The Performance of Syphonic Rainwater Outlets within Gutters.

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fulfilment of the requirements for the degree of
Doctor of Philosophy.

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Abstract

Throughout Europe, roof areas are commonly drained using a conventional gutter and downspout system. These are usually large in volume and have the capacity to discharge rainwater at high rates of flow. There is now increased awareness of syphonic roof drainage systems. Historically, the definitive method for the design of gutters within the United Kingdom is BS6367: 1983 British Code of Practice for the Drainage of Roofs and Paved Areas. This publication clearly sets out the theoretical model to predict the hydraulic performance of a gutter. In 2000, this Code was superseded by BS EN 12056-3 which, shares a common theoretical basis and method of derivation as BS 6367:1983. These codes do not specifically address syphonic systems and currently there are no design criteria for such systems.

Hence, there is an urgent need for a better understanding of the hydraulic performance of syphonic systems. This is particularly relevant to systems that are installed in gutters that drain large industrial and commercial buildings.

The work reported in the thesis describes a series of experimental investigations that were carried out to improve knowledge and understanding of the way in which syphonic systems perform. Initially the study concentrated on the construction of a full-scale experimental system to test the hydraulic performance of syphonic system outlets located within a 600mm wide gutter. Tests were completed with single (primary) outlets and primary outlets in combination with independent overflow outlets (secondary outlets). The outlets were positioned at a number of different locations along the length of the gutter and combinations of both primary and secondary outlets were tested.

The thesis has concluded that the performance of syphonic rainwater systems is much more complex than conventional roof drainage systems. Specific findings of the study are:

- The application of existing theoretical models for the design of conventional rainwater drainage systems should not be transferred to syphonic systems. An additional factor of safety is required within the existing theoretical model.

- The position of the outlet in the gutter has a significant influence on the depth profile along the gutter length. Outlets located near to the gutter end resulted in an increase in the depth profile of the outlet.
- When an independent overflow system (secondary system) was used in conjunction with a number of primary outlets within a common gutter, it was found that the overflow system, dominated the flow profile within the gutter.
- A method, based on dispersion of solutes, was developed to determine the actual flow rate through each outlet of a syphonic system. It was shown that the flow rate through each outlet of the system was not the same and that the water level in the gutter was redistributed along the gutter length. This implies that the negative pressure created in syphonic systems is not a limiting factor. These findings have important design implications.
- A methodology to calculate the influence on water depth in any gutter and for any outlet position has been established and is recommended as a basis for the improved design of a syphonic system.

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9.1 Conclusions

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Notation

A	Internal cross sectional area of a pipe
A_o	Cross sectional area of flow at an outlet
A_1	Area of flow used within velocity profile calculations: Chapter 8
A_2	Area of flow used within velocity profile calculations: Chapter 8
A_T	Total Area of flow used within velocity profile calculations: Chapter 8
B_s	Sole width of gutter
B_o	Surface width of flow at an outlet
C_b	Background concentration
C_{In}	Initial concentration of dye
C_1	Concentration of dye at point 1
C_3	Concentration of dye at point 3
C_2	Concentration of dye at point 2
d	Internal diameter of pipe
D	Effective diameter of an outlet
D	Diameter when used in Colebrook White equation
D_f	Depth of flow at an outlets optimum position
D_{sp}	Depth of flow around an outlet accounting for gutter sole width and position
F_o	Froude number at an outlet
g	Acceleration due to gravity
h	Pressure head
i	Hydraulic gradient
K	Roughness of fittings
k_o	Outlet coefficient
k_s	roughness (e.g. of a pipe surface)
L	Length of pipe
L_g	Drainage length of a gutter
Q	Rate of flow
Q_1	Flow rate through outlet 1

Q_2	Flow rate through outlet 2
Q_3	Flow rate through outlet 3
Q_o	Flow calculated from the orifice flow equation
Q_w	Flow calculated from the weir flow equation
q_{In}	Injection flow rate of dye
R_D	Distance Ratio
x	Percentage increase in Y_u due to resistance effect of a gutter
Y_d	Flow depth at the downstream end of a gutter
Y_o	Depth of flow at an outlet
Y_u	Upstream depth within a gutter
Y_{uf}	Upstream depth of flow accounting for resistance
z	Potential head
ν	Coefficient of kinematic viscosity

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A study of this scale is only made possible through the help, assistance and support given by others. It is therefore befitting that the author should acknowledge the efforts of the people involved in this project.

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The laboratory work within this study would not have been possible without the assistance of the dedication and technical expertise of the technical staff working within the Department of Civil and Structural Engineering at the University of Sheffield. Of particular significance to this project were the efforts of Mr Paul Osbourne and Mr Glen Brawn who helped in overcoming seemingly impossible issues experienced during the construction and operation of the full-scale test facility. Additional gratitude must be given to the estates department of the University of Sheffield for their cooperation in locating the test facility.

Last but not least, I would like to express my thanks to my wife and family for their support and encouragement throughout the duration of the study.

Dedication

I would like to dedicate this thesis to the memory of my father.
His love and guidance was my inspiration.
He is greatly missed.

Declaration

Except where specific reference has been made to the work of others, this thesis is the result of my own work. No part of it has been submitted to any university for a degree, diploma or other qualifications.

Chapter One - Introduction

1.1 Background

In order to ensure that the drainage of the roof of a building is effective, the principal purpose of the roof drainage system is to convey the rainfall collected by a roof during a storm, to the underground drainage system without risk of the rainwater entering the building. Typically, roof drainage systems consist of three components; gutters, roof outlets and rainwater pipes. Two types of system may be used, conventional gravity systems and syphonic roof drainage. Figure 1.1 shows comparative installation layouts for conventional and syphonic drainage systems on a simple industrial building.

The schematic illustrations within figure 1.1 identify obvious differences between the two systems. For example, the syphonic system has only one down pipe therefore eliminating the need for a network of underground drainage around the perimeter of a building.

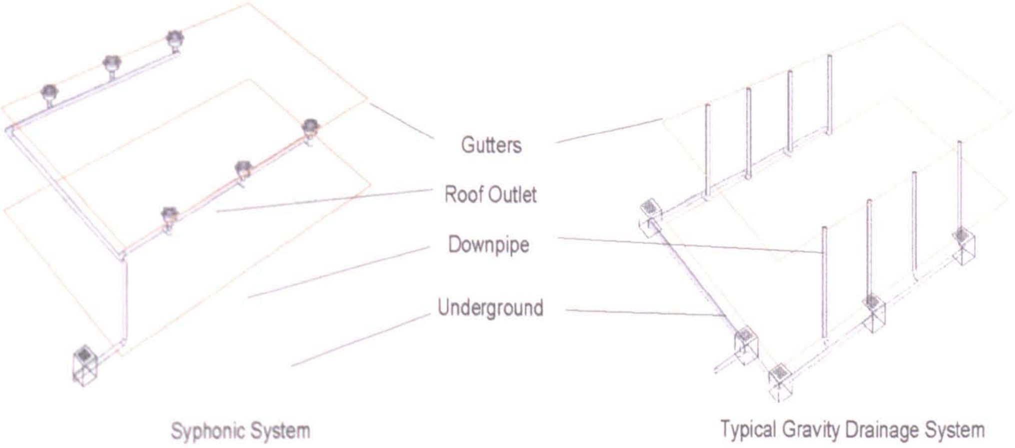

Figure 1.1 Comparison of a conventional system and a syphonic system
(Derived from original by Sommerheim 1996)

1.2 Conventional Roof Drainage Systems

Conventional rainwater systems rely on the properties of water and gravity for the motivation forces behind their operation. Water flows under the force of gravity and attempts to reach the lowest level possible, spreading out evenly over whatever surface is supporting it. This is exactly what happens when rainwater falls onto a roof and flows in a gutter. The depth of the water accumulating into the gutter is the driving force, which causes the rainwater to flow towards the roof outlet. These outlets may be defined as holes in the sole of a gutter or installed in a low point of a flat roof. As figure 1.2 illustrates, under design storm conditions the rainwater enters the outlet. At this time air is also drawn in to the outlet through the formation of a vortex action. By designing the systems to operate in this part filled state reduces the potential efficiency of the system.

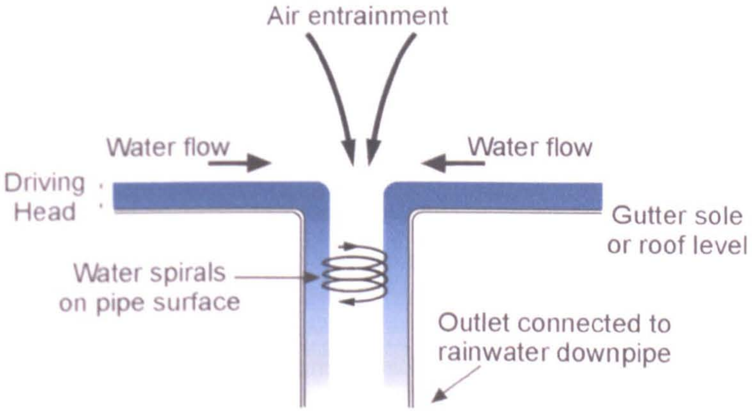

Figure 1.2 Operation of a conventional rainwater outlet

The most significant component within any roof drainage system is the roof outlet. The dimensions of the rainwater outlet determine the depth of the water in the gutter or on the roof. Rainwater pipes are dimensioned to operate at atmospheric pressure and with only one third to one quarter of the cross sectional area occupied by water. Typically, each outlet has its own down pipe, which conveys the rainwater to an associated underground drainage system. The design of such conventional systems is relatively simple, and is well documented within national specifications (Building Regulations 1991) and standards (BSI 2000).

1.3 Syphonic Rainwater Drainage Systems

There are two principal differences between conventional roof drainage systems and syphonic roof drainage systems (May & Escarameia 1996). Firstly, within a syphonic system the outlets are not holes in the gutter sole but are of a special type that restricts the entry of air and secondly, the rainwater pipes are designed to run 100 % full from roof level to ground level at the design rainfall intensity. By utilising the full height available between roof level and the point of discharge, at or near ground level, syphonic systems achieve significantly higher flow capacities than equivalent conventional systems. This improved performance is obtained by removing air from the pipes, enabling them to flow full over the whole network and to continue to flow full during the storm event. Once the pipes are forced to flow full of water, a transfer of energy can take place. In this way the potential energy that the water possesses at roof level can be used to produce high flow velocities. The motivation force driving the syphonic system is therefore the height of a building compared with the flow depth in the gutter of a conventional gravitational system, circa 100mm.

1.4 Flow Patterns

The flow regime within a syphonic system develops through a cycle as the duration of the rainstorm event increases (figure 1.3). Initially, the flow through a syphonic system is the same as that in a gravitational system resulting in a partially filled pipe.

This may be transformed into a full-bore flow as the storm intensity rises. Air is excluded from the system as the water level within the outlet approaches the anti-vortex plate, a key element of the outlet (described in more detail in section 1.5). Syphonic action is initiated within the pipe network as the flow velocity increases causing any remaining air to be entrained within the flow as a bubbly mixture and purged from the pipe work.

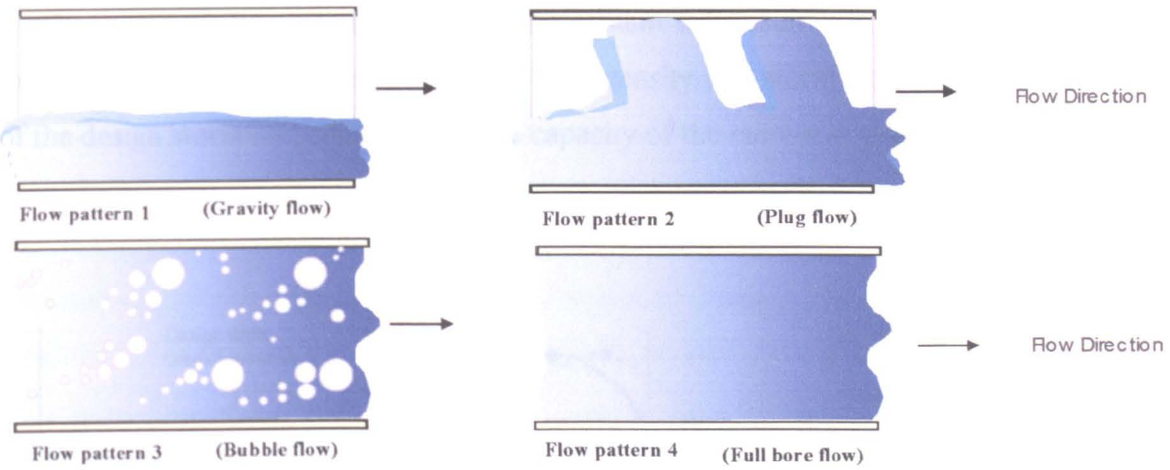

Figure 1.3 Development of flow within the high-level horizontal collection pipework of a syphonic rainwater system.
(Supplied courtesy of Fullflow Group Limited)

As this priming process progresses to the full bore flow condition, the flow capacity, and hence the quantity of water discharged from the roof or gutter, will increase.

If the rainfall intensity is able to satisfy the flow capacity of a syphonic system, the syphonic action will be sustained. As the rainstorm begins to dissipate there will be insufficient rainwater to support the capacity of a syphonic system. This will result in falling water levels, allowing air to be drawn into the piping network and breaking the syphon. As the pipework of a syphonic rainwater system flows full, the flow hydrograph recorded at the base of a vertical downpipe will closely match the hydrograph of the rainstorm. Figure 1.4 clearly demonstrates this, whilst also identifying the flow profile of the syphonic system within areas of the storm.

A Syphonic system therefore fluctuates from a gravitational flow regime to full syphonic action during any rainstorm. The period of time spent at full syphonic action will increase as the rainstorm intensity approaches the design condition. This ability to match the flow capability to the available flow is unusual in a system with no moving parts. The syphonic system has a low capacity when it needs one early in the storm event, yet can automatically increase its capacity up to its design flow condition should it need to do so when presented with increasing storm intensity. In a similar way to conventional systems, the syphonic system will result in a filling of the gutter and potential overflow, should the intensity of a storm exceed that of the design storm and consequently the capacity of the rainwater system.

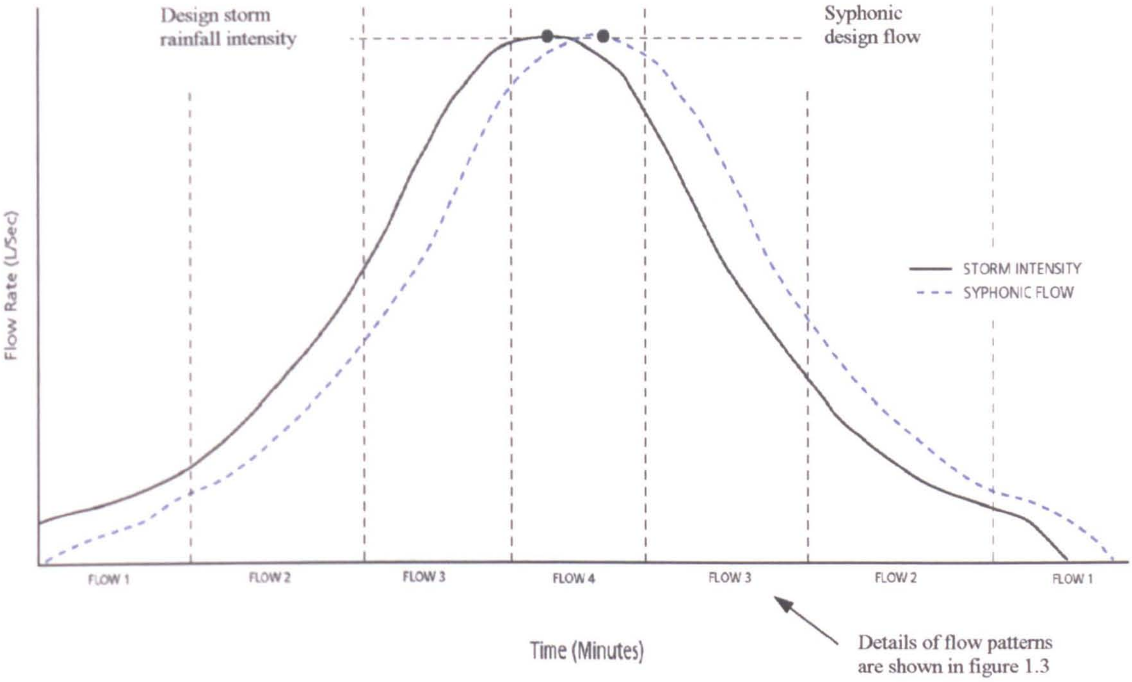

Figure 1.4 Hydrograph of rainstorm and the corresponding hydrograph at the base of the downpipe of a syphonic system.

The priming action is therefore a significant factor contributing to the performance of a syphonic system. The speed of removal of air from the pipe work depends on the air entraining properties of the flow and increases as the velocity and turbulence of the water is increased

The syphonic rainwater outlet design prevents air entering the pipe work and increases the velocity of water as it flows into the system

1.5 Syphonic Rainwater Outlets

The syphonic outlet is a key element in the drainage system. The design and form of the outlet are critical to the efficiency of the syphonic system.
The outlet and its component parts, shown in figure 1.5, trigger the priming process, which is fundamental to the establishment of the syphonic action. The outlet must prevent air entering the system otherwise the pipes will not be able to flow at full bore. A key component of the syphonic outlet is the anti-vortex plate. This prevents the formation of an open-air core, which would otherwise draw large amounts of air into the pipe work system. The syphonic action begins when there is sufficient water available to cover the top surface of the anti-vortex plate, thereby sealing the edge of the plate from the air by the rainwater itself.

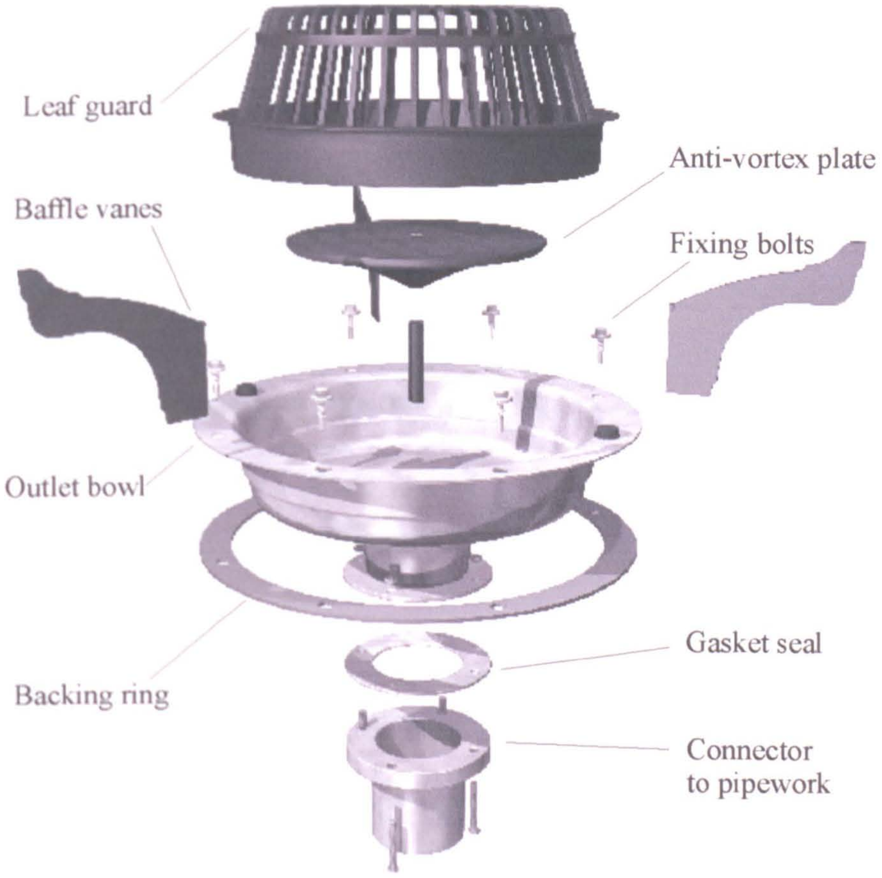

Figure 1.5 Component parts of a typical syphonic roof drainage outlet.
(Supplied courtesy of Fullflow Group Limited)

The location of the anti-vortex plate within the outlet, therefore, determines the water level at which the syphonic action begins to take place. A combination of the anti-vortex plate position and the outlet shape determines the priming activity. The increase in velocity achieved by the shape of the outlet (the smooth hydrodynamic form) and a low anti-vortex plate promote priming of the associated pipework (figure 1.6). This enables the syphonic action to be initiated at low flow rates by deliberately creating a dense, high-speed column of water at the exit of the outlet, which is travelling fast enough to overcome the natural buoyancy of air. This ensures that the air in the system is pushed forward along the piping network to be purged from the down pipe so that full syphonic action will occur throughout the entire system.

Therefore desirable features of a syphonic outlet are:

To minimise water depth in the gutter or on a roof.
Restricted air entry at minimum water depths.
Low hydraulic loss coefficients.
Smoothness of operation.
Increased flow velocity.
Rapid response to change in flow rate.

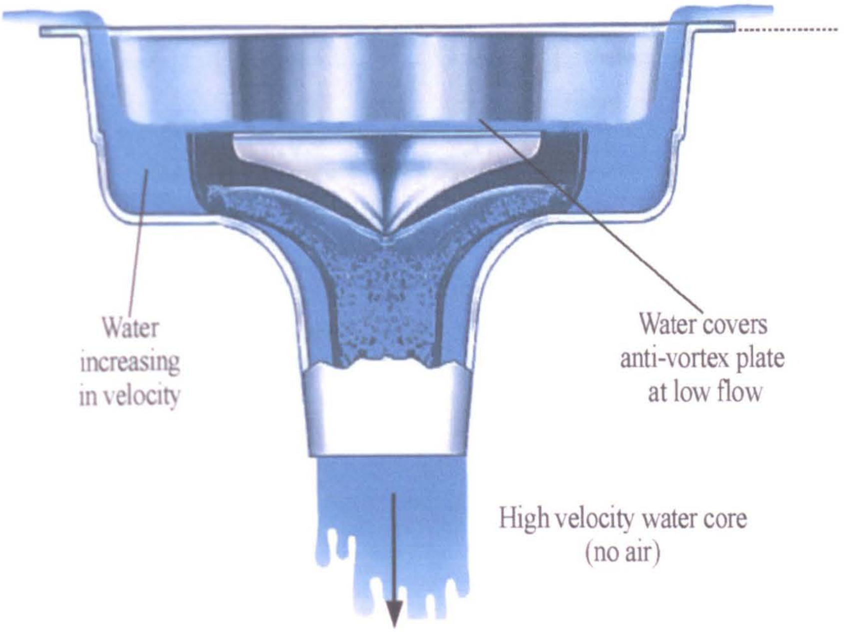

Figure 1.6 Operation of a syphonic roof drainage outlet
(Drawing supplied courtesy of Fullflow Group Limited, with annotation by the author)

1.6 Syphonic Systems Design Criteria

A Syphonic rainwater system designer has to solve the fluid mechanism problem presented by the height of the building and the quantity of rainwater generated by the storm event. All syphonic systems are currently designed through the application of Bernoulli's energy equation, assuming single phase and steady state flow. This equation is used to determine the change in flow conditions between any two points identified as node points within a system.

Figure 1.7 highlights that node points are located at changes of pipe direction, changes of pipe diameter, syphonic rainwater outlets and discharge points of the system these are shown by points 1 to 10 in figure 1.7. For example, with reference to figure 1.7, the application of the energy equation taken between points 1 and 2 results in equation 1.1.

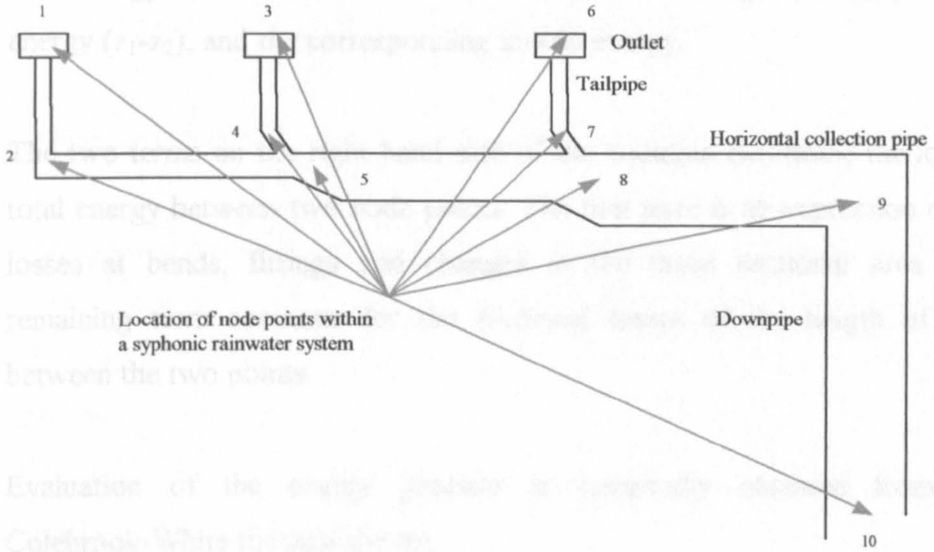

Figure 1.7 Typical locations of node points within a syphonic rainwater system.

$$(h_1 - h_2) + (z_1 - z_2) + \frac{Q^2}{2g}\left\{\frac{1}{A_1^2} - \frac{1}{A_2^2}\right\} = K_{1,2}\frac{Q^2}{2g A_2^2} + i_{1,2} L_{1,2}$$

Bernoulli's energy equation applied between nodes 1 and 2 within a system (Ref: Douglas et al 1985, transposition by author) (1.1)

Where:

h = Pressure head between nodes

i = Hydraulic gradient

K = Roughness values of fittings (including an allowance for discharge and entry)

Q = Rate of flow

A = Internal cross sectional area of a pipe

g = Acceleration due to gravity

z = Potential head

L = Length of pipe

The terms on the left-hand side of the equation indicate the changes in the total energy of the flow, attributable to the pressure energy, (h_1-h_2), potential energy (z_1-z_2), and the corresponding kinetic energy.

The two terms on the right hand side of the equation determine the loss of total energy between two node points. The first term is an expression of the losses at bends, fittings and changes in the cross sectional area. The remaining term accounts for the frictional losses of the length of pipe between the two points.

Evaluation of the energy gradient is commonly obtained from the Colebrook-White formula shown.

$$i = \frac{Q^2}{2g(A_1)^2}\left\{\log_{10}\left(\frac{ks}{3.7D} + \frac{2.51\nu}{D\sqrt{2gDi}}\right)\right\}^{-2}$$ Colebrook-White formula

(Ref: May 2004) (1.2)

Where:

- i = Hydraulic gradient
- ks = Pipe Roughness
- D = internal diameter of pipe
- Q = Rate of flow
- A = Internal cross sectional area of a pipe
- g = Acceleration due to gravity
- L = Length of pipe
- ν = Viscosity of water

This equation involves factors including the pipe diameter, surface roughness and viscosity of the liquid.

These two equations are applied across the whole piping network in order to obtain the syphonic system design.

Essentially the design of a syphonic system is a process of careful analytical sizing of a piping network, accurately matching the resistance of that network to the height of the building at the design flow capacity.

1.7 Primary and Secondary Syphonic Rainwater Drainage Systems.

Within the gutter of a building either single or dual pipe systems may be installed, this being the case, for ease of identification and to highlight the differing operations, the systems are known as either primary or secondary systems.

1.7.1 Primary Syphonic System

The rate of flow through a primary system outlet is derived from the agreed rainfall intensity and roof areas in accordance with the principles of the British Standard (BSI 2000). The pipework dimensions of a syphonic rainwater system are determined using commercially available analytical software (for details of software refer to appendix 1), as a multiple outlet system. The syphonic system typically extends from the outlets within the gutter of a building to a pre-determined discharge point usually sited at finished floor level. Plate 1.1 identifies a primary system outlet located within a gutter.

Plate 1.1 Primary system outlet in operation

(Photograph of primary outlet within the test facility, by author)

1.7.2 Primary and secondary syphonic systems

Through the adoption of this configuration, the total drainage provided within a gutter comprises of a primary syphonic system discharging to a designated point, typically underground drainage and a secondary syphonic system discharging to surface areas.

The design rainfall intensity is apportioned at some agreed division between the primary and secondary syphonic systems. The building "design" rainfall intensity is the sum of the primary system "design" rainfall intensity and the secondary system "design" rainfall intensity.

