ICFM 10
Adapting to Global Change:
Innovative Approaches to Flood Management and Resilience
May 20-22, 2026 | Western University, London, Ontario, Canada

Reducing flood risk by improving the hydraulic capacity of box culverts through inlet modifications

Thea M.D. Giliomee[1], Ione Loots[1] and Marco van Dijk[1]
Department of Civil Engineering, University of Pretoria, Lynnwood Road, 0002, Pretoria, South Africa[1]
E-mail: u20424028@tuks.co.za

ABSTRACT

Culverts are an important part of a stormwater drainage system. When culverts can discharge the required flows during flood events, they ensure sufficient drainage from roads, preventing flood risks, infrastructure damage, and safety hazards. However, culverts can become insufficient over time due to increasing flood peaks caused by climate change and urbanisation. Culvert capacity can be increased by retrofitting inlet modifications, which may help with adaptation to higher flows. These modifications create a more gradual flow transition at the inlet, reducing the impact of the contraction after the inlet and increasing discharge capacity. In many instances, this can negate the need to rebuild an insufficient culvert, offering a cost-effective upgrade with minimal traffic disruption.

This study used physical modelling to evaluate different inlet modifications for box culverts under inlet control, and the performance of the best inlet was then theoretically evaluated for an existing culvert as a case study. The tested modifications included adjustments to wingwall and headwall angles, as well as a rounded inlet edge. For box culverts, a 15º headwall with a 30º wingwall increased flow capacity by up to 15% at a headwater depth equal to the culvert height ($1D$) and up to 34% at a headwater depth equal to twice the culvert height ($2D$). A flow-improvement coefficient, C_{TG}, was used to quantify the increase in performance for each inlet configuration. This coefficient can be applied to existing equations for standard square-edge inlets to calculate the improved discharge capacity when inlet modifications are implemented.

Inlet modifications are a practical way to enhance culvert performance and reduce flood risks, particularly given the increasing hydrological pressures of climate change and urbanisation. Implementing such improvements can support the development of more resilient and sustainable drainage infrastructure.

KEYWORDS: risk reduction, inlet modification, wingwall, headwall, climate change, urbanisation, box culvert

1 INTRODUCTION AND BACKGROUND

Culverts are hydraulic structures that transport water from one side of a road, highway, or railway embankment to the other. Their design focuses on identifying the most economical configuration capable of conveying the required discharge without allowing upstream water levels to exceed acceptable limits (Houghtalen et al., 2010). However, higher peak floods are placing additional stress on stormwater drainage systems, which can result in culverts becoming insufficient and headwater levels exceeding acceptable limits. Extreme storm events are expected to occur more frequently due to climate change. The effect of ongoing urbanisation is evident, as reduced infiltration in urban areas means that heavy rainfall can rapidly increase runoff (Agonafir et al., 2023). When drainage capacity is insufficient, the risk of infrastructure damage, traffic disruption, and safety hazards increases.

Culverts are designed to convey a specific capacity, but the barrels often do not achieve full-flow conditions (Straub et al., 1953). The momentum of water entering a square-edge inlet culvert creates a flow contraction, or vena contracta, just after the inlet (West, 1956). At the vena contracta, the cross-sectional flow area is at a minimum, which reduces the culvert capacity (Jaeger, 2019). The contraction is more pronounced for a square-edge inlet than for a rounded-edge inlet or one with wingwalls, as shown in Figure 1. Improving the culvert inlet can either increase its capacity for a specific headwater depth or pass the design discharge at a lower headwater depth.

