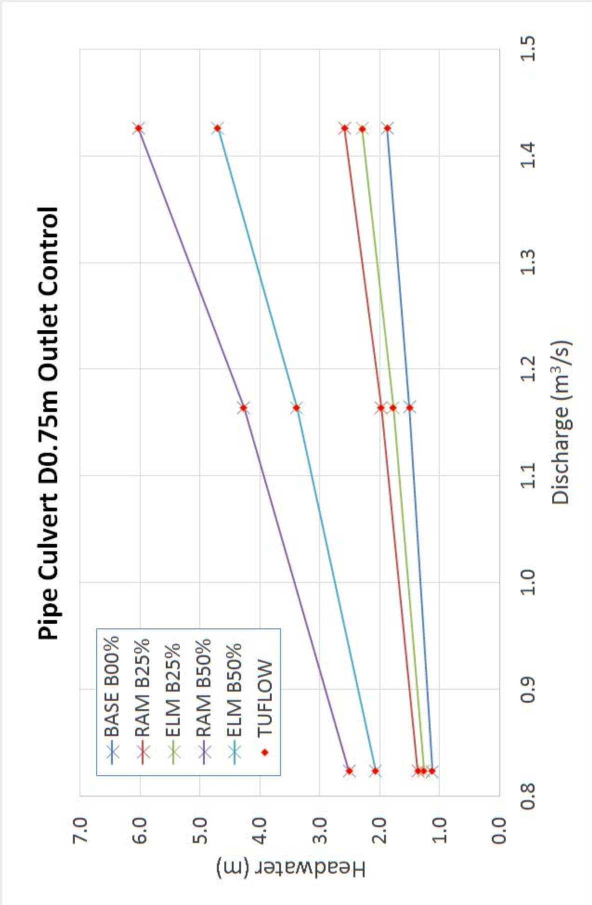


Figure 5.2. Pipe Culvert D 0.75m

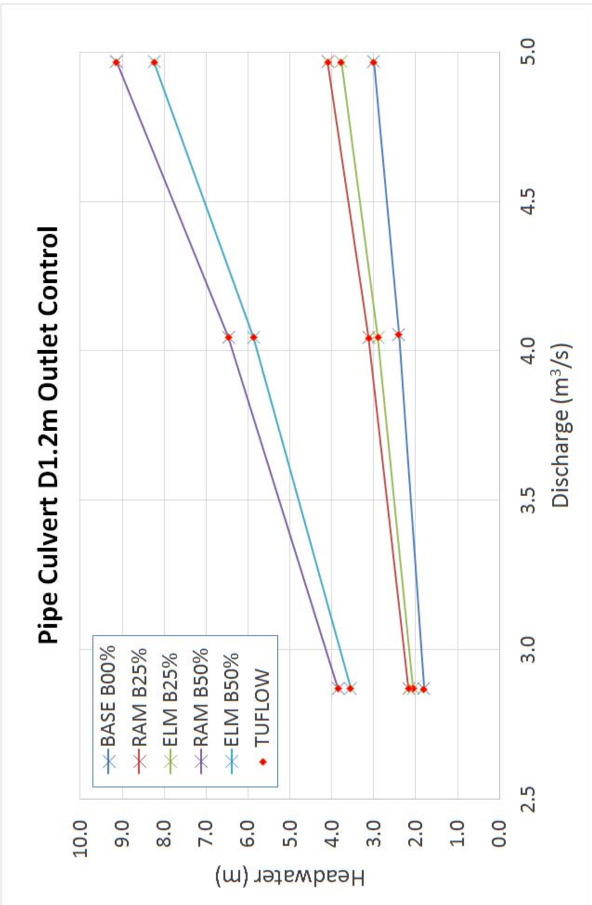


Figure 5.3. Pipe Culvert D 1.2m

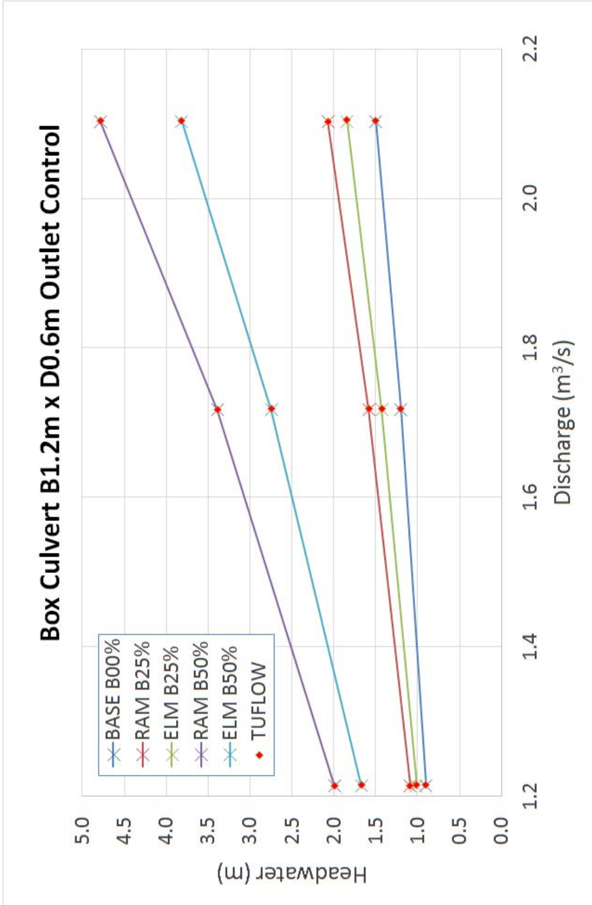


Figure 5.4. Box Culvert B 1.2m D 0.6m

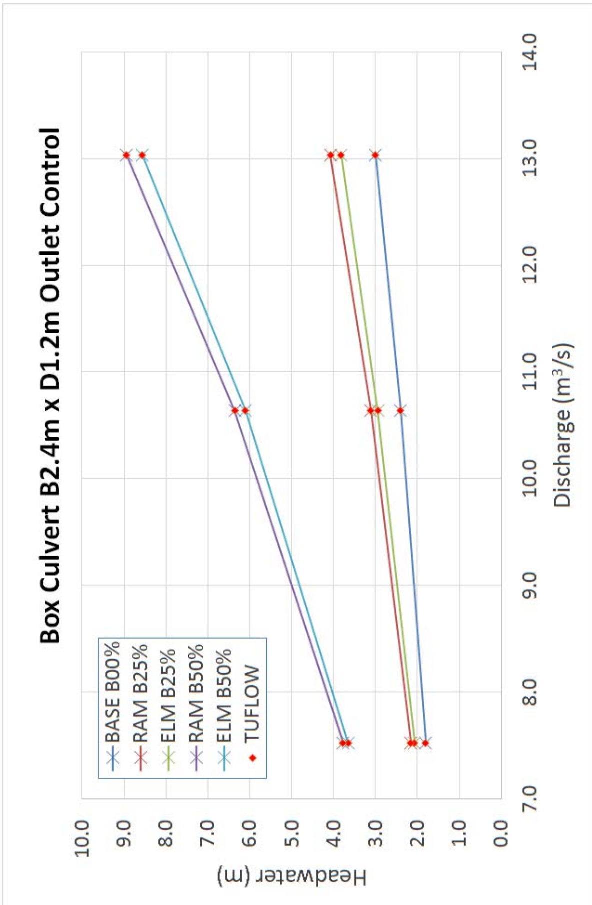


Figure 5.5. Box Culvert B 2.4m D 1.2m

Table 6.1 Flood Study Tested Culverts

Flood Study	ID	Location	Dimensions
Lota Creek	LC-35	Green Camp Rd (North)	4/ B 3.35m x D 1.35m
	LC-34	New Cleveland Rd	2/ B 1.5m x D 1.2m
	LC-51	Green Camp Rd (South)	1/ D 0.6m
Sheep Station Gully	SG-03	Ridgewood Rd	5/ B 3.67m x D 1.84m
	SG-06	Laurel Oak Dr	3/ B 2.75m x D 1.3m
	SG-11	Formby St	7/ D 0.6m
Lowood	LW-01	Subdivision Outlet	3/ B 2.1m x D 1.5m

Figure 6.1. Sheep Station Gully, Ridgewood Road.

Models were run for the 1% AEP flood for the critical storm duration only. Measurements of headwater were recorded for each scenario, along with the control regime (inlet control [IC] or outlet control [OC] at the flood peak). Where a scenario was run for the Energy Loss Method (ELM), if that culvert was operating under inlet control, then the software reverts back to the Reduced Area Method (RAM), due to this being the only method available under inlet control to simulate blockage. See Table 6.2 for results.

Case Study Results Summary. The RAM generally produced higher headwater levels than the ELM. In most cases however the differences were not large. In cases where culverts are completely submerged and velocity is low the two methods produce comparable results. For the 1% AEP flood where RAM headwaters are expected to be higher, road overtopping and floodplain storage may contribute to a tempering of the potential headwater increases.