The syphonic outlets for the primary (figure 1.7) and secondary system (figure 1.8) share a common gutter with the secondary outlets ideally located midway between the primary outlets. The pipework for each system is designed independently and is typically installed below the gutter level (Plate 1.2)

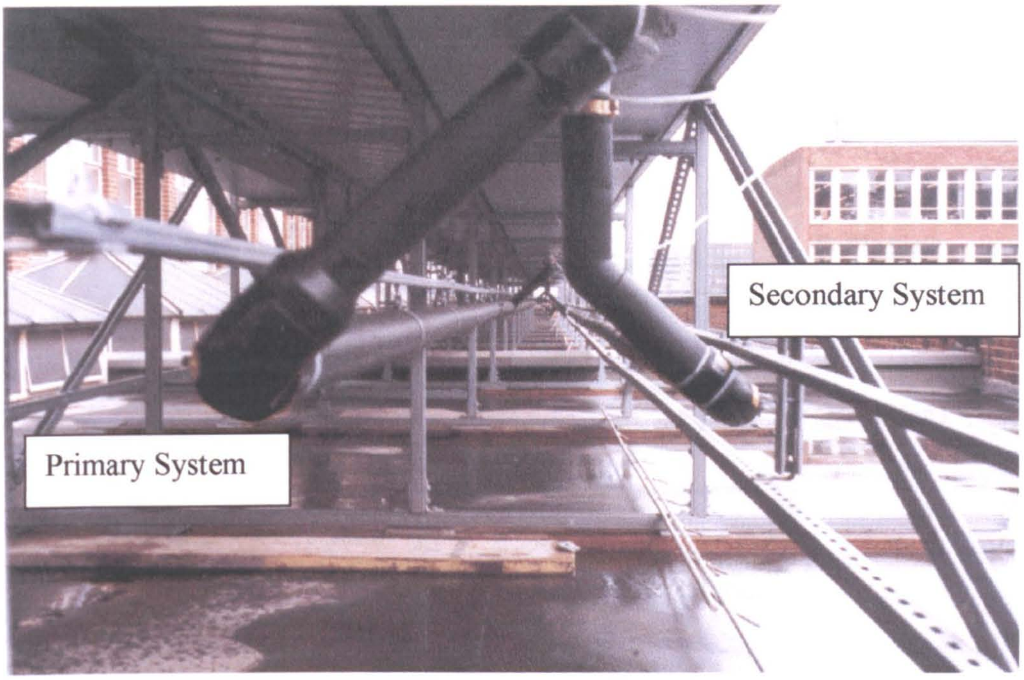

Plate 1.2 Pipework of primary and secondary systems, highlighting two independent systems within a common gutter.

(Photograph pipework within the test facility, by author)

The design philosophy for such systems is to identify the individual rainfall intensities for the primary and secondary systems then to proceed with the analysis as if the two systems were totally independent, concluding with a design flow for each system.

The secondary system outlets have an upstand to delay the operation of the secondary system in the rainstorm event. (Plate 1.3)

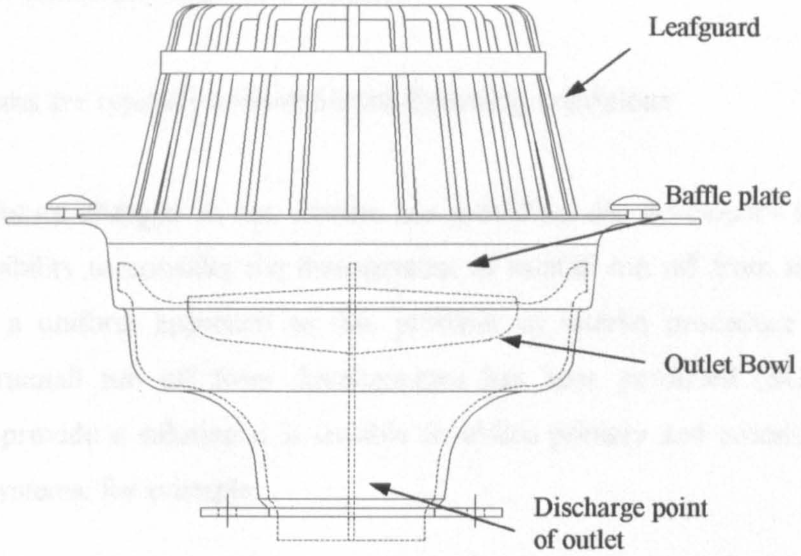

Figure 1.8 Sectional view of a typical primary system syphonic outlet.
(Figure supplied courtesy of Fullflow Group Limited with annotations by the author)

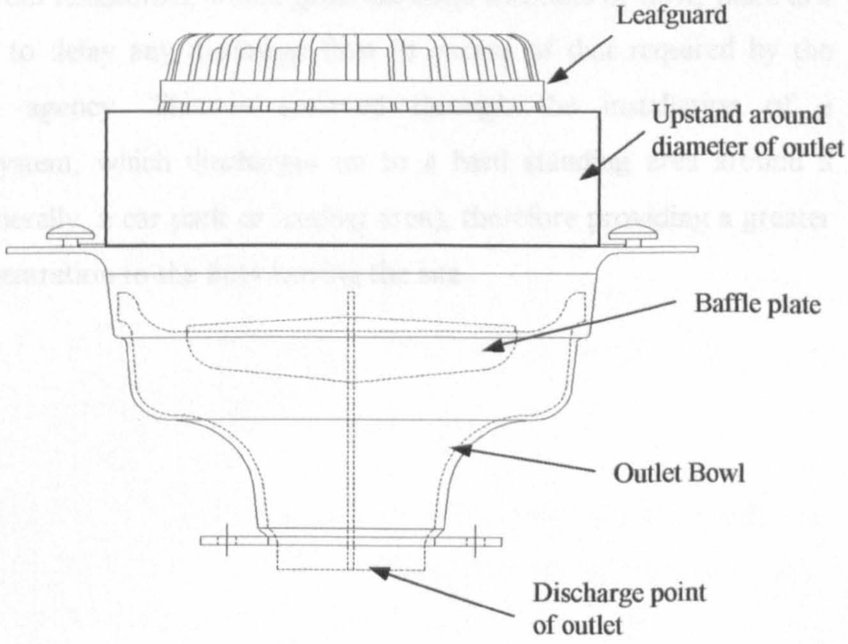

Figure 1.9 Sectional view of a secondary system syphonic outlet complete with upstand.
(Figure supplied courtesy of Fullflow Group Limited with annotations by the author)

1.7.3 Use of secondary syphonic systems

These systems are typically used under the following conditions:

Predicted future changes in our climate are providing site developers with the responsibility to consider the management of rainfall run off from sites. To ensure a uniform approach to this problem an interim procedure for managing rainfall run off from developments has been produced (SUDS 2004). To provide a solution it is feasible to utilise primary and secondary rainwater systems, for example:

A primary system, which will discharge directly into underground pipework, is designed to safely discharge a flow equivalent to that determined by an appraisal of the environmental impact of the development (SUDS 2004) this will guarantee that any restriction on the discharge rate will not be exceeded. However, as the building invariably requires protection from rainstorms, which generate large amounts of flow, there is a requirement to delay any discharge flow in excess of that required by the environment agency. This is achieved through the installation of a secondary system, which discharges on to a hard standing area around a building (generally, a car park or loading area), therefore providing a greater time of concentration to the flow leaving the site.

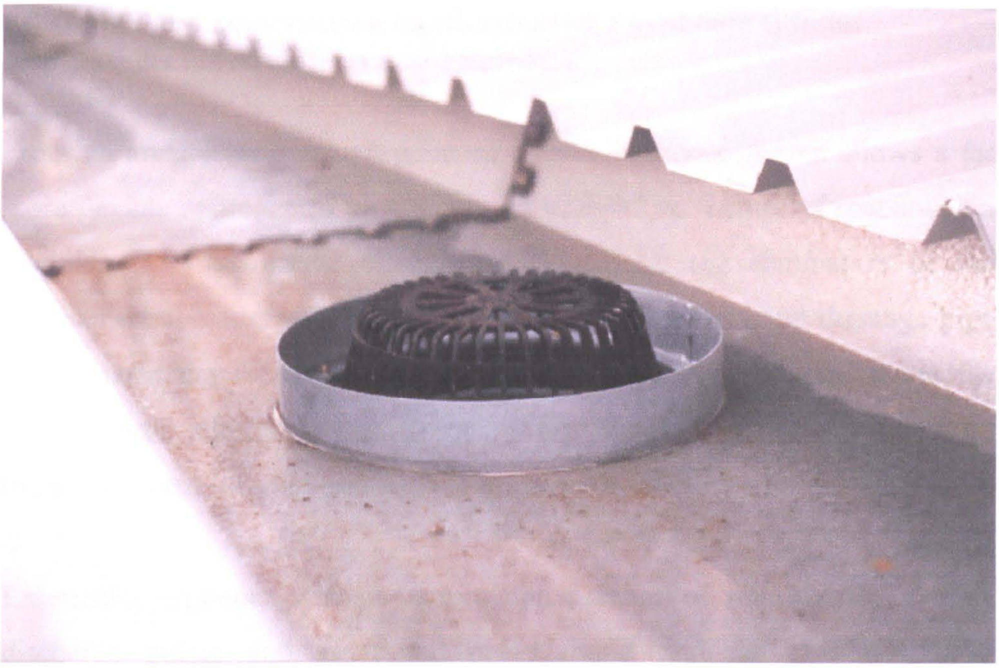

Plate 1.3 Secondary system outlet located within a gutter
(Photograph of secondary outlet within the test facility, by author)

The other condition, which would require the use of a secondary system, is that of a building with a very large roof area. Currently, for ease of handling and installation of the pipe at high level, syphonic system manufacturers utilise pipe diameters up to 315mm in diameter. Large roof areas combined with high values of rainfall intensity result in large discharge flow rates, which produce the requirement to be drained through pipes with diameters in excess of 315mm. In cases such as this, the total flow would be apportioned between a primary and secondary system therefore reducing the requirement for large diameter pipes.

When primary and secondary systems are installed within the same gutter it is important to examine the interaction between the two different types of outlets. This is a primary aim of this thesis.

1.8 Design and construction implications of a syphonic system: Implications for Architects and Engineers

From an architectural design point of view a syphonic system allows a far more flexible approach to be adopted with regard to the use of space within a building. Considering internal valley gutters, the elimination of the requirement for internal down pipes to individual outlets and drainage pipe work under the internal floor of a building, there is greater scope for uninterrupted internal spaces. The building's design is not compromised by the requirement for gradients as may occur with a gravity system.

Externally, syphonic systems reduce the number of required down pipe discharge points and associated underground drainage that would be necessary with conventional drainage, thereby simplifying detailing requirements. Further more, by removing the need for extensive associated underground drainage works, the architect is able to make full use of the available land.

For the engineer, syphonic systems provide a higher flow capacity whilst using smaller diameter pipe work. The elimination of an extensive amount of pipe work means that a syphonic system requires fewer connections to the building structure. External groundwork is minimised using syphonic systems and, consequently, there are significant cost savings and far simpler design. The benefit of reduced groundwork is magnified if the development is on a brownfield site. Using manufacturers design software (detailed in appendix 1), the engineer is able to fine tune and optimise the system design, producing demonstrably efficient and effective drainage solutions for individual buildings.

Clearly, the use of syphonic systems with the discharge of large volumes of water, which are considerably greater than a conventional system, reqires that specific attention is given to the underground drainage system to accommodate the impact of large flows. This is discussed further under the aspects of future work (see section 9.2.8).

1.9 Aims and Scope of Research

British Standard BS 6367:1983. 'Drainage of roofs and paved areas' is recognised by engineers and architects as being the Code of Practice used for the design of rainwater drainage systems. The theoretical model for the calculation of water depths within gutters and flow rates through conventional rainwater outlets is well proven (May 1982) and easily applied. The fundamental concept within this thesis is that the design principles are based on conventional rainwater systems and that such a design philosophy may not be appropriate for syphonic systems.

Recent years have seen an increase in the popularity of syphonic rainwater systems. This may be as a result of global warming and the need to drain storms of increasing intensities, or perhaps architects are becoming more aware of the architectural advantages, which may be gained through the use of syphonic systems. This increase in popularity of the systems has, to some extent, provided checking engineers with a slight dilemma. Currently there is no British Standard for the design of syphonic systems so therefore, engineers have been applying the principles of BS 6367:1983 to syphonic roof drainage. It was hypothesised that some areas of this standard may be directly transferable, however other vital areas do not seem applicable to syphonic roof drainage. This thesis aims to test this hypothesis with the work set out in 5 identifiable areas. Specific aims are:

1. To determinate the interaction between primary and secondary syphonic rainwater outlets installed within a common gutter.
2. To investigate the validity of adopting current theoretical methodology for the installation of syphonic rainwater outlets within gutters.
3. To determine a methodology for the prediction of the depth of water around a syphonic rainwater outlet for various rates of flow.
4. To investigate the effect that a sub-atmospheric pressure has on the performance of a syphonic rainwater outlet.
5. To determine a method of measuring flow through individual outlets of a syphonic system.

These aims are now discussed in turn in sections 1.9.1 to 1.9.5.

1.9.1 To determinate the interaction between primary and secondary syphonic rainwater outlets installed within a common gutter.

As the use of primary and secondary syphonic systems often provide a cost effective alternative to conventional systems, their use is becoming more widespread. However, there has been no research into the interaction of primary and secondary system outlets when located in the same gutter. The initial investigation examined the interaction of these outlets and provided guidance on their use.

1.9.2 To investigate the validity of adopting current theoretical methodology for the installation of syphonic rainwater outlets within gutters.

The British Standard (BSI 1983) may be used to calculate the flow rate through an outlet based on the conditions of flow around the outlet rim. This is completed by application of either a weir or orifice flow equation (May 1982). This calculation is fundamental to the correct sizing of the gutter, as all further design calculations are based on figures derived from these equations. Conventional rainwater outlets provide very little restriction to flow, they may be considered as holes in the sole of a gutter, which provide a circular weir through which the gutter is drained. BS 6367:1983 suggested profiles for these outlets in order to maintain a suitable design standard. Conversely, a syphonic rainwater outlet, as already discussed, requires component parts that whilst providing conditions to encourage syphonic action within the associated pipework, also place restrictions, which may affect flow conditions within the gutter. One other aspect is the calculation of flow through a syphonic outlet. Ultimately the flow through a syphonic outlet is controlled by the syphonic action, which is a result of the driving head of a system. This driving head is largely dependent upon the route, dimensions and height of the vertical downpipe. Conventional systems however, depend upon the depth of water around the rim of the outlet as the head of water, which determines flow.

Engineers are currently applying the conventional theoretical model found in BS 6367:1983 and derived by May (1982) to both syphonic and conventional systems in order to confirm the design of gutters. The scope of this study was to investigate the suitability of this method for application to syphonic systems. Additionally, there is often little consideration given to the location of an outlet within a gutter and the consequential effect this may have on the water depths. Do syphonic outlets placed at the ends of a gutter require the same head of water as outlets that are equi-spaced along the gutter sole? In a similar manner, does the proximity of an outlet to the gutter wall affect the operational head of water above that outlet?

1.9.3 To determine a methodology for the prediction of the depth of water around a syphonic rainwater outlet for various rates of flow.

In the absence of any design standards an aim of the thesis was to provide guidance and revise the methodology for the use of syphonic systems within gutters and to influence the publication of any future British standard Code of Practice for the design of syphonic rainwater systems.

1.9.4 To investigate the effect that a sub-atmospheric pressure has on the performance of a syphonic rainwater outlet.

Further investigations concentrated upon the effect negative pressures within the syphonic system have upon the performance of an outlet. It was determined by Slater (1998) that negative pressures are generated within an outlet as flow rates increase. He derived a theoretical computational model as a means of assessing the pressure and velocity profile within an outlet subjected to varying flow rates.

1.9.5 To determine a method of measuring flow through individual outlets of a syphonic system.

The flow capacity of a syphonic system may be measured in various ways, for example through the use of discharge measuring tanks or by measurement of the flow entering the gutter. However, an accurate and reliable method of measuring how this total rate of flow is distributed through individual rainwater outlets within the system has yet to be determined. A method of flow measurement was required that did not influence the performance of the syphonic system by providing additional, uncalculated energy losses within the pipework.

1.10 Thesis content.

Following the introduction to the thesis, chapter two presents a review of literature, of relevance to the present study. The areas covered by the review range from the investigations into the operation of syphons and syphonic rainwater systems through to the hydraulic design of the pipework of a syphonic system. The chapter concludes with a section on the flow performance of gutter systems.

Chapter three describes the design, construction and calibration of the full-scale experimental facility.

The interaction between primary and secondary systems is reported in chapter four. Initially, primary systems are examined followed by performance evaluations of primary and secondary systems and of their interaction. The chapter is concluded by a summary of findings.

The application of current theoretical models to the application of syphonic systems is discussed in chapter five. Within this chapter the experimental methodology is discussed in addition to test results.

The development of an original method of calculation for the influence on water depths a gutter sole width or location of the gutter end provides, is discussed in chapter six. A procedure and a worked example of the calculation method are discussed.

Chapters seven and eight investigate the affect that negative pressures within a syphonic rainwater outlet have upon the performance of the outlet.

Based on the findings in chapter eight, chapter nine investigates methods of measuring flow through an outlet without restricting the operation of the syphonic action. The use of dilution procedures presents a novel way forward to assess the hydraulic performance of syphonic roof drainage.

Conclusions and recommendations for future work are included as the final chapter of the thesis.

Chapter Two - Literature Review

2.1 Introduction

The fundamental design of conventional roof drainage systems has been utilised and remains largely unchanged since Roman times. Evidence of such systems has been found in the Roman cities of Bath and York (Plumbing & Mechanical magazine 1989). Today's systems typically comprise of a gutter and outlet arrangement with a large diameter vertical pipe connected to an underground sewer. Throughout the past 30 years numerous programmes of research work have resulted in the hydraulic design of such systems been well documented and encapsulated in BS CP308:1974, BS 6367:1983 and BS EN12056-3:2000 making their operation predictable and reliable. The fundamental operation begins as the intensity of a rainstorm develops and rainfall runs off the roof into the gutter. Within the gutter above the vertical pipe, a vortex begins to form. As the water enters the pipe section the action of the vortex draws in an air and water mixture, water then clings to the pipe walls allowing the air to form a central column (De Cuyper 1996). Consequently, only a small internal cross sectional area of the pipe is utilised to convey the water into the ground level drainage.

Almost every building throughout Europe was drained using this type of conventional system, primarily due to the fact that it was difficult to find an alternative commercially viable system. This was the case until the late 1960's when rainwater system design philosophies were questioned and syphonic systems were considered as a viable alternative to the well-established conventional systems.

2.2 Syphons

Syphonic principles have been utilised for the conveyance of liquids through pipelines, and for the overflow of reservoirs, for generations. Investigations into numerous aspects of the theory of the operation of syphons (Kelly 1965-66) took place in the mid sixties. The areas of reduction in water density, pressure drop, flow limitation, noise and priming of the syphon, which Kelly discussed, still provide issues of which today's designers have to be mindful.

During the 1970's even greater importance was placed upon the understanding of the operation of syphons and a symposium, held at the Scientific Society, London, discussed almost every aspect of syphon design and operation with papers on the subject of syphon modelling (Thatcher and Battson 1975) being of particular relevance to this thesis. Other papers (Kelly 1975) investigated the effect that the choice of tube material had on the performance of the syphon and it was concluded that the manner of the formation of bubbles within the flow was influenced by the choice of material. It would appear that when using plastics, bubbles tend to form on the surface of the pipe, whist, within steel tubes, bubble formation formed within the fluid itself. He concluded that syphon performance couldn't be modelled in one material to forecast results in different materials. As today's syphonic rainwater systems are installed in either plastic or metallic pipe, Kelly's findings were to provide guidance and advice for the construction of the facility utilised within the author's investigation. In addition to the discussions, which have taken place into the design and operation of syphons, many civil engineering hydraulics textbooks also carry sections devoted to the subject (Douglas et al 1985) (Hamill 1995). It is a subject of which there already exists a great understanding.

2.3 Syphonic Rainwater Systems

However, when syphons are adopted for the purpose of roof drainage there still seems to be a lack of fundamental knowledge. Although recent investigations have begun to address this, the problem may be partly due to the way in which the syphonic roof drainage industry developed, as described in appendix 2 of the thesis.

Two engineers from Finland developed the concept of syphonic roof drainage. Historically, architecture throughout Finland was based upon flat roof design. Following the Second World War a large-scale reconstruction programme was undertaken, providing modern economic buildings, which were ideally suited to the environmental climate of the country (Norri 2001). The built environment within Finland is by definition modern with only 13% of stock dating back to before 1920. In addition to architectural preferences and to the climatic considerations, the flat roof construction can accommodate the excessive snow loading conditions. Another outcome of this type of roof design results in the ponding of rainwater, either intentionally or otherwise.

During the mid 1960's Engineers, Olavi Ebling and Risto Lunden hypothesised (Patent specification 1216292) that if, during a rainstorm of a given intensity, rainwater pipes were designed to flow at full bore conditions, instead of part full like the conventional roof drainage, then cost savings could be achieved through the reduction of required pipe diameters. Nonetheless, this would present a totally different hydraulics problem, as the full flowing vertical pipe of the syphonic rainwater system would provide a working head of water equal to the height of the building. This working head would provide a siphoning effect that could be utilised in order to gain the commercial advantages required to compete against the well-established use of conventional systems.

Until now conventional rainwater outlets had an associated vertical pipe that would ensure water reached a sometime complex and expensive underground drain. In contrast the syphonic action within the pipework of a syphonic rainwater system allowed a number of syphonic outlets to be drained through one vertical pipe, therefore providing a series of new possibilities with regard to building design and pipe routing.

Economic advantages could be gained through a reduction in the amount of underground pipework required and through the possibility of routing horizontal pipework at high level within a building. Figure 2.1 shows a typical conventional piping configuration. It may be seen that each rainwater outlet has a vertical pipe connecting to the underground pipe network. The underground pipe extends not only along each side of the building but also beneath the floor of the building in the line of the valley gutter.

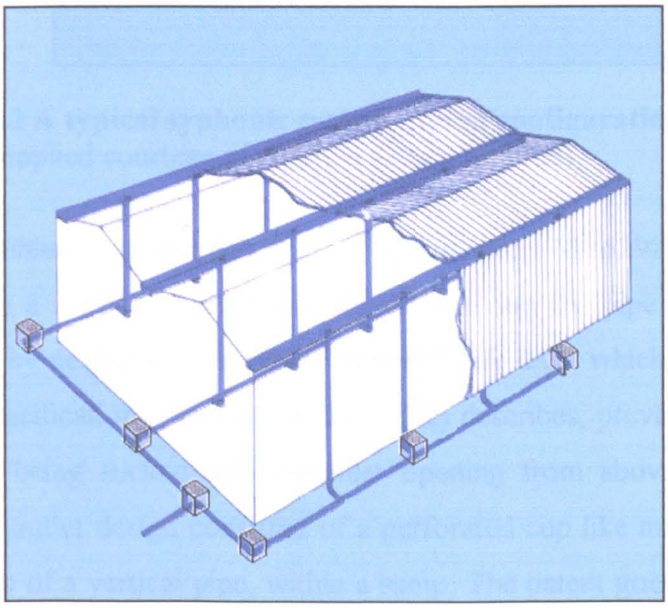

Figure 2.1 A typical conventional system piping configuration
(Figure supplied courtesy of Fullflow Group Limited)

By comparison, figure 2.2 shows the same building drained using a syphonic roof drainage system. All rainwater outlets are connected at high level by means of a horizontal pipe. All outlets and horizontal pipes drain into one downpipe, which in turn discharges into in the underground piping network. The flexibility of the system, with regard to position of both vertical and horizontal pipes, combined with the reduction in the material costs are the major advantages which Ebling and Lunden highlighted (Patent specification 1216292).

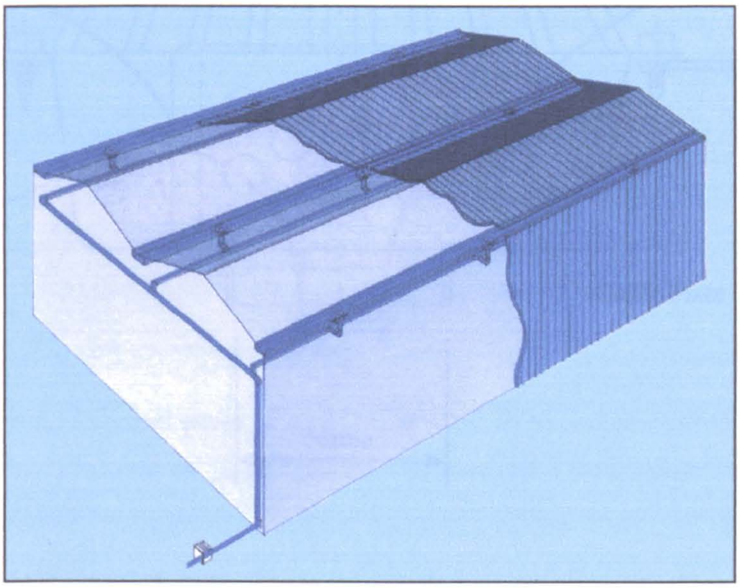

Figure 2.2 A typical syphonic system piping configuration
(Figure supplied courtesy of Fullflow Group Limited)

Initially Ebling and Lunden (Patent specification 1216292 (1970)) had to determine a method of inhibiting the air entering the pipe work. This they achieved by designing a rainwater outlet (figure 2.3), which as the 1968 UK patent specification (Patent Spec 1216292) describes, prevents 'surrounding air from being sucked into the inlet opening from above'. This original syphonic outlet design consisted of a perforated cup like mantle inverted on to the top of a vertical pipe, within a sump. The patent goes on to state that 'tests have indicated that one vertical pipe according to the invention having a diameter of 2¼" is able to discharge an equal amount of water per time unit as a rain drain conduit comprising one 6" vertical pipe and one 4" vertical pipe'.

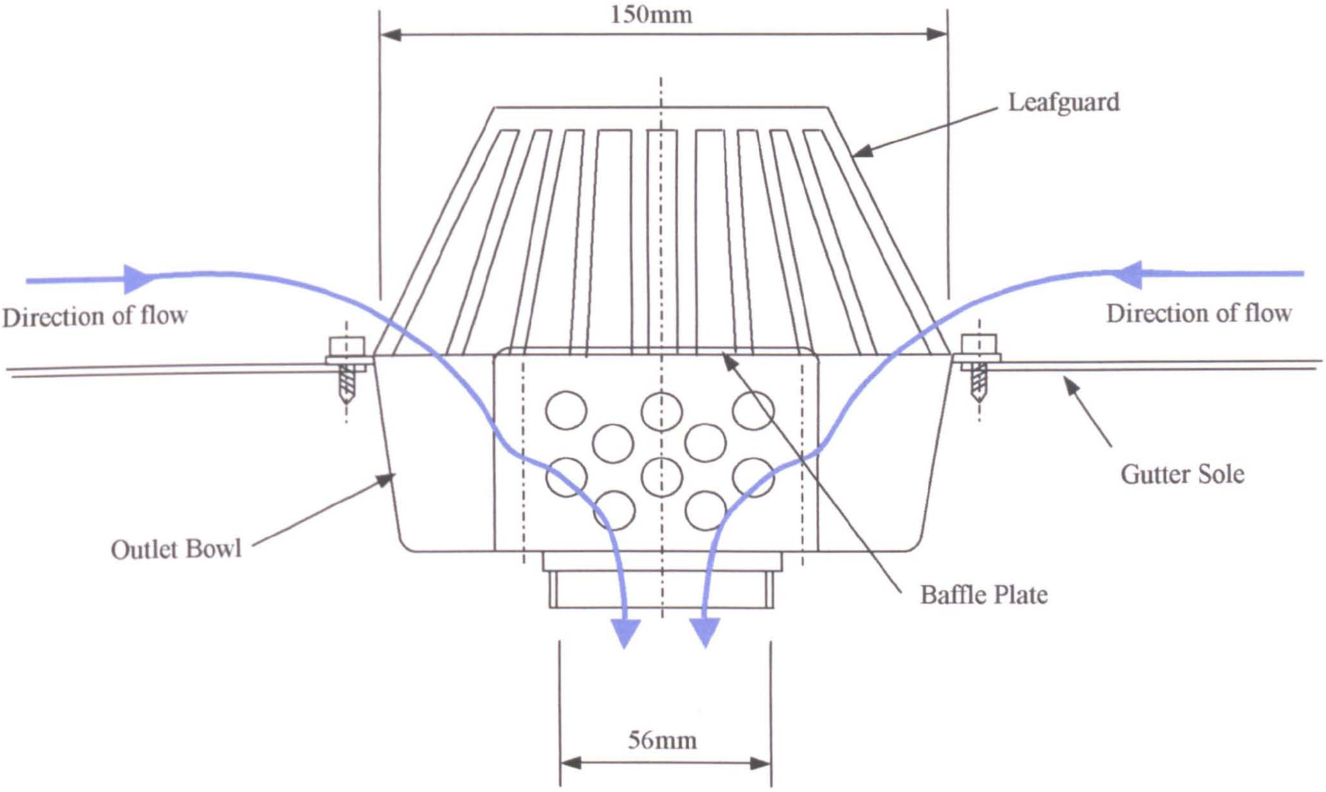

Figure 2.3 Original syphonic rainwater outlet

(Outlet design after Ebling and Lunden 1970, with annotations by author)

Based upon economic considerations, the philosophy of syphonic roof drainage seemed to provide a cost effective alternative to the well-established roof drainage systems. However, with the advantage of hindsight and subsequent testing (May and Escarameia 1996), it appears that full consideration was not given to the hydraulic principles of a syphonic system and especially to the required water depths above the outlet. Again, within the patent specification of the Finnish outlet, there is an indication as to the latent problems that existed. The patent states 'if the intensity of the rain is equal to or greater than the maximum receiving capacity of the pipe, the trough is filled with rainwater to its upper edge…the pipe discharges the amount of water as a continuous column'. This would suggest that a syphonic rainwater system would not only operate efficiently during the design rainfall intensity, but also during storms that exceed this intensity.

