Investigation into the Performance Characteristics of Multi-Outlet Siphonic Roof Drainage Systems

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Abstract

Siphonic roof drainage systems have been in existence for approximately 30 years, and are becoming an increasingly common element of urban drainage infrastructure. In that time, the construction sector in most developed countries have been gradually persuaded of the benefits that these systems offer when compared to conventional roof drainage technologies. However, current design practice is based on steady-state theory and, arguably, simplistic assumptions. In response to perceived deficiencies in current design practice, a siphonic roof drainage research programme was initiated at Heriot-Watt University in 1996. This has led to a better understanding of the performance characteristics of siphonic systems, with particular reference to the priming of such systems (the purging of air from the system). This has resulted in the development of a numerical model capable of accurately simulating the priming phase of single outlet siphonic roof drainage systems. However, the majority of installed systems incorporate more than one gutter outlet, and the interaction between such outlets is not well understood. It was therefore recognised that further research was required to extend the applicability of the existing numerical model to multi-outlet applications.

The work reported herein details an ongoing UK government funded research programme to investigate the performance characteristics of multi-outlet siphonic roof drainage systems. The experimental aims, apparatus and procedures are described, and results are illustrated. In addition, "real" data obtained from three installed siphonic roof drainage systems are discussed. Conclusions are drawn regarding the performance characteristics of multi-outlet siphonic roof drainage systems, and plans for future work are outlined.

Keywords

Siphonic roof drainage; multi-outlet; design.

## Introduction

Conventional roof drainage systems

Conventional roof drainage systems generally consist of a network of collection gutters connected, via open outlets[1], to vertical downpipes. The system components are sized to ensure annular flow through the downpipes, and system pressures therefore remain close to atmospheric (BSI, 2000). Consequently, the driving head for flow within conventional roof drainage 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

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[1] Throughout this paper the term *outlet* is used to refer to the system element connecting the collection gutters to the pipework. This applies to both conventional and siphonic roof drainage systems.

(typically 150mm) each of which must be connected into a suitable underground drainage network. Furthermore, the dimensions/gradients of the gutters and the underground drainage network must be designed to ensure sufficient capacity and self-cleansing flow velocities.

Siphonic roof drainage 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, such as those shown in Figure 1, 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. Although siphonic gutter outlets normally incorporate vortex reducing elements, the turbulent gutter flow conditions will invariably lead to small quantities of entrained entering the system air (up to 10%), even when the outlets are fully submerged.
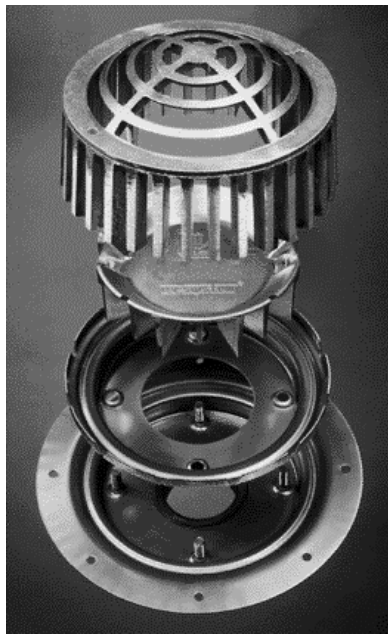
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Figure 1: Typical siphonic gutter outlets (reproduced with permission)

At its specific design condition, the driving head within an efficiently designed siphonic roof drainage system can be equal to the gutter flow depths *plus* the full vertical height between the outlets and the point of discharge. This yields significantly higher flow velocities than is possible in conventional systems, which means that attaining self-cleansing velocities is rarely a problem, and more than one outlet can be connected to a single downpipe. It also results in the need for fewer, and smaller diameter, downpipes. As the flow is full bore and de-pressurised (below atmospheric pressure), there is considerably more flexibility in pipe routing, allowing most of the horizontal collection pipework to be located just below roof level, and reducing the extent of costly underground drainage networks. In addition to these operational benefits, the small diameter pipework employed in siphonic roof drainage systems can have less of an architectural impact than conventional systems, and may even be incorporated within the building itself.

A siphonic roof drainage system will only operate efficiently at its design condition, under the specified rainfall criteria used for design purposes, 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, the system may fail due to overtopping of the gutters if the excess runoff cannot be diverted elsewhere. In some circumstances, this may necessitate the installation of a secondary conventional or siphonic system to drain any excess rainfall. 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 specific characteristics of the rainfall event. Similar conditions can occur if the flow distribution between gutter outlets is not as per design, possibly as a result of poorly installed roof surfaces/gutters or wind driven rainfall. Another disadvantage of siphonic roof drainage systems is that the restrictive outlets and small diameter pipework are relatively easily blocked by detritus in the flow, e.g. leaves. If a regular maintenance program is not adhered to, this can lead to operational problems and system failure (Bowler and Arthur, 1999).

Current State of Siphonic Roof Drainage Technology

Since their development in Scandinavia in the late 1960s, siphonic roof drainage systems have gradually become accepted by the construction sector in most developed countries. Their high capacities and low architectural impact have made them particularly popular for large, prestigious developments such as airports and major sporting stadia, e.g. Chep Lap Kok Airport (Hong Kong) and The Olympic Stadium (Sydney, Australia). However, siphonic roof drainage systems are virtually unheard of in the United States, with the authors knowing of only one such installation (Rattenbury, 2001). This is surprising, as siphonic technology is ideally suited to the type of large commercial, retail and manufacturing developments that are commonplace in the United States. It is considered that the lack of acceptance of such technology in the United States may be due to a lack of understanding of the underlying principles of siphonic systems and problems involved in changing the necessary national, state and local regulatory codes. Interestingly, there is no specific European standard for siphonic roof drainage systems.

