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Investigation into the performance characteristics of multi-outlet siphonic rainwater systems

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Abstract

Previous research at Heriot-Watt University has led to a better understanding of the performance characteristics of siphonic rainwater systems, with particular reference to the priming of such systems. This has resulted in the development of a numerical model capable of accurately simulating the priming phase of single outlet siphonic rainwater systems. However, the majority of installed systems incorporate more than one roof outlet, and the interaction between such outlets is not well understood. It was therefore recognised that further research was required to extend the existing numerical model to multi-outlet applications.

The work reported herein details an ongoing UK EPSRC research programme investigating the performance characteristics of multi-outlet siphonic rainwater systems. The experimental aims, apparatus and procedures are described, and preliminary results are illustrated. In addition, “real” data obtained from two installed siphonic rainwater systems are discussed. Conclusions are drawn regarding the performance characteristics of multi-outlet siphonic rainwater systems, and plans for future work are outlined.

Keywords

Siphonic rainwater systems; multi-outlet; design.

Introduction

Conventional rainwater systems

Conventional rainwater systems generally consist of a network of collection gutters connected (via open outlets) to downpipes, which are themselves connected to some form of underground drainage network. The system components are sized to ensure annular flow through the downpipes (with a continuous central air path), and system pressures therefore remain atmospheric. Consequently, the driving head for flow within conventional rainwater systems is limited to the gutter flow depths, which results in

relatively low flow velocities within the system. This necessitates many, relatively large diameter, downpipes (typically 150mm) each of which must be connected into an underground drainage network. The other main disadvantage of conventional systems is that the dimensions/gradients of the gutters, and any horizontal pipework, must be designed to ensure sufficient capacity and self-cleansing flow velocities.

Siphonic rainwater systems

In contrast to conventional systems, the siphonic approach to roof drainage aims to restrict the ingress of air into the system, and hence induce the full bore flow conditions necessary for siphonic action. This is achieved by utilising specially designed gutter outlets in conjunction with smaller diameter pipework. Once all of the air has been purged from the system, siphonic action occurs and the system is said to have *primed*. At its specific design capacity, the driving head within an efficiently designed siphonic rainwater system can be equal to the gutter flow depths *plus* the full vertical height between the outlets and the point of discharge. Clearly this yields significantly higher flow velocities than is possible in conventional systems, which means that attaining self-cleansing velocities is rarely a problem. It also results in the need for fewer, and smaller diameter, downpipes. As the flow is de-pressurised, there is considerably more flexibility in pipe routing, allowing most of the horizontal pipework to be located just below roof level, and reducing the extent of costly underground drainage networks. In addition, more than one outlet can be connected to a single downpipe.

A siphonic rainwater system will only operate efficiently at its *design condition*, under specified design rainfall criteria (e.g. a 1 in 30 year rainfall event); that is, only one rainfall event matches any particular system. Consequently, a siphonic system will rarely, if ever, operate at its design condition. If a siphonic system is exposed to a rainfall event which exceeds the design criteria, flooding will occur and the system may fail (the gutters overtop) if the excess runoff cannot be diverted elsewhere. However, the more likely scenario is that a system will be exposed to a rainfall event below the design criteria. When this occurs, the flow conditions will differ from those in a fully primed system, their exact nature depending on the characteristics of the rainfall event. Similar conditions can occur if the flow distribution between gutter outlets is not as per design; a scenario that may arise due to poorly installed roof surfaces and/or gutters. The other main disadvantage of siphonic rainwater systems is that the outlets and pipework are relatively easily blocked by detritus in the flow (e.g. leaves), which can lead to system failure⁽¹⁾.

Current design practice

Current design practice assumes that, for the specified design rainfall event, a siphonic system fills, and primes, rapidly with 100% water. This assumption allows siphonic rainwater systems to be designed utilising steady state hydraulic theory. This usually takes the form of the steady flow energy equation⁽²⁾, where the elevation difference between the outlets and the point of discharge is equated to the head losses in the system. It has been reported that this design approach yields operational characteristics similar to those observed in laboratory test rigs at the fully primed state⁽²⁾⁽³⁾. However, steady state design methods are not applicable when a system is exposed to a rainfall event below the design criteria. As such events are the norm, it is clear that current design methods may not be suitable for determining the day-to-day performance characteristics of siphonic rainwater systems. This is a major disadvantage,

as it is during these events that the majority of operational problems (noise, vibration and failure) tend to occur.