Through the adoption of the philosophy that a system would operate satisfactorily at rainfall intensities greater than the design storm and therefore beyond the systems maximum capacity, suggests that there is a requirement for storage of rainwater upon a roof. If the roof is flat and fully sealed, and if the loading capacities are not exceeded then there is no problem with storing rainwater in such a way. Conversely, if the roof architecture in Finland had been of a pitched design with gutters, then the available storage would have been greatly reduced. This would have affected the perceived efficiency of the syphonic systems, in some cases causing the gutter section to overfill, potentially resulting in water ingress into the building.

Another aspect of the early systems was that they were designed using well-established and recognised hydraulic pipework design nomographs (UV Systems 1996). The use of such design methods provided inherent design anomalies, which in turn questioned the accuracy of the design of a system. This later became more evident in the prediction of the sub-atmospheric pressures generated within the system and the choice of pipe material (Bowler and Arthur 1999)

Metallic pipes had been used in the installation of conventional systems for many years and therefore there were no foreseen problems when used for syphonic system design. The use of this type of material within a syphonic system allowed for the absorption of any inaccuracies within the hydraulic performance system. The affects of sub-atmospheric pressures were therefore not correctly considered; buckling loads and the occurrence of cavitation were either thought not to be an issue or not identified at all. The level of inaccuracy of these charts for the design of syphonic rainwater drainage systems was not fully realised, or the consequential effects fully recognised or understood until the implementation of purpose written software during the 1990's (Appendix 1)

The Finnish State Institute for Technical Research undertook the first independent testing of syphonic rainwater outlets during 1971 (Finland

1971). The series of tests compared the performance of a syphonic outlet, against that of a conventional outlet. The conclusions of the report infer that a maximum capacity of a syphonic outlet may be determined from its dimensions. Additionally, it also suggests that there is very little increase in water depth around an outlet, as the flow rate increases.

During the following years syphonic rainwater systems were successfully installed throughout Scandinavia, a major project being that of ABB Alston turbine factory in Sweden (UV System web page 2002). The flat roof architecture and the use of metallic pipes proved an ideal combination, and very few problems were associated with the use of these systems. Also during this time an association between Olavi Ebling and an engineer from Sweden named Per Sommerhein developed. The enhancements to the original system made by these two engineers resulted in the introduction of the UV system, whose naming is based on an acronym for the Finnish word "umpivirtaus" used to describe full-bore flow. Ebling and Sommerhein have continued to develop the rainwater outlets, which are used throughout the world (UV System web page 2002).

Coincidently, within the United States of America, a patent was filed entitled 'method for siphoning water from a ponding area on a flat roof' (Loftin 1977). The following year another patent entitled 'Device for siphoning water from a ponding area on a flat roof' was filed by the same person (Loftin 1978). A Further patent regarding siphons used in roof drainage was filed in 1983 (Wilson 1983). There is no evidence to suggest that these designs and methods are linked to the European systems. However, in 1985 a European link did develop when Ebling and Lunden applied for a US patent for their rainwater roof outlet (Ebling and Lunden 1985). Two years later the same engineers filed an additional patent entitled 'Drainage arrangement for roof' (Ebling and Lunden 1987). The current lack of popularity of syphonic rainwater drainage within the USA suggests the adoption of these principles of syphonic drainage has to date, been minimal. This may be as a result of inefficient marketing or the fact that the accreditation process of construction products within the United States of

America is often long and arduous. There is no single national accrediting body and products generally have to be assessed on a state-by-state basis.

The Scandinavian systems were introduced into the United Kingdom in 1981 at a project for Ikea in Warrington, following this introduction their use was minimal until 1987. The construction of Stansted airport provided an ideal opportunity and 'showcase project' for the system, as it became the first major UK project into which a syphonic system was installed. The architects for this project were Foster Associates and the consulting engineers Ove Arup and Partners. The fact that two high profile companies were seen to be endorsing the use of syphonic drainage gave other companies confidence in the product. Coincidentally, reminiscent of the Scandinavian architecture, the flat rainwater collecting areas and metallic pipes utilised on the airport building ensured that the systems operated without problems. Successful completion of this project and the advantages that such systems gave in pipe routing and underground drainage savings soon lead to interest from other clients. The first recognition of a syphonic system becoming an accepted part of the construction industry occurred in 1988 with an assessment being undertaken by the British Board of Agrément (BBA 88/2077).

Designers and installers saw the Scandinavian system being installed using traditional materials without any problems, and assumed that the systems would be suitable for use throughout the UK. However, the architecture within the UK was of pitched roofs and gutters, whilst uPVC was becoming the first choice for piping material within drainage systems.

Geberit, a Swiss company bought the original 1960's design from Ebling and Lunden and began to market the system throughout Europe. Within the UK these systems were sold through a network of agents. Clever marketing and a good recent history to the product ensured that their popularity began to grow. Articles extolling the virtues of syphonic drainage began to appear in trade magazines. One such article entitled 'Pulling Power' (Building Magazine 1990) was typical in marketing the product without full consideration being given to hydraulic operation. The article spoke of draining different levels of roof down a single downpipe and water velocities of up to 12 m/s. During 1991 the marketing bandwagon seemed to continue as further carefully worded articles appeared (Building products 1991, Roofing Cladding and Insulation 1991 and New Builder 1991). Whilst this marketing exercise was a great success and orders for syphonic systems began to grow, there was still the underlying fact that the hydraulic operation both of the pipework and of the systems use within gutters required further investigation.

As a consequence of the excellent marketing of the systems manufacturers began to examine the ways in which the slightest commercial advantage over a competitor could be gained. After the initial expense of design, the major cost element within a syphonic system is the pipework. The systems had moved away from the cast iron pipework of the original Scandinavian design and now utilised a more economic solution through the use of polyethylene. However, further cost savings were demanded by the manufacturers and as result systems designed and installed utilising uPVC pipes began to appear. This material had been used for the installation of conventional systems for many years, so therefore it seemed only right that it should be used for syphonic systems as they both drain rainwater. What the manufacturers failed to realise was that the negative pressure carrying capabilities of uPVC pipes was virtually non-existent. When systems that were installed with this pipe material were subjected to heavy rainfall, the negative pressures within the pipe caused catastrophic failure of the pipework within a building, resulting in flooding. Therefore, in addition to outlets designed for flat roofs requiring an additional head of water in excessive storms being used in gutters, this provided yet another potential area of concern.

A third and final element to the early system design was the interpretation of rainfall intensity. The British standard code of practice (BS 6367:1983) at that time suggested that 'a design rate rainfall of 75 mm/h was generally satisfactory for roof gutters'. Generally architects without question adopted this. It should be understood that values of rainfall intensity have an associated return period, For example, based on the methodology outlined in the flood studies report (1975) a rainstorm with an intensity if 75 mm/h has a 9 month return period for the central London area. If a syphonic system is designed to operate at 75 mm/h then when the rainstorm achieves this intensity, the system will be flowing close to its maximum capacity. If the rainstorm intensity should increase, then the systems' maximum capacity will be exceeded. The additional rainwater being collected by the roof area has to be stored. This storage cannot take place in the gutter due to the dimensional limitations, therefore the consequences are that the gutter will flood, with the possibility of serious water ingress to the building.

Such history of events has shown, for example through the court case of Bexall Securities Limited – v – Sheard Walshaw Partnership (Bowshaw 2000), that the choice of a 75mm/h rainfall intensity was inadequate. It was the responsibility of architects to ensure that buildings were adequately protected against rainfall in accordance with relevant standards. Today's systems are generally designed for an intensity in excess of 150mm/h with return periods of around 100 years.

Ironically the excellent marketing of syphonic systems seemed to have become it's downfall, as systems installed without due consideration of outlets in gutters, pipework material and choice of design rainfall intensity began to fail. Understandably the confidence in this type of roof drainage within some sectors of the construction industry began to diminish. This culminated in the publication of a paper by Ove Arup (Buckingham et al 1994) one of the country's leading construction consulting engineers who warned specifiers to 'Watch it!' when specifying syphonic roof drainage systems.

Conversely, the popularity of the systems within the rest of Europe increased with a number of companies adopting the syphonic principle and developing their own individual system. This would eventually lead to a number of rainwater outlet patents being issued in countries such as

Germany (Vahlbrauk 1993, Arm 1996, Broermann 1996), Holland (Berning 1994) and Switzerland (Geberit 1995). The majority of these systems are used today utilising cast iron pipes and flat roof construction.

Within the UK however, there were a number of consulting engineers who recognised the engineering and architectural advantages that the installation of a syphonic rainwater system within a building could give to clients. Though it would seem that anecdotal evidence sourced from UK manufacturers based on good marketing techniques, rather than facts based on sound research work, was still finding its way into trade publications. One such article (Roberts 1994) misinforms designers that 'the shortest practical stack height required for syphonic action to start is 3m, and the maximum design flow rate per outlet is usually of the order of 12 l/s'. Other articles (Building Services 1996) suggest that the syphonic system may only be used within buildings with flat roofs.

The message being sent to the construction industry was unclear. Manufacturers were marketing all the advantages that could be gained from the use of a syphonic systems, yet buildings were still experiencing problems through poor design and lack of consideration with regard to the interface between a building and a syphonic system. Coincidentally, the patent of the first UK designed syphonic rainwater outlet (Smith 1996) was registered as the confidence within the construction industry of the use of syphonic systems began to dwindle. These concerns eventually filtered through to researchers and 1995 saw the instigation of a number of projects (May and Escarameia 1995, Baker 1996) that would change the thinking of both manufacturers and users.

There were three fundamental areas of concern which required clarification, namely: a greater understanding of the hydraulic design of the pipework utilised within a system, an analysis of the hydraulic performance of syphonic outlets within gutters, and confirmation as to what effect the introduction of large flow rate at a high velocity had on the associated conventional underground pipework.

2.4 Hydraulic design of the pipework.

The first major piece of work, which increased awareness and understanding of syphonic rainwater systems, was commissioned by the Department of the Environment and undertaken by H.R.Wallingford (May 1995) (May & Escarameia 1996). The four major manufacturers of syphonic systems within the UK were invited to provide a system, along with the design calculations, which would be installed within a gutter test rig. All aspects of the systems were considered including:

- Theory for syphonic systems
- Aspects of syphonic performance
- Margin of safety
- Negative pressures
- Priming of syphon
- Integration of design and construction

May 1996 specifically concluded that:

- Tests on three different syphonic systems installed in a gutter have shown that, under full-bore conditions, they are able to achieve predicted flow rates.
- Syphonic systems represent a higher level of technology than conventional systems and their performance can be more sensitive to errors in design and construction.
- Syphonic systems have certain special operating characteristics and the following factors need to be considered in their design and specification: correct choice of rainfall intensity; effectiveness of outlets in restricting entry of air a small flow depths; magnitude of negative pressure within the pipe work: time for priming action to occur; and integration with other parts of the rainwater drainage system

This work was significant in alerting manufacturers, clients and other interested parties into the performance of syphonic systems, and was later to form the basis of a report published by H.R.Wallingford during 1996 (May and Escarameia 1996) and appeared in the journal of the Chartered Institution of Water and Environmental Management 1997 (May 1997)

At Salford University (Baker 1996), added further understanding to the influence that the location of a baffle plate within an outlet had on the outlets performance, providing control and stability. (All designs of syphonic rainwater utilise a baffle plate in order to exclude air from entering the pipe system)

During 1999 the CIB W62 Symposium on Water Supply and Drainage for Buildings was held at the Heriot Watt University in Edinburgh. This provided a platform for a number of UK based researchers and consulting engineers to present papers on the subject of syphonic roof drainage. Most of which (Sommerhein 1999), elaborated on the aspects of the system already highlighted by May 1996. The papers presented at this symposium were of great significance from a research viewpoint, providing in depth knowledge and understanding of the flow regime within the pipework of a syphonic rainwater system. Addressing issues, which were of concern to UK users of the early systems i.e. negative pressure effects on pipe choice (Bowler & Arthur 1999), loss factors within a system (Slater 1999), priming of a system, with a method being established which may be used to quantify the amount of air entering a system (Arthur & Swaffield 1999a). The numerical modelling of a system was further developed and reported upon at the 8th ICUSD conference in Sydney Australia, (Arthur & Swaffield 1999b) where the design approach utilised by manufacturers was questioned as being over simplified.

Whist the research projects were invaluable with regard to understanding the hydraulic operation of a system, they all invariably investigated the systems as independent entities. There was still very little understanding of the importance of recognising and accounting for the interface between the syphonic system, the gutters of a building and the underground pipe system.

A major project during 2000 was the construction of the Boston convention centre in the United States. A representative from the projects consulting engineers visited the UK in order to assess the possibility of utilising syphonic roof drainage. Following this visit, where he had opportunity to speak with almost all UK manufacturers and researchers, awareness of the systems within the United States began to increase. So much so that in collaboration with UK researchers, papers were published in trade magazines (Arthur 2000), eventually resulting in an ASTM specification being written for the design and installation of plastic syphonic roof drainage systems (ASTM F2021-00). Coincidently, within Germany guidelines for roof drainage with syphonic systems were also published in 2000 (VDI 3806:2000).

Within Europe there was an exercise to consolidate national and local roof drainage standards in to one European standard. The publication of BS EN 12056-3:2000 Gravity Drainage Inside Buildings, replaced the BS 6367:1983 Drainage for roofs and paved areas. As in its predecessor, within the new standard there was a methodology for the design of roof gutters, which identified the flow around a rainwater outlet as being either of weir or orifice type. Research work (May 1982) has shown that these formulae are based upon the operation of a conventional system, but the question remains as to the validity of these approaches for the design of syphonic systems. There is no evidence to suggest this is the case. The new standard also provided users with the first significant mention of syphonic systems within any British Standard. The National Annex NF provides a methodology for the testing of syphonic outlets, which is based upon, the work of May and Escarameia 1996. This work was also cited as being the design authority within the publication of the 2000 building regulations, rainwater drainage H3, where syphonic roof drainage systems are mentioned. However, there is little usable design information in the regulations.

During the late 1990's as the knowledge of the performance of syphonic system became more widespread, prestigious projects worldwide began to utilise the system. One such project was the Olympic stadium in Sydney, Stadium Australia. As a direct result of the construction of this stadium, the potential of the systems began to be realised. The Stormwater industry association of Australia stated that syphonic systems were 'probably one of the most important technology advances in roof drainage in the 20th – 21st century' (SIA 1999). Such was their confidence in these systems they undertook a series of nationwide seminars extolling the technological advantages. However, most of this work was based upon previously published work and as such the fundamental issues such as performance in gutters and choice of pipe work materials were not addressed. Nor were they fully addressed in the German guidelines VDI 3806(VDI 2000), which were published in 2000. The majority of the information was based upon the research work of Prof Rickmann of Munster Technical University, Germany (Authors discussions with Mr J Purser, Dallmer Ltd, 2004).

In recent years, other than the continuing work by Heriot Watt University (Arthur & Swaffield 2001) (Wright et al 2002), which has concentrated on the development of numerical modelling of a system, very few examples of new work have been reported. Roberts revised and republished his work of 1994 (Roberts 2001) stating that from investigations into the failures of syphonic systems failures were 'attributable either to errors in design or to problems caused by blockages'. Meanwhile separate papers entitled 'Syphonic roof drainage systems' (Galowin 2002) and 'Fundamentals of syphonic roof drainage' (Rattenbury 2001) maintained the interest in the Untied States, although the publications only reiterated facts that were known to the industry within Europe.

In 2003 Representatives from the industry along with clients and consulting engineers formed a working group and produced a set of guidelines (May 2004) that have been presented to the British Standards Institution with the prospect of them forming the first British Standard Code of Practice for the design of syphonic roof drainage. The author was a member of this working group.

Through the excellent and worthwhile work already cited, the awareness of syphonic rainwater drainage systems has increased and potential design difficulties have been highlighted. However, the fundamental issue of the interface with gutters and the validity of the use of established calculation methods developed for conventional drainage systems have not been fully addressed.

Conventional system design methods are published in current British Standards, and they remain the only real rainwater system design tool available to the independent checker. Therefore, further research work is required in order to investigate the water profiles within a gutter fitted with syphonic rainwater outlets, and how the performance of a syphonic outlet is affected by its position relative to the gutter wall and to other outlets. Primary and secondary systems are fast becoming the design 'norm' but it is not known how the installation of these systems within the same gutter affect their performance? In order to try and resolve these questions it is first required to review previous work on flows in gutters.

2.5 Flows within gutters

A number of research projects regarding flows in roof gutters had already been undertaken prior to syphonic systems being introduced into the United Kingdom. As long ago as 1934, (Benji 1934) discussed theoretical flow profiles in certain types of level gutter. His work involved tests on rectangular and semicircular gutters of various lengths and widths, both level and sloping, and on one gutter of irregular cross section. Alternative types of flow conditions were simulated. Flow freely discharging from the end of a gutter and the flow discharging through an outlet located within the sole of the gutter. The second scenario restricts the flow capacity of the gutter, therefore increasing the achievable water depths, for flow rates comparable to those within a freely discharging gutter. Additionally, Benji reported on the importance of the choice of rainfall intensity being a major factor to the integrity of the roof drainage system. He stated that ' their importance is a matter of judgement which must be left to the architect or design engineer' and also that ' the intensity should be picked in each case high enough so that the gutter dimensions determined from the graphs can be used directly without multiplying by some arbitrary factor of safety'. Paradoxically, even today some 70 years later, a large number of architects and specifiers still fail to understand the implication of the incorrect choice of rainfall intensity. From the results of his work, Benji, was able to derive empirical formulas for the capacity of most types of gutter profile, although his investigations were confined to level gutters.

Work completed by the Building research station (BRS 1958) stated that guttering had evolved through trial and error and that there were rules of thumb on which designs were commonly based. The BRS Digest presented data that provided a basis for the rational design of eaves gutters and down pipes. The importance of the choice of rainfall intensity was recognised although the suggestion made in the Digest could be easily mis-interpreted and lead to an incorrect choice. Flow capacities of gutters along with the effects of bends were also discussed. With regard to the utilisation of outlets, the Digest stated that 'round cornered outlets give a smoother flow than sharp cornered ones which has a marked effect upon the gutter capacity with the smaller outlet sizes'. In respect of down pipes the Digest reported ' The survey showed that the down pipe sizes commonly used are unnecessarily large, and smaller sizes may be used without affecting the capacity of the gutter. If smaller down pipes are used they will tend to run full under conditions of heaviest rainfall and joints should be sealed to avoid leakage'.

'The position of an outlet has a big effect on the flow capacity of a gutter but, in deciding at what point in the length of a gutter the outlet should be placed, the ease of connection to the underground drainage system and the appearance have to be considered. When an outlet is placed centrally in the

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length of gutter, the gutter capacity required will be one half of that needed for an end outlet'. The Digest touched on a number of issues, which would be needed by the designer of a syphonic system in order to produce a cost effective and accurate system. Full flowing pipes produce a different hydraulic problem to that of part full pipes. By allowing conventional down pipes to flow full, undesirable sub atmospheric pressures may be created within the pipework and it is important that the system components can accommodate such pressure. The statement that an outlet placed at the end of a gutter would reduce the capacity by half is an assumption that is in need of verification through experimentation. The Digests were updated in 1969 in order to incorporate the national adoption of the SI system of measurement.

The British Standards Institute published BS 1091 in 1963 (BSI 1963). The specification for pressed steel gutters, rainwater pipes and fittings contained no indication of a method of calculation of the hydraulic performance of a gutter. However, the Building Research Station provided worked examples of gutter calculations within Digest 34 (BRS 1963) entitled 'Design of Gutters and Rainwater Pipes'.

The determination of flow regimes within gutters had up until the late 1960's, been one of supposition and based upon experience. Many of the systems were designed using over simplified methods, which lead to gutters being typically undersized and designers working close to the maximum capacity. During 1968, a fundamental change occurred within the building industry, new materials were being developed, which allowed architects more freedom within their designs. One such material was Polyvinyl Chloride (PVC). The introduction of this material for use in the manufacture of gutters and more importantly pipes was to play a significant part in the history of syphonic systems. The utilisation of this new material within the manufacture of gutters produced a need for an investigation into the practical sizing of PVC eaves gutters (Marsh 1968). This work presented information for the sizing of PVC gutters, comparing the performance of PVC with other standard materials of the day i.e. aluminium, cast iron, asbestos cement and pressed steel. He discovered that the PVC gutters allowed for slightly greater flow capacities than their contemporaries, due mainly to the reduction in surface roughness of the PVC. He concluded that the determination of rainfall intensity was of economic importance and had to be assessed with knowledge of the buildings potential exposure. As stated previously, it has been shown that the choice of rainfall intensity is of fundamental importance when considering the design of a syphonic rainwater system.

The Building Research Station updated the 1963 Digest by the publication of digest 107 Roof Drainage (BRS 1969).

In 1974 the British Standards Institute published a Code of Practice for the Drainage of Roofs and Paved Areas (BSI 1974). CP 308 was cognisant of some of the design methods suggested by the previous work undertaken by the Building Research Station. Additionally, the design of valley gutters, rectangular gutters and gutters for larger buildings were based upon the theoretical work undertaken by Benji. Also incorporated within this Code of Practice were results of work conducted in Australia (Martin 1973) and South Africa (Schwartz & Culligan 1976). The wide-ranging scope of research work incorporated within this Code of Practice ensured that, at the time, it was the most comprehensive design document available to engineers.

In 1976 a decision was taken by the British Standards Institute to review CP 308. New work on both the meteorological and hydraulics aspects associated with the design of roof drainage was reviewed and, as part of this work, a research paper (Crow and Barnes 1980), reported on an investigation into the capacity of conventional roof outlets. May (1982) also produced a report that described the theoretical and experimental background to the design methods for roof gutters and gutter outlets. The Building Research Station also provided guidance on roof drainage with updates of Digests relating to roof drainage (BRS1976). A revised British Standard BS 6367: 1983 Code of Practice for the drainage of roofs and paved areas (BSI 1983) was published, once again providing a comprehensive design guide. However, what was omitted from the standard were any design guidelines relating to a syphonic roof drainage system. Such systems were beginning to be acknowledged within the construction industry as an alternative to conventional roof drainage.

The new standard was well received and quickly became the guide by which all roof drainage was designed. Information regarding the meteorological and hydraulic aspects of roof drainage was comprehensive. Despite the standard being issued in 1983 the meteorological information was based upon a report compiled in 1975 (Flood Studies Report 1975) by the Natural Environment Council. This report was published using data from a number of sources and the choice of rainfall intensity was an area liable to misinterpretation. Within the first pages of the Standard a design rainfall intensity magnitude of 75 mm/h was quoted as being generally satisfactory. This was often taken as read but within the Appendix there is a method of applying a probability factor to this figure, in order to gain additional levels of protection.

The Institute of Plumbing established a design guide (IOP 1988), that referred to rainwater systems, the design procedures were based upon BS 6367 and gutter design charts were derived in order to assist a design engineer in the process of rainwater system design.

In a further attempt to reduce the scope for misinterpretation of the British Standard, May (1996) produced a manual for the hydraulic design of roof drainage systems in 1996. Sub-titled 'A guide to the use of British Standard BS 6367: 1983', this manual provided comprehensive guidance on how roof drainage systems for buildings should be designed, using the information outlined in BS 6367: 1983. The manual addressed all aspects of roof drainage design including:

- Rainfall data
- Effective catchment area

- Design flow loads
- Gutter capacity
- Outlets and box receivers
- Combined gutter/outlet design
- Flat roofs
- Rainwater pipes
- Overflow weirs

In September 2000 the British Standard was replaced by a European Standard (BSI 2000), which includes guidelines on the testing of syphonic rainwater outlets. A National Annex within the Standard is produced for use within the United Kingdom. This is based upon BS 6367: 1983, and uses the same rainfall data and similar design methodologies as previous guidance.

Much of the previous research work on rainwater gutters has been conducted using relatively short gutters and a minimal number of rainwater outlets. With the exception of the study by May and Escarameia (1996), which examined depths above a syphonic outlet at set flow rates and in optimum positions, most of the rainwater systems tested were designed to operate under the principles of conventional gravity drainage. Therefore allowing the rainwater outlet to dictate the flow capacity of the system and the flow profile within the gutter. The introduction of syphonic rainwater systems has been hindered by the fact that as yet no meaningful work has been undertaken in order to gain an understanding of the hydraulic interaction between outlets, pipe work (working head) and gutter profile. The theoretical equations governing the flows within gutters are well established and give reliable predictions for conventional systems, Benji (1934) Crabb el al (1958) and BRS (1976). Through investigation it was observed that the measured values of capacity and water depth within a gutter agreed with the predicted values. Further work by May (1982) concluded that the depth of flow at the downstream end of a gutter depends upon the capacity of an outlet. The flow at an outlet is of weir type at low heads and orifice type at the higher heads. De Cuyper (1996) concurred with this statement during his investigations into the discharge capacity of rainwater stacks. As a result of the work by May (1982) there is a recommendation within BS 6367 (BSI 1983) that the flow rate through a rainwater outlet may be calculated through the use of either the weir flow or orifice flow equation depending on the head of water above the outlet. This method of calculation is based upon the operation of a conventional rainwater outlet, which may be considered to be no more than a hole within the sole of a gutter. Conversely, a syphonic rainwater outlet is a more complex form of rainwater outlet with the inclusion of a baffle plate. The primary function of this plate is to stop the formation of a vortex above the outlet and not allow air to be drawn in to the associated pipework. The inclusion of the baffle plate within the outlet and the greatly reduced diameter of the tailpipe of an outlet (figure 2.4) now brings into question the validity of the application of the weir and orifice flow equation for determining either the water depths around or the flow through a syphonic outlet.

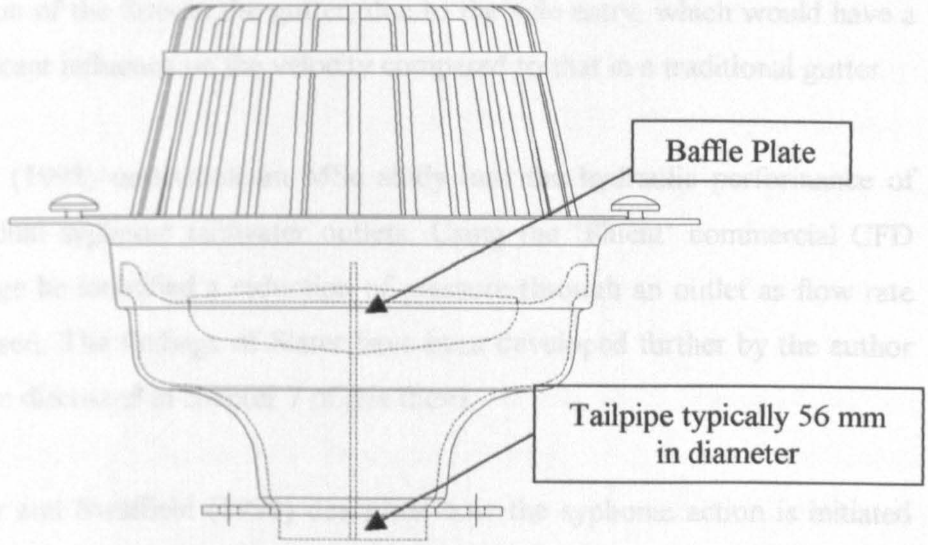


Figure 2.4 Detail highlighting baffle plate and small diameter tailpipe

(Figure supplied courtesy of Fullflow Group Limited, annotated by the Author)

During 1997 Salford University undertook a programme of undergraduate research work (Augris. J 1997), which investigated the velocity flow profile of water within a gutter installed with a syphonic rainwater system. A major conclusion of the investigation was that water within the gutter flowed towards the outlet, which provided the least resistance to flow, irrespective of the position of any other outlet. The author gave this work much consideration, as it was analogous to the aims and objectives of the current study. However, the reliability of the results within the work of Augris was questioned for the following reasons:

From the data provided within the thesis, changes in levels of the gutter sole of 20mm were recorded in a 2 m section of gutter and that water depth profiles followed these deviations. The changes in bed profile had a greater influence on the water depth profile than any of the 5 rainwater outlets, irrespective of their positions. In addition, the supply of water to the gutter entered the gutter from the side, at a level of the gutter sole, unlike a traditional gutter in which the water falls into the gutter from the roof section. It is argued that the results of the study were influenced by a rotation of the flow in the gutter, due to the side entry, which would have a significant influence on the velocity compared to that in a traditional gutter.

Slater (1998) undertook an MSc study into the hydraulic performance of individual syphonic rainwater outlets. Using the 'Fluent' commercial CFD package he identified a reduction of pressure through an outlet as flow rate increased. The findings of Slater have been developed further by the author and are discussed in chapter 7 of this thesis.

Arthur and Swaffield (1999) described how the syphonic action is initiated within the pipe network as the rainstorm intensity and consequently the flow velocity and magnitude increases.A result of this work was the development of a numerical model that is capable of representing the two-phase flow priming of a syphonic system. Such an approach has not yet been adapted to encompass the multi outlet systems typical of those utilised in most UK systems. The results from laboratory tests were comparable to the flows predicted by the model. May (1996) highlighted that low and negative pressures in a syphonic system should be considered for two reasons. One being the ability of the pipe material to resist the buckling forces implied by the negative pressure. This area of study has been reported upon by Bowler and Arthur (1999) who concluded that through the correct choice of pipe material the issue of pipe failure due to buckling should be eliminated. The phenomenon of cavitation was also considered by May (1996) who recommended that the potential for cavitation to occur in flowing water within a syphonic system might be determined from the value of a cavitation index for pipes and fittings. He recommended (May 2004) that a cavitation index should be incorporated into the design analysis of a syphonic system as a means of identifying any adverse effects that the existence of cavitation may have upon the capacity of a syphonic system.

