Prediction of scouring depth at the outlet of partially blocked box-culvert

S.Sorourian[1], A.Keshavarzi[2], B.Samali[3], J. Ball[4]

[1]PhD student, School of Civil and Environmental Engineering, University of Technology Sydney, Sydney, Australia, email: sayana.sorourian@student.uts.edu.au

[2]School of Civil and Environmental Engineering, University of Technology Sydney, Sydney, Australia, email: alireza.keshavarzi@ uts.edu.au

[3]School of Civil and Environmental Engineering, University of Technology Sydney, Sydney, Australia, email: bijan.samali@uts.edu.au

[4]School of Civil and Environmental Engineering, University of Technology Sydney, Sydney, Australia, email: james.ball@uts.edu.au

1 Abstract

Culverts are built at a location in waterway cross a road or railway. The narrowing cross section of waterway creates a limitation to flow passage and therefore blockage occurs during flood events with accumulation of debris at the inlet. The blockage of the culvert can accelerate bed scouring and consequently causes failure of the culvert. It subsequently produces high damage to private properties and public assets. This article is concerning scouring at the outlet of partially blocked culverts. In this context the blockage of culverts is studied as an important factor on the scouring pattern of culverts. Therefore, experimental tests were conducted to investigate the effects of culverts blockage on scouring downstream of a culvert. The experimental program was designed to investigate the relationship between the maximum scour depth, blockage ratio of the culvert and flow characteristics. The experimental tests were carried under non-blocked and partially blocked conditions. The sediment material used in this study was uniform non-cohesive sand particles. Results showed that the scoured area and maximum scour depth increases in partially blocked condition comparing with the non-blocked condition. The results were compared with the previous developed models and it was found that the previous model predict scouring depth less than the scouring depth at blocked condition.

Keywords: Culvert blockage; Flood damage; Scouring depth; Steady flow

2 Introduction

Culverts are locations in water courses where a construction occurs and therefore where blockage of some type is likely to occur. Week et al.(2009) reported the damage of culverts and waterways as an impact of these structures blockage.

Rigby et al. (2002) worked on blockage of bridges and culverts and found out that when the opening size of culverts is less than 6 m (measured diagonally) there is a high risk of culvert blockage. Barthelmess and Rigby (2011) estimated culvert and bridge blockage based on debris availability, mobility and transportability factors. Rigby and Barthelmess (2011) explored culvert blockage mechanisms and their impact on flood behaviour. They noticed one of the consequences of blockage considered as the flow diversions caused by blockage of culvert. Even small blockages created diversions that would not usually occur and considerably change flood behaviour.

The early studies on the nature of scouring beginning with Rouse(1938) and Laursen (1952) and followed by Smith (1957). Bohan (1970) investigated scour dimensions at the culvert outlet in large scale models. Abt et al. (1986) studied culverts slope effects scouring depth at outlet of the culvert and pointed out that a sloped culvert can increase the maximum scour depth from 10 to 40% over the scour dimensions for a horizontal culvert. Abt et al.(1987) investigated the influence of culvert shape on outlet scour and determined that dimensions of scour developed at the outlet of circular shaped culverts are significantly varies from other shapes of culverts.They developed an equation to correlate the maximum scour depth to modified discharge intensity. Ali and Lim (1986)investigated the effects of changing tailwater depth on scouring downstream the jet. Abt et al. (1996) estimated the dimension of outlet scour in relation to culvert discharge, hydraulic radius, time and material gradation. The effect of culvert slope and outlet drop is also considered in this equation. Although this formula is quite comprehensive it lacks simplicity. Abida and Townsend (1991) developed an equation for local scour downstream of box-culverts relating flow Froude number and sediment size.Lim(1995)conducted experimental tests on a circular un-submerged culvert. He compared his work with Abt et al.(1984) and Breusers and Raudkivi(1991) and stated that the range of applicability and limitations of those formulations are highlighted comparing with his work and some relevant data from other researchers. He proposed equations to envelope these data based on sediment densimetric Froude number. Day et al.(2001) investigated the effects of tail water depth and model scale on maximum depth of scouring based on experimental test of circular culverts. Liriano et al. (2002) studied scour at culverts influenced by turbulent flow and pointed out that the peak values of turbulence intensities over the fixed bed coincide with the location of the maximum scour depth for the fully developed scour hole. Emami and Schleiss (2010)conducted some experimental tests to evaluate the natural mobile bed erosion without any protection. They compared their work with some previous studies and proposed equation for maximum scour depth based on their experimental tests.