Previous relevant research

Although siphonic rainwater systems have been in existence for approximately 30 years, it has only really been since the mid 1990s that substantial research has been undertaken (or reported) into determining the actual flow conditions occurring within such systems⁽³⁾. In terms of the priming of single outlet siphonic rainwater systems, previous laboratory based research at Heriot-Watt University has identified a number of distinct phases, including the formation of full bore flow conditions and the movement of trapped air pockets⁽⁴⁾. The results of this work have been used as the basis of a numerical model capable of simulating the priming of single outlet siphonic systems.

Further laboratory experimental work has confirmed that, at low rainfall intensities (less than 40% of the fully primed system capacity), single outlet siphonic systems act in a similar manner to conventional rainwater systems⁽⁴⁾. This work also confirmed the unsteady nature of the flow conditions within siphonic systems at mid to high level rainfall intensities (above 40% of the fully primed system capacity). Such conditions were shown to be characterised by cyclical variations in gutter water levels and system pressures, and were observed to result in large quantities of air being drawn into the system, leading to noise generation and structural vibration.

Description of research programme

The main aim of the research detailed in this paper is to extend the existing numerical model (*ibid.*) to enable the simulation of multi outlet siphonic rainwater systems. In this context, the term *multi-outlet siphonic rainwater system* refers to a system where more than one gutter outlet is connected to the same downpipe. In order to achieve this aim, it was first necessary to gain a better understanding of the flow conditions occurring within such systems, with particular reference to system priming and the effect of different gutter inflow combinations. This was accomplished through laboratory experimental work and field observations.

Laboratory Investigation

Experimental work was undertaken using the laboratory test rig detailed in Figure 1. To ensure realistic flow conditions, each gutter was fed via a rear supply trough and a simulated sloping roof. Pressure transducers were installed in the base of the gutters to measure flow depths, and in the crown of the connected horizontal pipework to measure system pressures. All of the transducers were connected to a PC based data acquisition system, capable of sampling data at frequencies of up to 30000Hz. In addition, as all of the pipework was transparent, direct observations and digital video footage were taken to assist in the identification of relevant flow conditions.

Using the equipment detailed above, laboratory experiments were undertaken to determine the flow conditions arising as a result of the following realistic scenarios:

- Design criteria rainfall event (fully primed system).
- Rainfall events below the design criteria.

- Rainfall events above the design criteria.
- Total blockage of one of the outlets.