During the period 1998 – 2000, the author presented the initial finding of his investigations at a number of international conferences. A paper presented to the CIB W62 symposium in Rotterdam 1998 (Bramhall & Saul 1998) described the investigation of the performance of primary and secondary syphonic systems operating within a common gutter. The construction of the test facility located at the University of Sheffield was also detailed. The conference on Urban Storm Drainage (Bramhall & Saul 1999a) detailed further work, which further investigated the hydraulic performance of syphonic rainwater outlets. The same year a paper presented to the CIB W62 symposium in Edinburgh (Bramhall & Saul 1999b) considered the use of existing theoretical models presented in BS 6367:1983, for use with syphonic rainwater systems. A final paper in the series (Bramhall & Saul 2000) discussed the potential influence that negative pressures experienced within the pipework of a syphonic system, may have on the performance of the syphonic rainwater outlet. The work presented at these conferences has since been further developed and is reported accordingly within this thesis. For information purposes, a complete collection of the published work of the author may be found within appendix 7.

From the review of the literature it has been highlighted that there is a considerable shortfall in knowledge concerned with the following aspects of syphonic roof drainage.

1. Understanding of the hydraulic performance of syphonic rainwater outlets, when located within gutters.
2. The interaction between primary and secondary systems.
3. The validity of the use of weir and orifice flow equations.
4. There is a need to provide the syphonic rainwater drainage industry with clear and well-proven guidelines for use in the design and installation of syphonic rainwater drainage systems within gutters.

To satisfy these aims a new and novel experimental rig was designed, constructed and tested. The development of the rig is presented in the following chapter.

Chapter Three - The Gutter Test Facility

3.1 Introduction

In order to ensure that the objectives of this investigation were completed and that the data retrieved was not only accurate but also comparable to situations occurring within the construction industry, the design of an appropriate and full-scale test facility was a major challenge. The test facility had to be dimensioned in such a way that the data obtained would be practical and workable by the rainwater drainage industry. This had to be achieved within the economic constraints of the project.

Syphonic rainwater systems are typically installed on large commercial or industrial buildings, therefore the gutter is invariably relatively large. The spacing of individual rainwater outlets of primary and secondary syphonic systems within the same gutter, provide an additional requirement for the gutter to be long. The flexibility to install, remove and re-insert the primary and secondary outlets was also a desirable feature of the facility.

3.2 Previous Investigations

In his investigation, Benij (1934) adopted various gutter profiles in order to derive empirical formulae for the capacity of semicircular and rectangular gutters. Due to the complex nature of flow within sloping gutters, the investigation considered only level gutters, the maximum width of which was 6-inch and had a length of 41.5 feet. A 3-inch sprinkler pipe supplied water to the gutter along the length of the test facility via a run off sheet (see figure 3.1). It would appear that no consideration was given to the angle of the run off sheet. It is debatable if this would have any effect upon the flows within the gutter, however, the configuration was not typical of the construction industry and the high velocity of the water entering the gutter may have affected results.

Filling the gutter with water and adjusting the level until the depths were as uniform as possible allowed the levelling of the gutter sole.

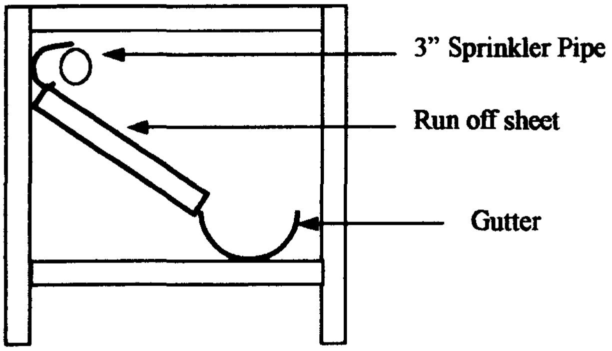


Figure 3.1: Schematic view of simulated gutter. Benji (1934)

Experiments were conducted on three basic configurations of open channel flow namely:

a. Freely discharging i.e. an open-ended gutter with no restriction to flow.
b. Outlet located at the extreme end of the gutter
c. Outlet located 10 feet from the end of the gutter

These configurations provided confirmation of theoretical values of gutter capacity, which are now the basis for the design of roof gutters. However, they were not used to investigate the interaction between the gutter and the size of an outlet nor its' position relative to other outlets and to the wall of the gutter.

Marsh (1968) undertook investigations into PVC eaves gutters, which required the construction of a test facility. The same basic rig design principles adopted by Benji were utilised in this series of work. The gutter was 40 feet long and water entered through a sprinkler pipe that ran the length of a simulated roof section. The investigation concentrated on PVC gutters, which are typically found on domestic dwellings.

Although on a slightly larger scale, this same basic approach to the design of a gutter test facility was taken by May (1996). This investigation included the analysis of syphonic systems therefore requiring the rig to be located in a position that would allow sufficient length of vertical downpipe to create a working head for the syphon. In this case the achievable working head was in the region of 6.5m above the discharge point. The rectangular gutter profile had a sole of 350mm and a length of 12 meters, with two syphonic rainwater outlets equally spaced along its length.

A pump provided a maximum flow rate of 75 l/s to a 200mm pipe manifold that was installed above a section of plywood roof, which had a slope of 1V:2H. The manifold pipe was designed to have a large number of 12.7 mm holes along its length. The spacing of these holes was such that it compensated for the proximity to the pump allowing an even flow over the roof section. Figure 3.2 shows a schematic view of the test facility.

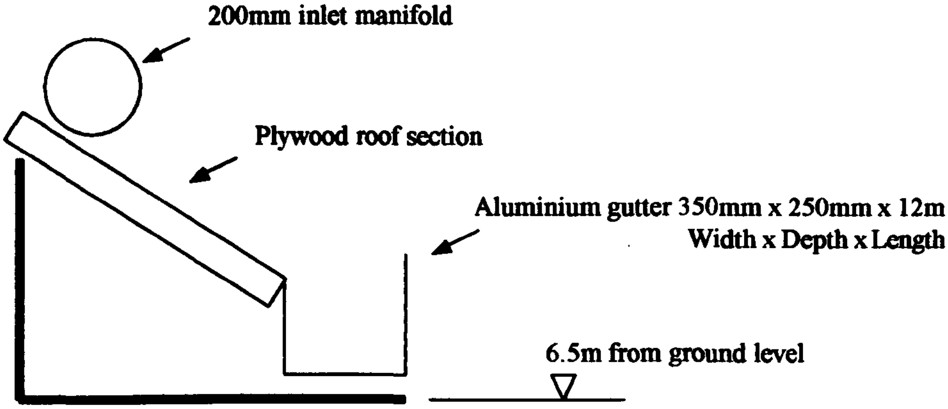


Figure 3.2: Schematic view of simulated gutter. May (1996)

From the previous work of Benij (1934), Marsh (1968) and May (1996), the basic design of the required test facility was determined. However, as the objectives of these investigations differed, further studies into the design of the facility were necessary.

As already stated it was of utmost importance that any data retrieved from the test facility would stand scrutiny of both academics and the construction industry. To achieve this, liaison with gutter manufacturers and roofing contractors was found to be invaluable in the design and installation of the test facility. Identification of the requirements of the facility ensured that the design was practicable and cost effective. The requirements were highlighted as being:

a) To recreate as closely as possible the flow regime within a gutter of a large industrial building.
b) To ensure that the run off from the roof area was typical of that experienced during any rainstorm.
c) Ensure that there was a sufficient working head between the gutter and the syphonic system discharge point to enable the installation of a system, which was typical of those installed within large industrial buildings.
d) The installation of individual primary and secondary syphonic systems in order to assess the interaction of the respective outlets.
e) To simulate wind driven rain through the varying of the flow rate across the facility.
f) To have the ability to recreate rainstorm profiles.
g) To be able to record water depths at any point within the gutter.
h) To accurately assess the effects of the position of a rainwater outlet relative to other outlets and to the gutters parameters.

3.3 Location of the test facility.

The location of the test rig required careful consideration as to the requirements of the investigation. Located close to a plentiful supply of water, the space needed to be of a sufficient area to accommodate a gutter approximately 35m in length. The need for a gutter of this length was determined through the consultation with a Syphonic system designer and examination of buildings installed with primary and secondary syphonic systems. A gutter of this length would provide adequate spacing between 2 primary and 3 secondary outlets to easily distinguish the interaction between the two systems, through the measurement of water depths within the gutter. The vertical length of the downpipe primarily determines the driving head of a syphonic system and therefore the maximum capacity. An external flat roof area within the Sir Fredrick Mappin Building of The University of

Sheffield provided the desired requirements. Utilising this area meant that a working head of approximately 9.5 metres could be achieved in addition to the gutter length of 35 metres. There was also adequate space to provide the additional requirements of the rig i.e. pitched roof, supply pipe. The only inconvenience that this location presented was that of the supply of water and the route of the syphonic system discharge pipes. In order to route the pipes to and from the water source there had to be some superficial construction work.

3.4 Dimensions

As in previous investigations the basic operation of the rig involved water flowing over a roof area and into a gutter along the full length. It was necessary to ensure that water could flow on to the roof section in a uniform manner. To achieve this it was decided that in place of the water supply manifold pipes used in previous experiments, a water supply box running the length of the gutter would provide the best method of achieving uniform flow. Flow would run onto the roof section via an adjustable weir.

The rig design was based on averages. The dimensions and profile of the gutter is typical of any which may be found on a commercial or industrial building and the pitch of the roof is 6° again very typical. The roof section is constructed from Calzip profiled roofing sheet again to provide authenticity. Collaboration with a gutter manufacturer ensured that all these standard construction industry practices were achieved. Plate 3.1

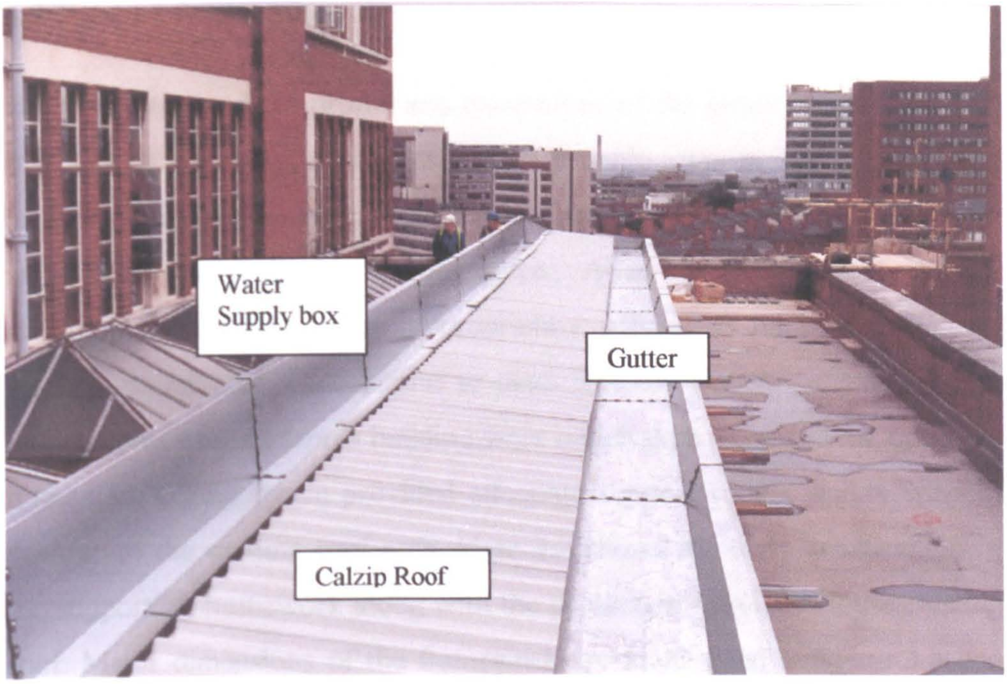


Plate 3.1: Configuration of Supply Box, Roof Section and Gutter

The profile and major dimensions of the gutter and water supply box are shown in figure 3.3

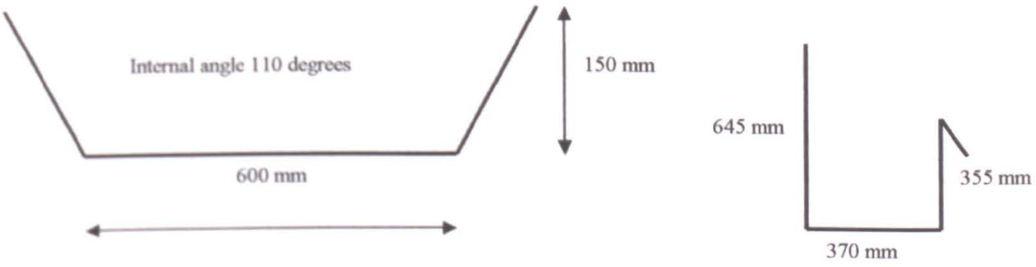
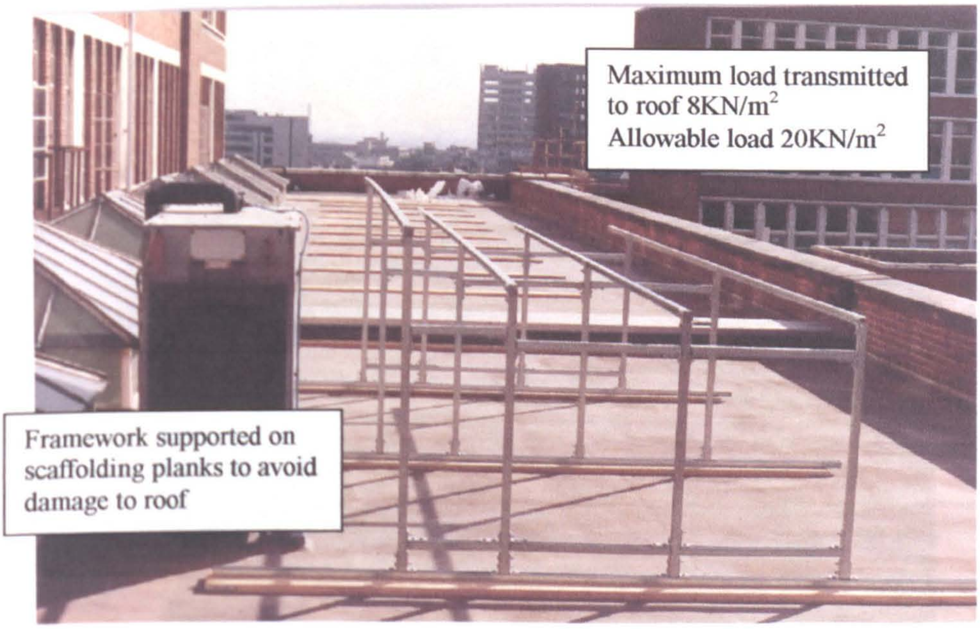


Figure 3.3: Major Dimensions of Gutter and Supply Box

3.5 Support framework

Having determined the profile and dimensions of the gutter, supply box and roof section the next issue was to provide a stable support. The gutter had to be raised above the ground in order that the syphonic system may be installed to the underside of the gutter. After consideration of various materials for the framework a proprietary galvanised mild steel support system was adopted. Calculations to determine the loadings imparted on to the roof area of the Mappin building were undertaken to ensure the optimum framework configuration provided adequate support to the facility without damage to the existing roof area. Plate 3.2 shows the early construction of the supporting framework along with the protection provided to the existing roof. Major dimensions of the framework are highlighted in figure 3.4 and the final framework configuration is shown in plate 3.3.



Maximum load transmitted to roof 8KN/m^2
Allowable load 20KN/m^2

Framework supported on scaffolding planks to avoid damage to roof

Plate 3.2: Framework of Test Facility

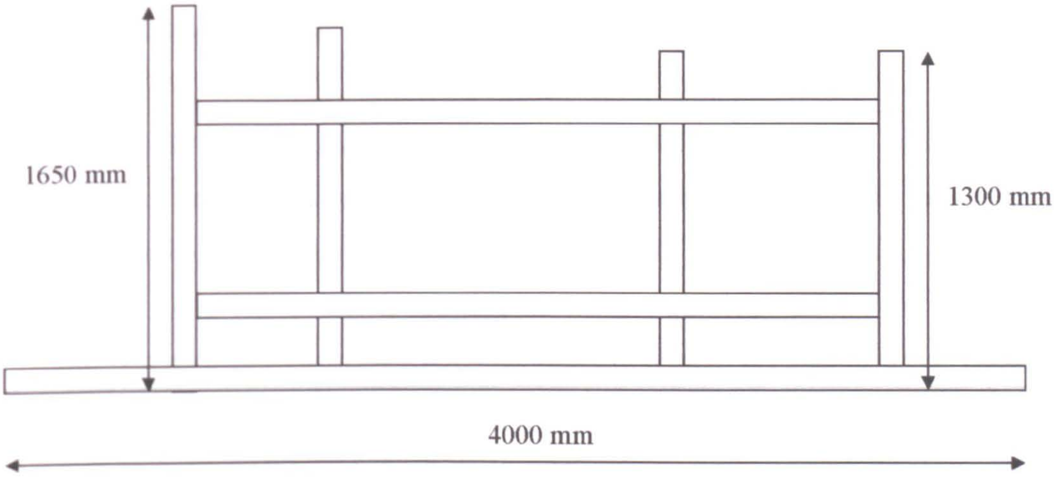


Figure 3.4: Major Dimensions of Framework

Plate 3.3: Completed Construction of the Framework

3.6 Syphonic System

Both a primary and secondary system was installed within the gutter. The design of these systems was undertaken using commercially available design software (appendix 1). Based on Bernoulli's energy equation the user enters a pipe route and a specific flow rate through an outlet and the software provides the required pipe diameters and achievable flow rates. Through the use of this software it was possible to achieve maximum flow capacities of 38.19 l/s for the 3 outlet secondary system and 25.66 l/s for the 2 outlet primary system. The accuracy of the software calculation was to be later assessed and is discussed in chapter 8. The two systems were installed using polyethylene pipe with diameters stated in table 3.1. Both systems discharged to the supply tank located 9.5 meters below the sole of the gutter.

	Range of pipe diameters. Horizontal section	Range of pipe diameters. Vertical section
Primary System	75 mm – 90 mm	110mm
Secondary System	63 mm – 110 mm	110 mm – 125 mm

Table 3.1: Range of pipe diameters used in the syphonic rainwater systems installed within the test facility.

3.7 Supply Pipes

One of the attributes required of the test facility was that of the simulation of wind driven rain. Following the design and installation of the syphonic rainwater systems and the determination of the maximum required flow rates, it was possible to size the submersible pumps. To achieve wind driven rain effects the supply box had to be sectioned in to 3 parts, with each section being independently supplied via a submersible pump (plate 3.4) and control valve (plate 3.5). As the route of the supply pipes was complex the loss factors within the supply pipes had to be assessed in order to establish the required capacity of the pumps. The electric aluminium submersible pumps were sourced from flygt limited and had a capacity of approximately 27 l/s at 17 metres working head. As already stated 3 pumps, supplied three independent sections of supply box via three control valves.

Plate 3.4: Submersible pumps

Plate 3.5: Example of a pneumatic control valve

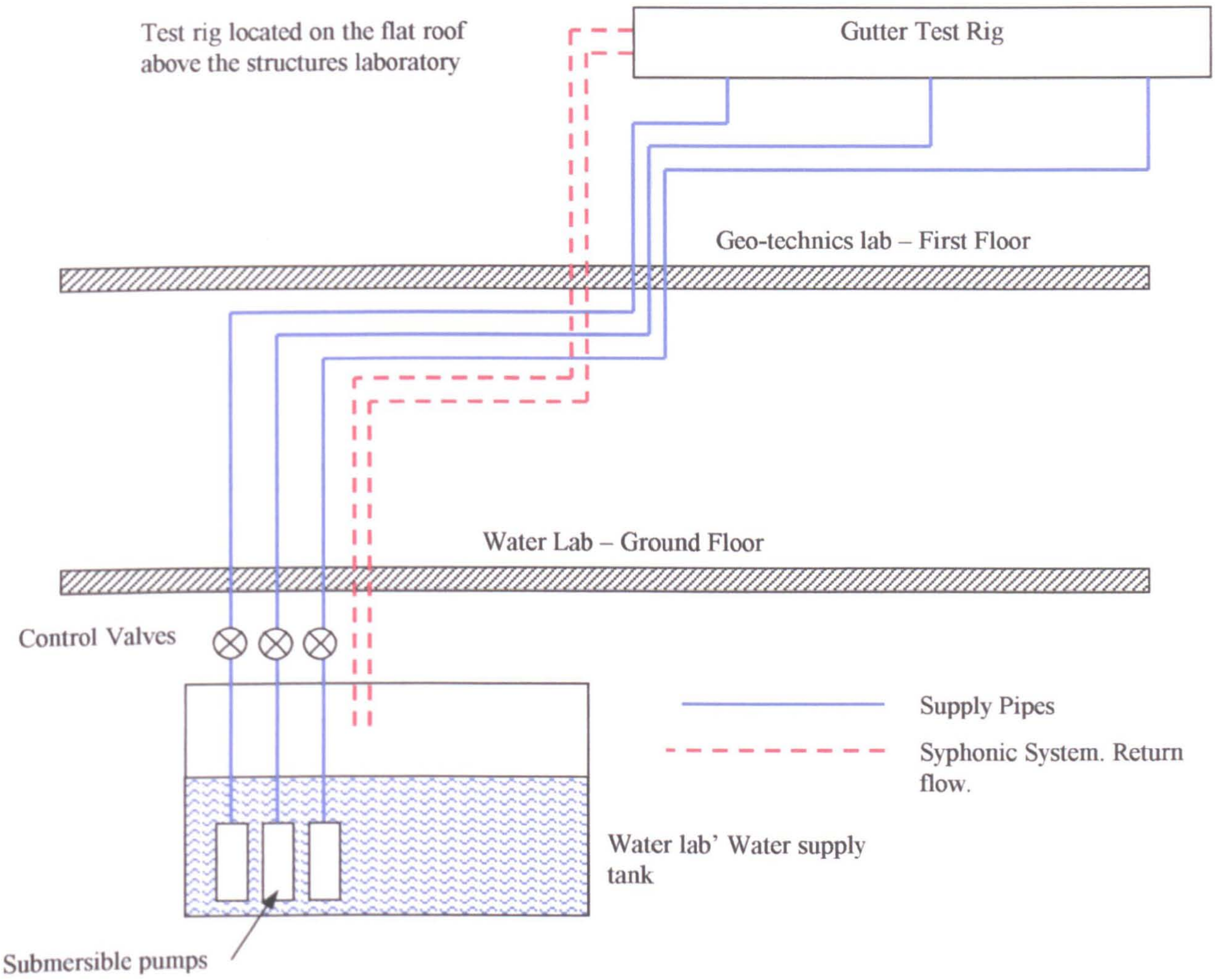


Figure 3.5 Schematic layout of test rig viewed from inside the Sir Fredrick Mappin Building.

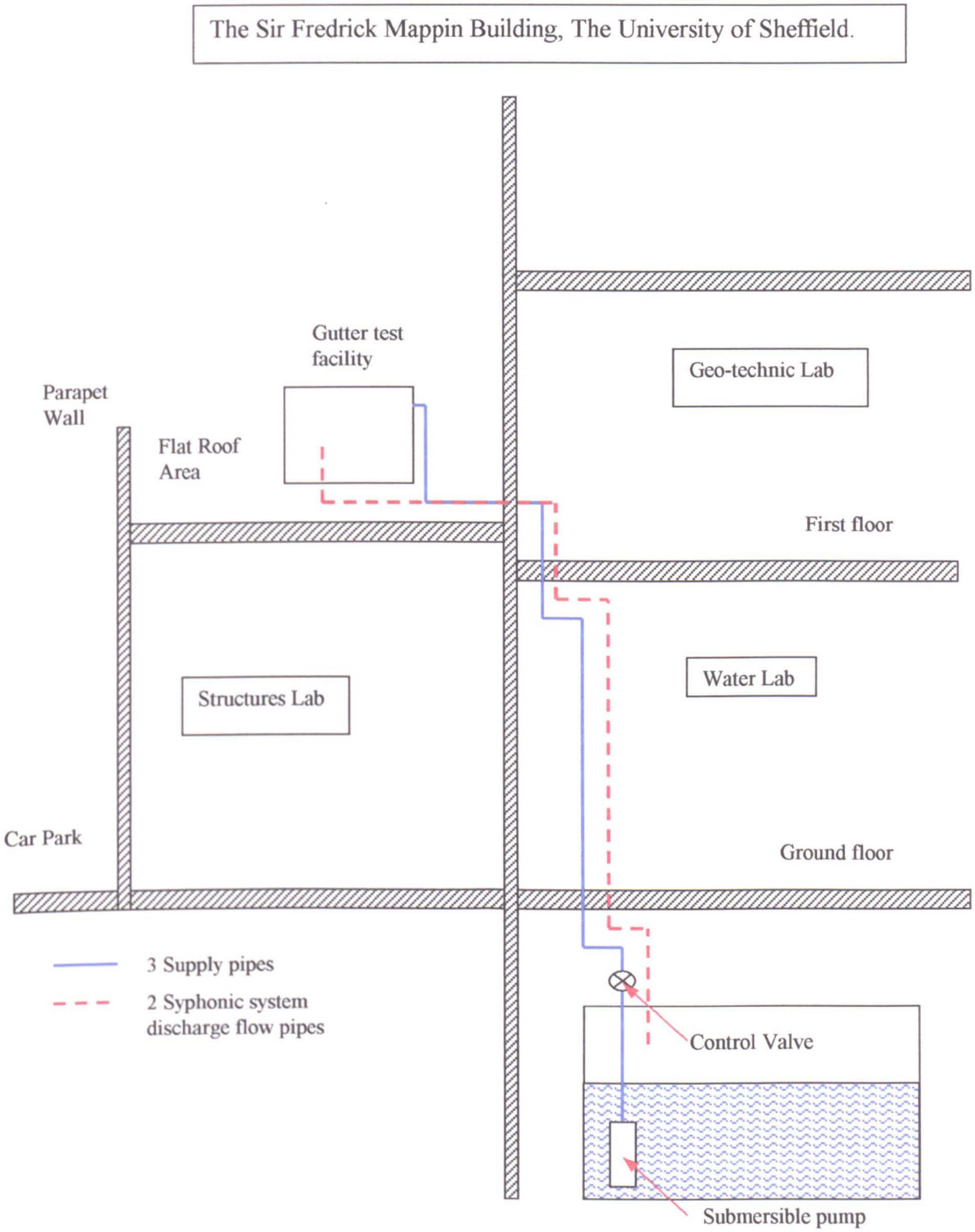


Figure 3.6 Schematic layout of test rig side view from outside the Sir Fredrick Mappin Building.

3.8 Calibration of the test facility

The control valves were operated via software developed by the University of Sheffield. The software allows for the input of hydrographs of any given flow rate and over any given periods of time. The valves could be operated independently of each other with respect to time and flow rates and were calibrated through the use of measuring tanks. The discharge from the syphonic system was temporarily redirected into the measuring tank. This allowed the measurement of flow to be recorded against valve gate position, measured as a percentage. Due to the mechanics of the valve, profiles were recorded for both opening and closing. An average value of flow was then calculated and inputted in to the control software. Profiles of each of the three valves may be seen in figure 3.7, 3.8 & 3.9.

Initially, the supply box to the rear of the rig formed a weir over which the water would flow on to the roof section of the rig. The levelling of the main framework, gutter, supply box and roof section had been achieved through the use of a Leica optical level to an accuracy of ± 2.0mm. Figure 3.10 highlights the slope of the gutter, which is within the 1:350 recommended by BS 6367:1983 (BSI 1983). As the gutter was considered nominally level (within the definition of BS 6367) it was assumed that this would be sufficient to allow water to flow into the gutter at a uniform depth. At low flow rates this was not the case therefore the weir section of the supply box required an alternative method of levelling. The solution was the installation of a knife edged weir (plate 3.6) along the total length of the supply box, situated at the top of the roof section. The weir was constructed in such a way as to be fully adjustable along its length and calibration took place using the minimum flow rate to ensure uniform flow over the edge.

