

Australian Rainfall and Runoff guidance on blockage of hydraulic structures: numerical implementation and three case studies

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Abstract

General industry-wide guidance on the blockage of hydraulic structures within flood simulation has in the past been lacking, and potentially has been too simplified in application. Guidance on the blockage of cross drainage structures, in particular culverts and small bridges, has now been provided to the industry through the Australian Rainfall and Runoff (ARR) Book 6 Chapter 6. The underpinning research reports offer an energy-based method for calculation of blockage discharge, which differs significantly in its approach from conventional industry practice. The effect of this additional methodology on flood and stormwater studies is largely unknown. The new ARR guidance also produces blockage factors that are both Annual Exceedance Probability (AEP) dependent and location dependent within a catchment, and are therefore difficult to implement in flood modelling software. 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 methods are compared using three recent TUFLOW flood models. Two of the models are large creek models from the Brisbane local government area and the third model is of a recent large subdivision application where the impacts on lot yield are important. The study found the alternative energy loss method produced more realistic headwater levels compared to those resulting from the common industry approach of reducing culvert area, which can exaggerate energy losses. Due to the non-linear nature of kinetic energy, high blockage factors can lead to a four-fold increase in headwater level compared with low blockage factors. Sensitivity testing is recommended using both the energy loss and reduced area procedures in culvert design, along with an assessment of risk (especially consequences) to determine where additional attention is needed in confirming blockage factors.

Keywords

Australian Rainfall and Runoff, ARR, blockage, culvert, energy loss, flood, hydraulics, matrix, modelling, TUFLOW

Introduction

Australia's national guideline on flood estimation, Australian Rainfall and Runoff (ARR), was updated in late 2016,

approximately 30 years since the previous major release in 1987. The 2016 update was the result of a ten-year project, which initially identified knowledge gaps in the industry and comprised a series of Revision Projects to fill these gaps. The main revision project relevant to this paper, Revision Project 11 Blockage of Hydraulic Structures, was 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 2016 Book 6 Chapter 6** Blockage of Hydraulic Structures – Advanced Draft for Industry Comment, July 2016 (Weeks and Rigby, 2016).

A review of these reports was undertaken to determine the requirements for 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 this 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.

ARR blockage overview

The purpose of this section is to identify the key features of the new ARR blockage guidance, and then where flood software enhancements are necessary to facilitate implementation of the new ARR guidelines.

Location of structure and risk dependence

Weeks and Rigby (2016), in the advanced draft of the ARR chapter on blockage of

hydraulic structures, suggest nine debris potential categories, based on debris availability, mobility, and transportability. 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. Weeks and Rigby (2016) also discuss 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 $2xB_{DES}$ to assess increased flooding upstream. Here B_{DES} refers to the percentage of area blocked in the structure as determined by the design engineer and $2xB_{DES}$ represents a severe case for the purposes of risk assessment.

In Weeks and Rigby (2016), Monte Carlo or stochastic modelling of debris blockage is discussed; however, the approach is limited by our current lack of knowledge on distributions of blockage values.

Annual exceedance probability dependence

Heavier rainfall events are more likely to produce and mobilise debris. The advanced draft of the ARR chapter on blockage of hydraulic structures (Weeks and Rigby, 2016) gives specific guidance on debris potential in relation to storm annual exceedance probability (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 of Weeks and Rigby (2016) would produce adjusted blockage estimates as in Table 1.

Positioning of debris at inlet

The positioning of debris at the inlet is outlined by three blockage types (see Section 6.5.2 of Weeks and Rigby (2016)), being 'top down' (accumulation at obvert), 'bottom up' (usually sediment deposition), and a 'porous

Table 1 – AEP-adjusted debris blockage ($B_{DES}\%$) for case $W < L_{10}$.

AEP [Average recurrence interval]	Debris potential at structure		
	High	Medium	Low
>5% [<20 years]	50%	25%	25%
5%-0.5% [20 to 200 years]	100%	50%	25%
<0.5% [>200 years]	100%	100%	50%

plug’ where debris covers the entire entrance with some porosity remaining to pass flow. Added to these types (but not included in Weeks and Rigby (2016)) is the potential for side blockage, especially in the case of unsubmerged flow, and a general all-round perimeter-type blockage.