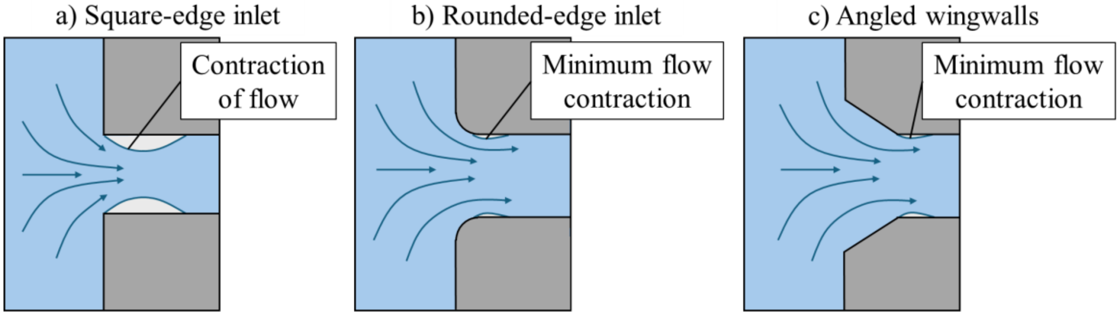


Figure 1: Plan view of flow contraction at a) a square edge inlet, b) a rounded edge inlet, and c) wingwalls

Some of the most promising inlet configurations include tapered inlets (Schall et al., 2012), 15º headwalls (Ashour et al., 2014), 45º wingwalls (West, 1956), and rounded inlets (at least 0.15*D* or 0.15*B*) (Jaeger, 2019). Headwalls and wingwalls are already widely used as retaining structures. Limited research has examined combinations of different wingwall and headwall angles, typically using the same angle when combined or testing wingwalls and headwalls separately. Therefore, different wingwall and headwall angles were tested and compared to a rounded-edge inlet. A new coefficient to quantify capacity improvements was developed to assist in designing or upgrading culverts, and it was then used to theoretically upgrade an existing culvert as a case study using inlet modifications.

2 METHODOLOGY

Physical modelling was conducted in a hydraulic flume to evaluate culvert inlet performance under inlet-control conditions. Each tested model culvert was positioned in the hydraulic flume, as shown in Figure 2. The flume is 450 mm wide, 500 mm high and 10 m long. A depth gauge (①) was placed 4*D* upstream of the model culvert, where *D* is the culvert height. A measurement ruler (②) was placed 0.75*D* upstream of the culvert inlet, which measured the headwater, H_1, and another depth gauge (④) was positioned 4*D* downstream of the culvert outlet. The slope was set to 1%, as recommended by SANRAL (2013), as the minimum slope to prevent silt deposition. The steep slope also ensured inlet control conditions for all the tests performed. Under inlet control conditions, the inlet geometry has a greater influence on the flow through the barrel than under outlet control (West, 1956).

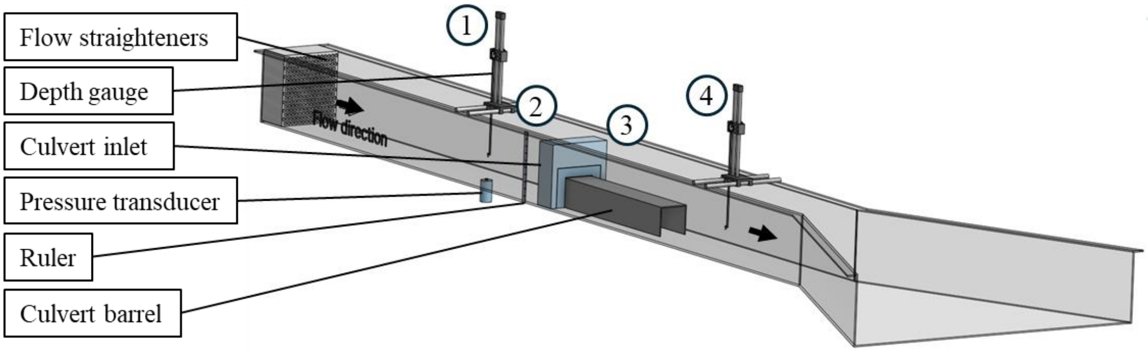


Figure 2: Physical model setup in the hydraulic flume

The physical models consisted of various inlet configurations for a 200 x 200 mm square box culvert. 0º, 45º and 90º wingwalls as well as 15º, 30º, 45º and 90º headwalls were combined and tested.