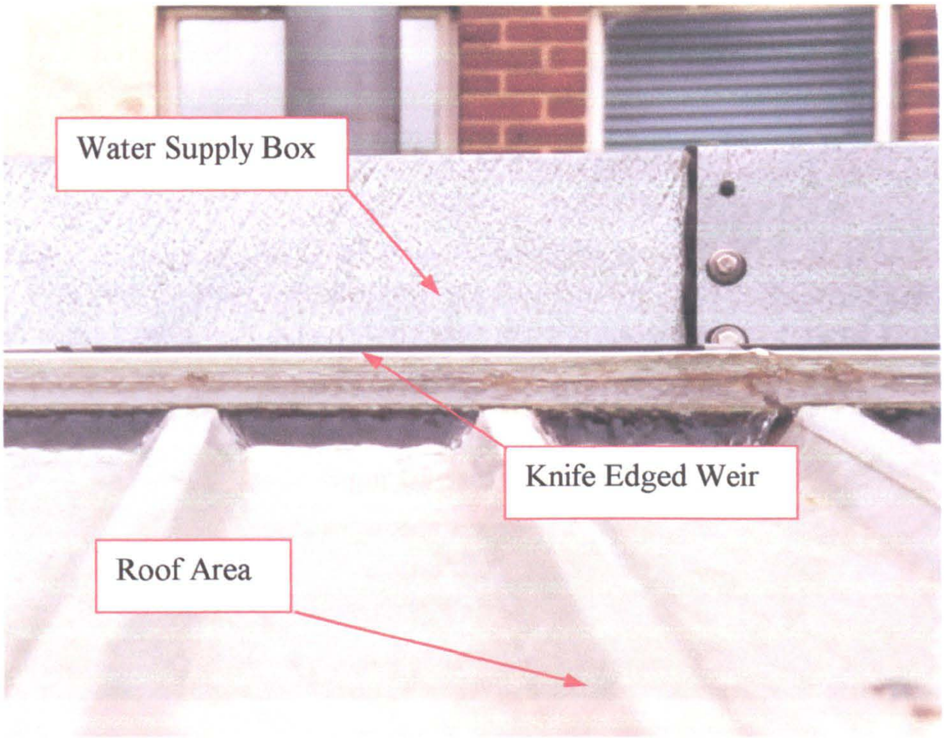


Plate 3.6 Knife edged weir along the water supply box

One final element, which ensured the accuracy of the recorded water depths within the gutter, was the installation of sight glasses. These were connected via a tube to the sole of the gutter at the rim of each outlet and mid-way between outlets (plate 3.7). Connected to the side of the gutter the hydrostatic pressure created by the depth of water in the gutter created a comparative depth in the sight glass. The sight glasses were fully adjustable and calibrated using a steel rule. This allowed for the measurement of both upstream and downstream water levels. Any water depths measurements that were required elsewhere within the gutter were taken using a rule.

Clearly, the depth measurements were subject to an error in measurement. Depths in the sight glasses were measured to an accuracy of ± 0.25 mm, whilst those taken with a rule were accurate to ± 0.5 mm. In order to minimise errors within the data, water depths were recorded at 4 positions, then repeated (See appendix 3 & 4).

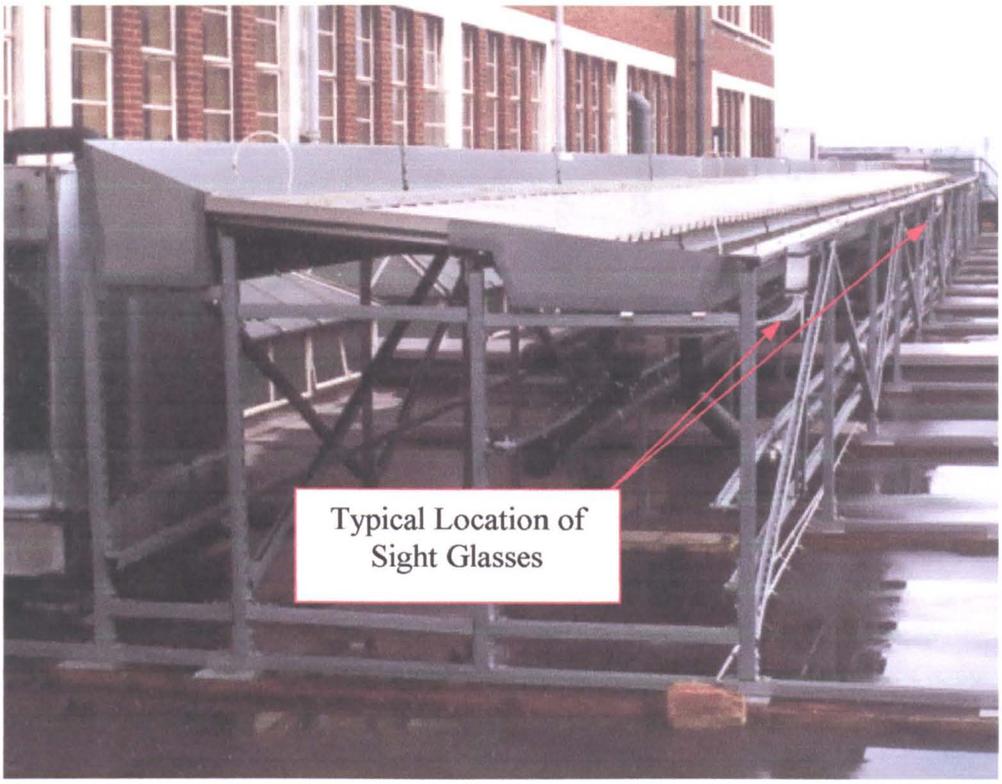


Plate 3.7 Locations of Sight Glasses

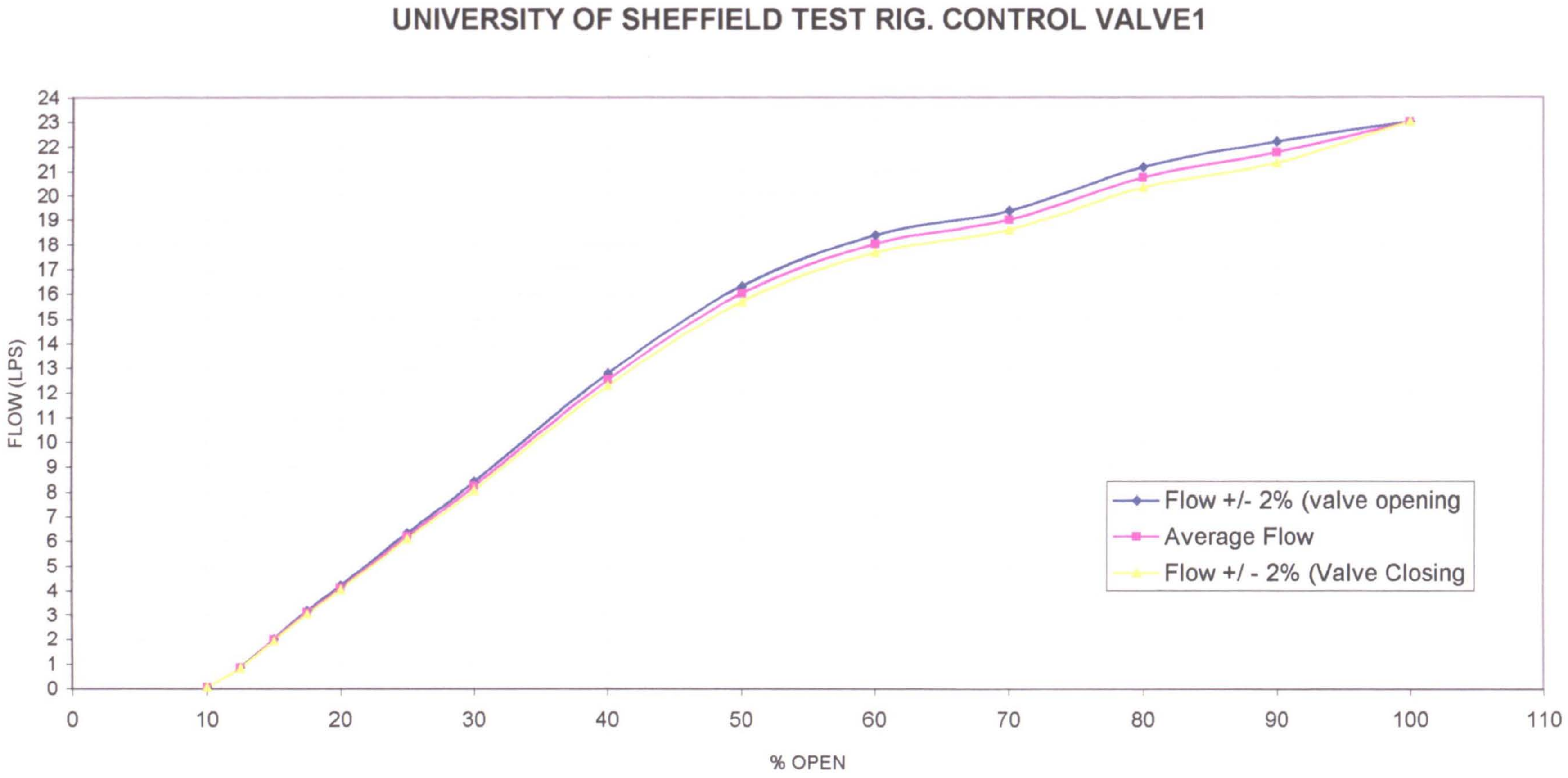


Figure 3.7: Calibration Data – Control Valve 1

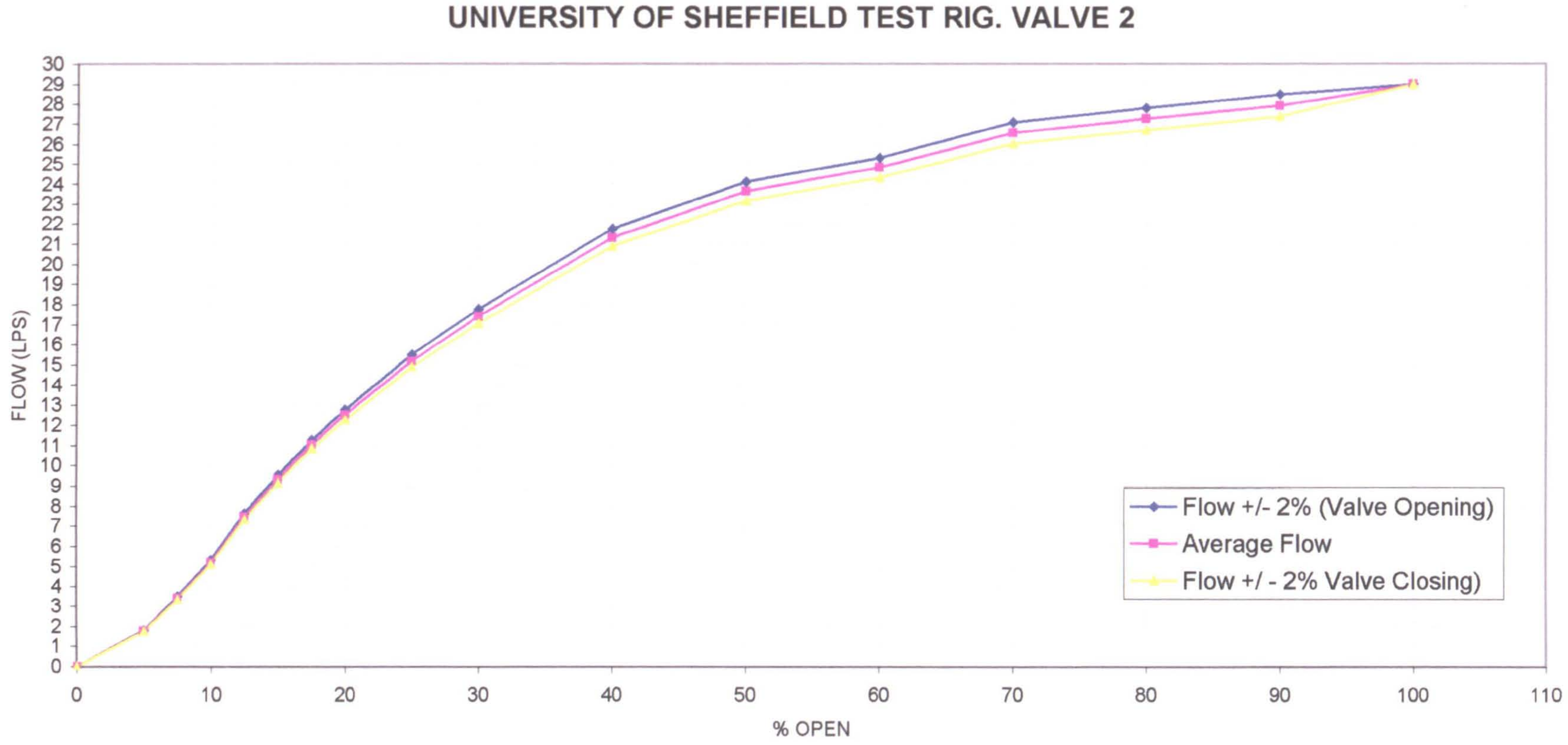


Figure 3.8: Calibration Data – Control Valve 2

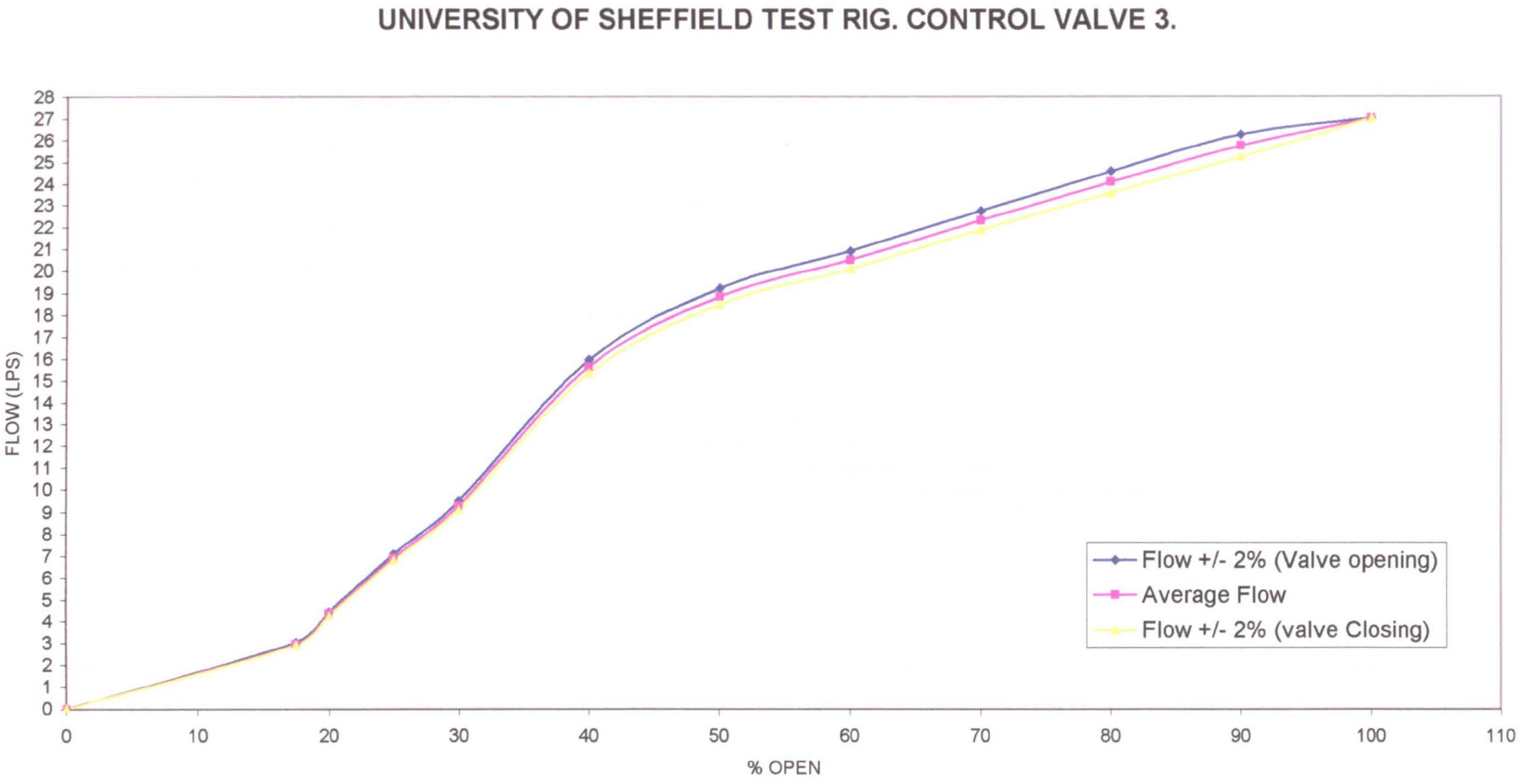
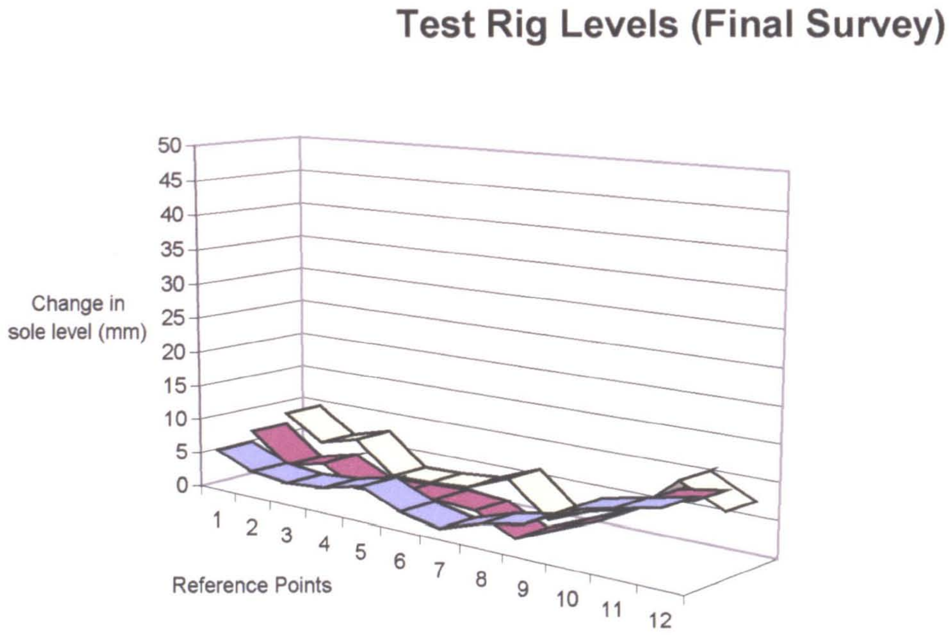


Figure 3.9: Calibration Data – Control Valve 3

Distance Between reference points = 2.9m.
Measurement taken at 3 location across the 600mm gutter sole, front, centre & rear.
All measurements are relative to the lowest point (valued 0, at point 8)



■ FRONT
■ CENTRE
□ REAR

	1	2	3	4	5	6	7	8	9	10	11	12
■ FRONT	5.9	3.8	3.2	3.7	5	2.7	1.6	3.5	4.6	7.8	9.1	10.3
■ CENTRE	7.5	3.5	4.8	2.3	2.7	3	2.6	0	2.5	4.9	8.8	9.8
□ REAR	9.1	5.6	7.1	2.7	2.9	3.4	5.7	1.1	3.5	4.9	9.9	7

Figure 3.10: Gutter Sole Levels

Chapter Four - Investigation into the interaction of primary and secondary syphonic rainwater outlets

4.1 Performance of syphonic roof outlets

A preliminary test procedure was devised in which the performance of the primary and secondary outlets within the gutter were initially independently determined. Additionally, measurements of the performance of the combined systems were undertaken. In order to obtain an objective and worthwhile understanding of the performance of syphonic rainwater outlets, two alternative commercially available outlets were tested. For the purposes of this thesis the outlets were identified as type A and type B. Schematic details of both outlets may be seen in figures 4.1 and 4.2.

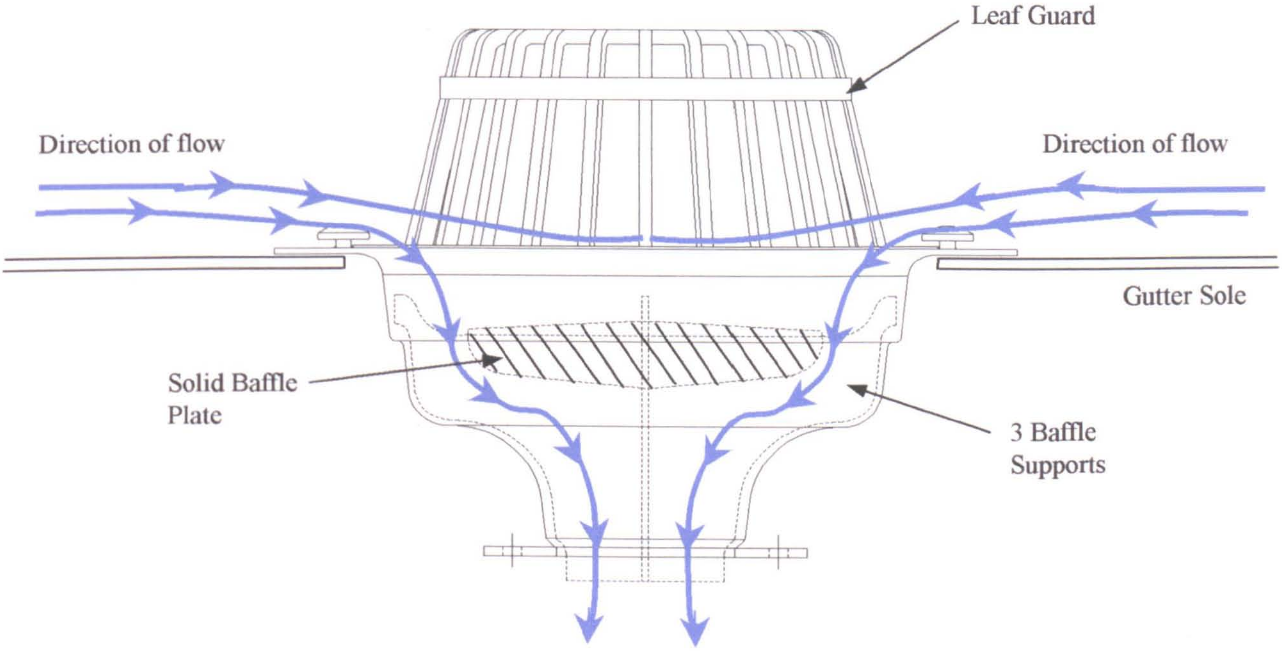


Figure 4.1: Type 'A' Outlet.

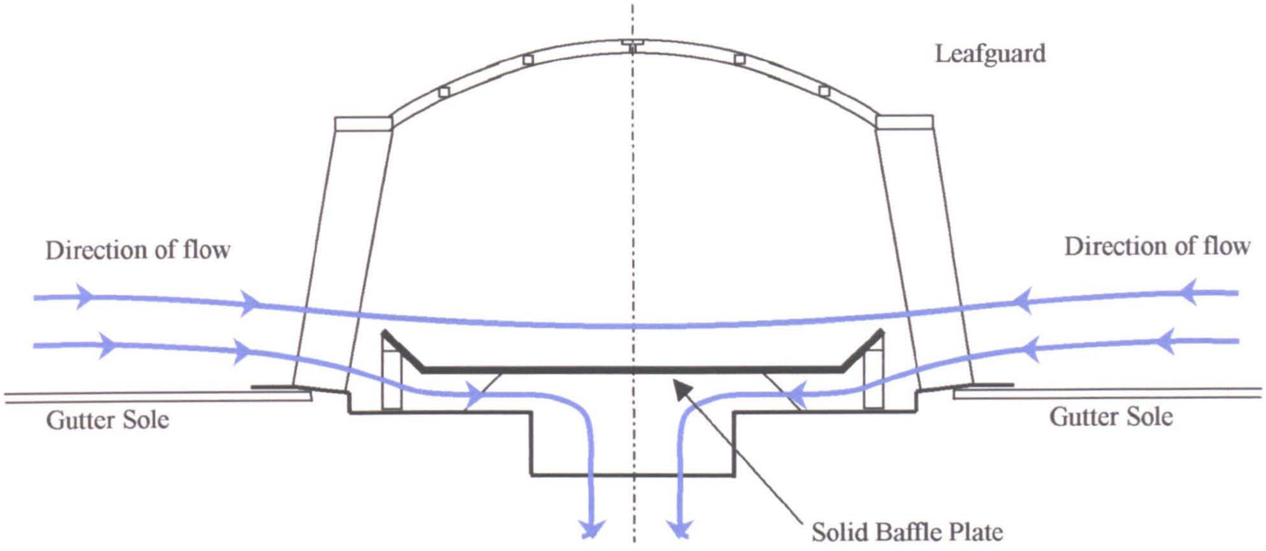


Figure 4.2 Type 'B' Outlet

4.2 Operation of a primary system

The primary system consisted of two syphonic rainwater equal spaced along the 35m length of the gutter. As highlighted within chapter 3 of this thesis, the flow entering the gutter did so over the entire 35m length of the gutter, via the 6° pitched roof section. The flow rate to the outlets was increased in small increments and depth measurements were taken at the positions detailed in figures 4.3a, 4.3b, 4.3c & 4.3d. These positions were chosen to ensure that the method of presenting recorded data was comparable to the method provided in the theoretical model outlined within BS 6367:1983. The secondary outlets (effectively a primary outlet with a 50mm upstand around the rim) located within the gutter were sealed off and therefore had no detrimental effect upon the performance of the primary system.

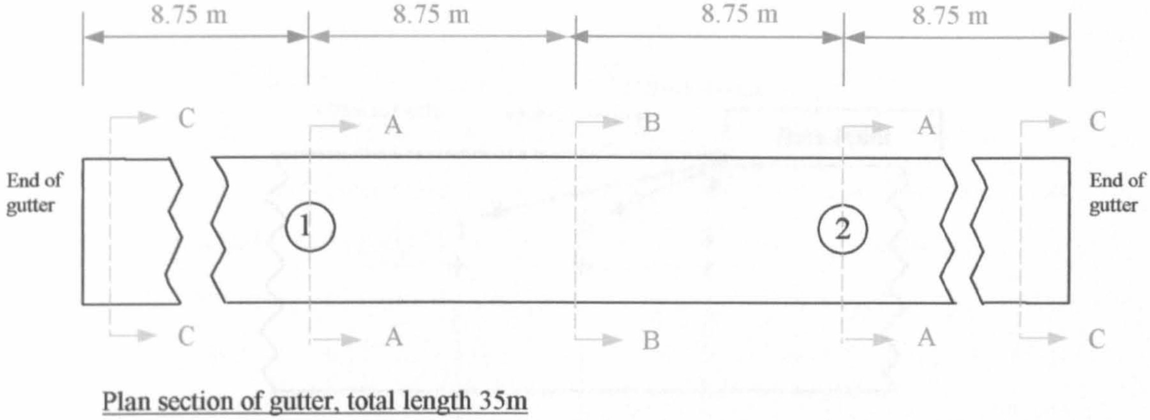


Figure 4.3a: Principal locations at which water depths within the gutter were measured during the operation of the primary system. (Identifying syphonic primary outlets 1 & 2)

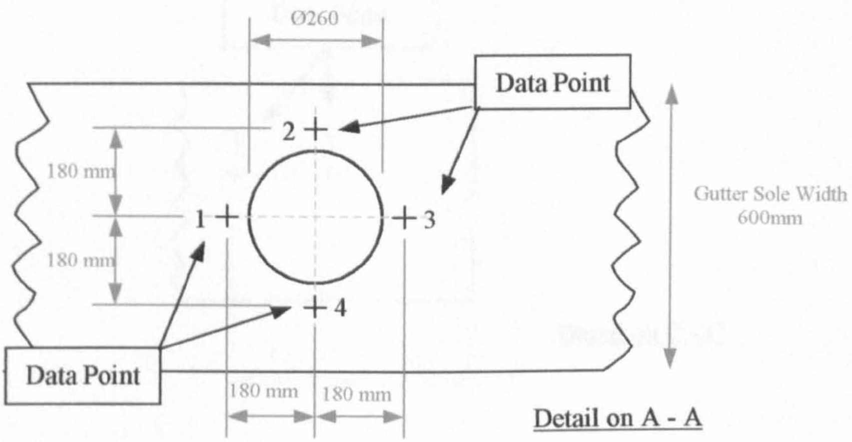


Figure 4.3b: Detail on A-A (figure 4.3a).
4 points around the proximity of a primary outlet at which water depths were measured.

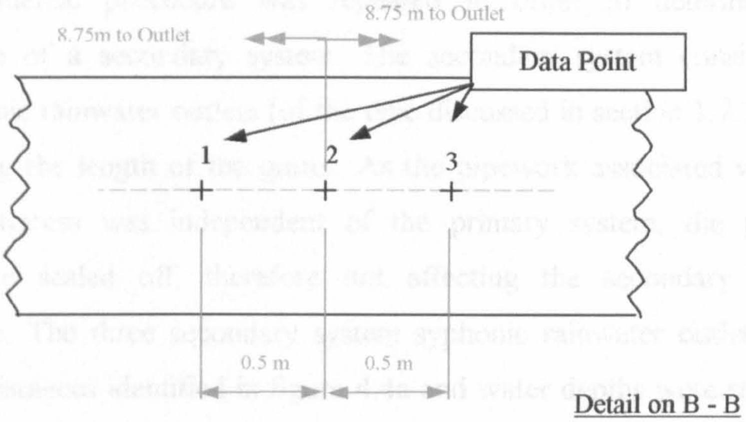


Figure 4.3c: Detail on B-B (figure 4.3a).
3 points mid-way between two primary outlets where water depths were measured.

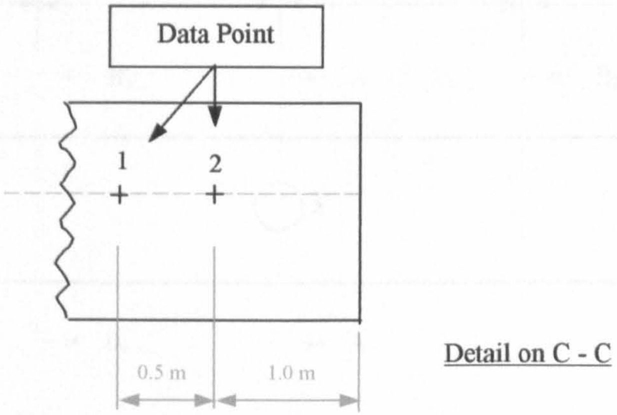


Figure 4.3d: Detail on C-C (figure 4.3a).
2 points at the gutter ends where water depths were measured.

