

Hydraulic Behavior of Conventional Rainwater Drainage Systems Under High Rainfall Intensity: Experimental Insights on Vertical Down-Pipe Flow

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ABSTRACT : *This study reports on an experimental programme that aimed to examine the behavior of flow in a 64 mm vertical down-pipe as part of a conventional rainwater drainage system. Parameters including flow rate, pressure, air entrainment, and water depth in the gutter were investigated. Additionally, the effects of different contraction sizes and discharge bends on system performance were examined. A laboratory test rig was developed, consisting of a 3.8 m vertical down-pipe connected to a gutter supplied by a simulated sloping roof. Flow rates were monitored using magnetic induction meters, while pressure was measured by transducers installed along the down-pipe. The results showed that as flow rate increased, full-bore flow developed within the down-pipe, and that freely discharging outlets achieved the highest capacity (18 l/s under sub-atmospheric pressures). Restrictions at the discharge point significantly reduced capacity: a 20% reduction lowered capacity to 14 l/s, and a 50% reduction reduced capacity to 6.3 l/s, with all system parts operating above atmospheric pressure. The findings confirm that conventional drainage systems can operate in a siphonic manner at higher flow rates, but restrictions at the discharge point inhibit siphonic action and overall performance.*

KEYWORDS - *Climate change, Conventional systems, Siphonic systems, Hydraulic*

I. INTRODUCTION

Urban water management has emerged as one of the central challenges of the 21st century, particularly in the context of accelerating climate change. A substantial body of research indicates that global warming has altered the hydrological cycle, resulting in significant changes in precipitation patterns across many regions of the world [1,2]. Unlike the past century, when hydrologists and engineers could often rely on the assumption of stationary rainfall statistics, contemporary evidence demonstrates that rainfall extremes are becoming more frequent and more intense [3]. This non-stationarity in rainfall intensities has profound implications for the design and operation of urban drainage systems, which form the first line of defense against flooding in densely populated cities.

Traditionally, drainage infrastructure was designed using historical rainfall records and based on return periods such as the “1-in-50” or “1-in-100” year storm [4]. However, with climate change shifting rainfall extremes outside previously observed ranges, these conventional design approaches are increasingly being questioned [5]. Recent urban flooding events in Europe, Asia, and the Middle East highlight that even relatively new drainage networks often fail to cope with sudden cloudbursts. These failures are not only costly in terms of property damage but also carry public health and safety implications.

Among urban drainage technologies, two principal categories dominate: conventional gravity-driven systems and siphonic rainwater drainage systems. Conventional systems are the most widespread, especially in older or small-scale

building stock, relying on gravity to drive the flow of water from roofs through down-pipes to ground drains. These systems typically operate under atmospheric pressure with partially filled pipes, meaning that their capacity is limited by pipe diameter and gradient [6]. By contrast, siphonic systems are engineered to induce sub-atmospheric pressures, eliminating air entrainment, creating full-bore pressurized flow, and therefore achieving substantially higher flow capacities per unit pipe diameter [7].

The prevailing design methodology for siphonic roof drainage systems assumes that once rainfall begins, the system fills quickly and primes completely with water, thereby achieving full-bore conditions [8]. Under this assumption, the hydraulic behavior of the system can be represented using basic steady-state flow principles, which considerably simplify the design process [8]. In practice, the steady-flow energy equation is typically employed as the foundation of siphonic design procedures [8-9].

The capacity of the system and the pressure drop between any two points along the flow path can be determined from the energy balance expressed as:

$$\left(h_1 + \frac{V_1^2}{2g} \right) - \left(h_2 + \frac{V_2^2}{2g} \right) = \Delta h_{12} - \Delta z_{12}$$

Where h_1 and h_2 are the piezometric heads, and V_1 and V_2 are velocities at points 1 and 2, respectively.

Siphonic systems have been widely adopted in the design of large buildings, stadiums, and commercial complexes, where roof areas and expected runoff volumes are considerable. Their advantages in terms of efficiency, material savings, and space flexibility are well documented [10-11]. However, conventional drainage systems remain prevalent in smaller buildings and domestic infrastructure, where the installation of siphonic systems may not be economically justified. Despite their ubiquity, the behavior of conventional systems under extreme rainfall intensities has not been extensively studied. A few reports suggest that conventional systems may exhibit siphonic behavior at higher flow rates, but the mechanics, limitations, and performance thresholds of such behavior remain poorly understood [12].