The 90º wingwall and 90º headwall represent the standard square edge inlet. The wingwalls and headwalls were compared to a 0.25*D* rounded-edge inlet. The model culvert dimensions and the physical model, constructed from acrylic plastic with a 3D-printed inlet sealed in place with silicone, are shown in Figure 3. The wingwalls extended 0.4*D* to the sides of the barrel, and the headwall extended 0.4*D* upward to ensure the enlarged inlet cross-sectional area of 360 x 280 mm was kept the same for all the tests, providing a consistent inflow area.

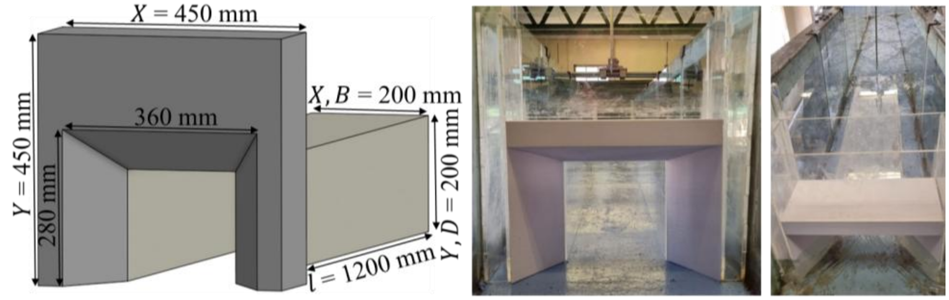


Figure 3: Model culvert dimensions and model culvert installed in the hydraulic flume

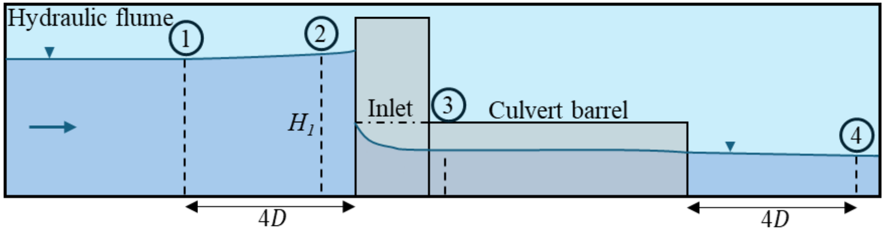
Water was pumped into the flume, and different flow rates were achieved by adjusting three control valves. Approximately 20 flow rates, ranging from 4 l/s to 82 l/s, were tested for each inlet modification. The flow rates were recorded using an ultrasonic flow meter. Furthermore, the flow depths corresponding to each flow were measured just upstream (H_1) and at 4*D* upstream and downstream of the culvert.

3 RESULTS

3.1 Physical modelling testing

Figure 4 illustrates the difference in upstream ① and downstream ④ water levels between a) a standard square-edge inlet and b) a modified inlet. The flow through the culvert in Figure 4a) and Figure 4b) is the same. Therefore, as water flows through a square-edged inlet culvert, the cross-sectional area decreases ③ while the velocity increases, in accordance with the continuity equation. For the same flow rate, inlet improvements allow for a larger cross-sectional area to be utilised inside the culvert barrel ③ with a smaller increase in velocity compared to the square edge inlets. This reduces the upstream headwater level, (H_1) or ②, which lowers the risk of upstream flooding and road overtopping.

a) Square edge inlet



b) Angled wingwalls and headwall

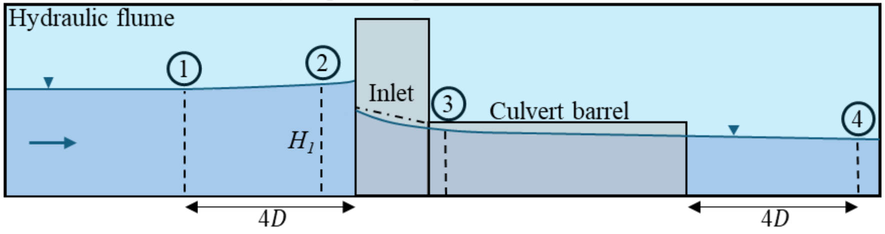


Figure 4: Side view of hydraulic flume illustrating the flow through a culvert with a) a square edge inlet and b) an angled wingwalls and headwall for the same flow rate

During the tests, the water level upstream of the culvert inlet ② was higher than downstream ④, indicating a damming effect. Subcritical flow upstream of the culvert went through critical flow after the inlet and then to supercritical flow in the barrel due to the steep slope (West, 1956). Figure 5 verifies this behaviour for the 90º wingwall and 90º headwall box culvert by plotting the Froude numbers at the three depth-measurement locations defined in Figure 4. All other inlet modifications showed similar behaviour.