Timing and growth of blockage

Section 6.5.3 and Table 6.6.9 of Weeks and Rigby (2016) provide guidance on the growth and timing of the fully developed blockage (B_{DES}) during the flood event, for floating and non-floating debris.

Blockage methods

Witheridge (2009), Weeks *et al.* (2009) and Weeks (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 that 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, 2016).

In addition to these methods, 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 and compared below.

Culvert hydraulics

The purpose of this section is to establish the standard culvert hydraulic equations as documented in Henderson (1966) and used in the TUFLOW software, and which form the basis of the subsequent research based on these first principles. A “schematic” culvert arrangement, along with dimensions and measurement locations as referenced in this paper, is shown in Figure 1 and a common entrance with and without blockage is shown in Figure 2. The standard equations that govern culvert discharge under inlet control and outlet control conditions are discussed.

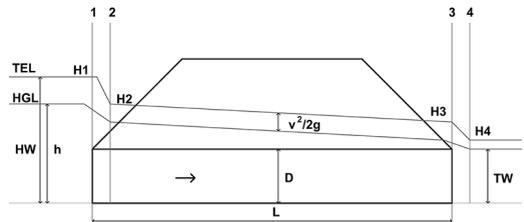


Figure 1 – Culvert flowing full.

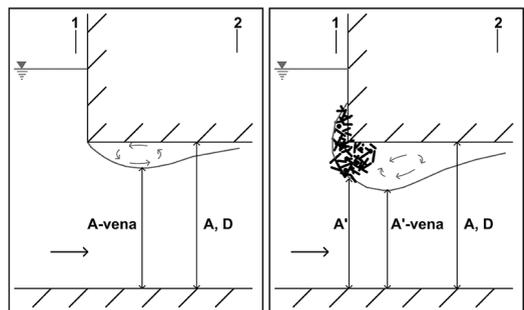


Figure 2 – (a) Clear culvert (left) and (b) blocked culvert (right).

Inlet control

Under inlet control conditions discharge becomes supercritical near the culvert entrance and is often supercritical along the barrel (Dyhouse *et al.*, 2007). 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 *et al.* (2007) and Henderson (1966). The TUFLOW software used for this paper utilises the inlet control equations for box culverts and circular culverts in Henderson (1966). The box culvert equations are reproduced below (Eqs. 1 and 2).

For unsubmerged flow where $H/D < 1.2$:

$$Q = \frac{2}{3} C_B B H \sqrt{\frac{2}{3} g H} \quad (1)$$

And for submerged flow where $H/D > 1.2$:

$$Q = C_h B D \sqrt{2g(H - C_h D)} \quad (2)$$

Outlet control

Under outlet control conditions flow is subcritical along the culvert and the Energy Equation (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, to determine the headwater level at Station 1 (Fig. 1). The different types of energy losses comprise an inlet contraction loss between Stations 1 and 2, friction loss between Stations 2 and 3, and outlet expansion loss between Stations 3 and 4.

The energy level at a station is computed by:

$$H = h + \frac{v^2}{2g} \quad (3)$$

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

$$H_1 = H_4 + \text{losses} \quad (4)$$

where losses comprise an inlet contraction loss (Eq. 5), friction loss (Eq. 6) and outlet expansion loss (Eqs. 7a and 7b).

$$\Delta H_{1-2} = k_e \frac{v_2^2}{2g} \quad (5)$$

$$\Delta H_{2-3} = v_{2-3}^2 \frac{n^2 L}{R^{4/3}} \quad (6)$$

$$\Delta H_{3-4} = k_o \frac{(v_3 - v_4)^2}{2g} \quad (7a)$$

$$\Delta H_{3-4} = k_o \left(\frac{v_3^2 - v_4^2}{2g} \right) \quad (7b)$$

Two outlet expansion loss equations are available in the literature, both being discussed in Henderson (1966) and with their own unique k_o values. If the outlet velocity is assumed to be zero (as is commonly advised in engineering manuals), the two equations become equivalent. Different equations are available to calculate friction loss, the one adopted above (and in TUFLOW) being the Manning's Equation, where ΔH_{2-3} is 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.