According to previous studies it can be concluded that main factors which are influencing the maximum scour depth downstream of culverts are recognized as sediment properties such as median grain size and geometrical standard deviation, flow conditions and depth of tail water. Some research also indicated that geometry of the culvert and its slope also affects the formation of scour hole. Most formulas proposed in this regard are functions of densimetric Froude number, median grain size of bed material, depth of water downstream the culvert and size of culvert opening. In all of previous studies, it is attempted to consider scoring pattern at the outlet of culvert in a non-blocked condition. Therefore, the focus of this study is to investigate the flow characteristics and scouring pattern at blocked condition.

3 Experimental set up

An experimental program was designed to investigate the relationship between the maximum scour depth, blockage ratio of the culvert and flow characteristics. The experimental tests were carried on, in two different conditions; non-blocked and partially blocked condition and the effect of culvert blockage are studied. The sediment material used in this study is uniform non-cohesive sand. The median grain size for sands equals 0.85 mm and 2.0 mm.

Experimental tests conducted in the scour testing facility depicted in Figure 1. Water was supplied to the static tank from the laboratory supply. The water introduced to the flume through a valve which controls the water flow rate, and then it runs through the box-culvert that is settled in the sand basin. At the end of the flume a sluice gate is installed to the downstream water depth and velocity.

Figure 1 Experimental test facility in Hydraulics Laboratory

The flume in UTS Hydraulic Laboratory is a 19 m long concrete flume. The width and depth of the flume are 605 mm and 600 mm, respectively. In the middle of the flume there is a space provided for sand basin which is 150 mm deeper than culvert's bed level.

The culvert model is shown in Figure 2. The opening of culvert is 200×200 mm and the length of culvert's barrel is 900 mm. There are transitions with 30° flare at the inlet and outlet of the culvert. To make the blockage a plate was installed at the opening of the culvert. Two sizes of plates (200×80 mm and 200×120 mm) were used so far to get the variant blockage ratio in the experimental tests.

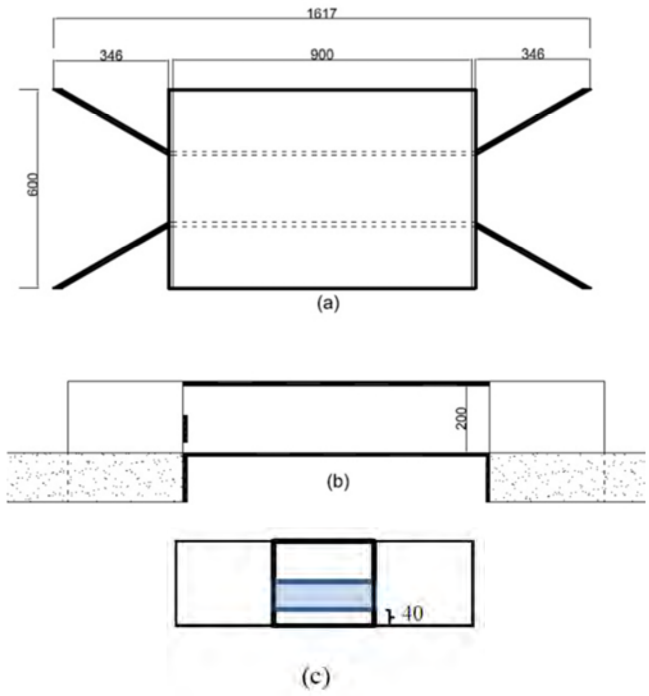


Figure 2 Culvert model ; (a) Paln view (b) Profile view (c) inlet view (all units are in mm)

Prior to each test the sand was levelled with the culvert inlet and outlet in the sand basin. Experimental tests were conducted in steady state condition. The range of flow rate varies from 5 to 25 (lit/s). Tests duration was generally continued to each test to ensure to reach the equilibrium state for the scouring process.

Table 1 depicts the test classifications. In this table h_d is the depth of water at the outlet of the culvert, h_u is the upstream water level , h_t represents the tail water depth and F_d is the densimetric Froude number. The blockage of culvert is represent by B which defines as (h_B/h_u) where h_B is the height of the plate used as the blockage in the inlet of culvert.