Current design practice assumes that, for the specified design criteria, a siphonic system fills and primes rapidly with 100% water. This assumption allows siphonic roof drainage systems to be designed utilising steady state hydraulic theory. The steady flow energy equation is normally employed (May and Escarameia, 1996), with the elevation difference between the outlets and the point of discharge being equated to the head losses in the system. Although this design approach neglects the small quantities of entrained air that always enter a siphonic roof drainage system, it has been reported to yield operational characteristics similar to those observed in laboratory test rigs at the fully primed state (May and Escarameia, 1996; Arthur and Swaffield, 2001). However, steady state design methods are not applicable when a siphonic system is exposed to a rainfall event below the design criteria, when the flow may contain substantial quantities of air, or an event with time varying rainfall intensity. 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 roof drainage systems. This is a major disadvantage, as it is during these events that the majority of operational problems tend to occur, e.g. noise, vibration and failure.

In addition to the type of everyday operational problems outlined above, a number of more serious problems are known to have occurred with siphonic roof drainage systems. An interesting example concerns a manufacturing plant in the midlands of England, where the site layout necessitated the use of a "U bend" arrangement to connect the siphonic roof

drainage system under an existing road into the surface water sewer network. Following installation, the gutters were observed to regularly overtop during rainfall events with lower intensities than the design criteria. Inspection of the system indicated that this was due to the large air pocket that formed in the upward leg of the "U bend" arrangement; that is, the gutters overtopped before the system pressures had built up to the levels necessary to purge the system of this air. It is considered unlikely that current design methods would be capable of predicting this type of system failure Another example of the failure of a siphonic roof drainage system occurred at a storage depot in the south of England. In this case, the siphonic system was subjected to a rainfall event which, although substantial, was less than the total system capacity (design capacity plus emergency provision). The resulting system pressures dropped below approximately $-8mH_2O$, causing the pipes to implode. This resulted in a reduction in system capacity, which led to overtopping of the gutters, flooding of the facility and an insured loss of several million pounds. Failures such as this illustrate the importance of considering system pressures, as well as total system capacity, during the design process. It should be noted that, although the siphonic roof drainage industry and its clients are understandably reticent in publicising problems, it is considered that the number of system failures is only a tiny percentage of the large number of systems installed throughout the world. Blockages remain the most common cause of operational problems and failures, and can be avoided with a regular maintenance programme. Furthermore, there is no evidence to suggest that siphonic systems are more prone to failure than conventional systems.

Previous Relevant Research

Although siphonic roof drainage systems have been in existence for approximately 30 years, it has only really been since the mid 1990s that substantial research has been reported into determining the actual flow conditions occurring within such systems (Arthur and Swaffield, 2001). In terms of the priming of single outlet siphonic roof drainage systems, previous laboratory based research at Heriot-Watt University (Edinburgh, Scotland) has identified a number of distinct phases, including the formation of full bore flow conditions and the movement of trapped air pockets (Arthur and Swaffield, 1999). 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 rainfall intensities less than 40% of the fully primed system capacity, single outlet siphonic systems act in a similar manner to conventional roof drainage systems (Arthur and Swaffield, 1999). This work also confirmed the unsteady nature of the flow conditions within siphonic systems at 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 roof drainage systems. In this context, the term multi-outlet siphonic roof drainage 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 conditions occurring within such systems, with particular reference to priming and the effect of different gutter inflow combinations. This was accomplished through laboratory experimental work and field observations.

Laboratory Investigation

Overview

Experimental work was undertaken using the laboratory test rig detailed in Figure 2. 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. In addition, magnetic induction flowmeters were used to measure the gutter inflow rates. The transducers and flowmeters were connected to a PC based data acquisition system, capable of sampling data at frequencies of up to 30kHz. As the pipework was transparent, direct observations and high speed video footage were also taken to assist in the identification of relevant flow conditions.
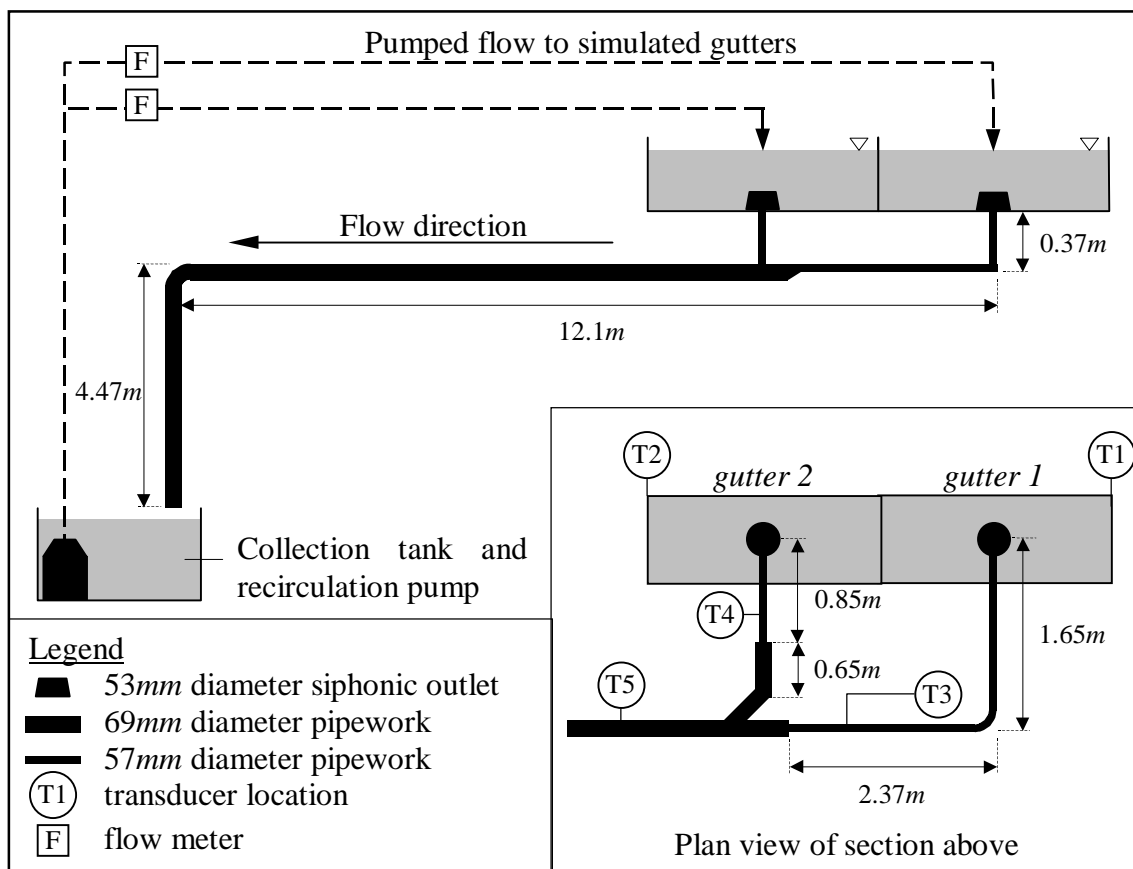