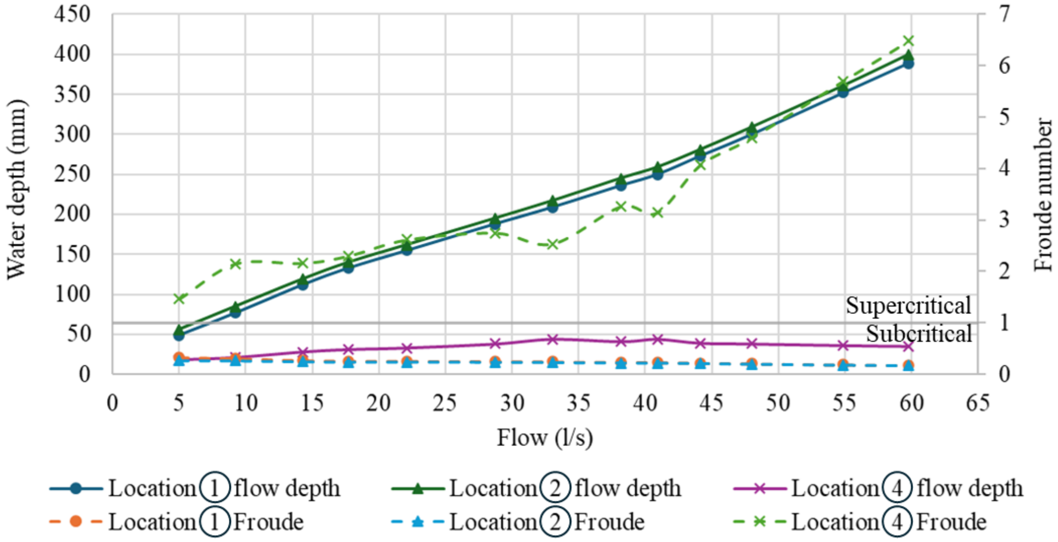


Figure 5: Water depth and Froude numbers for the 90º wingwall and 90º headwall box culvert at i, ii and iv in the hydraulic flume

Figure 6 shows the performance curves for each inlet modification, generated using third-degree polynomial fits to the flow versus headwater data. A 1*D* line marks the point of inlet submergence, and a 2*D* line represents the maximum allowable headwater for a given design recurrence interval defined in the South African design guideline (SANRAL, 2013). Once submerged, the influence of the modifications became significant (>15%). The 30º wingwall with a 15º headwall performed best, increasing flow by 34% at $H_1/D = 2$. It was followed by a rounded-edge inlet and a 45º wingwall with a 15º headwall.