As previously stated in chapter 3, the syphonic system pipework configuration was designed using commercially available software, based on Bernoulli's energy equation (see appendix 1)

4.3 Operation of a secondary system

The experimental procedure was repeated in order to determine the performance of a secondary system. The secondary system consisted of three syphonic rainwater outlets (of the type discussed in section 1.7.3) equi-spaced along the length of the gutter. As the pipework associated with the secondary system was independent of the primary system, the primary outlets were sealed off, therefore not affecting the secondary system performance. The three secondary system syphonic rainwater outlets were located at distances identified in figure 4.4a and water depths were recorded as indicated in 4.4b and 4.4c at the outlet rim and mid points between outlets.

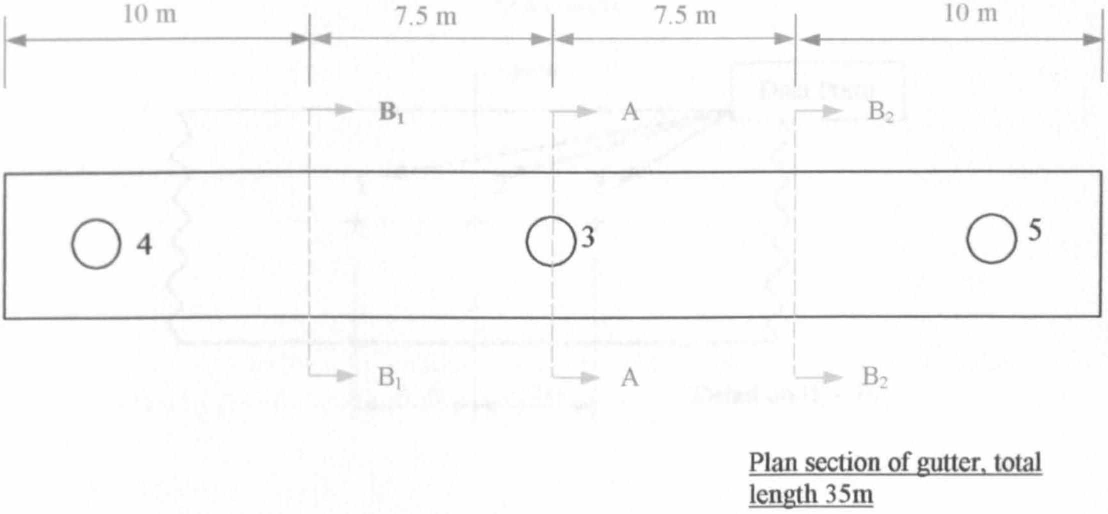


Figure 4.4a: Location at which water depths within the gutter were measured during the operation of the secondary system (identifying outlets 3, 4 & 5).

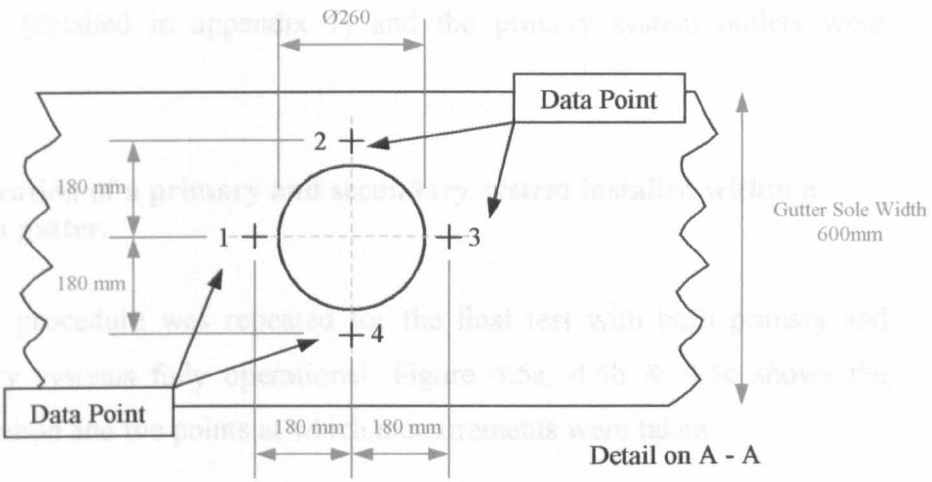


Figure 4.4b: Location at which water depths within the gutter were measured during the operation of the secondary system.

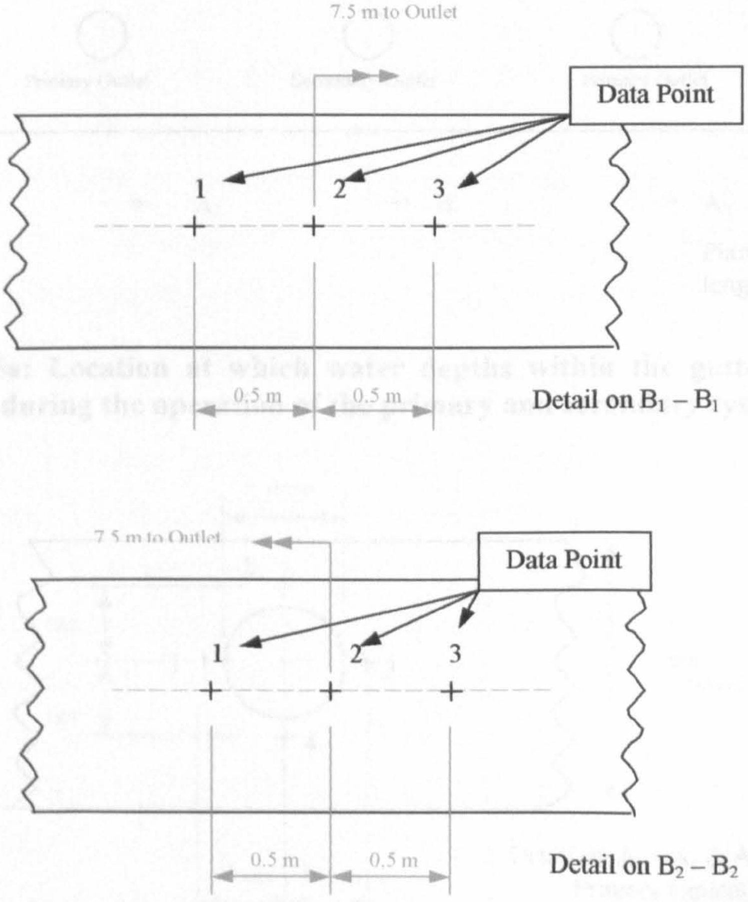


Figure 4.4c: Location at which water depths within the gutter were measured during the operation of the secondary system.

Once again the pipework was designed using commercially available design software (detailed in appendix 1) and the primary system outlets were sealed.

4.4 Operation of a primary and secondary system installed within a common gutter.

The test procedure was repeated for the final test with both primary and secondary systems fully operational. Figure 4.5a, 4.5b & 4.5c shows the configuration and the points at which measurements were taken.

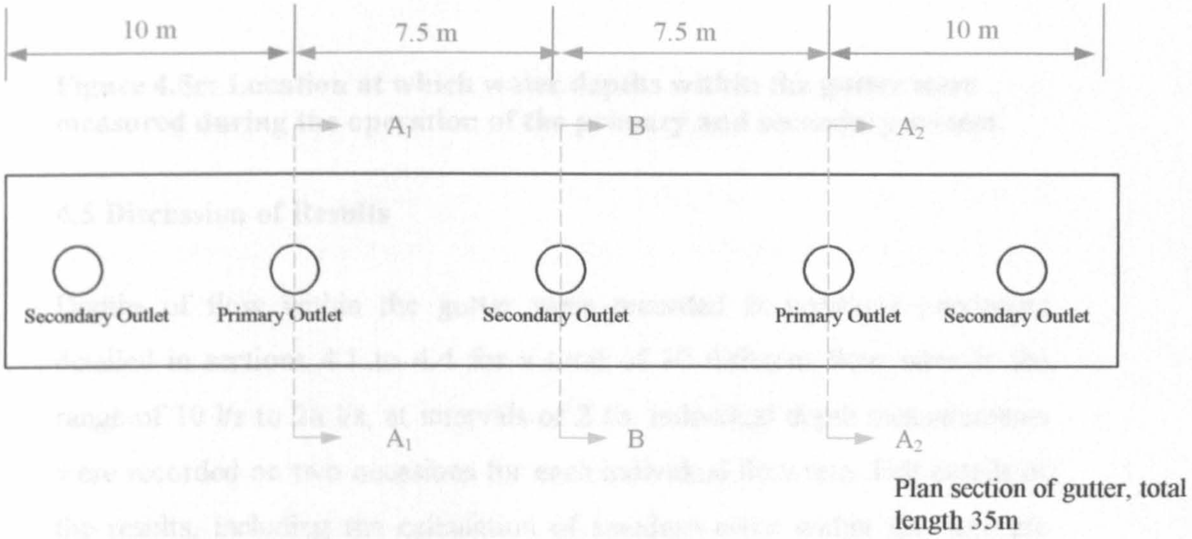


Figure 4.5a: Location at which water depths within the gutter were measured during the operation of the primary and secondary system.

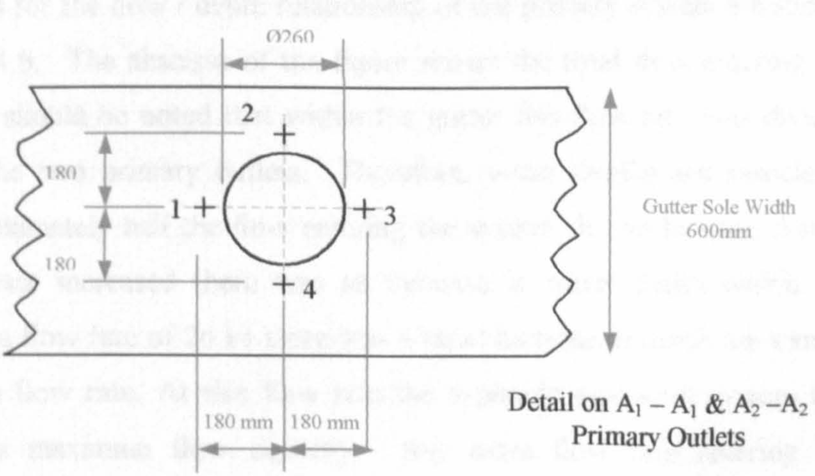


Figure 4.5b: Location at which water depths within the gutter were measured during the operation of the primary and secondary system.

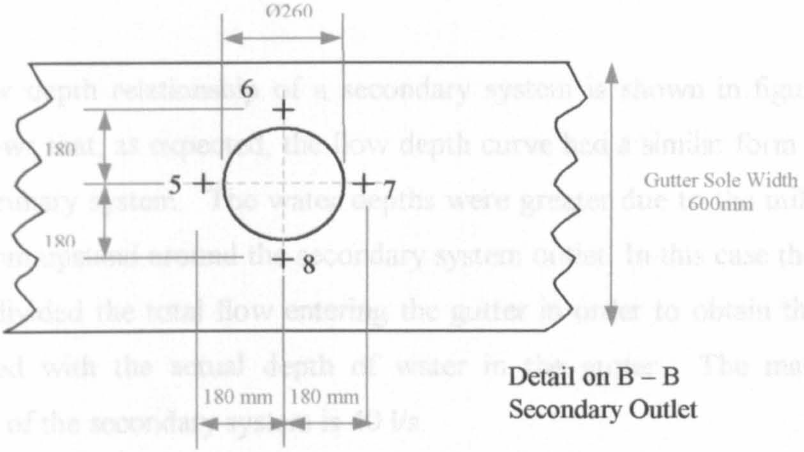


Figure 4.5c: Location at which water depths within the gutter were measured during the operation of the primary and secondary system.

4.5 Discussion of Results

Depths of flow within the gutter were recorded at positions previously detailed in sections 4.1 to 4.4 for a total of 10 different flow rates in the range of 10 l/s to 28 l/s, at intervals of 2 l/s. individual depth measurements were recorded on two occasions for each individual flow rate. Full details of the results, including the calculation of standard error within the data are presented in appendix 3, tables A3.1.1 to A3.3.2.

The results for the flow / depth relationship of the primary system are shown in figure. 4.6. The abscissa of the figure shows the total flow entering the gutter. It should be noted that within the gutter this flow rate was divided between the two primary outlets. Therefore, water depths are associated with approximately half the flow entering the system. It can be seen that as the flow rate increased there was an increase in water depth within the gutter. At a flow rate of 26 l/s there was a rapid increase in depth for a small increase in flow rate. At this flow rate the syphonic pipework system had reached its maximum flow capacity. Any extra flow rate entering the system above this value was taken up as an increase in flow depth within the gutter. Unlike a conventional roof drainage outlet, where the dimensions of the outlet and the working head determine capacity, it is the pipework and available head difference of a syphonic system that determines the flow capacity of syphonic outlets.

The flow depth relationship of a secondary system is shown in figure 4.7. This shows that, as expected, the flow depth curve had a similar form to that of the primary system. The water depths were greater due to the utilisation of a 50mm upstand around the secondary system outlet. In this case the three outlets divided the total flow entering the gutter in order to obtain the flow associated with the actual depth of water in the gutter. The maximum capacity of the secondary system is 40 l/s.

Measurements from the testing of the combined primary and secondary system are shown in figure 4.8. It may be seen from this figure that it is the performance of the secondary system that dictates the water depth within the gutter. Having established this, further investigations undertaken and reported on within this thesis concentrate on single systems. Results from the subsequent tests may be applied to a secondary system with an allowance made for the height of the upstand around the rim of the outlet. The flow, which enters the system, is now discharged through a total of 5 syphonic rainwater outlets. Figure 4.8 also highlights that at a flow rate of 26 l/s, i.e. when the primary system has reached its maximum capacity; the secondary system takes control of the water depth within the gutter.

4.6 Summary

When the maximum capacity of a syphonic rainwater system is reached there is a rapid increase in water depth within the gutter.

The depth / flow profile of a secondary system is comparable to that of the primary system with the addition of the upstand height,

When a primary and secondary system operate within the same gutter, at water depths below the secondary outlet upstand it is the primary system that dictates the flow profile within the gutter. However, once the levels of water have reached the upstand the secondary system becomes dominant. Therefore, where primary and secondary systems are installed within the same gutter it is vital that the water depths associated with the secondary system are considered and not neglected as a type of additional overflow.

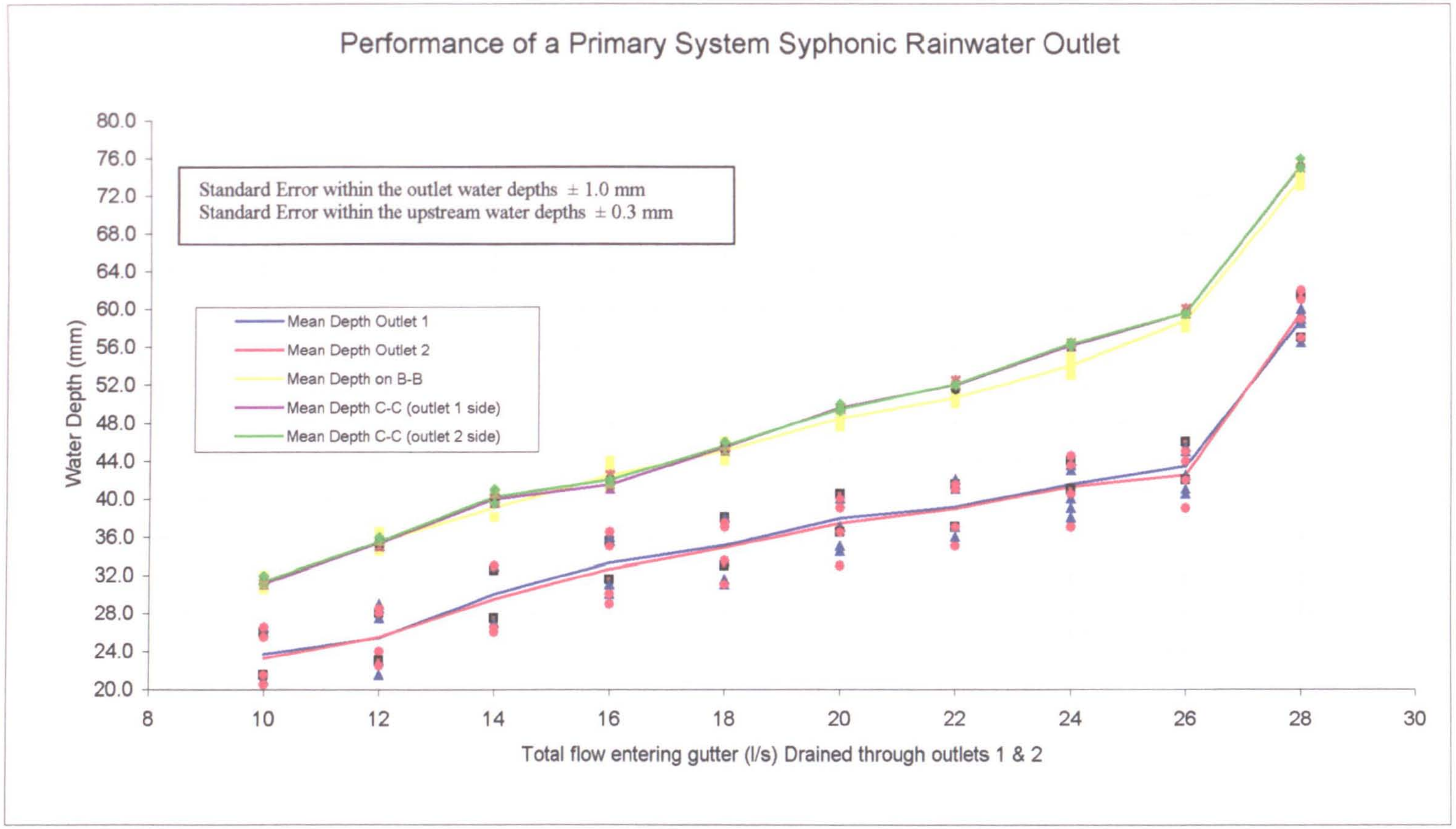
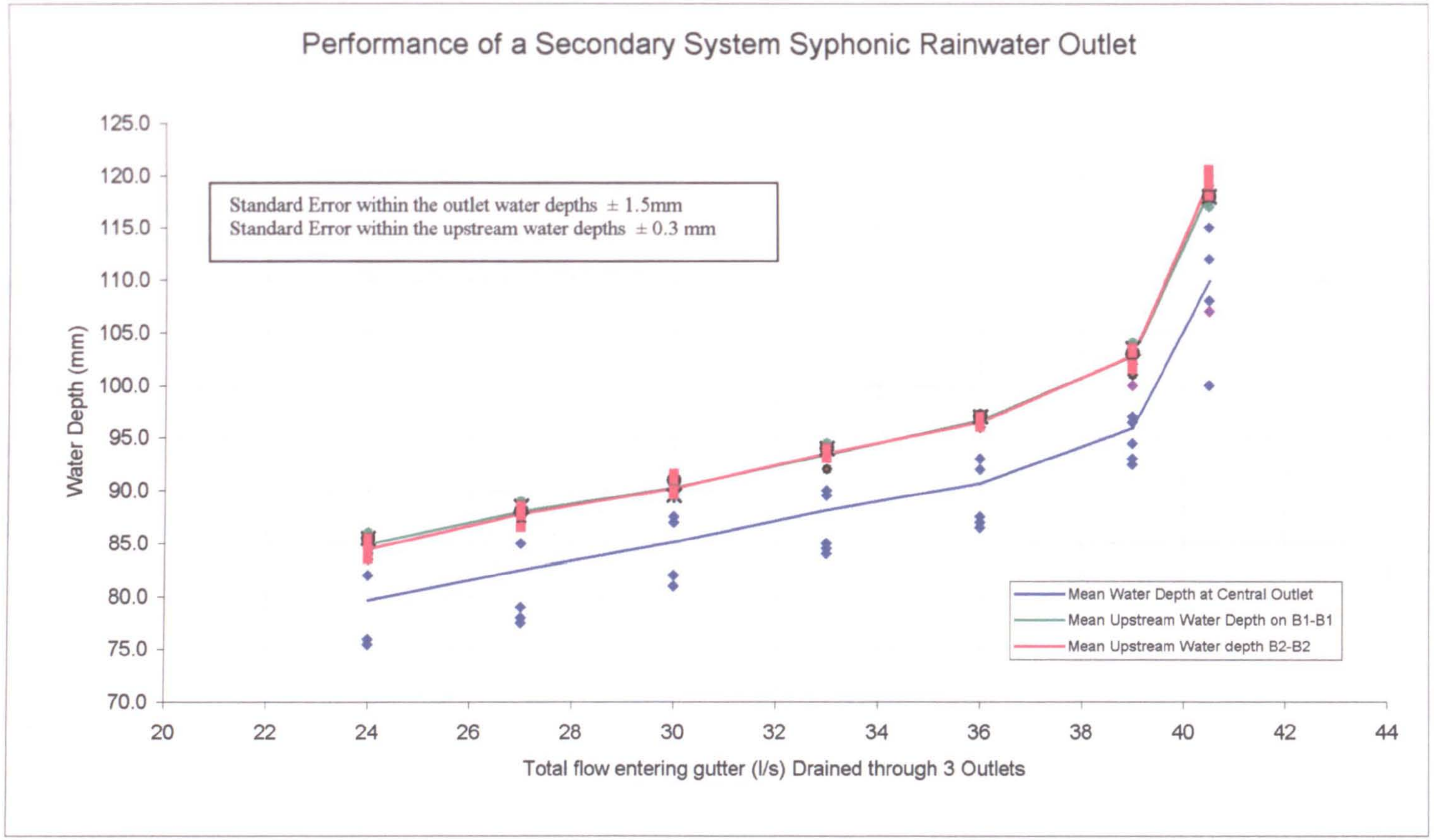


Figure 4.6: Record of water depths above a primary outlet of a syphonic system located within a gutter of 600mm sole

(Recorded data and the calculation of standard error are documented within Appendix 3: Tables A3.1.1 to A3.1.5)



Standard Error within the outlet water depths ± 1.5mm
Standard Error within the upstream water depths ± 0.3 mm

Figure 4.7: Record of water depths above a of a secondary outlet of a syphonic system with located within a gutter with a sole of 600mm
(Recorded data and the calculation of standard error are documented within Appendix 3: Tables A3.2.1 to A3.2.3)

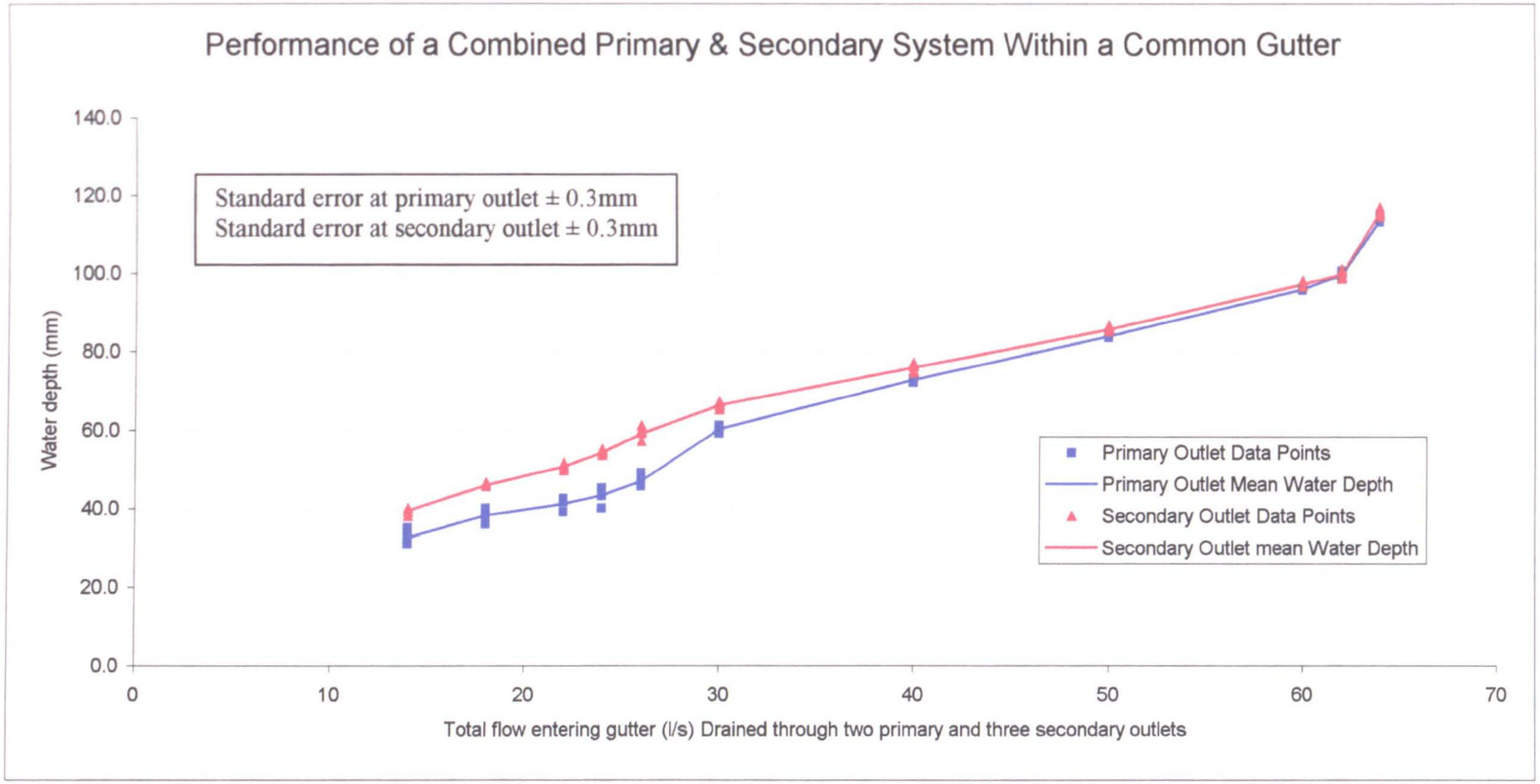


Figure 4.8: Record of water depths within a gutter installed with a primary and secondary syphonic system.
(Recorded data and the calculation of standard error are documented within Appendix 3: Table A3.3.1 & A3.3.2)

Chapter Five - Investigation into the validity of adopting current theoretical methodology for the design of syphonic roof drainage

5.1 Introduction

Throughout Europe, roof areas of industrial and commercial buildings are commonly drained using valley and eaves gutters. These are usually large in volume and have the capacity to discharge rainwater at high rates of flow. The definitive method for the design of gutters within the United Kingdom is BS6367: 1983 British Code of Practice for the Drainage of Roofs and Paved Areas. This publication clearly sets out the methodology to predict the hydraulic performance of a gutter. However, within the Code no design criteria for syphonic rainwater systems are outlined.

The location of rainwater outlets within a gutter determines the overall hydraulic performance of the system and the distance interval at which the outlets are placed has a significant influence on the flow depth within the gutter. In turn, this flow depth is a function of the head discharge relationship for the particular outlet. To reduce costs it is desirable to place rainwater outlets at ever increasing intervals; this obviously has a detrimental effect upon the upstream depth within the gutter. This practice maybe acceptable if the outlets are used in systems which drain a flat roof area or where a certain volume of storage is available. However, within a typical gutter, there is no allowable storage and consequently even a small rise in upstream depth could have catastrophic consequences for the building and its contents.

The objective of this study, in addition to the basic assessment of the hydraulic performance of a syphonic system with two outlets, was to examine the acceptability of utilising the existing theoretical design model of a conventional system to the design of a syphonic system. The theoretical model of conventional systems is based on Equations 5.1- 5.6. The relationship of these equations was derived through the work of May

(1982) who undertook investigations in to the design of gutters and gutter outlets. This investigation provided data upon which BS 6367:1983 was written. May (2004) revealed that within the standard there is a factor of safety, the value of which is dependent upon the type of flow within the gutter and around the outlet. More details regarding the factor of safety may be found in May (1982) and May (2003). Following the author's discussions with May during 1997 and in line with the recommendations of May, for the purpose of this investigation a factor of safety of 20% was adopted.

Within this investigation the theoretical values obtained from the application of the equations 5.1 – 5.6 are amended values that incorporate the factor of safety, these are compared with measured values using a syphonic system.