This research contributes to addressing this gap by conducting controlled laboratory

experiments on a vertical down-pipe within a conventional drainage system. The study investigates whether such systems can indeed transition to siphonic operation under high rainfall intensities, and how discharge restrictions influence performance. Understanding these phenomena is particularly timely given the growing mismatch between conventional system design criteria and the realities of changing rainfall patterns. By linking climate change impacts, hydraulic behavior, and system design, this study aims to provide new insights that could guide both retrofitting strategies for existing infrastructure and the development of more resilient standards for the future.

II. MATERIALS AND METHODS

The laboratory work was carried out using a test rig (Fig. 1) comprised of a gutter simulation tank, with 1.95-meter length, 0.6 m height and 0.3 m depth, connected at its base with a 0.064 m transparent down-pipe 3.8 meters in length.

Water was pumped from a collection tank, located about 4 m below the test rig, using a submersible pump, up into a rear supply trough, through two inflow pipes. Each of the two pipes is enclosed with two valves; one is situated at the top (the test rig) and the other at the bottom (above the collection tank), which could be used independently to control the flow rate. Also, a bypass valve was located at the collection tank.

Water reached into the simulated tank via the rear supply trough and a simulated sloping roof, with gradient of about 18 degrees to the horizontal, from where it then flowed through the down-pipes to the collection tank. As the down-pipe was transparent, direct observation and digital footage could be taken to assist in the identification of flow conditions.

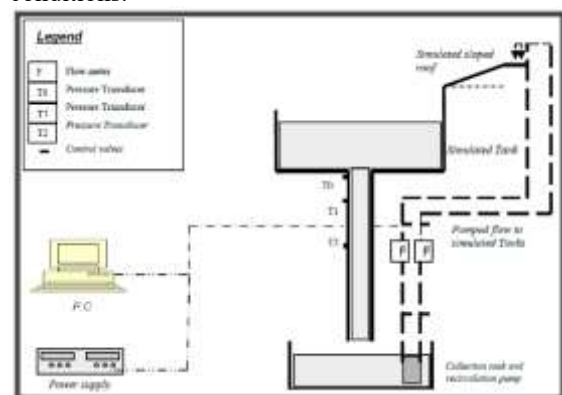


Fig. 1 A laboratory test rig.

Two pressure transducers were located at different points in the down-pipe to measure the voltage resulting from the flow pressure in the pipe. The two transducers were 0.75 m apart, with the upper one situated 294 mm below the gutter. Another pressure transducer was connected to the bottom of the simulation tank to measure the flow depth in the gutter.

For analysis flow conditions in the system, two magnetic induction flow meters were connected to the two supply pipes. All the pressure transducers and flow meters were connected to a voltmeter which in turn was linked to a computer for recording the data in voltages. Before the experimental work could be carried out, pressure transducers had to be calibrated. This was done to ensure that the transducers and the computer were performing appropriately.

III. RESULTS AND DISCUSSION

Based on the current design approach of siphonic rainwater drainage systems aforementioned (section I), the flow capacity and pressure distributed for the system used in conducting the practical work were estimated, and compared with those resulting from physically testing the system.

The System with a Freely Discharging 64 mm Vertical Down-Pipe

Flow capacity and pressure distributed for the system with a freely discharging point were estimated using the above equations, and compared with the measured ones. An over view of the analysis is given in following Table 1:

Table 1 Comparison of calculated and measured flow conditions for the system with a freely discharging point.

Parameter	Computed	Measured	Error %
Flow capacity (l/s)	18.02	~18.0	-0.11
Pressure at Upper Transducer (in H_2O)	-1.976	-1.976	0
Pressure at Lower Transducer (in H_2O)	-1.628	-1.693	-3.8

Fig. 2 demonstrates the pressure profile for the whole system with a freely discharging pipe once it was primed. There are considerable calculated variations in pressure throughout the

system, resulting from the hydraulic resistance of the pipe wall and losses at the point of entry and point of discharge of the vertical pipe.

At the gutter base just upstream from the gutter's outlet, the pressure is positive and equal to the depth of water in the gutter. As flow enters the vertical pipe via the outlet, the pressure decreases to the minimum value below the atmospheric pressure (-2.145 m water). This is a result of the loss resulting from the gutter's outlet. As the flow falls down through the vertical pipe, the change in potential energy is more than the frictional loss; thus the pressure increases until the flow discharges under atmospheric pressure. It can also be seen from the profile that most parts of the system function under negative pressures when it was operating under the full-bore flow conditions, hence all parts of the system are operating siphonically.