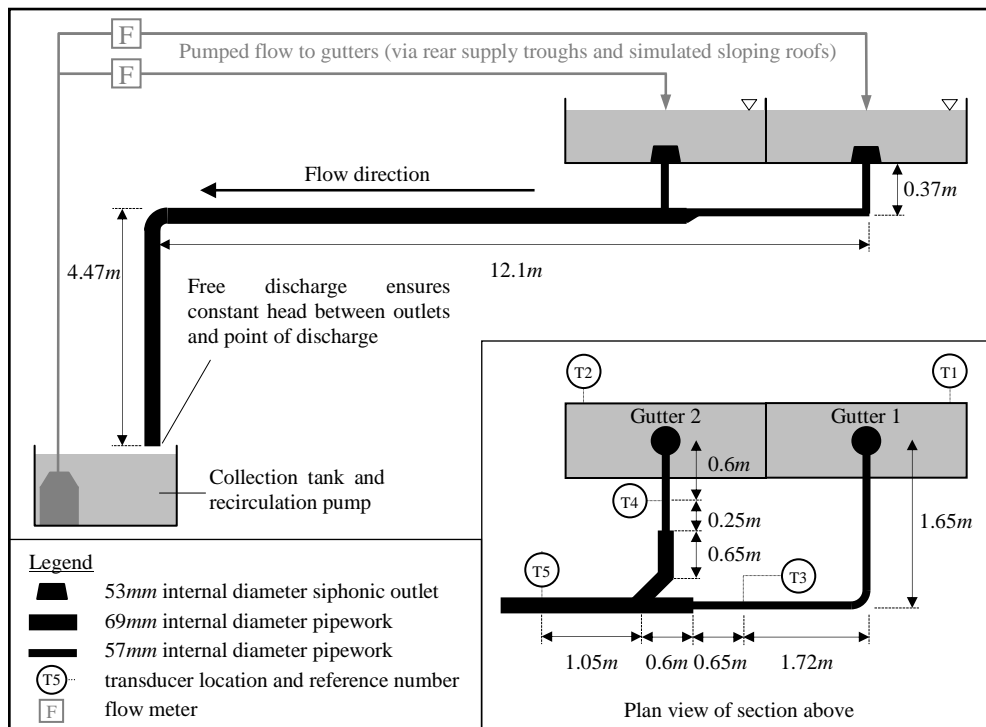


Figure 1: Siphonic rainwater experimental test rig

With reference to Figure 1 and the experimental data detailed below, *branch 1* refers to the pipework connecting gutter 1 to the branch junction, *branch 2* refers to the pipework connecting gutter 2 to the branch junction and *common pipe* refers to the pipework downstream of the branch junction. It should also be noted that, in all of the experimental work detailed below, the gutter inflow rates were constant throughout the testing periods, i.e. the simulated rainfall events were assumed to “instantaneously” reach a constant intensity.

Design criteria rainfall event (fully primed system)

Priming of the laboratory siphonic test rig was observed to occur when the inflow to gutter 1 was set to 5.85l/s and the inflow to gutter 2 was set to 7.78l/s. As the two gutters were located at the same elevation above the point of discharge, the difference in inflows required for siphonic conditions was due solely to the different branch configurations. This is confirmed by inspection of Figure 1, which indicates that the head losses associated with the branch 2 configuration would be significantly less than those associated with the branch 1 configuration.

The priming procedure of the siphonic test rig was observed to occur as follows:

1. *Initial gutter inflow:* At the start of the simulated rainfall event, the gutter water levels and the system inflows were relatively low, leading to free surface flow (subcritical) within the horizontal pipework and annular flow within the vertical pipework.
2. *Formation and movement of hydraulic jumps:* As the gutter water levels increased, so the system inflows increased, leading to supercritical flow at the

upstream end of the branches and the formation of hydraulic jumps immediately upstream of the branch junction (refer to Figure 2a). As the system inflows increased further, the hydraulic jump in branch 1 moved upstream and its height increased. Although the height of the hydraulic jump in branch 2 also increased, it did not move significantly upstream.

3. *Formation and propagation of full bore flow:* Eventually the downstream depth of the hydraulic jump in branch 1 became equal to that of the pipe diameter, and full bore flow developed (refer to Figure 2b). Once full bore flow conditions formed, they were seen to propagate downstream (into the common pipe) and, to a lesser extent, further upstream into branch 1. Similar observations were made with respect to the flow conditions in branch 2, although full bore flow did not propagate significantly upstream.
4. *Depressurisation of flow:* When full bore flow conditions reached the vertical section of the common pipe, the mass of water collecting in the vertical pipework caused depressurisation of the upstream flow, which itself resulted in an increase in the system inflows. This led to the development of full bore flow conditions at the upstream ends of both branches. In turn, this trapped volumes of air between the upstream end of the jumps and the upstream end of the branches (refer to Figure 2c). It should be noted that the volume of air trapped in branch 2 was significantly less than that trapped in branch 1.
5. *Partial re-pressurisation of flow:* As the systems inflows continued to increase, the airpocket trapped in branch 1 moved downstream at the ambient velocity of the flow. When this air pocket passed into the vertical pipework it caused a partial re-pressurisation of the entire system. The smaller airpocket in branch 2 also moved downstream, although it appeared to become mixed with the water flow at the branch junction, and it did not have a noticeable effect on system pressures.