Table 1 Test classification for the steady state experimental test

Test	Sediment		Plate		Flow characteristics				
	d_{50} (mm)	σ_g	h_B (mm)	h_d (mm)	h_t (mm)	h_u (mm)	Q (lit/s)	B	F_d
S2B01	2	1.23	0	125	125	125	10.1	0	2.2
S2B02	2	1.23	0	155	155	155	12.3	0	2.2
S2B03	2	1.23	0	100	105	105	12.8	0	3.6
S2B04	2	1.23	0	120	120	120	8.6	0	2.0
S2B05	2	1.23	0	100	105	100	6.6	0	1.8
S1B01*	0.85	1.37	0	200	197	198	14.61	0	2.0
S1B02	0.85	1.37	0	157	157	160	15	0	2.7
S1B03	0.85	1.37	0	170	170	174	18.7	0	3.1
S1B04	0.85	1.37	0	138	145	150	13.2	0	2.7
S1B05**	0.85	1.37	0	95	108	95	14.2	0	4.2
S1B06	0.85	1.37	0	90	95	90	4.9	0	1.5
S1B07	0.85	1.37	0	55	50	75	7.04	0	3.6
VS1B05	0.85	1.37	0	142	142	142	7.80	0	2.4
S2B401	2	1.23	80	140	145	170	10.7	0.5	2.1
S2B402	2	1.23	80	155	160	185	12.3	0.4	2.2
S2B403	2	1.23	80	105	105	175	12.8	0.5	3.4
S2B404	2	1.23	80	110	115	145	8.8	0.6	2.2
S2B405	2	1.23	80	105	110	125	6.6	0.6	1.7
S1B401*	0.85	1.37	80	195	195	210	14.67	0.4	2.1
S1B402	0.85	1.37	80	165	168	196	14.61	0.4	2.5
S1B403*	0.85	1.37	80	60	60	195	15.12	0.4	7.0
S1B405	0.85	1.37	80	210	213	230	19.8	0.3	2.6
S1B406*	0.85	1.37	80	150	145	200	20.65	0.4	3.8
S1B407*	0.85	1.37	80	80	70	230	25	0.3	8.7
S1B408	0.85	1.37	80	70	70	120	4.86	0.7	1.9
S1B409	0.85	1.37	80	80	95	160	10.11	0.5	3.5
VS1B405	0.85	1.37	80	143	143	153	7.8	0.5	2.4
S2B601	2	1.23	120	130	130	190	10.3	0.6	2.2
S2B602	2	1.23	120	170	170	210	12.5	0.6	2.0
S2B603	2	1.23	120	50	100	195	12.8	0.6	7.1
S2B604	2	1.23	120	110	115	160	8.8	0.8	2.2
S2B605	2	1.23	120	90	105	135	6.6	0.9	2.0
S1B601	0.85	1.37	120	60	70	150	7	0.8	5.0

* Culvert without transition

4 Results and discussion

4.1 Flow structure

Figure 3 shows the distribution of streamwise velocity in a 50 mm layer of flow from the bed in non-blocked (VS1B05) and blocked conditions (VS1B405) at similar flow condition.