Table 6.2 Flood Study Test Results

ID	Para-meter	BASE	RAM		ELM	
		0%	20%	50%	20%	50%
LC-35	HWL	4.15	4.20	4.29	4.19	4.29
	Control	OC	OC	OC	OC	OC
LC-34	HWL	13.34	13.37	13.40	13.37	13.38
	Control	IC	IC	IC	IC	OC
LC-51	HWL	3.90	3.90	3.90	3.90	3.90
	Control	OC	OC	OC	OC	OC
SG-03	HWL	14.57	14.77	15.08	14.74	15.06
	Control	OC	OC	OC	OC	OC
SG-06	HWL	22.29	22.45	22.63	22.38	22.56
	Control	IC	IC	IC	OC	OC
SG-11	HWL	23.00	23.00	23.00	22.99	22.99
	Control	OC	OC	OC	OC	OC
LW-01	HWL	71.02	71.38	71.98	71.38	71.37
	Control	IC	IC	IC	IC	OC

In some cases, inlet control was found to occur for the RAM, however for the ELM (especially the 50% blockage case) the culverts were found to operate under outlet control (see LC-34, SG-06, LW-01). From this it may be deduced that the RAM promotes inlet control (which seems sensible given the reduction in area), and that the ELM may promote an outlet control condition. Further testing is needed to explore this potential relationship.

In cases where outlet control exists, and there is a significant build-up of headwater behind a culvert, then there will be potential for significant differences between the RAM and ELM approaches, with ELM producing lower headwater levels.

For example, see LW-01 where the HW for ELM-50% is RL 71.37m, and RAM-50% RL 71.98m. The difference is over 600mm. In this particular case, use of the ELM would result in a reduced flood level estimate.

In situations where culverts and roads are completely drowned, velocities are low, and floodplain storage exists upstream, the differences between the RAM and ELM is expected to be minor.

7 CONCLUSIONS

A review of the recently produced Australian Rainfall and Runoff (ARR) literature on the blockage of hydraulic structures has been undertaken in order to determine how the new practices may be implemented into flood modelling and Hydraulic Impact Assessments. Some key points which may impact on current practices were:

Blockages quantities are now calculated based on catchment conditions, culvert inlet configuration, and Annual Exceedance Probability (AEP) of the design flood. The TUFLOW flood modelling software was enhanced so that blockage can be assigned to structures by way of a blockage-matrix, according to its nominated "category" and the storm AEP being run in the model. The modelling of multiple blockage scenarios can now be automated.

Under inlet control conditions TUFLOW utilises Henderson's equations to determine culvert discharge capacity for a given headwater level. These equations were validated by comparison with the Concrete Pipe Association of Australia (CPAA) inlet control nomographs and found to be in close agreement. Based on this testing, the CPAA nomograph calculations for inlet control may now be undertaken in a spreadsheet (subject to the limits of the parameters tested).

Extended guidance was also developed for the Henderson inlet control equations, by extension to the various culvert inlet configurations in the CPAA nomographs.

An alternative energy loss method (ELM) is given in the ARR Project 11 reports for the calculation of flood levels or culvert headwater due to blockage, which differs significantly to current industry practice of reducing a culvert's area (Reduced Area Method). Detailed tests between these two methods were carried out on both an idealised test model, and also in three recent flood studies. The alternative energy loss method (ELM) was also implemented in the TUFLOW software for testing.

A number of differences were highlighted between the Reduced Area Method (RAM) and the Energy Loss Method (ELM) of applying blockage to culvert entrances. Some of these differences are outlined as follows.

The RAM approach reduces the culvert geometry to match the area due to the debris positioned at the culvert inlet. This approach however reduces the culvert's area for the entire length and is not confined to the inlet. The smaller culvert area leads to higher culvert velocities (twice as high for 50% blockage), leading to over-estimated outlet expansion losses, friction losses along the barrel, and an under-estimated inlet contraction loss.

The overall result of the RAM is to produce higher headwater and flood levels upstream of the culvert. In the majority of cases the increase in headwater is only minor to moderate, however in some cases can be substantial. Higher upstream flood levels can lead to increased construction costs for infrastructure and land development. In addition to this, the higher velocities are misleading, potentially leading to an over-design of culvert outlet works (scour protection and energy dissipation) and exceedance of maximum barrel velocities under QUDM (2013, p.7-43).

Another observation made which pertains to both the RAM and ELM approaches is that head water increase is not a linear relationship to blockage but an exponential one. The increase in headwater from 20% to 50% blockage can be 4-fold that compared with an increase from 0% and 20% blockage. This highlights the importance of competent blockage assessment in culvert design, as the consequences from a culvert which should have been assigned a high blockage factor can be much more severe than anticipated than if it were assigned a nominal blockage factor.

Whichever method is used (RAM or ELM), it is recommended that the hydraulic engineer undertake sensitivity testing using both methods in order to understand any potential differences which may occur.

Traditional use of the RAM may have in the past led to an inbuilt factor of safety in culvert design. If an ELM approach is to be used for future design which may eliminate this safety buffer, the design must also be coupled with a competent assessment of blockage potential and application of debris management techniques as provided in the new ARR guidelines.