Figure 2: Siphonic roof drainage experimental test rig

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) – constant gutter inflows
- Rainfall events below the design criteria
- Design criteria rainfall events (fully primed system) – varying gutter inflows
- Rainfall events above the design criteria
- Total blockage of one of the outlets

In addition to the above, experimental work was also undertaken to determine the effect, upon system performance, of different types of system terminations. This was considered an essential element of the investigation, as it is this section that represents the interface between the siphonic roof drainage system and the surface water sewer network.

With reference to Figure 2 and the experimental data detailed herein, *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, unless otherwise stated, 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) – constant gutter inflows

Priming of the laboratory siphonic test rig was observed to occur when the inflow to *gutter 1* was set to 5.85*l/s* and the inflow to *gutter 2* was set to 7.78*l/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 highlighted by inspection of Figure 2, 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 generally 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 subcritical flow 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 3a). As the system inflows increased further, the hydraulic jump in *branch 1* moved upstream and its height increased. Similar observations were made with respect to the flow conditions in *branch 2*, although the upstream movement of the hydraulic jump was less marked.
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 3b). 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 the propagation of full bore flow was less marked.
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 system, 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 3c). 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 system inflows continued to increase, the airpocket trapped in *branch 1* moved downstream at the local 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 at the branch junction, forming a "bubbly flow" that did not have such a significant effect on system pressures.
6. *Fully primed system:* Once all of the initial air pockets had left the downstream end of the vertical downpipe, the pressures decreased and remained relatively constant. The system was then fully primed, although it was observed that quantities of entrained air continued to enter with the water inflows.
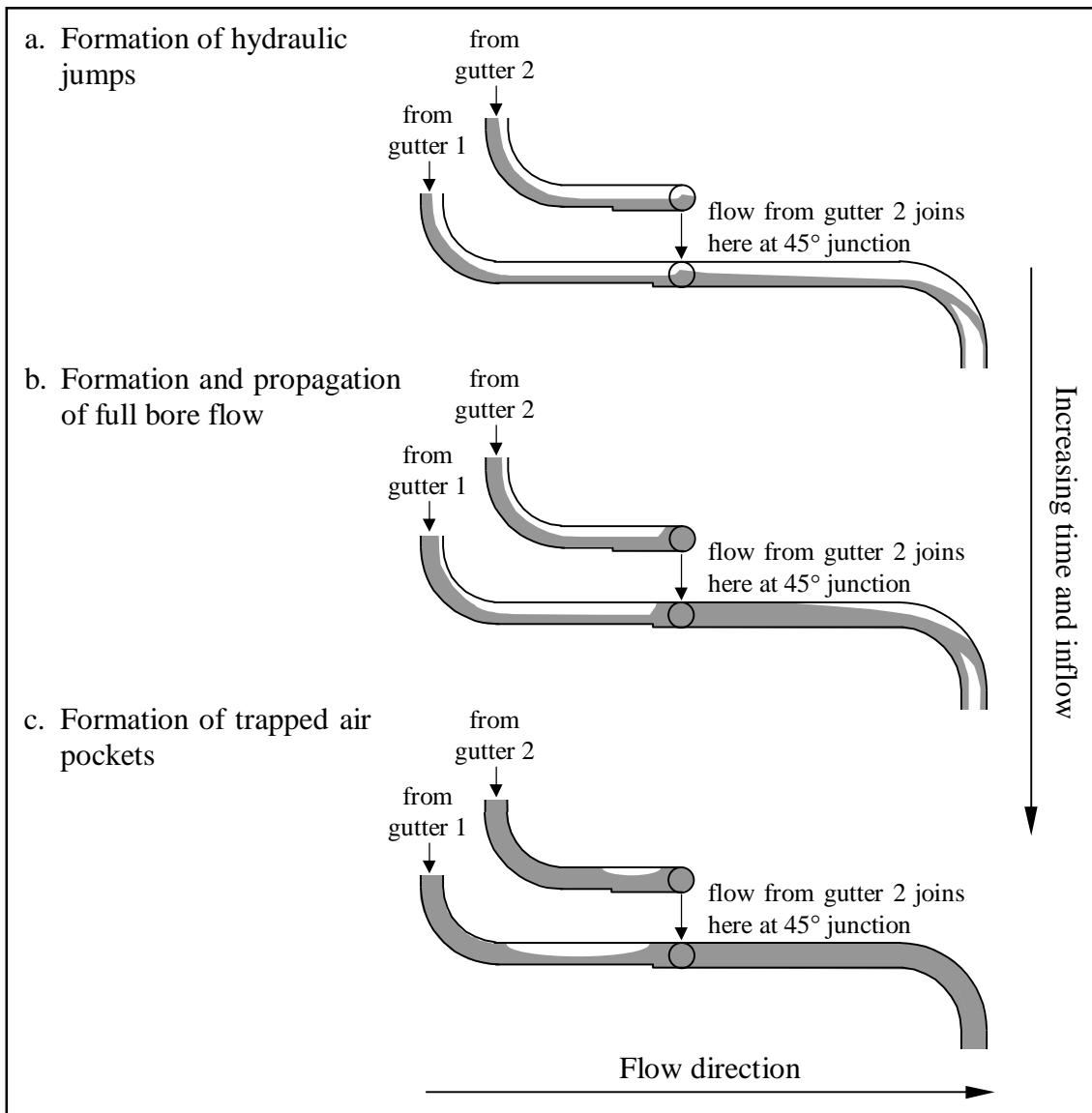
a. Formation of hydraulic jumps