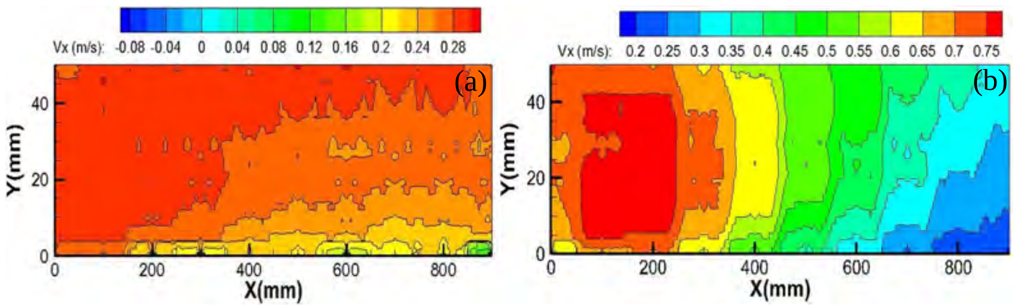
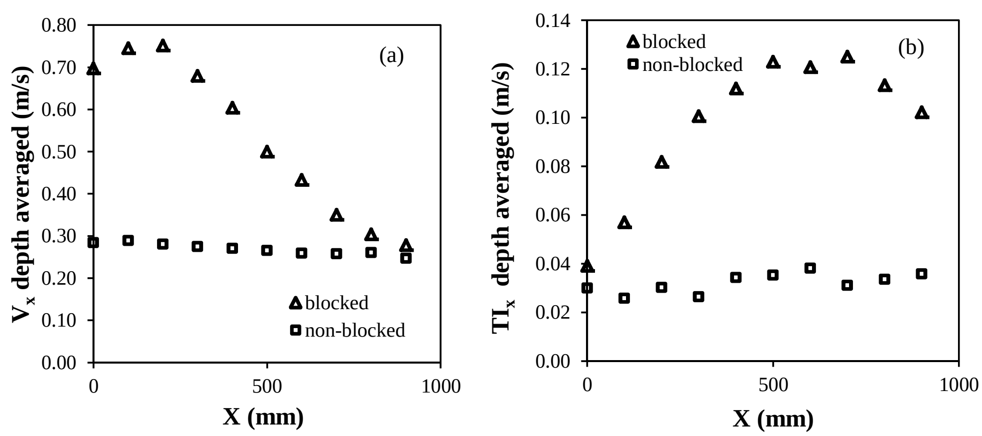


Figure 3 Velocity distribution in horizontal direction along the culvert barrel; (a) non-blocked (b) partially blocked

The maximum velocity in non-blocked condition is 0.28 m/s but in partially blocked condition increased to a maximum of 0.75m/s which is 2.7 times more than non-blocked condition. Likewise gradation of velocity in the culvert in partially blocked condition rapidly changes.

Figure 4 shows flow structure interaction in culvert for non-blocked and partially blocked conditions. Depth averaged of the velocity in the partially blocked condition increases to 0.7 (m/s) in the 200 mm from the inlet and decreases to about 0.3 (m/s) at the outlet while in non-blocked condition, the depth average of velocity reduces to 0.3(m/s) (Figure 4a).



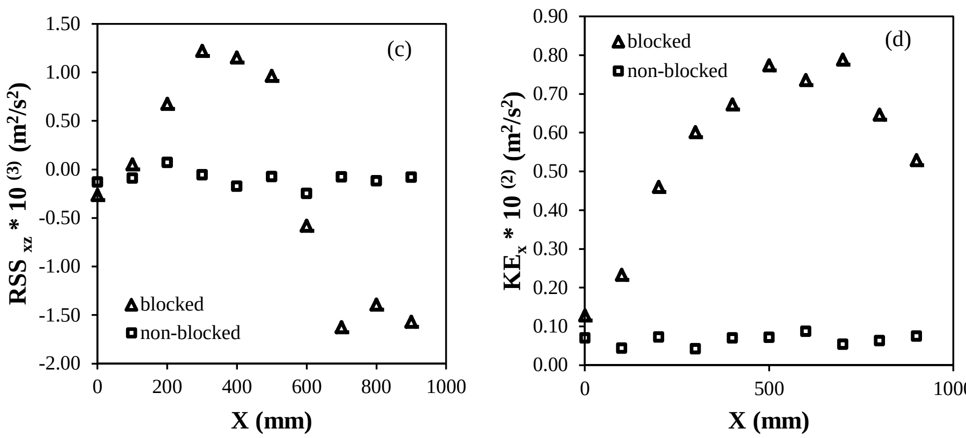


Figure 4 Flow structure of blocked and non-blocked condition; (a) V_x depth average (b) Turbulent Intensity (TI_x), (c) Reynolds Shear Stress (RSS_{xz}) (d) Kinetic Energy (KE_x)

The total average turbulent intensity in x-direction of the non-blocked condition is about 0.03 (m/s) and in partially blocked condition and it increases to 0.1 (m/s). Comparing the turbulence intensity showed that in blocked condition it is 3 times more than non-blocked condition (Figure 4b).

The Reynolds Shear Stress at the inlet of the culvert is around -0.2×10^{-3} and at the outlet of the culvert increases to -1.5×10^{-3}, but, in the non-blocked condition no much change was observed (Figure 4c).

The total average of kinetic energy in x-direction (KE_x) for non-blocked condition is about 0.06×10^{-2} (m^2/s^2) whereas in partially blocked condition this average is about 0.5×10^{-2} (m^2/s^2) (Figure 4d).