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 that are blocked under inlet control, Witheridge (2009), Weeks *et al.* (2009) and Weeks (2014) apply a basic equation which may be used to approximate the reduction in discharge capacity:

$$BF = BR^{5/4} \quad (8)$$

This empirical equation was derived from inlet control charts to determine the effects of variations in inlet area. As Henderson's (1966) inlet control equations (Eqs. 1 and 2) directly calculate culvert discharge capacity, Equation 8 was not required in the software implementation.

Under outlet control conditions, two methods are available: the RAM (as discussed) and the Energy Loss Method (ELM). The ELM was derived by Witheridge (2009), using Miller (1990):

$$k_e = \left(1 - \frac{A_{vena}}{A}\right)^2 \left(\frac{A}{A_{vena}}\right)^2 \quad (9)$$

to modify k_e by incorporating the geometry of the blockage, so that Equation 5 becomes:

$$\Delta H'_{1-2} = k'_e \frac{v_2^2}{2g} \quad (10)$$

where

$$k'_e = \left(\frac{1 + \sqrt{k_e}}{BR} - 1\right)^2 \quad (11)$$

Where no blockage exists, then BR (or A'/A) (see Fig. 2) becomes unity and Equation 11 reduces to k_e . For nominal values of k_e , Table 2 gives the computed values of k'_e . The 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) and valve loss coefficients (Miller, 1994).

Table 2 – 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	∞	∞	∞	∞

Software implementation

Phased approach

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

- **Phase 1** (1-dimensional structures): Structure location and risk; AEP dependence; implementation of alternative outlet expansion loss Equations 10 and 11; and implement the RAM and ELM methods.
- **Phase 2** (2-dimensional structures): Extension of functionality to 2-dimensional structures; 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.

Phase 1 overview

Structure location, risk, and 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 based on location within a catchment, likelihood of collecting debris, all clear case, extreme blockage, and sensitivity testing (risk). For each class or type, associated blockage values may also be specified for AEPs. An example matrix is provided below (Table 3). Matrix scenarios may be specified for structures based on a user-defined default value, an override value, or by individual structure values. The blockage-AEP is linked to the model simulation AEP, with intermediate values being interpolated.

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.

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.10 (see Fig. 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 Equation 11. The ELM is only available under outlet control conditions.

It is important to note that the RAM should be applied to ‘bottom up’ blockage, caused, for example, by sedimentation. This is because the RAM reduces the culvert area along the entire length of the barrel, replicating sedimentation. The ELM should be applied in cases where the blockage occurs at the entrance of the structure, as barrel dimensions downstream will remain unchanged. These considerations are important, as the RAM and ELM use different approaches to calculate energy losses along the structure, depending on how the blockage forms.

Table 3 – Example blockage matrix ($B_{DES}\%$)

AEP (%)	Average recurrence interval (years)	A	B	C	D	E
63.2	1	00	20	20	50	100
9.5	10	00	20	20	50	100
4.9	20	00	20	50	100	100
0.5	200	00	20	50	100	100
0.2	500	00	50	100	100	100
Probable maximum flood		00	50	100	100	100

Testing of software and methods

Verification of Henderson (1966) for inlet control

The inlet control equations for box culverts documented in Henderson (1966) 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). The CPAA nomographs comprise six different inlet types (three for pipes, three for boxes) whereas Henderson (1966) only distinguishes between round and square-edged culverts.

A range of tests was undertaken to fit the Henderson (1966) 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, 1.8 m for a unit width), HW/D (0.5, 1.0, 1.5, 3.0), and inlet types (1, 2, and 3). The Henderson box culvert 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. Out of interest, the same tests were performed for circular culverts (D 0.75, 1.2, 1.8 m) using the Henderson (1966) box culvert equations. The results are given in Table 4.