from gutter 2

from gutter 1

flow from gutter 2 joins here at 45° junction

b. Formation and propagation of full bore flow

from gutter 2

from gutter 1

flow from gutter 2 joins here at 45° junction

Increasing time and inflow

c. Formation of trapped air pockets

from gutter 2

from gutter 1

flow from gutter 2 joins here at 45° junction

Flow direction

Figure 3: Priming process of the siphonic roof drainage experimental test rig

The gutter depths and system pressures recorded during the priming of the siphonic test rig are shown in Figure 4. 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. Noting that the laboratory pipework was not restrained against radial or longitudinal movement, an iterative solution of the appropriate wave speed equation (Wylie and Streeter, 1993) 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 (Arthur and Swaffield, 1999).

Using a 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 inaccuracies in the predicted head losses across fittings and the simplifying assumptions employed within the program.
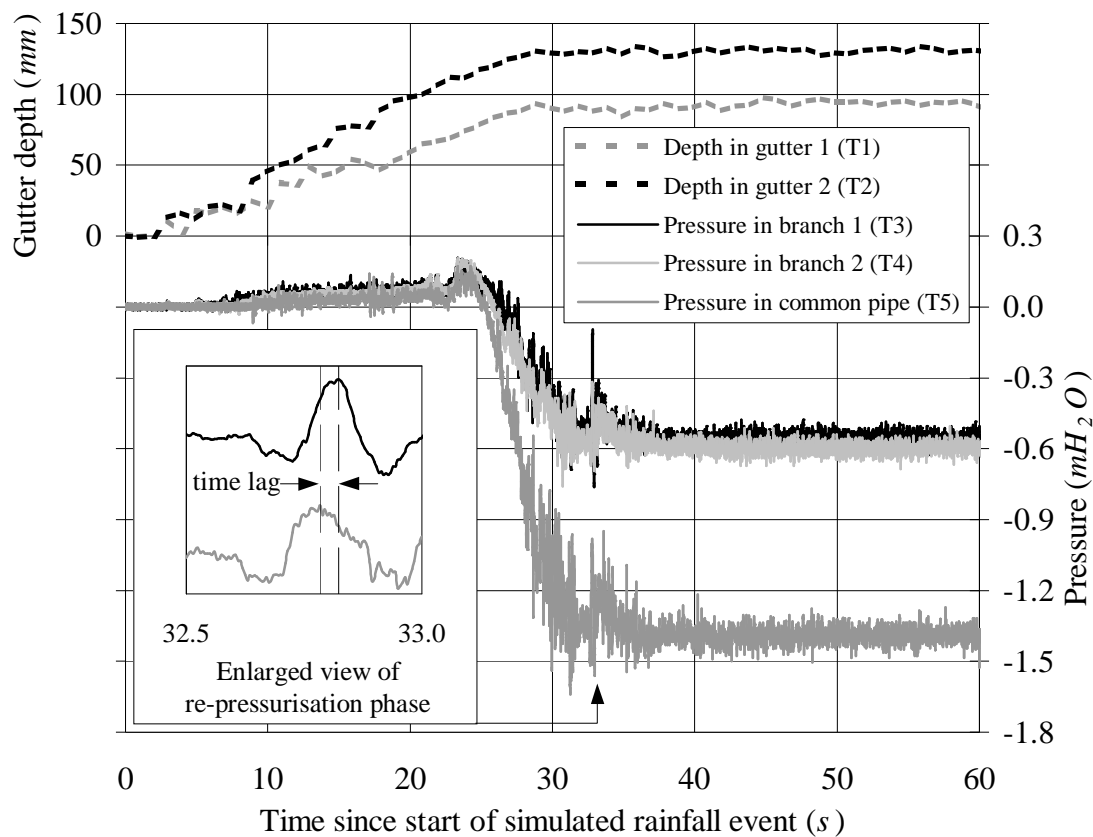

Figure 4: Measured gutter depths and system pressures for the design criteria rainfall event (*gutter 1* inflow = 5.85*l/s*, *gutter 2* inflow = 7.78*l/s*)

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 (Arthur and Swaffield, 1999). 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 the movement of the air pocket from *branch 2* occasionally varied from the general case outlined previously. High speed video footage indicated that the air pocket from *branch 2* would move downstream as a single entity if it reached the branch junction at the same time as the air pocket from *branch 1*. If it reached the junction after the air pocket from *branch 1*, the full bore flow conditions at the junction represented such a restriction that the air pocket could not move downstream as a single entity. Instead, the turbulent conditions in this region led to the formation and downstream movement of a section of "bubbly flow" (air and water mixture).

Rainfall events below the design criteria
Experimental work has indicated that, at flow rates up to approximately 15% of the design criteria inflows, the laboratory test rig behaved as a conventional roof drainage system; that is, the flow conditions remained free surface/annular throughout. At all other flow rates

below the design criteria inflows, the system conditions were observed to be unsteady. With reference to Figure 5, it was determined that the flow would exhibit one of the following sets of characteristics:

1. *Regime 1 - system inflows between 15% and 40% of the design criteria inflows:* These levels of inflow resulted in highly unsteady conditions, characterised by cyclical periods of positive and negative pressures. 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.

2. *Regime 2 - system inflows between 40% and 60% of the design criteria inflows:* 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 in turn resulted in lower flow rates and higher pressures than those associated with the fully primed system (95% - 100% water).