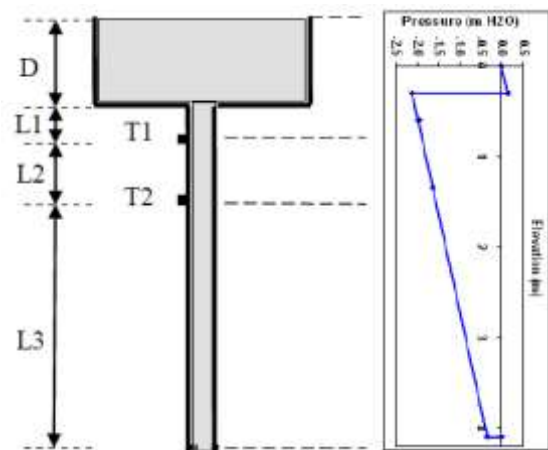


Fig. 2 pressure profile for the whole system with a freely discharging pipe.

The System with Various Restrictions at the Pipe Exit

The following Tables (2-7) show flow capacity and pressure distributed for the system with different size contractions and degree of bending at the point of discharge. These were estimated using the current design approach of siphonic system, and compared with the measured ones.

Table 2 Comparison of calculated and measured flow conditions for the system with 51 mm contraction at the point of discharge.

Parameter	Computed	Measured	Error %
Flow capacity (l/s)	13.64	~14.0	+2.5
Pressure at Upper Transducer (in H_2O)	-0.894	-0.894	0
Pressure at Lower Transducer (in H_2O)	-0.396	-0.407	-2.7

Table 3 Comparison of calculated and measured flow conditions for the system with 41 mm contraction.

Parameter	Computed	Measured	Error %
Flow capacity (l/s)	9.25	~9.5	+2.61
Pressure at Upper Transducer (in H_2O)	-0.185	-0.185	0
Pressure at Lower Transducer (in H_2O)	0.447	0.392	+13.7

Table 4 Comparison of calculated and measured flow conditions for the system with 32 mm contraction.

Parameter	Computed	Measured	Error %
Flow capacity (l/s)	6.33	~6.0	-5.5
Pressure at Upper Transducer (in H_2O)	0.165	0.164	-0.6
Pressure at Lower Transducer (in H_2O)	0.864	0.832	-3.84

Table 5 Comparison of calculated and measured flow conditions for the system with 20.5 mm contraction.

Parameter	Computed	Measured	Error %
Flow capacity (l/s)	2.43	~2.5	+2.8
Pressure at Upper Transducer (in H_2O)	0.316	0.316	0
Pressure at Lower Transducer (in H_2O)	1.058	1.033	-2.42

Table 6 Comparison of calculated and measured flow conditions for the system with 45-degree bend.

Parameter	Computed	Measured	Error %
Flow capacity (l/s)	12.57	~14.0	+3.07
Pressure at Upper Transducer (in H_2O)	-0.870	-0.869	+0.11
Pressure at Lower Transducer (in H_2O)	-0.364	-0.369	+1.35

Table 7 Comparison of calculated and measured flow conditions for the system with 90-degree bend.

Parameter	Computed	Measured	Error %
Flow capacity (l/s)	12.95	~12.0	-7.91
Pressure at Upper Transducer (in H_2O)	-0.532	-0.532	0
Pressure at Lower Transducer (in H_2O)	-0.040	-0.036	+11.1

From a general observation of the tables (1-7), one can see a good correlation between the computed and the measured flow conditions developed in the vertical down-pipe. The discrepancies which exist between these results may

be accounted for by the variations in the in-air content and inaccuracies in the estimation of head loss across fittings [13].

Fig. 3 illustrates pressures profiles for the system with 51, 41, 32 and 20.5 mm contractions at the discharging point. These profiles represent the system at the full-bore flow condition. As can be seen, there are considerable variations in pressure throughout the system, which are dependent on frictional losses through fittings and change in static height.