The terms of a Froude number (F_O) may be used in order to express the flow conditions at the downstream end of a gutter.

$$F_O = 1.01 \times 10^4 \left(\frac{B_o \times Q^2}{A_o^{\,3}} \right)^{0.5}$$

Ref: BSI 1983 & May 1986 (5.1)

Where: F_o = Froude number at an outlet

B_o = Surface width of flow at an outlet

Q = Rate of flow

A_o = Cross sectional area of flow at an outlet

The upstream depth of flow within a gutter, corresponding to the water depth at an outlet (Y_o), the surface width of flow at the outlet (B_o) and the sole width of a gutter (B_s), may be determined through the use of the dimensionless Froude number and the following equation:

$$Y_u = \left(1 + \left[0.4795 + \left(0.5205 \times \frac{B_s}{B_o}\right)\right] \times F^{1.4}\right) \times Y_o$$

Source: BSI 1983 & May 1986 (5.2)

Where: Y_u = Upstream depth of water

Bs = Sole width of gutter

B_o = Surface width of flow at an outlet

F = Froude number

Y_o = Depth of water at an outlet

If a gutter is long in relation to the depth of flow, resistance effects may cause the upstream depth Yu to be greater than in a short gutter. The percentage increase x, in the value of Yu can be calculated by utilising the following equations:

$$x = 0.186 \times \left[1 - \left(1 - F_o^{\,2}\right)^{6.7}\right] \times \left[\frac{L_g}{Y_d}\right]^{0.75}$$

Source: May 1986 (5.3)

Where:

x = Percentage increase in Y_u due to resistance effect of a gutter

L_g = Drainage length of gutter

Y_d = Flow depth at the downstream end of a gutter

$$Y_{uf} = Y_u \times \left(1 + \frac{x}{100}\right)$$

Where: (5.4)

Y_{uf} = Upstream depth of flow accounting for resistance

The flow through an outlet may be determined from application of either a weir flow equation or an orifice flow equation dependent upon the depth of flow within the gutter and the diameter of the outlet. The coefficients used within these formulae were determined through the experimental work of May (1982) and are reported on in the British Standard BS 6367:1983 (BSI 1983)

$$Q_w = \frac{D \times h^{1.5}}{7500} \quad \text{for } h \le D/2 \tag{5.5}$$

$$Q_o = \frac{D^2 \times h^{0.5}}{15000} \quad \text{for } h > D/2 \tag{5.6}$$

Source: BSI 1983 & May 1982

Where:

Q_w = Weir flow

D = Effective diameter

h = head of water above the outlet

Q_o = Orifice flow

5.2 Experimental methodology.

Previous studies (BRS 1958, May 1982) had shown, when a conventional outlet is located at the end of a gutter the outlet became less efficient than when placed in such a way that equal flow could approach the outlet from either side. Therefore, it was an aim of the author to conduct a series of tests which compared the effect upon the efficiency of two syphonic rainwater outlets located within a gutter, when the outlets were positioned:

A) Equi-spaced along the length of the gutter

B) When placed at the extreme ends of the gutter.

Using the data recorded from this experiment and which is reported on in tables 5.1 to 5.4 and detailed further in appendix 5, the validity of adopting conventional theoretical models for the purpose of designing syphonic rainwater systems would be assessed and design recommendations provided.

Figures 5.1 and 5.2 show the schematic outlet arrangement for each case.

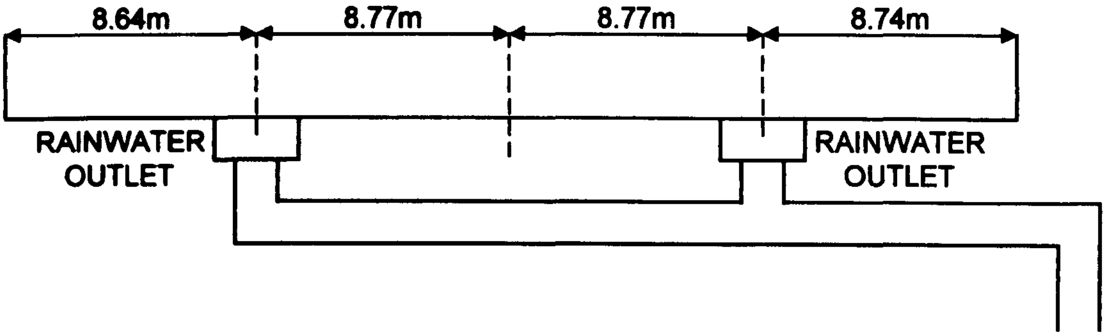


Figure 5.1 Outlets spaced equidistant along the length of the gutter

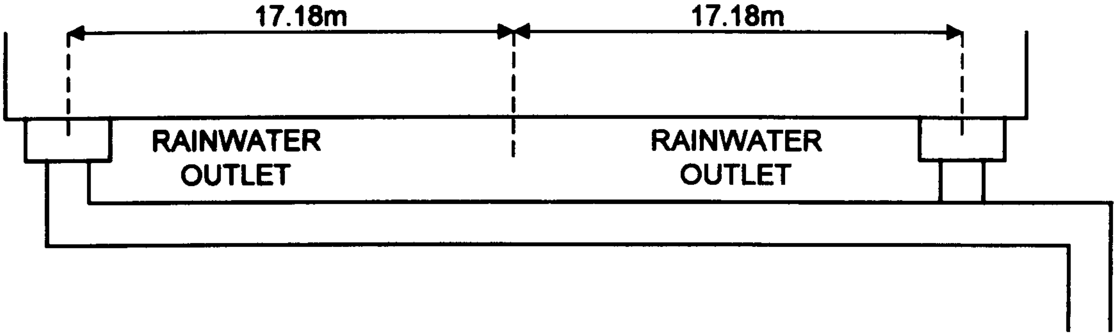


Figure 5.2 outlets located at extreme ends of a gutter

The pipe diameters were almost identical for both experiments, with a slight variance in horizontal length of the pipe in method B. The extra pipe that drained the upstream outlet had no vertical component therefore did not significantly add to the driving head of the system. As a result the flow capacity for each system was comparable. A number of steady state flows were introduced into the gutter. Water depths were recorded using sight glasses (previously detailed in section 3.8) connected to the gutter sole and located at both the outlet rim and mid way between the outlets i.e. the upstream point of greatest depth, determined through measurement of the water depths in an array of positions.. Outlets of type A and B (previously shown in figures 4.1 and 4.2) were tested in order to provide a commercial balance to the results.

5.3 Results of tests

Figure 5.3 highlights the division of flow between two outlets within the gutter when the outlets are equi-spaced along the gutter sole length.

Table 5.1 shows the results of the tests when the syphonic rainwater outlets were equi-spaced along the gutter sole. Equations 5.1 – 5.4 were used to calculate the upstream depth highlighted in tables 5.1 and 5.2. The data provided by these tables is detailed further in appendix 4, tables A4.2.1 to

A4.3.3 where the standard error within the data is quantified. Additionally, figures A4.2.1 and A4.3.1 provide a graphical representation of the data.

For continuity throughout this element of the investigation, the assumption is made that at all flow rates (other than the maximum capacity of the system), the flow entering the gutter is divided equally between the number of outlets installed within the gutter. This hypothesis is based upon the knowledge that all aspects of the test facility i.e. outlet position, gutter profile and flow entering the gutter are uniform.

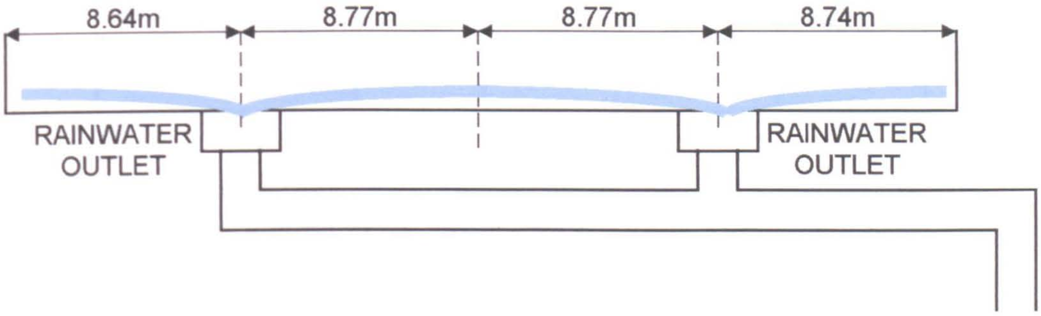


Figure 5.3 Highlighting division profile of flow between equi-spaced outlets

Flow through an outlet (l/s)	Measured depth at outlet rim (mm)		Measured depth upstream (mm)		Calculated upstream depth (BS6367) (mm) (Eq^n 5.1 – 5.4)		%age difference measured against calculated upstream depth
	Type A	Type B	Type A	Type B	Type A	Type B	
7.5	37	37	43	44	42.55	42.58	17
9	40	41	46	48	46.00	47.15	15
10	41	43	48	50	47.15	51.17	15
11	44	47	51	51	50.60	53.11	15
12	45	50	53	54	53.55	56.50	15

Table 5.1: Measured and calculated water depths (outlets equi-spaced). Standard error ± 0.5mm at an outlet and ± 0.4mm upstream
(Appendix A4, tables A4.2.1 to A4.3.3 identify the standard error within the data presented in this table. Standard deviation is defined in appendix 3)
Standard deviation is defined in appendix A3

Figure 5.4 shows the division of flow between outlets located at the extreme ends of the gutter with a summary of the results of the experiment shown in table 5.2, which corresponds to the outlets located at the extremes of the gutter. Further details, including the calculation of the standard error within the data may be found in appendix A4.4, tables A4.4.1 to A4.5.3, figures A4.4.1 and A4.5.1.

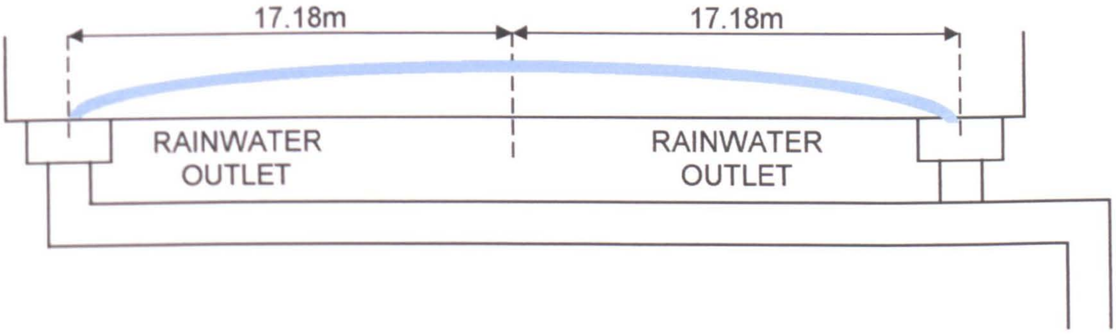


Figure 5.4: Highlighting division profile of flow between outlets at extreme ends of the gutter

Flow through an outlet (l/s)	Measured depth at outlet rim (mm)		Measured depth upstream (mm)		Calculated upstream depth (BS6367) (mm) (Eq^n 5.1 – 5.4)		%age difference measured against calculated Upstream depth
	Type A	Type B	Type A	Type B	Type A	Type B	
7.5	43	42	63	62	62.53	61.83	16
9	50	48	72	70	71.80	69.24	18
10	55	50	77	74	78.10	71.80	17
11	60	58	82	80	81.43	79.02	17
12	65	62	86	85	87.42	83.93	17

Table 5.2: Measured and calculated water depths (outlets located at the extreme ends of the gutter) Standard error ± 0.4mm
(Appendix A4.4, tables A4.4.1 to A4.5.3 identify the standard error within the data presented in this table)

In addition to the monitoring of flow depth, the pressure was recorded at each flow rate within the syphonic system pipes, through the use of a Bourdon tube pressure gauge, manufactured by Wika, reading −1.0 bar to +1.5 bar full scale, with an accuracy of ±0.01 bar. This data, highlighted in Tables 5.3 and 5.4, was recorded in order that an examination could be made to establish whether the syphonic action within the pipework produced a 'pull down' effect on the water around the outlet rim. The measured water depths were compared with the actual flow through the outlet with that estimated by equation 5.5 and 5.6.

Measured water depth at outlet rim (mm)		M'sured flow rate (l/s)	Calculated flow rate (l/s)				Negative pressure within the pipework (bar)	
Type A	Type B		Weir flow equation Eq^n 5.5		Orifice flow equation Eq^n 5.6			
			Type A D = 258mm	Type B D = 215mm	Type A D = 258mm	Type B D = 215mm	Type A	Type B
37	37	7.5	6.16	5.16	21.6	15.00	0.03	0.03
40	41	9	6.96	6.02	22.48	15.78	0.04	0.04
41	43	10	7.22	6.46	22.72	16.17	0.05	0.05
44	47	11	8.03	7.39	23.52	16.90	0.05	0.05
45	50	12	8.30	8.11	23.84	17.44	0.06	0.06

Table 5.3: Flow rates through equally spaced outlets, standard error ± 0.5mm
(Appendix A4, tables A4.2.1 & A4.3.1 identify the standard error within the data presented in this table)

Measured water depth at outlet rim (mm)		Measured flow rate (l/s)	Calculated flow rate (l/s)				Negative pressure within the pipework (bar)	
			Weir flow equation Eq^n 5.5		Orifice flow equation Eq^n 5.6			
Type A	Type B		Type A D= 258mm	Type B D= 215mm	Type A D= 258mm	Type B D= 215mm	Type A	Type B
43	42	7.5	7.68	6.24	23.28	15.97	0.03	0.03
50	48	9	9.73	7.62	25.12	17.08	0.04	0.04
55	50	10	11.22	8.10	26.32	17.43	0.05	0.05
60	58	11	12.78	10.13	27.52	18.77	0.05	0.05
65	62	12	14.42	11.20	28.64	19.41	0.06	0.06

Table 5.4: Flow rates through outlets placed at each end of the gutter standard error ± 0.4mm
(Appendix A4.4, tables A4.4.1 & A4.5.1 identify the standard error within the data presented in this table)

5.4 Discussion of Results

5.4.1 Upstream water depths

It can be seen from the data outlined in table 5.1 and verified within appendix A4, that when type A outlets are equally spaced and subjected to a flow of 11 l/s, there is a requirement for a 44mm head of water above the outlet rim. For the same flow rate type B outlet required a head of water of 47mm. In both cases the measured upstream depth was 51mm. This compares to a upstream depth calculated through the use of the theoretical model of 43.59mm (type A) and 44.65mm (type B). Table 5.2 shows that when located at the extreme ends of a gutter and subjected to a flow rate of 11 l/s, type A outlets required a water depth of 60mm at the rim, whilst type B outlet required 58mm at the rim. The upstream depth was recorded as 82mm and 80mm respectively. For comparison the calculated upstream depths of 68.4mm and 68.7mm are shown in the columns headed 'calculated upstream depth' of table 5.2.

These results (detailed in tables 5.1 & 5.2) highlight that there is a difference between the recorded values and the calculated values of 16.5% ±1.5%. This difference suggests that either an increased estimate of the flow depth is required when a syphonic system is used in conjunction with the model or that the constants used in the equations do not take full account of all the parameters e.g. the sole width of the gutter.

5.4.2 Outlet Capacity

When the outlets were equally spaced along the length of the gutter this series of experiments has shown that there is an approximation of the flow rate through the outlet and that calculated using the weir flow equation, but only at low flow rates (table 5.3). For example, type A outlet had a measured flow rate of 9 l/s with a theoretical prediction of 6.97 l/s. When subjected to the same measured flow of 9 l/s, outlet type B had a predicted flow of 6.02 l/s. As flow rates increased the theoretical prediction became less accurate as shown by comparison of the measured flow of 12 l/s compared with the calculated flow rates of 8.30 l/s for type A outlet and 8.11 l/s for type B. Additionally, table 5.3 shows that the use of the orifice equation (eq^n 5.6) is inaccurate when applied to syphonic rainwater outlet.

As the flow rate through the system increases there is a reduction of pressure within the pipework. Examination of the data within tables 5.3 and 5.4 comparing the decrease in pressure with an increase in flow, could suggest that the influence of the syphonic action created within the pipework may also influence the water depths around the rim of an outlet. The greater the flow rate through the outlet the more inaccurate the application of the weir equation becomes. This may also be an indication that the hypothesis of the influence of negative pressure may be justified Additionally, the investigation has shown the orifice flow equation is inappropriate for the estimation of flow through a syphonic rainwater outlet.

5.5 Findings

The findings of the investigation detailed within this chapter and recorded in appendix A4 question the validity of using the theoretical model given in BS 6367:1983, in order to determine the depth of water around a syphonic rainwater outlet for a given flow rate. It may also be hypothesised that the variation between the recorded data and the prediction of the theoretical model may be due to the influence of negative pressures in the pipework, which increase the suction force at the entry to the pipework. The recorded negative pressures, and a comparison between the measured and calculated flow rates are shown in Tables 5.3 and 5.4 for each series of experiments. The effect of the negative pressure may be subsequently transmitted to the region of gutter flow in the vicinity of the outlet. Further investigations were undertaken in order to examine this hypothesis and are discussed in chapter 7.

With regard to the location of the rainwater outlets along a gutter length, comparison of results shown in table 5.3 with those in table 5.4 identify that when an outlet is placed at the extreme ends of a gutter, and receives flow from only one direction, the capacity of the outlet is reduced for an equivalent head of water around the outlet rim. This is due to the effective weir diameter of the outlet being reduced as a result of the outlets' position. As a result of the position of the outlets there is a requirement for a much greater water depth around the outlet rim. In this particular series of experiments the outlets that were placed at the extremes of the gutter (figure 5.4), were found to be 65% -77% less efficient than those equally spaced along the gutter sole (figure 5.3). This is consistent with the findings of the building research station (BRS 1958). Who highlighted that 'when a conventional rainwater outlet is placed centrally in the length of a gutter, the gutter capacity required would be one half of that needed for an end outlet'. It should be noted that the outlets' position only affected the water depths within the gutter. There was no detrimental effect upon the overall system performance due to the outlet's position. However, it is argued that the water depth is a critical parameter, particularly in valley gutters, and hence due regard of this increased flow depth should be taken into account by the design engineers.

5.6 Summary

Initial inspection of the results suggested that there is a discrepancy between the theoretical upstream water depths obtained from the BSI model and water depths recorded from experiments.

As tables 5.3 and A4.2.1 to A4.3.2 indicate, when syphonic rainwater outlets are equally spaced along the sole of a gutter the conventional theoretical model becomes less accurate as the flow through an outlet increases.

The theoretical orifice flow equation was not applicable to syphonic rainwater outlets as the predicted flow rates were in excess of the recorded rates of flow.

Negative pressures within the pipework of a syphonic system may influence the rate of flow through an outlet; further work is required in order to assess the degree of the influence.

Comparison of the data for the calculated upstream depth and measured upstream depth for outlets equispaced along the gutter length, against the same measurements for outlets located at the extreme ends of a gutter (see tables 5.1 and 5.2), show that when outlets are placed at the ends of a gutter they are 65% - 77% less effective than those equally spaced along the gutter sole. However, the position of an outlet has no detrimental effect upon the performance of the syphonic system, providing all the design parameters (May 2004 & detailed within appendix 1) of the pipework system are met.

Chapter Six - Investigation into the prediction of water depths around syphonic rainwater outlets when installed within gutters

6.1 Experimental methodology

The results of previous work presented in table 6.1, carried out by May and Escarameia (1996), showed that for a given flow rate, the recorded depths of water above a syphonic rainwater outlet were significantly greater within a gutter than those depths above an identical outlet located within a flat roof, for an equivalent flow rate. For example, at a flow rate of 11 l/s the depth of water required around the rim of a type B outlet is 55mm when located within a gutter. At an equivalent rate of flow the same outlet requires a water depth of 36mm around the rim when located in a flat roof. In these experiments a gutter test rig with a sole width of 350 mm was utilised, along with syphonic outlets located within a simulated flat roof. This increase in water depth is due to the effect the gutter wall has on restricting flow to outlet.

It may be maintained that this work forms the two extremes in which rainwater outlets are most likely to be situated. i.e. the narrowest gutter sole, restricting flow into an outlet and a flat roof leading to complete radial flow around an outlet.

	Water depth (mm) above a Syphonic Outlet Within a gutter (350mm sole) (May 1996)		Water depth (mm) above a Syphonic Outlet Within a Flat Roof (Escarameia & May 1996)	
Flow (l/s)	Type A Outlet	Type B Outlet	Type A Outlet	Type B Outlet
7.5	40	42	28	28
9	45	49	31	30
10	47	50	34	34
11	50	55	36	36
12	54	57	37	39
12.5	56	61	38	39.5

Table 6.1: A comparison of water depths around identical outlets located within a gutter and a flat roof, highlighting significant differences in measured water depths for given rates of flow.

6.2 Outlets equi-spaced within a gutter

Unlike conventional drainage systems, it is the pipework of a syphonic system that dictates the flow capacity of the system, not the dimensions of the rainwater outlet. Within a syphonic system correctly sized pipe work and available working height of the downpipe, may in some cases allow an outlet, of a given diameter, to accept a maximum flow rate of no more than 4l/s. Conversely, the same outlet connected to a different pipe configuration (larger diameters and greater working head), may accept flow rates as high as 30 l/s, however, the depth of water around the rim of an outlet would rise accordingly.

It was hypothesised by the author that there may be a linear relationship between the depths of water around an outlet placed in a flat roof and an outlet placed in a small gutter. Consequently, it should be possible to interpolate this data to determine theoretical values for the head of water required above an outlet at any given flow rate in a gutter of any sole width.

Table 6.1 highlights results from previous investigations (May and Escarameia 1996), who examined the performance of syphonic rainwater outlets in the two extreme scenarios i.e. the smallest gutter sole of 350mm and a flat roof. To test the hypothesis that the prediction of water depths around an outlet located within gutters of any sole width, linear interpolation was applied to the results presented by May and Escaramia (1996) as shown in table 6.1, to establish the performance of a 600mm gutter width, corresponding to that tested by the author. The results of this interpolation are shown in figure 6.1

Figure 6.1 highlights the theoretical water depths for a type A outlet, whilst figure 6.2 shows the same interpolation for a type B outlet.

For example, using figure 6.1, at a flow rate of 10 l/s the depth of water above the rim of a type A outlet, when installed in a 600mm wide gutter is be 42mm. The corresponding depth in a gutter with a 400mm sole width is approximately 47mm for the same flow rate of 10 l/s. By examination of figure 6.2, the results of the linear interpolation for the type B outlet are the same, 42mm in a 600mm sole gutter and 47mm in a gutter with a sole width of 400mm at a flow rate of 10 l/s.

Hence figures 6.1 and 6.2 clearly demonstrate the effect that a reduction in the gutter sole width has on results in an increase in the flow depth at both type A and type B outlets for any given flow.

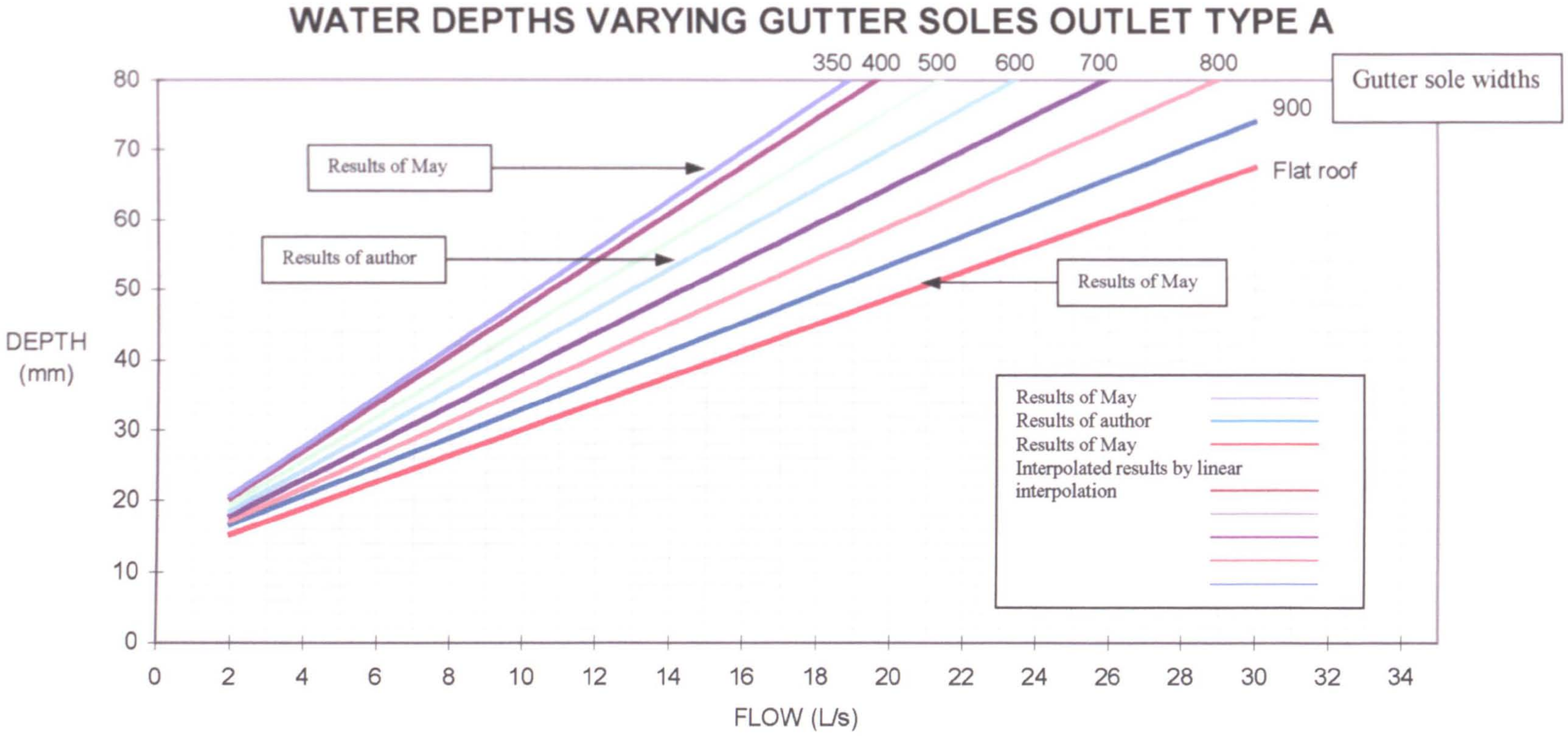


Figure 6.1 The Effect on Flow Depth Within Gutters of Varying Width (Type A outlet)
(Interpolated by the Author from data provided in May 1996)

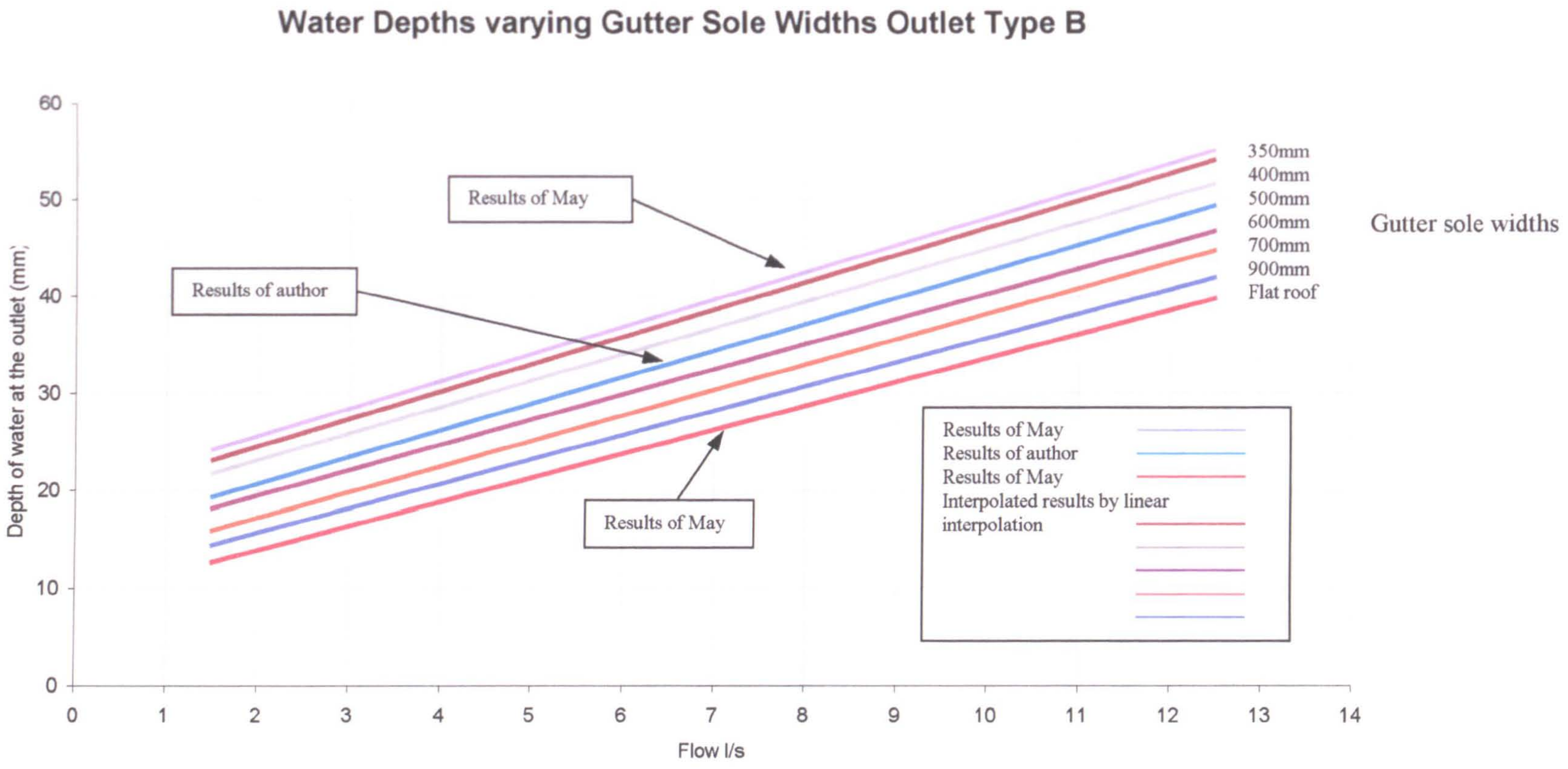


Figure 6.2 The Effect on Flow Depth Within Gutters of Varying Width (Type B outlet)
(Interpolated by the Author from data provided in May 1996)

6.3 Investigation into the validity of adopting the method of interpolating data highlighted in figures 6.1 & 6.2

To confirm the validity of the hypothesis the author carried out a series of tests using syphonic rainwater outlets spaced equi-distant along the length of the experimental system as shown in figure 6.3. This was considered as the position in which the outlets would achieve the optimum flow condition for a minimum head of water i.e. equal flow from two directions. In addition to the gutter sole width, the only difference between the system tested by May and Escarameia (1996) and the system within the current investigation was that the Sheffield rig had a trapezoidal gutter, whereas the Wallingford rig had a gutter with vertical walls.