4.2 Scouring area

Figure 5 shows the scoured area below the bed level in partially blocked and non-blocked conditions. The general trend of scoured area (A_s) for partially blocked condition is more than non-blocked condition. It is also demonstrated that the difference between scoured area in partially blocked and non-blocked conditions increases with the rise of F_d (Figure 5a and Figure 5b).The Scoured area (A_s) in partially-blocked conditions for sediment with median grain size equals 2 mm is 20% to 60% more than scoured area in non-blocked conditions (Figure 5b).

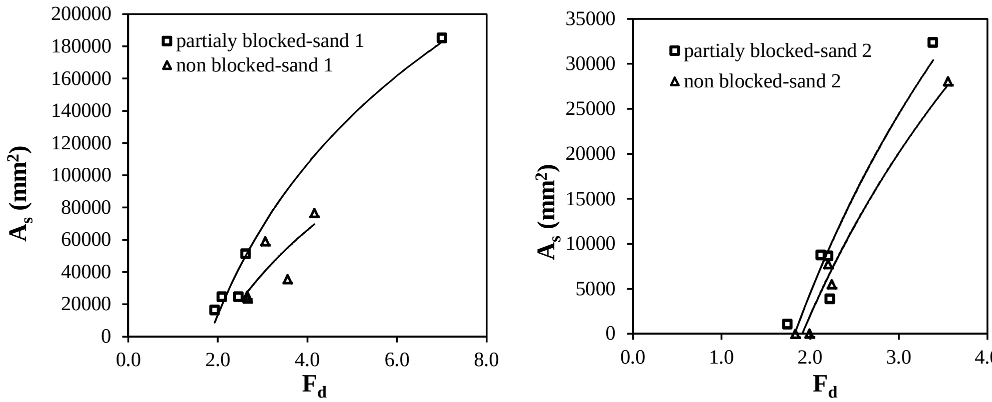


Figure 5 Scoured area versus densimetric Froude number: (a) sediment median size (d50=0.85mm) (b) sediment median size (d50=2.0 mm)

4.3 Comparing with previous studies

Table 2 indicates a summary of the compared experimental works conducted by other researchers with present study.

Table 2 Summary of range of experimental scouring tests from other researchers

Researchers	Densimetric Froude Number Range (F_d)	Culvert Shape	Sediment Median Grain Size, d_{50} (mm)
Present study	1.5-8.7	Box	0.85
			0.2
Abida(1991)	0.9-20.9	Box	0.47
			0.57
			1.35
Lim (1995)	2.5-24.6	Circular	1.65
Ade, Rajaratnam (1998)	6.3-88.2	Circular	0.24
			7.2

Figure 6 shows the comparison of the maximum scour depth versus densimetric Froude number between present study and other researches. Based on this figure the maximum scour depth (d_{sm}) of the present study which is partially-blocked is more than other experimental tests for the same range of F_d.

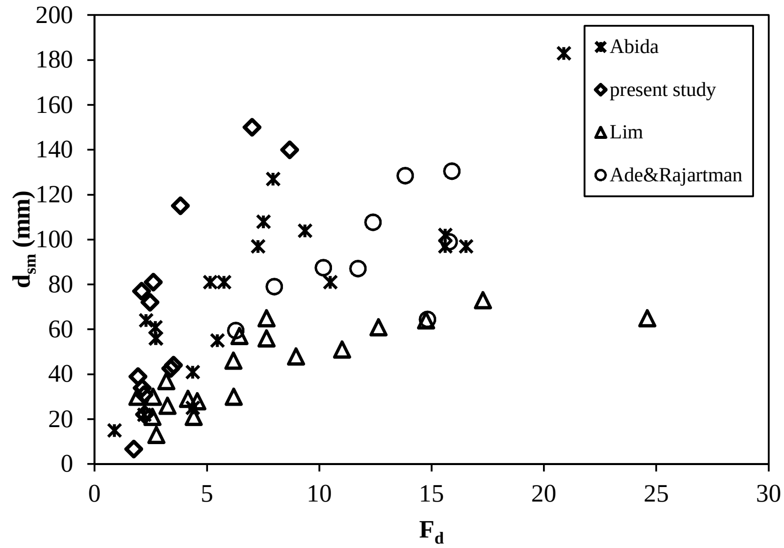


Figure 6 Comparison of maximum scour depth versus Fd

5 Conclusion

Blockage has not been considered as a key element in studying and estimating the scouring at the outlet of the culverts, however, this study shows that it has a considerable effect on flow structure and scouring hole geometry at the outlet of the culvert. The velocity distribution is rapidly changes in the culvert barrel in blocked condition and the average turbulent intensity was found 3 times greater than the non-blocked condition. The scoured area at the blocked culverts is 20% to 60% more than non-blocked conditions. The results of the blocked condition was compared with the previous studies and was found that the previous model predict scouring depth less than the scouring depth at blocked condition.