In the case of the 51 mm contraction, as can be seen from Fig. 3.a, half of the system operates in a siphonic manner characterized by the negative pressures in the upper half of the vertical pipe with a minimum value of (-1.08 m of water) at the point of entry, whereas the lower half of the system operates under positive pressures with a maximum value of (1.433 m of water) just above the contraction.

The pressure profile for the system with the 41 mm contraction is illustrated by graph 3b. As shown, only a small part of the system operates under sub-atmospheric pressure; the length of the system is between the point of entry and the upper transducer, with a minimum value of (-0.433 m of water) at the point of entry, while the major part of the system is operating under pressures above that of the atmospheric pressure, with a maximum value

of (2.77 m of water) just above the contraction.

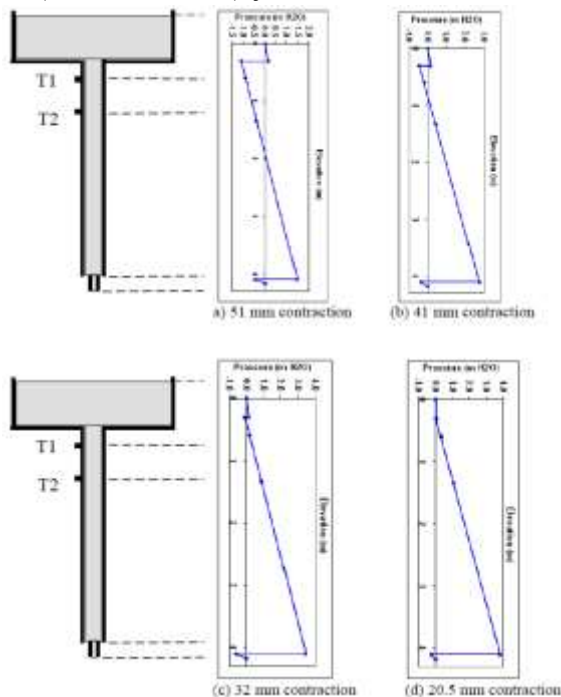


Fig. 3 Pressure profiles for the whole system with different size contractions at pipe exit.

For the narrowest contractions, 32 and 20.5 mm, as shown in Fig. (3c) and (3d) respectively, all parts of the system are operating at pressures above the atmospheric pressure, with maximum values of 3.43 and 3.78 m of water for 32- and 20.5-mm contractions respectively. It is interesting to note that these pressure values are close to the length of the vertical down-pipe, which equals 3.8 m.

From Fig.3 it can also be seen that the impact of all the four contractions on the system has led the system to discharge the water at pressure values almost equal to the atmospheric pressure.

Fig. 4 shows the pressure profile for the system with 45° and 90° bends at the discharging point. 4.a & 4.b, respectively. As can be seen from graphs (a) and (b), in both cases the system works partially under negative pressures.

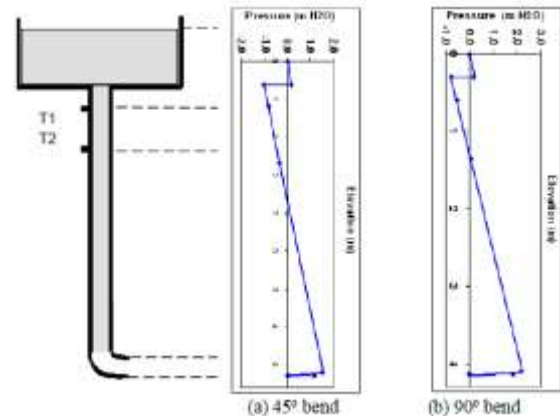


Fig. 4 Pressure profiles for the system with bending at the point of discharge

In the case of the 45° bend, the pressure pattern for the system is almost identical to the one with 51 mm contractions (Fig. 3.a), where in both cases half of the system operates at sub-atmospheric pressure, while the other half operates under pressures above the atmospheric pressure. Based on this, it could be said that the 45° bend and 51 mm contraction have the same effects on the system.

The pressure profile for the system with 90° bend is shown in Fig. 4b. As can be seen from this figure, only a small part of the system is operating under sub-atmospheric pressure, the upper part of the vertical pipe, with a minimum value of (-0.755 m of water) located at the point of entry. The other part of the system is operating under pressures above atmospheric pressure, with a maximum value of (2.14 m water) just above the bend.

Based to the above discussion, there is a greater impact on the system resulting from the 90° bend compared with the 45° bend. This is evidenced by the shorter siphonic length and the lower system's flow capacity 12 l/s; whereas in the case of the 45° bend, the system capacity was 14 l/s.