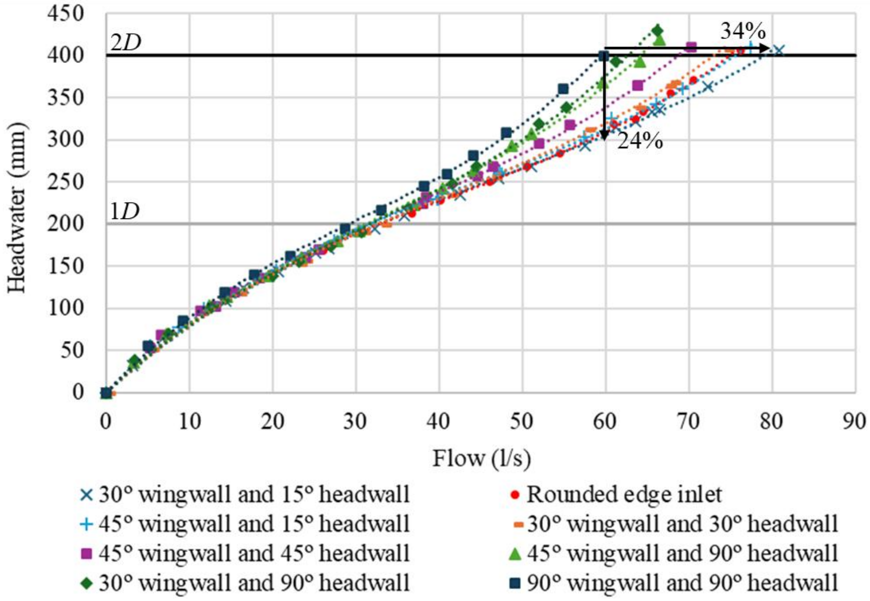


Figure 6: Headwater to discharge relationship for improved square box culvert inlets tested, ranked from most to least effective, after Giliomee et al. (2025)

Figure 7 shows the percentage improvement for different wingwall and headwall angle combinations at different levels of submergence. When the inlet is unsubmerged, only the wingwalls influence the flow, but once submerged, the headwall angle has a much greater effect. At $H_1/D = 1.5$, the wingwall and headwall contribute almost equally, while at $H_1/D = 2$ the headwall governs. The 15º headwall reduces contraction losses notably, with the 30º wingwall and 15º headwall conveying 28% more flow than the same wingwall angle with a 90º headwall. Overall, the optimal wingwall angle lies between 0º and 30º, and the optimal headwall angle between 0º and 15º. Among the configurations tested from the literature, the 30º wingwall and 15º headwall provided the greatest increase in discharge.

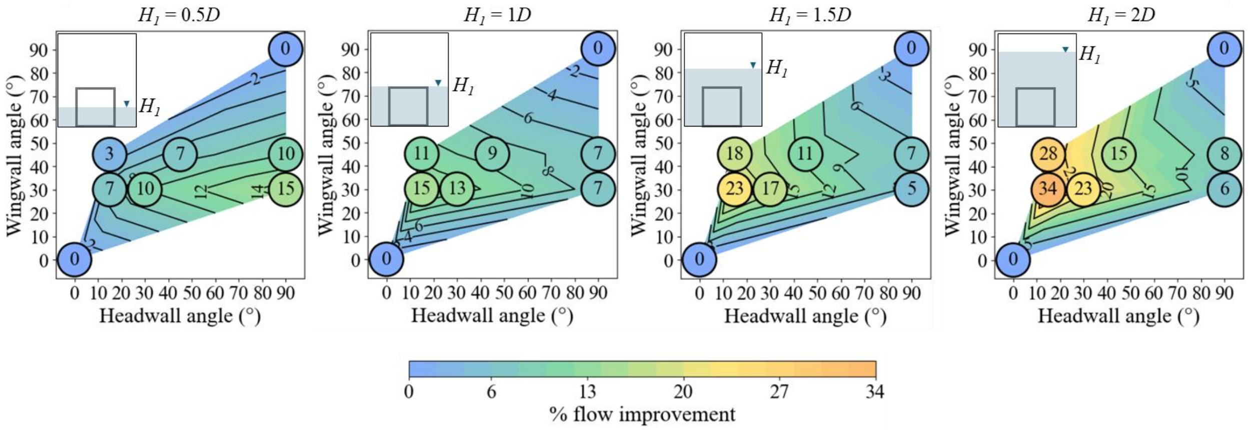


Figure 7: Percentage flow improvement at headwater levels of 0.5*D*, 1*D*, 1.5*D* and 2*D*

3.2 Flow improvement coefficient

The capacity improvement results were used in Giliomee et al. (2025) to develop a coefficient for flow improvement, C_{TG}, which quantifies the increase in discharge provided by each inlet modification. It can be applied as an adjustment factor to the standard square-edge culvert discharge calculated using existing guidelines, as shown in Eq. (1). A higher C_{TG} indicates better performance; for example, a C_{TG} of 1.34 corresponds to a 34% increase in flow at that headwater depth. For any specific headwater level larger than $H_1/D = 0.5$, the coefficient was calculated with Eq. (2).