6 References

Abida, H. & Townsend, R. 1991, 'Local Scour Downstream of Box Culvert Outlets', *Journal of irrigation and drainage engineering*, vol. 117, p. 425.

Abt, S.R., Kloberdanz, R.L. & Mendoza, C. 1984, 'Unified culvert scour determination', *Journal of Hydraulic engineering*, vol. 110, no. 10, pp. 1475-9.

Abt, S.R., Ruff, J., Doehring, F. & Donnell, C. 1987, 'Influence of culvert shape on outlet scour', *Journal of Hydraulic engineering*, vol. 113, no. 3, pp. 393-400.

Abt, S.R., Ruff, J.F. & Doehring, F.K. 1986, 'Culvert Slope Effects On Outlet Scour', *Journal of Hydraulic Engineering*, vol. 111.

Abt, S.R., Thompson, P.L. & Lewis, T.M. 1996, 'Enhancement of the Culvert Outlet Scour Estimation Equations', *Transportation Reaserch Record*, no. 1523, pp. 178-85.

Ali, K. & Lim, S. 1986, 'Local scour caused by submerged wall jets', *ICE Proceedings*, vol. 81, Ice Virtual Library, pp. 607-45.

Barthelmess, A.J. & Rigby, E. 2011, 'Estimation Culvert & Bridges - A Simplified Procedure'.

Bohan, J.P. 1970, *EROSION AND RIPRAP REQUIREMENTS AT CULVERT AND STORM-DRAIN OUTLETS*, DTIC Document.

Breusers, H. & Raudkivi, A.J. 1991, *Scouring*, AA Balkema Rotterdam,, The Netherlands.

Day, R.A., Liriano, S.L. & White, W.R. 2001, 'Effect of tailwater depth and model scale on scour at culvert outlets', *Proceedings of the ICE-Water and Maritime Engineering*, vol. 148, no. 3, pp. 189-98.

Emami, S. & Schleiss, A.J. 2010, 'Prediction of Localized Scour Hole on Natural Mobile Bed at Culvert Outlets', *Scour and Erosion*, ASCE, pp. 844-53.

Laursen, E.M. 1952, 'Observations on the nature of scour', *Proceedings of Fifth Hydraulic Conference, Bulletin*, vol. 34, pp. 9-11.

LIM, S.Y. & LIM, S. 1995, 'Scour below unsubmerged full-flowing culvert outlets', *Proceedings of the ICE-Water Maritime and Energy*, vol. 112, no. 2, pp. 136-49.

Liriano, S.L., Day, R.A. & White, W.R. 2002, 'Scour at Culvert Outlets as Influenced By The Turbulent Flow Structure', *Journal of Hydraulic Research*, vol. 40.

Rigby, E.H. & Barthelmess, A.J. 2011, 'Culvert Blockage Mechanisms and Their Impact On Flood Behaviour-Are All Blockages Created Equal?'.

Rigby, E.H., Boyd, M.J., Roso, S., Silveri, P. & Davis, A. 2002, 'Causes and Effects of Culvert Blockage during Large Storms', paper presented to the *9th International Conference on Urban Drainage*, Oregon , USA, September 8–13, 2002.

Rouse, H. 1938, 'Experiments on the mechanics of sediment suspension', *Fifth International Congress for Applied Mechanics*, John Wiley and Sons, Inc., New York.

Smith, G.L. 1957, 'An analysis of scour below culvert outlets', Colorado State Univ., [S.l.].

Weeks, W., Barthelmess, A., Rigby, E. & Witheridge, G. 2009, 'AUSTRALIAN RAINFALL AND RUNOFF REVISON PROJECT 11: BLOCKAGE OF HYDRAULIC STRUCTURES'.