IV. CONCLUSION

The experimental investigation provided clear evidence that conventional rainwater drainage systems can exhibit siphonic behavior under high flow conditions. When the flow rate approached the hydraulic capacity of the 64 mm vertical down-pipe, the system transitioned to sub-atmospheric pressures, establishing a full-bore flow regime. In

this state, the effective driving head was defined by the vertical distance between the roof surface and the outlet, resulting in increased flow velocity and enhanced discharge capacity.

The development of full-bore flow was consistently associated with the expulsion of entrained air as the inflow increased, a mechanism analogous to the priming process observed in siphonic drainage systems. This demonstrates that conventional systems are capable of operating beyond their nominal gravity-driven limits under certain hydraulic conditions. However, the experimental data confirmed that the performance of the system was highly sensitive to outlet geometry. Specifically:

Flow capacity: With a freely discharging outlet, the 64 mm vertical down-pipe achieved a maximum flow capacity of approximately 18 l/s. The introduction of outlet contractions significantly reduced this capacity. Contractions to 51, 41, 32, and 20.5 mm diameters lowered system capacities to roughly 14, 9.5, 6, and 2.5 l/s, respectively. Similarly, outlet bends diminished performance: a 45° bend reduced capacity to ~14 l/s, while a 90° bend reduced it further to ~12 l/s.

Pressure distribution: At free discharge, the entire system operated under sub-atmospheric pressures, confirming siphonic action. In contrast, moderate restrictions (e.g., 51 and 41 mm contractions, or 45° and 90° bends) allowed siphonic conditions to develop only in parts of the system. With severe contractions, pressures throughout the system remained above atmospheric levels, preventing siphonic behavior entirely.

Overall, these findings demonstrate that while conventional drainage systems can function siphonically under extreme flow rates, their performance is significantly constrained by outlet restrictions. Freely discharging outlets maximize capacity and promote siphonic behavior, whereas contractions and bends reduce capacity and suppress sub-atmospheric operation. These insights have important implications for the design and retrofitting of conventional drainage systems, particularly in light of projected increases in rainfall intensity under

climate change.

REFERENCES

- [1] R.P. Allan and B.J. Soden, Atmospheric warming and the amplification of precipitation extremes, *Science*, 321(5895), 2008, 1481–1484.
- [2] K.E. Trenberth, Changes in precipitation with climate change, *Climate Research*, 47(2), 2011, 123–138.
- [3] IPCC, *Climate Change 2021: The Physical Science Basis* (Cambridge, UK: Cambridge University Press, 2021).
- [4] D. Butler and J.W. Davies, *Urban Drainage* (4th ed., Boca Raton, FL: CRC Press, 2018).
- [5] P. Willems, et al., Impact of climate change on rainfall extremes and urban drainage systems, *Urban Water Journal*, 9(2), 2012, 87–98.
- [6] R.W.P. May, *Hydraulic Design of Rainwater Drainage Systems* (London: CIRIA Report C539, 2003).
- [7] S. Arthur and G. Wright, Siphonic roof drainage systems: Current knowledge and practice, *Building and Environment*, 42(2), 2007, 1029–1038.
- [8] S. Arthur and J.A. Swaffield, Siphonic roof drainage analysis utilising unsteady flow theory, *Building and Environment*, 36(7), 2001, 939–948.
- [9] R.W.P. May and M. Escarameia, *Performance of Siphonic Drainage Systems for Roof Gutters* (Report SR 463, HR Wallingford, England, 1996).
- [10] D. Campbell and J.A. Swaffield, Hydraulic design of siphonic roof drainage systems, *Building Services Engineering Research and Technology*, 16(1), 1995, 13–20.
- [11] G. Wright, S. Arthur, and J.A. Swaffield, Performance of siphonic roof drainage systems under climate change scenarios, *Proceedings*

- of the ICE – Water Management*, 163(8), 2010, 391–400.
- [12] J.A. Swaffield and D. Campbell, Development of siphonic roof drainage, *Building and Environment*, 30(4), 1995, 585–596.
- [13] S. Arthur and J.A. Swaffield, Numerical modeling of the priming of a siphonic rainwater drainage system, *Building Services Engineering Research and Technology*, 20(2), 1999, 83–91.