ACKNOWLEDGEMENTS

Tuflow Programing – Phillip Ryan, Bill Syme (BMT WBM Pty Ltd)

Peer Review – Steve Roso (Just Roso Pty Ltd), Peter Griffith (City of Gold Coast)

Provision of Brisbane Flood Models – Evan Caswell (Brisbane City Council)

ARR Team & Principal Blockage Authors – Bill Weeks, Ted Rigby, Grant Witheridge

SYMBOLS AND NOTATION

A	cross sectional area of conduit (m^2)
A'	residual free space cross sectional area (m^2)
A_{vena}	cross sectional area of vena contracta (m^2)
B	width of conduit or channel (m)
$B_{DES}\%$	Blockage percentage (1-A'/A)100 or (1-BR)100. (ARR Book 6 Chapter 6)
BF	blockage factor (Q'/Q)
BR	blockage ratio (ratio of free space area to the unblocked conduit area) (A'/A)
C_B	width-contraction coefficient (A_{vena}/A)
C_h	vertical-contraction coefficient (A_{vena}/A)
D	diameter or height of conduit (m)
g	acceleration due to gravity (9.81 m^2/s)
H	energy head or level (m)
HW	headwater (upstream energy depth) (H_1 - I.L.)
h	pressure level (water surface where exposed to atmospheric pressure) (m)
HGL	hydraulic grade line
k_e	entry head loss coefficient
k_e'	entry head loss coefficient with blockage
k_o	outlet head loss coefficient
L	length of culvert along stream (m)
L_{10}	average length of longest 10% of debris reaching site (m) (ARR Book 6 Chapter 6)
n	Manning's resistance coefficient ($s/[m^{1/3}]$)
P	wetter perimeter of flow cross section (m)
R	hydraulic mean radius (A/P) (m)
R^2	coefficient of determination
S_f	Friction slope used in Manning's equation
Q	volumetric rate of discharge (m^3/s)
Q'	volumetric rate of discharge with blockage (m^3/s)
TEL	total energy line
TW	tailwater depth (m)
TWL	tailwater level (m)
v	velocity (m/s)
W	control dimension inlet clear width (m) (see ARR Book 6 Chapter 6) or B above
Δ	change in quantity
$_{1\ to\ 4}$	stations along culvert
'	variable inclusive of blockage

REFERENCES

Aagren, P., (ed), 2003. Hydraulics of Precast Concrete Conduits (Pipes and Box Culverts) – Hydraulic Design Manual. The Concrete Pipe Association of Australia, Pymble NSW 2073, Australia. [www.cpaa.asn.au]

Ball, J.E., (ed), 2015. Australian Rainfall & Runoff (draft) – A Guide to Flood Estimation, Engineers Australia, Barton ACT, 2015. [book.arr.org.au].

DEWS, 2013. Queensland Urban Drainage Manual. Third Edition - Provisional. Department of Energy and Water Supply, the State of Queensland, Australia. [www.dews.qld.gov.au]

Dyhouse, G.R., *et. al.*, 2007. Floodplain Modelling Using HEC RAS. Bentley Institute Press. ISBN 978-1-934493-02-1.

Henderson, F.M., 1966. Open Channel Flow. MacMillan Series in Civil Engineering, New York. ISBN-10: 0023535105

Miller, D.S., 1990. Internal Flow Systems, British Hydrodynamics Research Association, Edition 2. Gulf Publishing (1990) ISBN-10: 0872010201.

Miller, D.S., 1994. Discharge Characteristics – Hydraulic Structures Design Manual, International Association for Hydraulic Research (IAHR). Taylor & Francis Publishing, ISBN 90 5410 180 6.

Syme, B., 2016. TUFLOW Author and Manager. BMT WBM Pty Ltd, Brisbane.

Weeks, B., *et. al.*, 2009. Project 11: Blockage of Hydraulic Structures. Stage 1 Report, Engineers Australia, Barton ACT, 2009. ISBN 978-085825-9539

Weeks, B., *et. al.*, 2013. Project 11: Blockage of Hydraulic Structures. Stage 2 Report, Engineers Australia, Barton ACT, 2013. ISBN 978-0-85825-956-0

Weeks, B., 2014. Project 11: Blockage of Hydraulic Structures. Stage 3 Blockage Guidelines – Draft for Discussion, Engineers Australia, Barton ACT, 2014

Weeks, B., Rigby, T., 2015. Blockage of Hydraulic Structures. Book 6 Chapter 6 in Australian Rainfall & Runoff (draft) – A Guide to Flood Estimation, Engineers Australia, Barton ACT, 2015. [book.arr.org.au].

Witheridge, G.M., 2009. Hydraulic Analysis of the Debris Blockage of Culvert Inlets. Catchments & Creek Pty Ltd, Ferny Hills, QLD. [www.catchmentsandcreeks.com.au]