3. *Regime 3 - system inflows above 60% of the design criteria inflows:* 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 associated with *Regime 2*. 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.
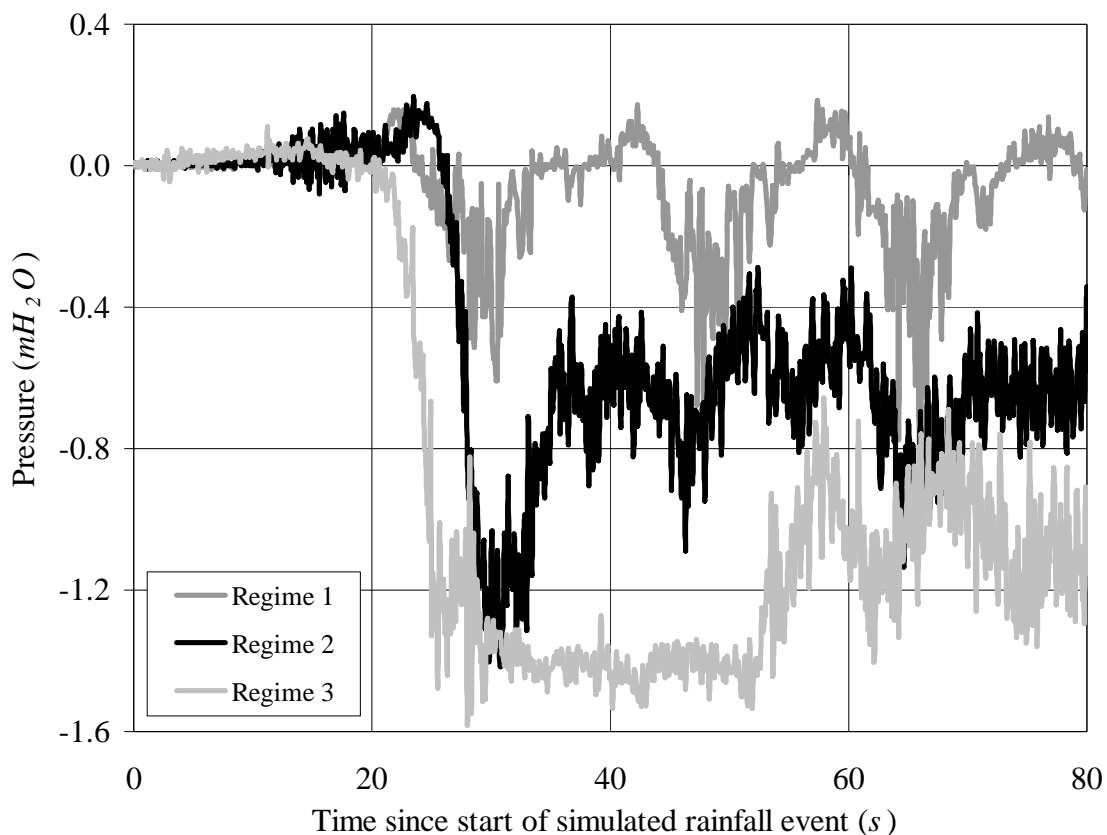

Figure 5: Measured *common pipe* pressure (T5) for three rainfall events below the design criteria

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 ($Q_{gutter\,1}$: $Q_{gutter\,2}$) approached that of the fully primed system (7.78:5.85 ≈ 1.33:1). 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.

The disparity between the transition from free surface/annular to unsteady/siphonic conditions in the multi-outlet system (15% of design criteria inflows) and the single outlet system mentioned previously (40% of design criteria inflows) is considered to be due to the smaller pipe diameters employed and the flow distorting effect of the branch junction in the multi-outlet system.

Design criteria rainfall event (fully primed system) – varying gutter inflows.
As many real rainfall events progressively build in intensity, experimental work was undertaken to assess the effect of gradually increasing the gutter inflows up to design criteria levels. The only significant difference between these results and those obtained with constant gutter inflows was that it took longer for the system pressures and gutter flow depths to build up to those necessary purge the air from the system, and hence initiate siphonic action

Additional experimental work was also undertaken to determine the effect of staggering the gutter inflow start times, which would represent systems incorporating widely varying roof geometries, e.g. one gutter outlet serving a steeply pitched roof and one gutter outlet serving a shallower pitched roof. As may be appreciated, the resulting flow conditions were very complicated, exhibiting two or three of the unsteady flow regimes identified previously. However, it was apparent from the data collected that, after a short period at the design criteria inflows, the gutter flow depths and system pressures mirrored those obtained with synchronised inflow start times (refer to Figure 4).