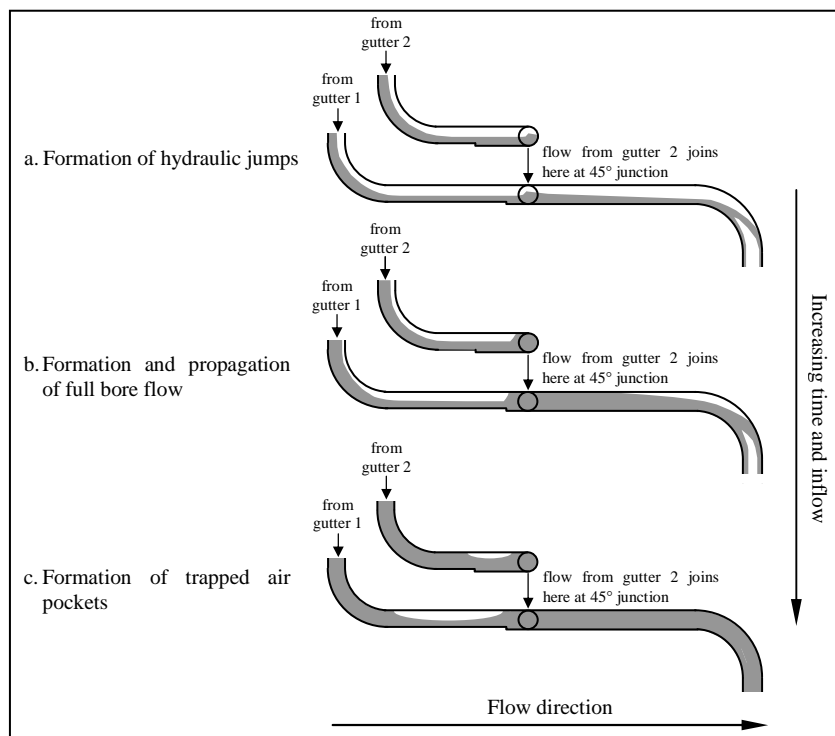


Figure 2: Priming process of the siphonic rainwater experimental test rig

6. *Fully primed system:* Once the air pockets had left the downstream end of the vertical pipe, the pressures decreased and remained constant. The system was then fully primed, although it was observed that relatively large quantities of entrained air continued to enter with the water inflows.

The gutter depths and system pressures recorded during the priming of the siphonic test rig are shown in Figure 3. The time lag between pressure peaks clearly illustrates that the re-pressurisation wave was generated at the downstream end of the common pipe, and propagated upstream. The 0.04 second time lag shown between transducers 3 and 5, which were 2.3m apart, yields a wave propagation velocity of 57.5m/s. Using the appropriate wave speed equation⁽⁵⁾, and assuming that the relatively small pressure changes do not result in pipe distortion, an iterative solution technique yields an air content of 5.4% for a wave propagation velocity of 57.5m/s. Although this can only be considered to be an approximation of the actual air content within the flow, it is of a similar magnitude to that previously estimated for single outlet systems⁽⁴⁾.