$$Q_{Improved} = Q_{Square\ edge\ inlet\ culvert} \times C_{TG} \tag{1}$$

$$C_{TG} = \frac{Flow\ improvement\ (\%)}{100} + 1 = \frac{(Q_{Improved\ inlet} - Q_{Square\ edge\ inlet})}{Q_{Square\ edge\ inlet}} + 1 \tag{2}$$

The flow improvement provided by each inlet modification varies with headwater depth. Therefore, C_{TG} coefficients were linked to ranges of H_1/D using separate equations for unsubmerged conditions ($0.5 \leq H_1/D \leq 1.2$) and submerged conditions ($1.2 < H_1/D \leq 2$). Table 1 presents the C_{TG} equations for the 30º wingwall with a 15º headwall and the 45º wingwall with a 15º headwall, allowing the coefficient to be calculated for any headwater depth. Table 1 also lists the percentage flow improvement at $H_1/D = 1.2$ and $H_1/D = 2$, along with the standard square-edge inlet equations from SANRAL (2013) as an example of existing guidelines to which the C_{TG} values can be applied.

Table 1: Inlet-controlled square box culvert improvement coefficient equations and their percentage improvement in discharge capacity after Giliomee et al. (2025)

SANRAL (2013)	**C_{TG} coefficient equations**
For: $0 < H_1/D \le 1.2$ $Q = \frac{2}{3} C_B B H_1 \sqrt{\frac{2}{3} g H_1}$ Where: $C_B = 0.9$	Equations only apply for $0.5 \le H_1/D \le 1.2$
	30° wingwall and 15° headwall (18% at 1.2*D*) $C_{TG} = 0.1532(H_1/D) + 0.9953$
	45° wingwall and 15° headwall (14% at 1.2*D*) $C_{TG} = 0.1477(H_1/D) + 0.9645$
For: $H_1/D > 1.2$ $Q = C_h BD \sqrt{2g(H_1 - C_h D)}$ Where: $C_h = 0.6$	Equations only apply for $1.2 < H_1/D \le 2$
	30° wingwall and 15° headwall (34% at 2*D*) $C_{TG} = 0.0897(H_1/D)^2 - 0.0836(H_1/D) + 1.1517$
	45° wingwall and 15° headwall (28% at 2D) $C_{TG} = 0.0632(H_1/D)^2 - 0.0346(H_1/D) + 1.0919$

4 CASE STUDY

The physical modelling results were theoretically applied to an existing culvert as a case study to demonstrate how discharge capacity can be increased and flood risks reduced through inlet modifications. The culvert is a single-barrel box culvert with a width of 1.2 m and a height of 0.6 m, installed on a 0.069 m/m slope and a total length of 17.55 m. This culvert functions under inlet control.

Table 2 shows the culvert analysis comparing the design flood with the culvert capacity, both without and with inlet modifications, at different levels of submergence. The South African design criteria specifies that inlet submergence should be limited to H_1=1.2*D* for the design flow Q_T, while for the higher flow Q_{2T}, the upstream level should be limited to the minimum of 2*D* or the shoulder break point (SBP) level (SANRAL, 2013). The C_{TG} coefficient for the 30° wingwall with a 15° headwall was used to calculate the increased discharge capacity. Before the inlet modifications, the culvert was insufficient for its design floods, but calculations show that the improvements now allow the culvert to convey the 1:20 return-period flood under the South African performance criteria. This is important because it is critical to prevent roadway overtopping during high flood conditions. The culvert with inlet modifications would not convey the desired flow at 1.2*D* for the 1:10 design flood, but it would do so at approximately 1.3*D*, which remains acceptable for design purposes.