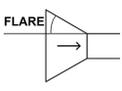
Generally, the Henderson (1966) box culvert equations and coefficients fitted well with the CPAA nomograph data. As the Henderson equations provided such a close fit, it is suspected that the two methods may have similar origins. A reasonable correlation also occurred for circular culverts using the box culvert equations.

Verification of ELM and RAM for outlet control

The purpose of the ELM and RAM testing was twofold. First, the implementation of the ELM and blockage matrix in TUFLOW was tested against the equations above to check agreement. Second, the tests undertaken comprised typical design scenarios in order to compare the ELM and RAM approaches.

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. Model results for discharge were recorded. Blockages

Table 4 – Inlet control contraction coefficients using box culvert equations

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	-

(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 (DEWS, 2013, p.10-9). A culvert length of 20 m was used assuming a road width of 10 m, 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.

Values of calculated for the tests are given in Table 2. For $k_e=0.5$ and $B_{DES}=20\%$ & 50%, values of were 1.3 and 5.8, respectively.

Results of headwater (HW) versus discharge (Q) are shown in Figure 3. The results show similar trends for all culverts

Table 5 – Blockage method test results for conventional Reinforced Concrete Pipe $D=0.75$ m 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

tested, therefore specific discussion is made only in relation to the $D=0.75$ m 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 above. Table 5 gives values of energy loss and energy level in relation to the measuring Stations 1 to 4 (see Figs. 1 and 2).

The final headwater level (H_1) for the RAM is 6.04 m, which is significantly higher than the ELM of 4.71 m. 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}). In 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 4 illustrates these results by way of comparing total energy lines (TELS).

In 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 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 losses. 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 headwater levels than the ELM method, and this difference grows with an increase in blockage; i.e., for an increase in B_{DES} from 20% to 50% there is an exponential increase in headwater (Fig. 3). This is due to the squared relationship of energy loss with velocity. Potential outcomes for civil design and flood risk assessment are discussed in the conclusion.

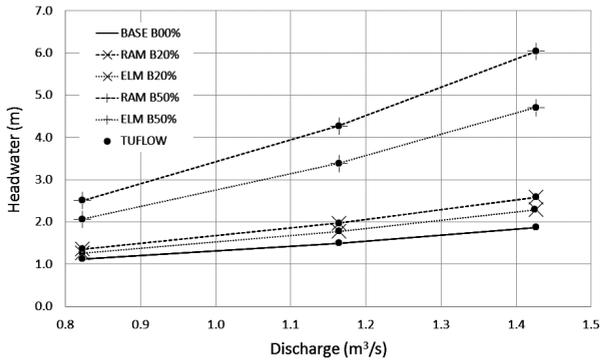


Figure 3a – Pipe culvert test results for $D=0.75$ m and outlet control.

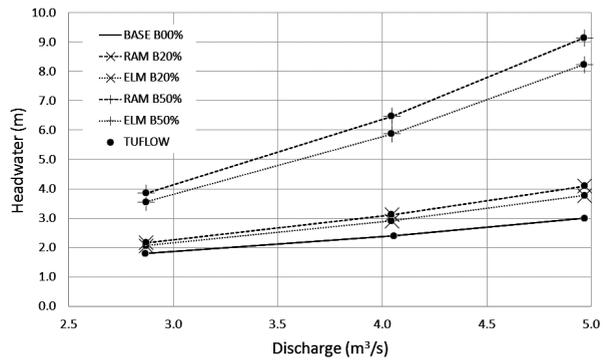


Figure 3b – Pipe culvert test results for $D=1.2$ m and outlet control.