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 criteria 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 6. 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).
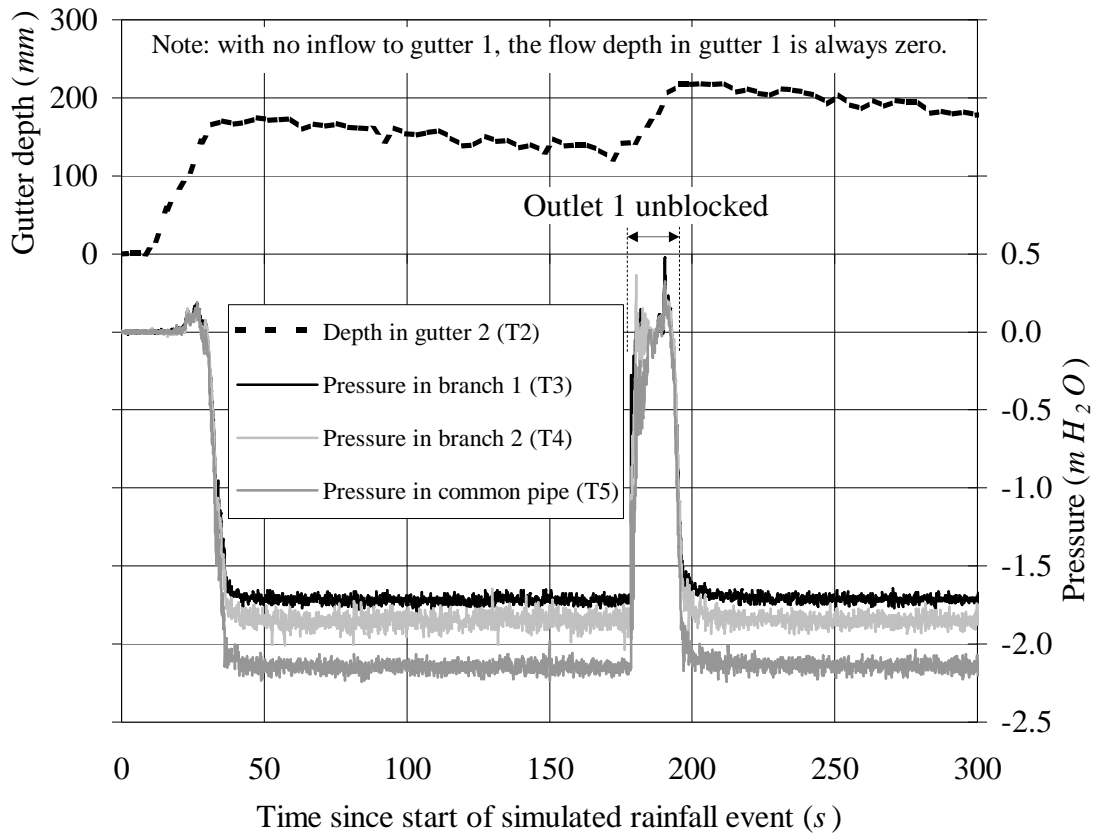

Figure 6: Measured gutter depths and system pressures with the outlet in *gutter 1* blocked/unblocked/blocked (*gutter 1* inflow = 0*l/s*, *gutter 2* inflow = 11.3*l/s*)

Table 1 summarises the salient system conditions pertaining to Figures 4 and 6. 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 approximately $-7mH_2O$), a complete blockage of one of the outlets might result in the onset of cavitation and/or failure of the system by pipe deformation.

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_2O*)		
			transducer 1	transducer 2	transducer 3
none	13.63	7.78	-0.552	-0.595	-1.388
outlet 1	11.30	11.30	-1.719	-1.846	-2.147

Effect of different system termination configurations
To ensure the efficient operation of a siphonic roof drainage system, it is essential that full bore flow conditions are broken upstream of any connection to the surface water sewer network. If not, the flows within the siphonic system and the sewer network may interact, leading to unpredictable conditions and potential problems. Breaking of full bore flow

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conditions can only be guaranteed by ensuring that the flow exits the siphonic system above the highest water level in the surface water sewer. However, surface water sewers occasionally surcharge, with the relevant European standard (BSI, 1997) stipulating a 2 year surcharge return period for commercial and industrial areas (with a flood return period up to 30 years). Therefore, experimental work was undertaken to determine the effect of terminating a siphonic roof drainage system under water. In addition, data was also collected to determine the effect of a right angled termination, which often proves necessary due to the site layout. The four different system terminations that were investigated are shown in Figure 7. It should be noted that, due to space restrictions, the length of the vertical downpipe in these configurations was reduced to 4.07m.
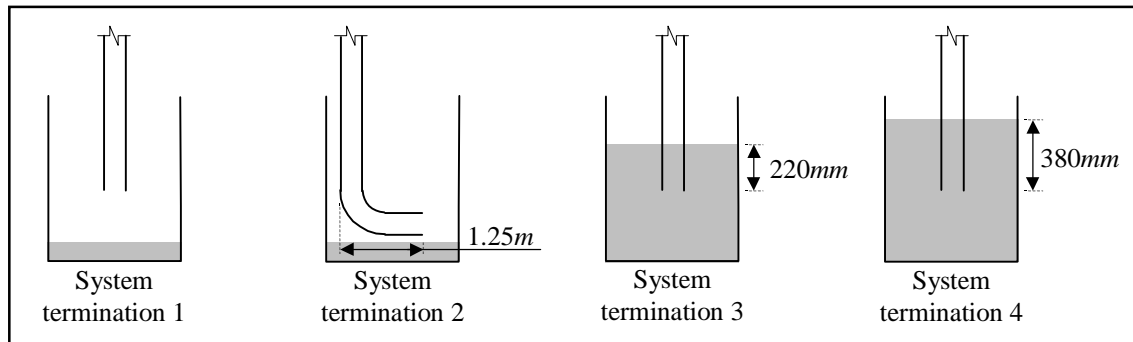

Figure 7: Siphonic system termination configurations investigated

As the driving head for a siphonic roof drainage system is defined as the elevation difference between the gutter outlets and the point of discharge (free discharge case) or the point at which the downpipe enters water (submerged discharge case), it can be deduced from Figure 7 that the driving head for each of the four configurations was different. In addition, it is clear from Figure 7 that the head losses associated with each of the four configurations varied. As a result, the gutter inflows necessary to cause priming of the four different configurations were different. From the data shown in Table 2, it is clear that the use of any configuration other than a freely discharging vertical downpipe will result in a lower system capacity.