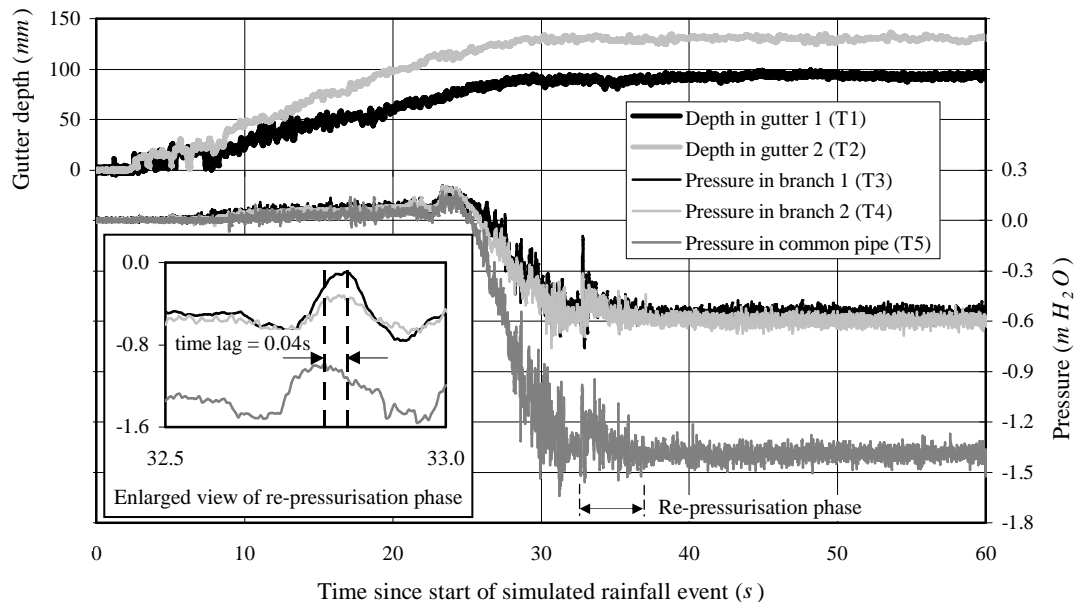


Figure 3: Measured gutter depths and system pressures for the design criteria rainfall event (gutter 1 inflow = 5.85l/s, gutter 2 inflow = 7.78l/s)

The recorded data and visual observations confirm that the priming process for a multi-outlet siphonic system is very similar to that which occurs with a single outlet siphonic system⁽⁴⁾. The only significant difference is that the increased complexity of the multi-outlet system results in more complex flow conditions, particularly with respect to the formation and movement of trapped air pockets within the system. This is evidenced by the erratic nature of the pressure traces prior to the priming of the system. This was also confirmed during the experimental work, where it was observed that very slight alterations in the experimental procedure (e.g. gutter 1 inflows starting a few seconds before gutter 2 inflows) would yield significantly different flow conditions.

Using a computerised design program (based on the steady flow energy equation), it was predicted that siphonic conditions would occur at the measured gutter inflow rates if the internal roughness of the pipework was 0.028mm. Although such a roughness value is considered to be reasonable for the type of pipework employed in the laboratory

test rig, the system pressures predicted by the design program were up to 39% lower than those actually measured in the laboratory. These discrepancies were considered to be due to variations in the air content of the measured flows and inaccuracies in the predicted head losses (across fittings) within the program.

Rainfall events below the design criteria

An extensive experimental investigation into the flow conditions arising from rainfall events below the design criteria highlighted that, at all inflow rates, the system conditions were unsteady. Depending on the system inflow characteristics, it was determined that the flow regime would be as follows:

1. *System inflow less than 40% of the fully primed system capacity:* These levels of inflow resulted in highly unsteady conditions, characterised by cyclical periods of positive and negative system pressures (refer to Figure 4, *Regime 1*). Such conditions were caused by low gutter flow depths, which meant that siphonic action could only be sustained for short periods. That is, once initiated, siphonic action would quickly drain one or both of the gutters, creating an airpath to the atmosphere and hence breaking the siphon.

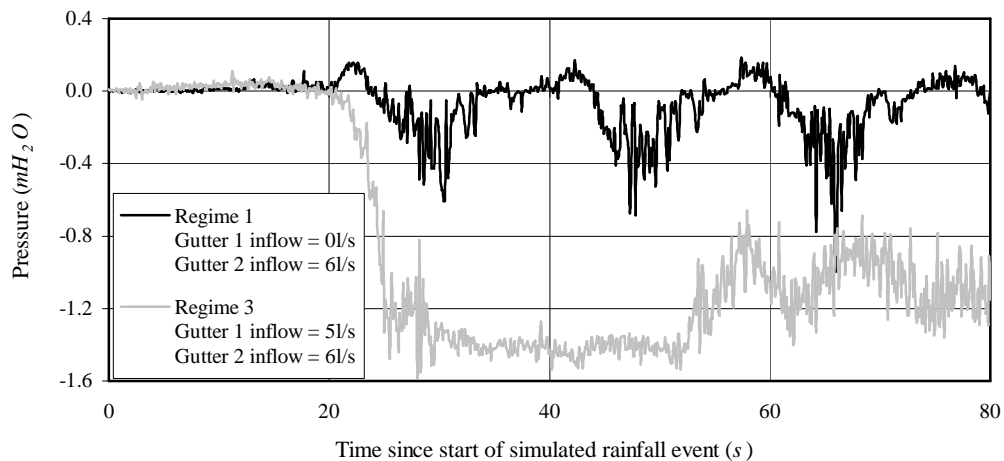


Figure 4: Measured common pipe pressure (T5) for two rainfall events below the design criteria