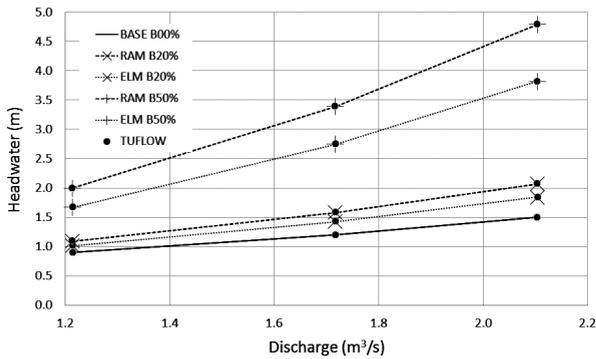


Figure 3c – Box culvert test results for $B=1.2$ m, $D=0.6$ m and outlet control.

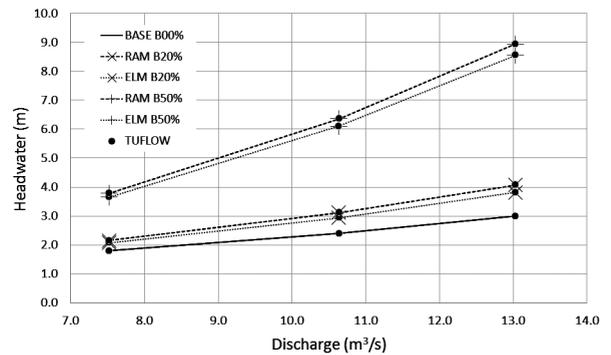


Figure 3d – Box culvert test results for $B=2.4$ m, $D=1.2$ m and outlet control.

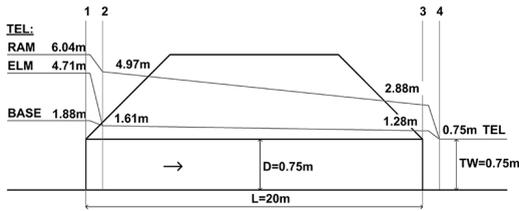


Figure 4 – Total energy line (TEL) results for $D=0.75$ m, B_{DES} 50%.

Case study tests

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 recent Queensland, Australia flood models – Lota Creek, Sheep Station Gully and Lowood – for a range of culvert configurations under fully dynamic conditions. The Lota Creek Flood Study was completed by Brisbane City Council in June 2015 and comprises a catchment area of 18.2 km² which is relatively flat and low-lying, and of residential-rural and rural land-use. The Sheep Station Gully Flood Study was completed by Brisbane City Council in June 2015 and comprises a catchment area of 6.6 km² which is relatively steep and elevated, and of mostly residential and rural-residential land use. Finally, the Lowood Flood Study (Somerset local government area) was completed as part of a development application in October 2015 and has a total catchment area of 3 km². The

site is steep with rural land use. The area of the subdivision is approximately 34 ha.

Three culverts were selected for testing in each of the Lota Creek (LC-34, 35, 51) and Sheep Station Gully Flood Studies (SG-03, 06, 11) (Table 6; Fig. 5). 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 (LW-01) (Table 6), which forms the subdivisions detention and controls development levels, was selected.

The flood models were run for the 1% AEP flood for the critical storm duration only. Model results for headwater were recorded for each scenario, along with the control regime (inlet control [IC] or outlet control [OC] at the headwater 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.

The RAM did not produce higher headwater levels as expected from the previous test cases. In cases where culverts were submerged or overtopping the ELM and RAM produced comparable results (Table 7). For the 1% AEP flood, where RAM headwaters are expected to be higher,

Table 6 – Details of culverts selected for the case study

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

Table 7 – Headwater results (m) for the RAM and ELM blockage methods with 0%, 20% and 50% blockage, 1% AEP flood event

ID	Parameter	BASE 0%	RAM		ELM	
			20%	50%	20%	50%
LC-35	HWL	4.11	4.16	4.25	4.15	4.26
	Control	OC	OC	OC	OC	OC
LC-34	HWL	13.39	13.40	13.42	13.40	13.42
	Control	OC	OC	OC	OC	OC
LC-51	HWL	3.89	3.89	3.89	3.89	3.89
	Control	OC	OC	OC	OC	OC
SG-03	HWL	14.57	14.77	15.08	15.19	15.30
	Control	OC	OC	OC	OC	OC
SG-06	HWL	22.30	22.44	22.62	22.37	22.59
	Control	IC	IC	IC	OC	OC
SG-11	HWL	22.99	23.00	23.00	23.00	23.00
	Control	OC	OC	OC	OC	OC
LW-01	HWL	71.06	71.46	71.99	71.46	72.05
	Control	IC	IC	IC	IC	OC

road overtopping and floodplain storage may contribute to a tempering of the potential headwater increases.