Table 2: Variation in design criteria gutter inflows with termination configuration

System termination type	Fully primed capacity (*l/s*)		Fully primed capacity (as *%* of type 1 inflows)	
	gutter 1	*gutter 2*	*gutter 1*	*gutter 2*
1	7.46	5.71	100	100
2	7.35	5.45	98.5	95.4
3	7.28	5.54	97.6	97.0
4	7.11	5.57	95.3	97.5

Figures 8a and 8b show a sample of the experimental data obtained using the four different termination configurations. As shown, the configurations that discharged under water resulted in significantly longer priming times and higher gutter flow depths than those discharging directly to the atmosphere. This was because greater (positive) system pressures were required to purge the initial air pockets.
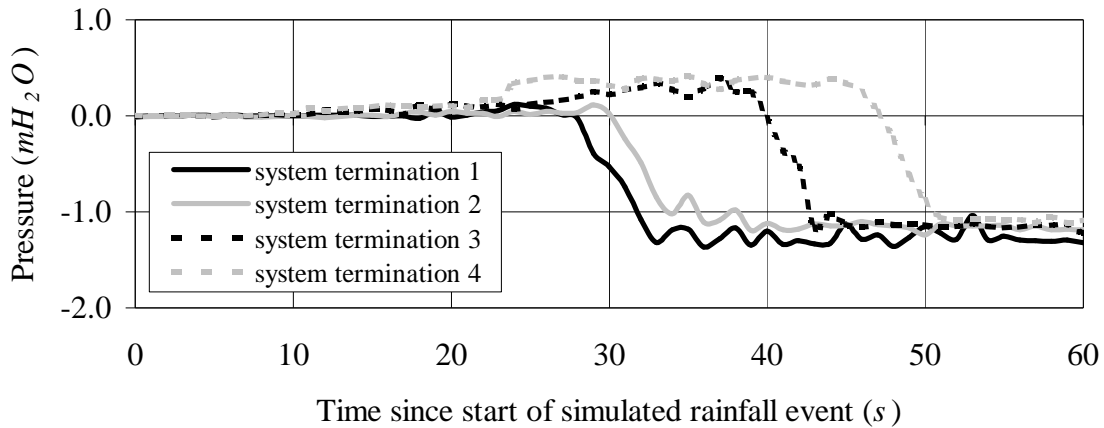
Figure 8a: Variation in *common pipe* pressure (T5) with system termination configuration (fully primed conditions)
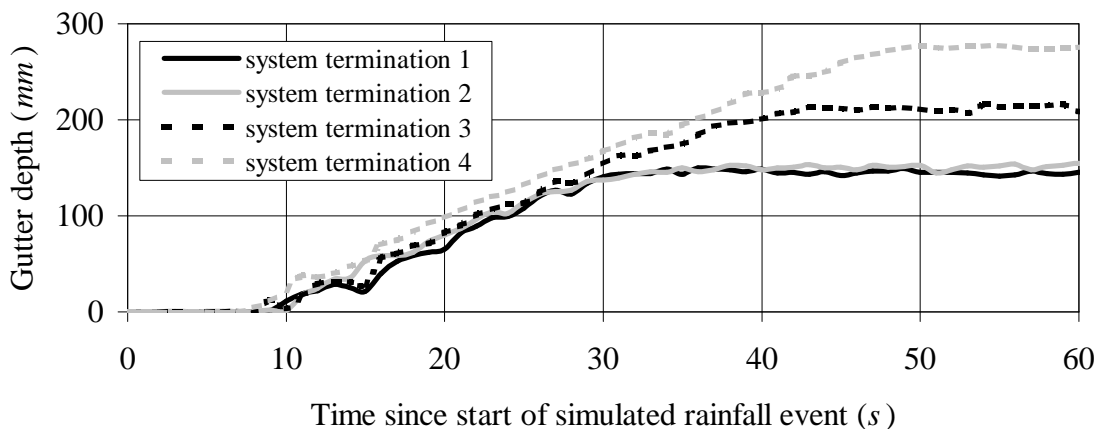

Figure 8b: Variation in *gutter 1* flow depth (T1) with system termination configuration (fully primed conditions)

The experimental data discussed above highlight the importance of the interface between a siphonic roof drainage system and a surface water sewer. For example, consider the conditions within a siphonic roof drainage system during a severe rainfall event. Theoretically, there should be no operational problems if the rainfall intensity is less than the design criteria. However, if the downstream surface water sewer happens to surcharge, and the water level in the manhole rises above that of the siphonic system discharge point, the driving head of the siphonic system will reduce. This could increase the time required to prime the system, and will certainly reduce the total capacity of the system. Such a scenario could lead to failure of the system by gutter overtopping.

Field Observations

To complement the laboratory investigation, flow conditions have been monitored within three siphonic roof drainage systems installed at the National Archives of Scotland Document Repository Building (Edinburgh, Scotland). Whilst a detailed description of the monitoring equipment and protocols is given elsewhere (Arthur and Swaffield, 2000), a schematic of the systems that are being monitored is shown in Figure 9. Since June 2000, system pressures have been recorded when the rainfall intensity exceeds 5*mm/hour*, and rainfall intensities have been recorded using a tipping rain gauge. In addition, gutter flow depths have been monitored since September 2001, using modified air pressure transducers.
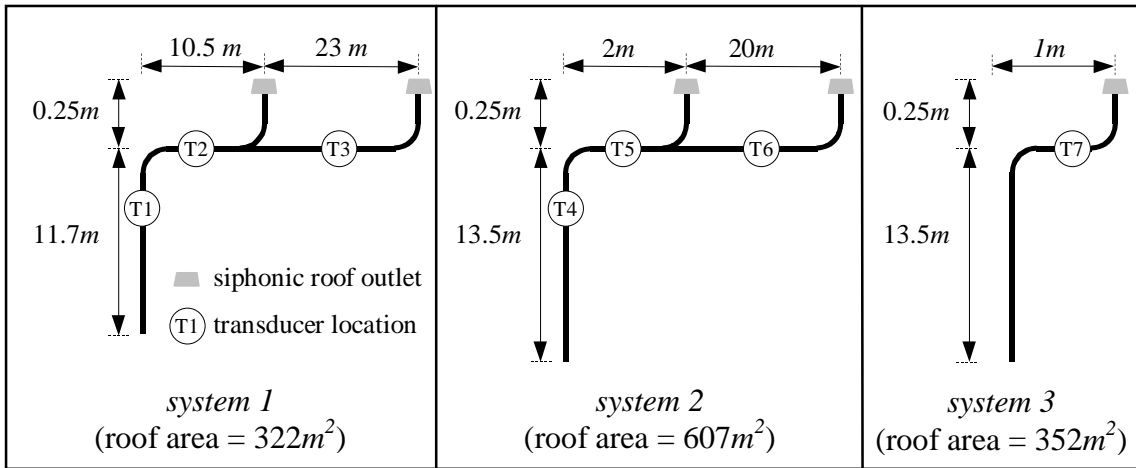
Figure 9: Schematic of the siphonic roof drainage systems being monitored at the National Archives of Scotland Document Repository Building (Edinburgh, Scotland)