2. *System inflow between 40% and 60% of the fully primed system capacity:* These levels of inflow resulted in oscillating, constantly negative system pressures (above those associated with the fully primed system). Such conditions were caused by intermediate gutter flow depths, which were sufficiently high to ensure a continuous siphonic action but were not high enough to “swamp” the vortices that occurred around the gutter outlets. These vortices led to large amounts of air being entrained into the water flows, which resulted in lower flow rates and higher pressures than those associated with the fully primed system (95% - 100% water).
3. *System inflow above 60% of the fully primed system capacity:* At these levels of inflow, the system pressures initially mirrored those occurring in a fully primed system, although they shortly returned to the type of higher, oscillatory pressures discussed above (refer to Figure 4, *Regime 3*). Such conditions arose as the gutter flow depths were only sufficient to sustain full siphonic action for a short period.

After this, the gutter depths decreased to levels that enabled large quantities of air to become entrained with the water inflows.

In general it was determined that, with the inflow to one of the gutters set to a constant rate, increasing the inflow into the remaining gutter resulted in steadier and lower system pressures. This was as expected, as an increase in total system inflow leads to a decrease in the volume of air being drawn into the system. It was also apparent that, for the same total system inflow, overtopping became less likely as the ratio of the gutter inflows approached unity. This was again as expected, a more even gutter flow distribution increasing the probability of siphonic events, and hence increasing the average flow velocities within the system.

Rainfall events above the design criteria

Laboratory experiments undertaken with rainfall events above the design criteria indicated that the system pressures were almost identical to those obtained at the design condition. However, the additional system inflows (above the design condition levels) resulted in continuously increasing gutter depths, which would have eventually lead to overtopping of the gutter(s). If the slight variations in driving head associated with higher gutter depths are disregarded, these observations confirm that the system pressures occurring once a siphonic system has become primed are the minimum possible, and the capacity is the maximum possible, for that particular system.

Total blockage of one of the outlets

An example of the data obtained from laboratory experiments undertaken with one of the outlets blocked is shown in Figure 5.

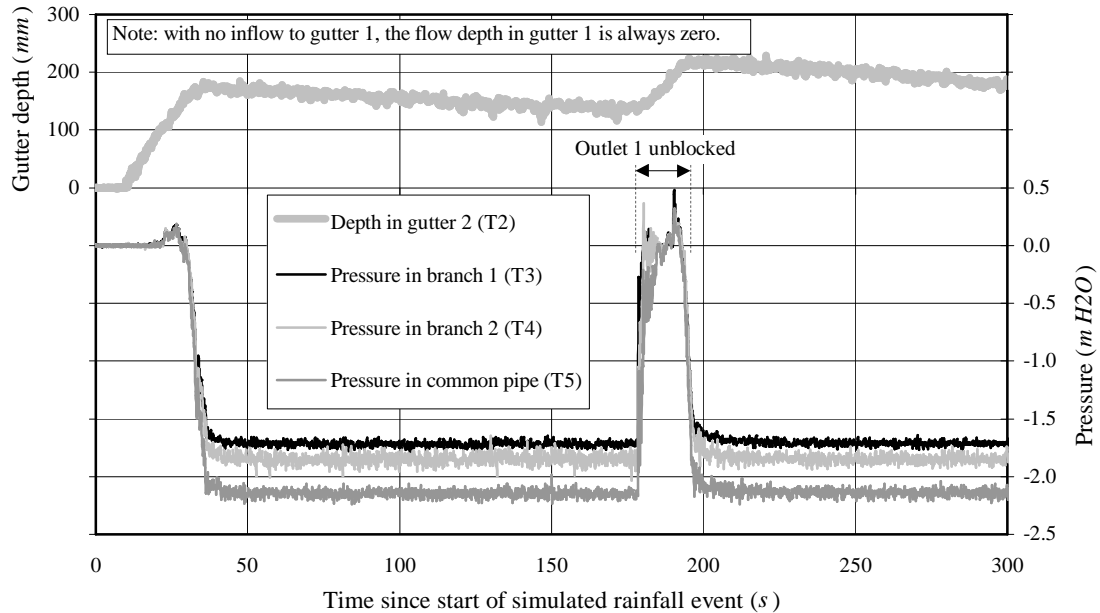


Figure 5: Measured gutter depths and system pressures with the outlet in gutter 1 blocked/unblocked/blocked (gutter 1 inflow = 0l/s, gutter 2 inflow = 11.3l/s)