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 SG-06, LW-01 in Table 7). 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 the case of ELM 50% for LW-01, the higher entrance loss coefficient may have dissipated enough energy so as to force the culvert to remain sub-critical flow and therefore outlet control.

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. However, testing in the previous section showed the opposite, that in cases with high headwater levels, high velocity, and low potential for upstream storage or weir overflow, the RAM can produce exaggerated headwater levels.

Conclusions

A review of the recently-produced ARR literature on the blockage of cross drainage structures (culverts and small bridges) was undertaken to determine how the new recommended methods may be implemented into flood modelling and Hydraulic Impact Assessments. The key findings were:

(1) Blockage quantities are now recommended to be calculated based on catchment conditions, culvert inlet configuration, and AEP of the design flood. The TUFLOW flood modelling software has been modified 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.

(2) Under inlet control conditions TUFLOW utilises Henderson's (1966) equations (Eqs. 1 and 2) for circular and box culverts to determine culvert discharge capacity for a given headwater level. These equations were validated by comparison with the CPAA inlet control nomographs and found to be in close agreement. Extended guidance was also developed for the Henderson (1966) inlet control equations, by extension to the various culvert inlet configurations in the CPAA nomographs.

(3) 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 (the RAM). Detailed tests between these two methods were carried out on both an idealised test model and on culverts in three recent flood studies. The alternative ELM was also implemented in the TUFLOW software for testing.

(4) A number of differences were highlighted between the RAM and the ELM techniques for applying blockage to culvert entrances. In general the RAM has the potential to produce higher headwater and flood levels upstream of the culvert. In the majority of cases if road overtopping and floodplain storage exist, then the RAM increase in headwater may be only minor. Higher upstream flood levels (a risk with RAM) can lead to increased construction costs for infrastructure and land development. In addition to this, the higher structure 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 the Queensland Urban Drainage Manual (DEWS, 2013).

(5) Another observation which pertains to both the RAM and ELM approaches is that headwater increase has an exponential, rather than a linear, relationship to blockage. The increase in headwater from 20% to 50% blockage can be 4-fold compared to the increase from 0% to 20% blockage. This highlights the importance of careful blockage assessment in culvert design, as assigning a nominal blockage factor to a culvert that should have been assigned a high blockage factor may have serious consequences.

(6) The RAM should be applied to 'bottom up' blockage, caused, for example, by sedimentation. This is because the RAM reduces the culvert area along the entire length of the barrel, replicating sedimentation. The ELM should be applied in cases where the blockage occurs at the entrance of the structure, as barrel dimensions downstream will remain unchanged. These considerations are important, as the RAM and ELM use different approaches to calculate energy losses along the structure depending on how the blockage forms, and it is considered that the method adopted should fit with reality.

(7) Whichever method is used (RAM or ELM) it is recommended that the hydraulic engineer undertake sensitivity testing using both methods. Traditional use of the RAM may have led to an inbuilt factor of safety in culvert design in the past. 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 such as provided in the new ARR 2016 guidelines.

Notation

The following symbols are used in this paper:

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)
h	pressure level (water surface where exposed to atmospheric pressure) (m)
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)
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)
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

Abbreviations

The following abbreviations (excluding publications) are used in this paper:

AEP	annual exceedance probability
ELM	energy loss method
HW	headwater (upstream energy depth) ($H_1 - IL$)
HGL	hydraulic grade line
IL	invert level
L ₁₀	average length of longest 10% of debris reaching site (ARR Book 6 Chapter 6)
RAM	reduced area method
TEL	total energy line
TW	tailwater depth
TWL	tailwater level

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