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. The data shown in Figure 10 represents the most significant rainfall event, in terms of prolonged siphonic action, that has been recorded to date. This event had a maximum rainfall intensity of 105 *mm/hour*, which equates to a return period of 32 years (CEH Wallingford, 1999), and appeared to result in continuous siphonic action for a period of approximately 500 seconds.
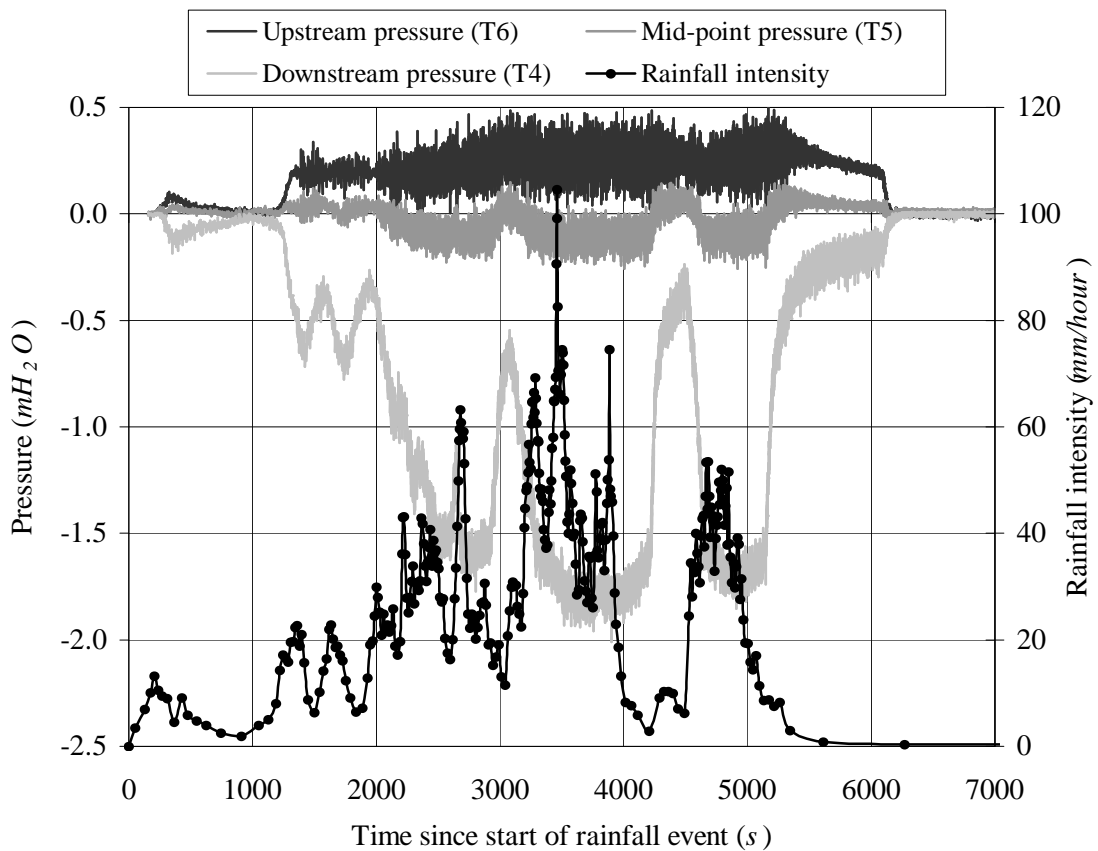

Figure 10: Measured conditions (*system 2*) on 2nd August 2000
(refer to Figure 9 for system and transducer layout)

An analysis of the field data collected to date indicates that 7% of recorded events resulted in prolonged siphonic action and 50% of recorded events resulted in significant negative system pressures.

Development of the Numerical Model

As mentioned previously, the existing numerical model developed at Heriot-Watt University (SIPHONET) is capable of simulating the priming phase of a single outlet siphonic roof drainage system. This model utilises a method of characteristics based solution technique, which has been employed successfully at Heriot-Watt University in the simulation of both free surface and full bore flow conditions. However, during the development of the model it became clear that the method of characteristics was not particularly suited to the simulation of moving hydraulic jumps. In addition, numerical stability problems were also encountered with the transition between free surface and full bore flow conditions. As these deficiencies would become more limiting in the more complex case of multi-outlet systems, it was decided to employ a new modelling approach. This will incorporate the Lax-Wendroff finite difference solution technique.

Conclusions and Future Work

The conclusions of this ongoing research programme may be summarised as follows:
- The priming of a multi-outlet siphonic roof drainage system is similar, although more complex, to that of a single outlet system.
- Current design programs may yield inaccurate system pressures, which could lead to operational problems and/or system failure.
- At rainfall intensities below the design criteria, the flow conditions within a multi-outlet siphonic roof drainage 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 roof drainage system may lead to system pressures falling below their design levels, and could result in system failure by cavitation and/or pipe deformation.
- To ensure efficient operation of a siphonic roof drainage system, consideration must be given to its interaction with the downstream surface water sewer network.

The final phase of this current research programme involves the further development of the numerical model. It is intended that the final model will be capable of accurately simulating the flow conditions within multi-outlet siphonic roof drainage systems for all realistic rainfall events. It is anticipated that such a model will be used for diagnostic design purposes and code formulation, which should reduce the occurrence of the type of operational problems and system failures detailed previously.

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