It can be seen that, whilst the outlet in gutter 1 (outlet 1) was completely blocked (0s to 178s), the laboratory test rig acted as a single outlet siphonic system, with the pressures stabilised at the relevant fully primed levels and the flow depth in gutter 2 approaching a steady state. This figure also indicates that, when outlet 1 was unblocked

(178s to 197s), the system reverted to a multi-outlet mode of operation. With no inflow into gutter 1, an airpath to the atmosphere was created, leading to the cessation of siphonic action, an increase in system pressures and a decrease in system flow rates. This resulted in a very rapid increase in the water level within gutter 2, and would have led to overtopping of this gutter if outlet 1 was not re-blocked (after 197s).

Table 1: Measured system conditions with outlet 1 unblocked and blocked

Outlet blocked	Fully primed capacity (l/s)	Capacity of outlet in gutter 2 (l/s)	Minimum measured pressure (mH ₂ O)		
			transducer 1	transducer 2	transducer 3
None	13.63	7.88	-0.552	-0.595	-1.388
Outlet 1	11.30	11.30	-1.719	-1.846	-2.147

Table 1 summarises the salient system conditions pertaining to Figure 5. As shown, although the total system capacity was lower with outlet 1 blocked, the capacity of the open outlet (in gutter 2) was actually higher than was the case in an unblocked system. The data in Table 1 also highlight that system pressures were considerably lower when outlet 1 was blocked. This would indicate that, if a system were designed to operate at very low pressures (below -70KN/m^2), a complete blockage of one of the outlets might result in the onset of cavitation and/or failure of the system by pipe deformation.

Field Observations

To complement the laboratory experimental investigation detailed previously, flow conditions have been monitored within two siphonic rainwater systems installed at the National Archives of Scotland Document Repository Building, located in Edinburgh, Scotland. Whilst a detailed description of the systems monitored and the instrumentation employed is given elsewhere⁽⁶⁾, they may be summarised as follows:

- Two systems are being monitored; one incorporating two gutter outlets and one incorporating a single gutter outlet.
- System pressures are being recorded when the rainfall intensity exceeds 5mm/hour (using transducers similar to those used in the laboratory investigation).
- Rainfall intensities are being recorded using a tipping rain gauge.

The instrumentation has been in operation since June 2000, and a great deal of data have now been collected. As anticipated, the vast majority of the recorded rainfall events have been below the design criteria of the monitored systems, and much of these data have confirmed the laboratory findings. In addition, the pressure data collected suggests that at least one of the recorded rainfall events has resulted in full siphonic action. This event, which had a maximum rainfall intensity of 105mm/hour and a return period of 32 years⁽⁷⁾, occurred on 2nd August 2000 and appeared to result in continuous siphonic action for a period of approximately 500 seconds. However, in the absence of clear re-pressurisation evidence and/or gutter depth instrumentation, it is not possible to say for certain that siphonic action has occurred in the monitored systems.

Conclusions and Future Work

The preliminary conclusions of this ongoing research programme are as follows:

- The priming of a multi-outlet siphonic rainwater system is similar, although slightly more complex, to that of a single outlet system.
- At rainfall intensities below the design criteria, the flow conditions within a multi-outlet siphonic rainwater system are unsteady, and may exhibit one of three different flow regimes.
- The complete blockage of one of the outlets in a multi-outlet siphonic rainwater system may lead to system pressures falling below their design levels, and could result in system failure by cavitation and/or pipe deformation.

To progress this research programme, it is proposed to undertake the following work in the near future:

- Further investigate the formation and movement of air pockets within multi-outlet siphonic rainwater systems.
- Investigate the effect of different rainfall intensity/time relationships, particularly with respect to the initial stages of rainfall events.
- Develop a reliable and accurate method of determining the air content of flows within the siphonic rainwater experimental test rig.
- Improve the data acquisition system used for the field observations, including the installation of gutter depth instrumentation.
- Investigate different below ground terminal connection types between a siphonic rainwater system and the downstream drainage network.
- Extend the existing numerical model to multi-outlet applications.

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Acknowledgements

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