Table 2: Case study culvert analysis comparing the design flood to the culvert capacity without and with inlet modifications at headwater depths of 1.2*D*, 2*D*, and the shoulder breakpoint (SBP)

Headwater data			**Design return period**	**Before inlet modifications**		**After inlet modifications**	
H_1 (m)		**H_1/D**	**Q_T=Q_{10} (m^3/s)**	**Q (m^3/s)**	**Sufficient (Y/N)**	**$Q_{improved}$ (m^3/s)**	**Sufficient (Y/N)**
1.2*D*	0.720	1.20	1.624	1.125	No	1.326	No
H_1 (m)		**H_1/D**	**Q_{2T}=Q_{20} (m^3/s)**	**Q (m^3/s)**	**Sufficient (Y/N)**	**$Q_{improved}$ (m^3/s)**	**Sufficient (Y/N)**
2*D*	1.200	2.00	2.025	1.754	No	2.356	Yes
SBP	1.392	2.32	2.025	1.944	Almost	2.605	Yes

Figure 8 presents the performance curve for the current culvert and when a 30° wingwall with a 15° headwall is retrofitted. For the 1:20-year flood, a 30% (0.44 m) reduction in headwater is observed, or alternatively, a 34% (0.66 m^3/s) increase in discharge is observed at a headwater depth equal to the height from the invert to the SBP. At a headwater depth up to the road level (SBP), the culvert could convey only a 1:15-year return-period flood without an inlet modification, but with the inlet modification, it is able to convey a 1:49-year return-period design flood.

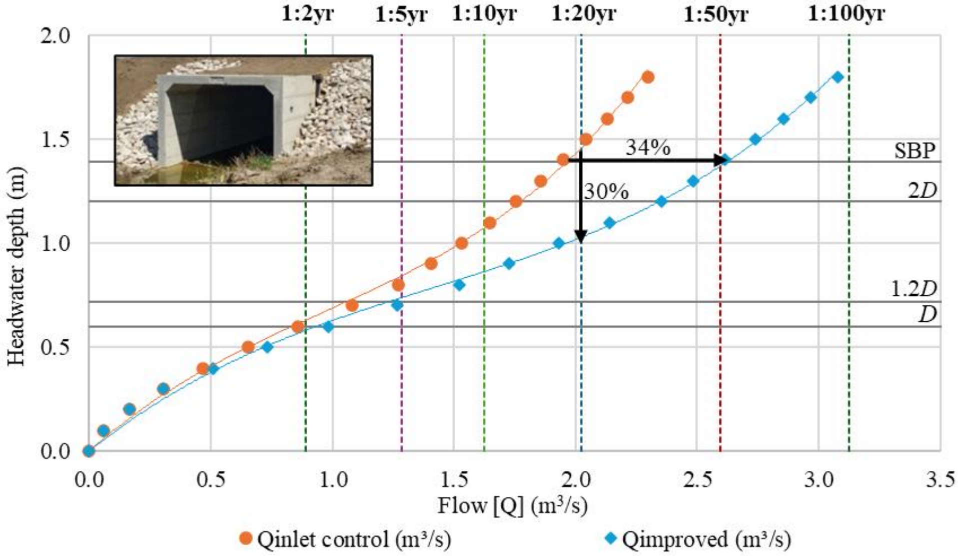


Figure 8: Case study box culvert performance curve analysis under inlet control, without, and with a modified inlet

Figure 9 indicates the percentage reduction in headwater levels when the inlet modification is theoretically applied to the case study culvert under different return-period design floods. Reducing the upstream headwater depth lowers the risk of culvert overtopping. This is expected to improve road safety and protect infrastructure.

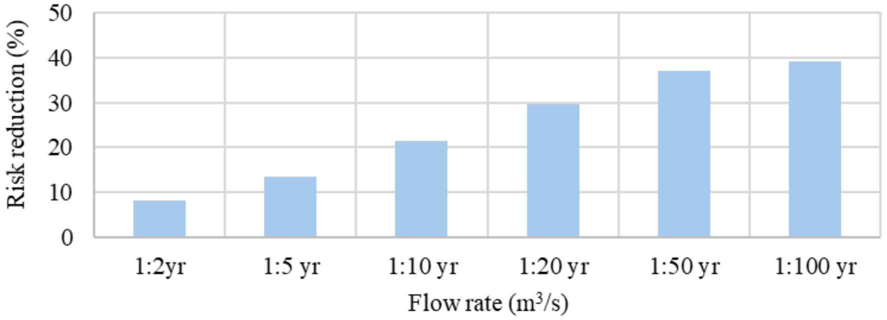


Figure 9: Percentage reduction in headwater levels when the inlet modification is applied to the case study culvert, analysed under different return-period design floods

5 CONCLUSION

A modified inlet reduces flow contraction at the entrance, lowers headwater levels for a given flow, or increases discharge capacity for a similar headwater depth. The results showed that a box culvert's capacity can improve by up to 15% at 1*D* and up to 34% at 2*D* when an inlet modification is applied, providing a cost-effective alternative to adding barrels or rebuilding an inadequate structure. The combination of a 30º wingwall with a 15º headwall performed the best, even better than the rounded-edge inlet. Once the inlet was submerged, the headwall had a greater influence on flow than the wingwalls.

Flow improvements were quantified using the C_{TG} coefficient and theoretically applied to a case study culvert. The inlet modification enabled the insufficient case study culvert to convey its required design flood, reducing headwater levels enough to prevent road overtopping; for the 1:20-year event, the headwater depth decreased by about 30%. The reduction in headwater depth was more pronounced at higher flows, lowering flood risk during extreme events and supporting more sustainable drainage infrastructure.

6 ACKNOWLEDGEMENTS

Special thanks to Mr. Jan Ngwenya for assisting with lab testing, to Mr. Jordan Mostert for installing instrumentation and managing the 3D printing. This work was supported by the South African National Roads Agency SOC Limited (SANRAL) (Project number: 1002-58600-2018-P7a.10) and the Water Research Commission (WRC) (Project number: C2023/2024-01295).

7 DATA DISCLOSURE

The dataset used in this study was originally generated by the authors and first reported in Giliomee et al. (2025). The present paper builds on that work through additional analyses and new interpretations that extend the original findings.

REFERENCES

Agonafir C., Lakhankar T., Khanbilvardi R., Krakauer N., Radell D. and Devineni N. (2023). A review of recent advances in urban flood research. Water Security, 19, 100141. https://doi.org/10.1016/j.wasec.2023.100141.

Ashour M.A., Aly T.E. and Abdou A.A. (2014). Inclined headwall is an efficient tool for maximizing the discharge efficiency through culverts in 3rd International conference (Water resources and wetlands), Tulcea, Romania, September 8-10, 2016, pp. 184-193. https://www.researchgate.net/publication/355209300.

Giliomee T. M. D., Loots I. and van Dijk M. (2025) Increasing culvert hydraulic capacity for improved climate resilience: a physical modelling analysis. Water and Climate Change, 16, 8, 2503-2518. https://doi.org/10.2166/wcc.2025.033.

Houghtalen R.J., Akan A.O. and Hwang N.H.C. (2010). Fundamentals of Hydraulic Engineering Systems. 4th ed. Upper Saddle River, NJ: Pearson Education.

Jaeger R. (2019). Hydraulic improvements in culverts for climate change adaptation. Unpublished Doctor of Philosophy thesis, University of the Sunshine Coast, University of the Sunshine Coast's Research Repository (UniSC Research Bank).

South African National Roads Agency SOC Limited (SANRAL). (2013). Drainage Manual. 6th Edition, Pretoria, Available from: https://www.nra.co.za/uploads/27/Drainage-Manual-6th-Edition-Sept-2013.pdf.

Schall J.D., Thompson P.L., Zerges S.M., Kilgore R.T. and Morris J.L. (2012). Hydraulic Design of Highway Culverts Third Edition, Hydraulic Design Series Number 5. FHWA-HIF-12-026, Colorado, United States of America.

Straub L.G., Anderson A.G. and Bowers C.E. (1953). Importance of Inlet Design on Culvert Capacity. University of Minnesota, Minneapolis, Minnesota, United States of America, http://purl.umn.edu/108023, consulted 11 November 2025.

West E.M. (1956). Hydraulic Model Studies of Culvert Operation. Commonwealth of Kentucky Department of Highways. Lexington, Kentucky, United States of America, Report No.1, http://dx.doi.org/10.13023/KTC.RR.1956.118.