Test 1

Water depth measurements were recorded at each outlet and the results are presented in Table 6.2. For comparison this table also includes the values derived from the linear interpolation of the results after may and Escaramia (1996), taken from figures 6.1 and 6.2 for a gutter with a 600 mm sole width.

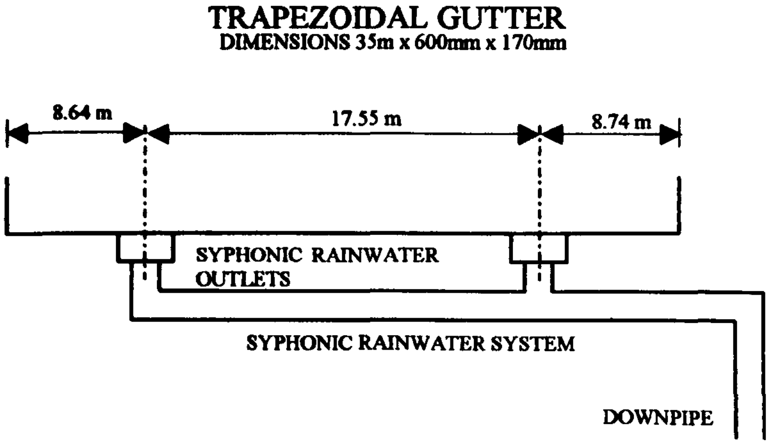


Figure 6.3 Schematic configuration of experimental system during test 1

Flow rate l/s	Type A Outlet			Type B Outlet		
	Test 1:University of Sheffield. Depth above an outlet (mm)	Interpolated data: (May 1996) Depth above an outlet (mm)	%age difference	Test 1:University of Sheffield. Depth above an outlet (mm)	Interpolated data: (May 1996) Depth above an outlet (mm)	%age difference
7.5	37	34	8.0	37	36	2.7
9	40	39	2.5	41	40	2.5
10	41	42	2.4	43	43	0
11	44	45	2.2	47	45	4.2
12	45	47	4.0	50	48	4.0

Percentage difference recorded as difference in measured and interpolated divided by measured results x 100

Table 6.2: Comparison of experimental and interpolated data

(Standard error within the recorded data ± 0.5mm, see appendix 5, tables A5.1 & A5.2)

Table 6.2 shows that good agreement was observed between the values of the recorded water depths and interpolation from the data provided by May 1996 with the average difference of 3.25% and a maximum difference of 8%. This investigation utilised a trapezoidal gutter detailed in chapter 3, whilst May conducted his investigation within 350mm square gutter. This may have resulted in the small percentage difference record in table 6.2. Figure 6.4 shows the distribution of the recorded water depths for type A and type B outlets, compared with the values interpolated by the author from the data reported on by May 1996. Figure 6.4 also highlights good agreement between the values of water depth recorded by the author and the values interpolated from Mays investigation.

This area of investigation has established that the closer the proximity of the gutter wall to the outlet, a greater head of water is required for a given rate of flow. As a result it may be concluded that as the gutter sole narrows the effective diameter of the outlet reduces. The next stage of the study was to transfer this knowledge to the effects a gutter stop end may have upon an outlets flow capacity.

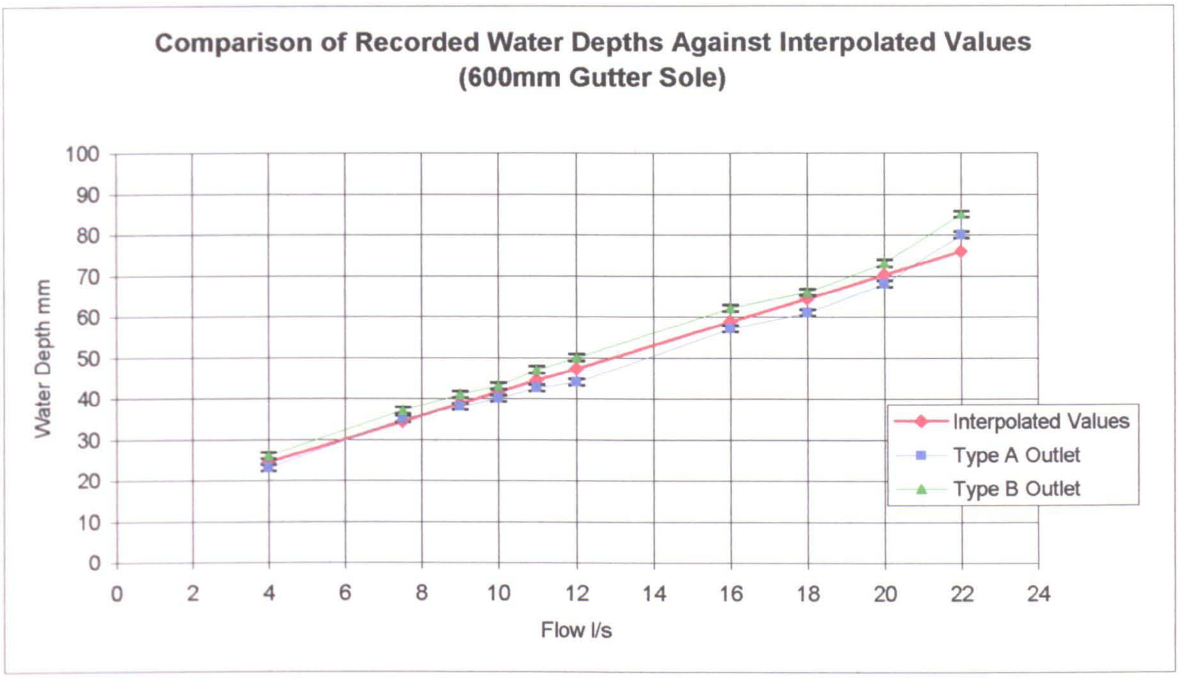


Figure 6.4 Comparison of recorded water depths against values interpolated from the data obtained by May (1996) in flat roof and gutter investigations.

6.4 Outlets at the end of the gutter (Test 2)

In order to assess the effect the gutter ends would have on the performance of the outlets they were positioned within the experimental system as shown in figure 6.5 and the tests undertaken in the first part of the study were repeated. Water depth measurements were again recorded at each outlet.

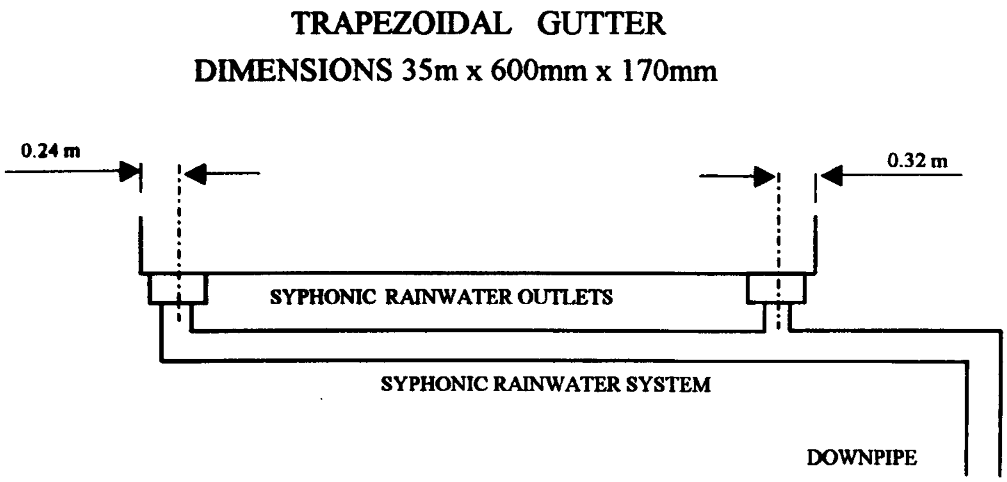


Figure 6.5
Schematic configuration of experimental system during test 2

The author hypothesised the following: assume that when the total flow through an outlet approaches from two directions (figure 6.6) that the optimum position of the outlet is equi-spaced along the length of the gutter. This is identified as point O in figure 6.8. If D is the distance from the outlet at O to the point at the gutter end or the mid point between outlets accepting equal flows then 0.25D, 0.5D and 0.75D describe points that are 25% of D, 50% of D and 75% of D from the gutter outlet. When an outlet is placed at the extreme end of a gutter with the total flow through the outlet approaching from one direction, the outlet is at its least efficient position (figure 6.7) and in this case is at a distance D from point O.

Using this terminology it is possible to define a term that relates the position of an outlet from the point O. This has been termed the distance ratio R_D Hence, for example, $R_D = 0.25$ at 0.25D

Therefore, applying the hypothetical linear relationship as determined in section 6.3, it would be possible to determine the efficiency of an outlet at any position between O (optimum) and D (least efficient). This is indicated in figure 6.8

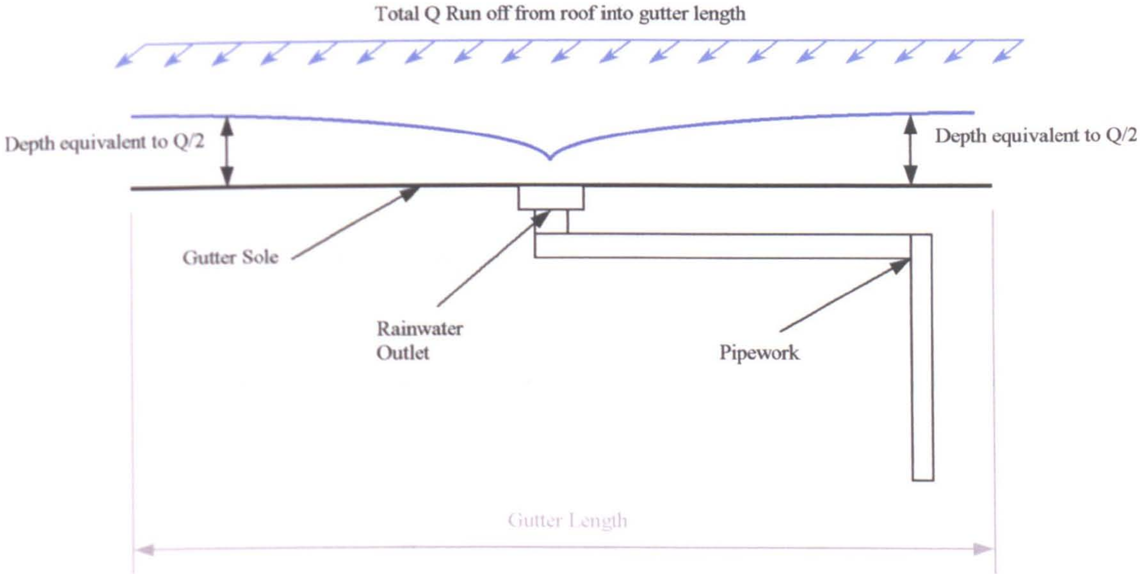


Figure 6.6 Optimum position (O) of a rainwater outlet within a gutter

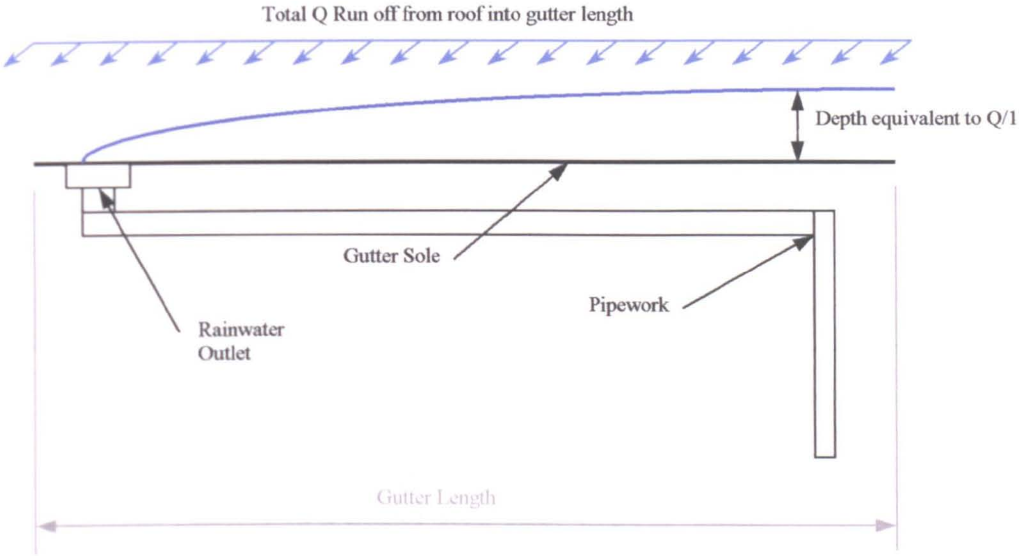


Figure 6.7 Least efficient position (D) of a rainwater outlet within a gutter

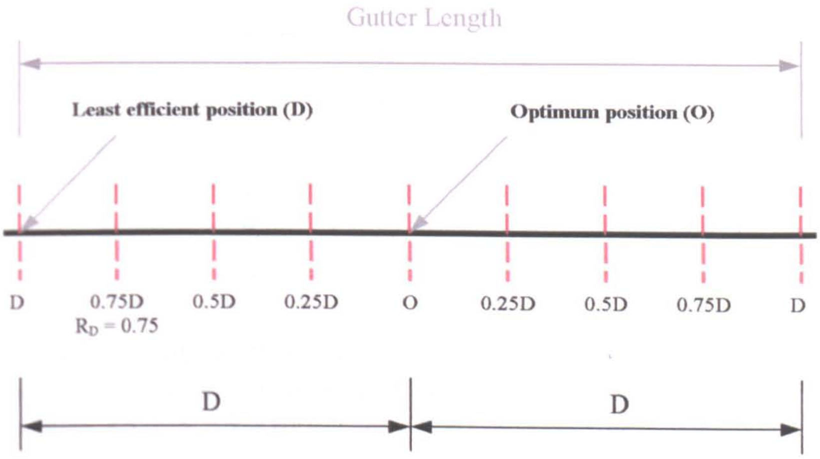


Figure 6.8 Values of the distance of outlets relative to the optimum position within a gutter

Theoretical water levels based on the linear assumption for outlets positioned at 0.25D, 0.5D and 0.75D were interpolated again using linear interpolation, and are shown in table 6.3 for outlet type A and table 6.4 for the type B outlet.

Flow (l/s)	Optimum flow (test 1) Depth above outlet at O	Gutter end (test 2) Depth above outlet at D	Interpolated values of water depth above an outlet		
			0.25D	0.5D	0.75D
7.5	37	43	37	39	41
9	40	50	41	44	47
10	41	55	43.75	47.5	51.25
11	44	60	46.89	51.25	55.62
12	45	65	49.25	54.5	59.75

Table 6.3 Recorded and theoretical values of water depth at varying outlet positions relative to a gutter stop end. Type A outlet
Appendix 5, tables A5.1 & A5.3 detail the standard error of 0.5mm for outlets in the optimum position and 0.4mm for outlets located at the end of a gutter within this table

Flow (l/s)	Optimum flow (test 1) Depth above outlet at O	Gutter end (test 2) Depth above outlet at D	Interpolated values of water depth above an outlet		
			0.25D	0.5D	0.75D
7.5	37	42	38.25	39.5	40.75
9	41	48	42.75	44.5	46.25
10	43	50	44.75	46.5	48.25
11	47	58	49.75	52.5	55.25
12	50	62	53	56	59

Table 6.4 Recorded and theoretical values of water depth at varying outlet positions relative to a gutter stop end. Type B outlet
Appendix 5 tables A5.2 & A5.4 detail the standard error of 0.5mm for outlets in the optimum position and 0.4mm for outlets located at the end of a gutter within this table

From table 6.4 at a flow rate of 10 l/s the recorded depth of water required above an outlet located in such a way that the flow approaches equally from 2 directions (O) is 43mm. When the same outlet is repositioned to the end of the gutter (D) a recorded head of 58mm is required for the same flow rate of 10 l/s. Interpolating between these two measurements provides theoretical values of 49.75mm at 0.25D, 52.5 mm at 0.5D and 55.5 mm at 0.75D.

To confirm this hypothesis and the linear relationship a final series of experiments were undertaken in order to verify the theroretical values derived in tables 6.3 and 6.4. As may be seen in figure 6.9 the rainwater outlets were located at the mid point of the previous experiments (ie 0.5D). Water depths were recorded at the outlets (test 3). Comparisons of the recorded depths and the theoretical values are shown in table 6.5

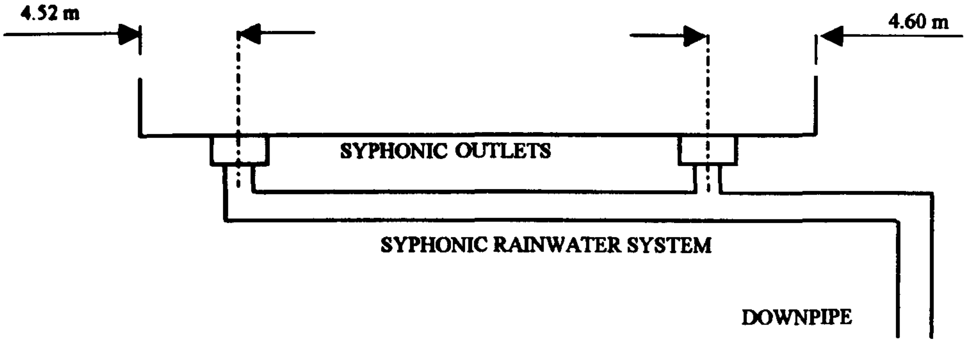


Figure 6.9
Schematic configuration of experimental system during test 3

Flow (l/s)	Recorded data (depth above an outlet mm) (0.5D)		Interpolated data (depth above an outlet mm)	
	Type A	Type B	Type A	Type B
7.5	39	39	39	39.5
9	45	46	44	44.5
10	49	49	47.5	47
11	55	56	51.25	53
12	58	69	54.5	65

Table 6.5: Comparison of recorded and interpolated values

Appendix, tables A5.5 & A5.6 detail the standard error of 0.5mm within this table

At a flow rate of 10 l/s the recorded depth of water above an outlet was 49 mm for type A outlet, this compared closely to the theortical prediction of 47.5mm. Clearly at the higher flow rates there is some discrepancy between the actual depth and that obtained by Interpolation. As good agreement i.e. a perentage difference of 3.25% between the measured and the linearly interpolated results, it was decided that no other forms of interpolation i.e. non-linear interpolation were necessary.

Examination of the data recorded in previous tests (May 1996) and the current series of tests, undertaken by the author, has shown that there is a restriction to the flow through an outlet due to the proximity of the gutter walls. Figures 6.1 and 6.2 clearly highlight that this close proximity increased the water depth required around an outlet for a given flow rate. Therefore, users of the current design standards should understand that an outlets position within a gutter signifcantly effects the water profile along the gutter length and needs to be addressed when using the theoretical model described in the British Standard BS 6367.

As an aid to determining the restricting effect a gutter places upon the flow rate of an outlet, a chart has been derived for a flow rate of 12 l/s and is shown in figure 6.10. The flow rate of 12 l/s was chosen as this is typical of the design values of flow adopted by syphonic system designers when installing outlets in commercial and industrial buildings.The data used in this chart is a function of flow rate and is one of a family that has been recorded throughout this series of experiments. Data has been interpolated and shown as a percentage increase in water depth above an outlet for a given flow rate, in various gutter sole widths. The chart identifies how the head of water above an outlet increases as the gutter sole width decreases. In addition, there is an obvious inrease in water depth due to the outlets proximity to the gutter end. Within the chart the optimum position for an outlet is shown as O, whilst D indicates an outlet located at the gutter end.

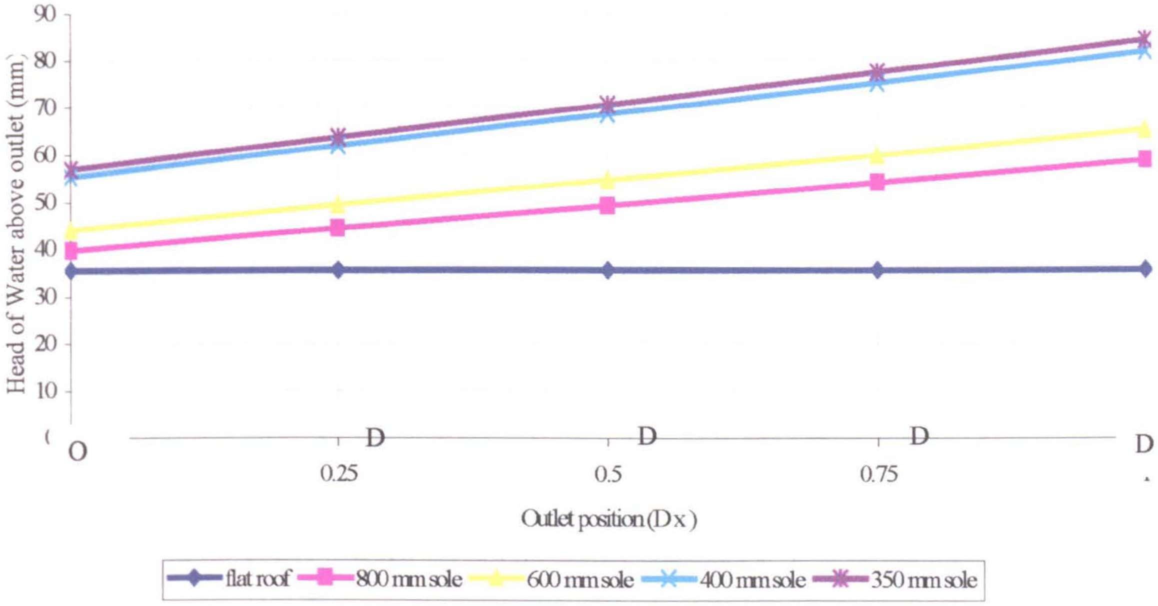


Figure 6.10 : Increase in head above an outlet due to its position within a gutter for a given flow rate of 12 l/s.

This chart may therefore be used to establish the actual depth in a gutter due to the position of the outlet relative to the gutter end. Theoretical upstream depths are a close approximation of the recorded upstream depths. As already discussed in chapter 5, page 82, included within the theortical model there is a factor of safety of 20% (May 2004). Therefore, if the syphonic systems were to conform precisly to the theoretical model, one would expect the recorded depth to be less than the values provided by calculation. However, testing undertaken by the author and reported on in chapter 5, shows that the actual measured depths are almost equal to the depths that are calculated using the theoretical model after May (1982). Hence it is clear that most of the factor of safety of 20% in the theoretical model is taken up such that there is only a small factor of safety. Therefore, it is recommended that the factor of safety in the theoretical model should be increased. The results of the author, presented in tables 5.1 and 5.2, highlight that the average difference between measured depths and theortical depths was 16.8% and hence it is recommended that to ensure a 20% factor of safety in the theortical model, that the factor of safety should be increased from 20% to 36%.

From analysis of the data recorded within figure 6.10 an equation has been derived from which the water depth above an outlet may be determined with consideration given to the position of an outlet within a gutter. The linear relationship between the head of water with the outlet at the optimum position (placed equi-spaced from the two ends of the gutter) and the outlet placed at the end of the gutter, has been used to develop an equation in the form of

$$D_{wp} = A \times R_D + D_f \qquad (6.0)$$

Where: D_{wp} = Depth of flow around an outlet accounting for gutter sole width and position

R_D = Distance ratio

D_f = Depth of flow at an outlets optimum position

A = Constant

It should be noted that, as the analysis and results described within this investigation are based upon dimensionless ratio values, the methodology developed by the author is directly transferable to any design of syphonic rainwater outlet, irrespective of diameter. From the data presented in table A5.4 the constant in equation 6.0 becomes 23.38 and hence becomes:

$$D_{sp} = 23.38 \times R_D + D_f \qquad (6.1)$$

Where: D_{sp} = Depth of flow around an outlet accounting for gutter sole width and position

R_D = Distance ratio

D_f = Depth of flow at an outlets optimum position

A procedure and worked example have been defined and are now discussed.

6.5 Procedure for the calculation of the depth of water above a syphonic rainwater outlet relative to its position within a gutter.

a. Through testing a manufacturer shall determine the depth / flow relationship for an outlet placed in a small width gutter and on a flat roof (A method of testing outlets may be found within the natioanl annex of BS EN 12056-3:2000).
b. Interpolate between the values obtained in (a) to determine depth / flow relationship for the required gutter sole width.
c. Alternatively, using figure 6.1 determine the depth of water above an outlet for a given flow rate within a gutter of sole of required width.
d. Determine the distance ratio R_D of the outlet, based on the location of the outlet from point of an equi-spaced outlet (optimum position see figure 6.6)
e. Using equation 6.1, determine the required depth of water above an, outlet for a given flow rate, with consideration for the outlets position within a gutter D_{sp}
f. The value of the water depth above an outlet, with respect to its position within a gutter (D_{sp}) may now be used within the theoretical

model detailed in BS 6367:1983. With the requirement for an additional safety factor of 16% discussed in chapter 5

6.6 Worked example

The problem

A syphonic rainwater outlet accepts a flow rate of 10 l/s and architectural constraints dictate that the outlet has to be located 1.5m from the end of a 12m trapezoidal gutter with a sole of 800mm sole and internal angles of 20°. In order to calculate the upstream depth of flow, determine the required depth of water above the outlet giving consideration to its position and dimensions of the gutter sole,

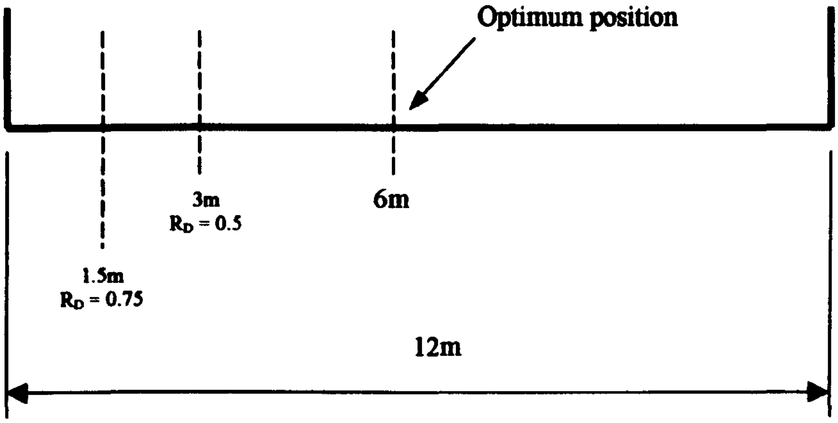


Figure 6.11 worked example

a. Using test data obtained from manufacturers tests or figure 6.1 determine the water depth required above an outlet accepting a flow of 10 l/s within a gutter with a sole width of 800mm (D_f)

$D_f = 36$ mm

b. Determine a distance ratio R_D

$R_D = 0$ when outlet is in optimum position

ie in this case mid point

$$= \frac{\text{gutter length}}{2} = \frac{12}{2} = 6\text{m}$$

$R_D = 0.5$ when outlet is 3m from optimum position

$R_D = 0.75$ when outlet is 4.5m from optimum position

Therefore $R_D = 0.75$

c. Using equation 6.1 calculate the head of water required around an outlet with respect to the width of the gutter sole and the outlet position along the length of the gutter sole (D_{sp})

$$D_{sp} = (23.38 \text{ x } R_D) + D_f$$

$$D_{sp} = (\ 23.38 \text{ x } 0.75) + 36$$

$$D_{sp} = 53.53 \text{ mm}$$

Therefore, this value of water depth around the outlet rim may now be utilised within the theortical model stated within BS 6367:1983 for the calculation of required upstream depth. Note: as previously stated there is a requirement for an additional safety factor of 16% when adopting the therortical model to syphonic rainwater systems. Appendix 5, tables A5.8 & A5.9 compare the calculation of required gutter depth without consideration to an outlets position of gutter width to a gutter depth determined from the above example.

6.7 Conclusions

Flow rate through an outlet is affected by the outlets' position within a gutter.

Outlets placed at the extreme ends of a gutter require an increase in the head of water to achieve the same flow when compared to the same outlet positioned at its optimum point (equal flow from both sides).

The gutter sole width and position of an outlet along the length of a gutter, has an influence upon the water depth required around an outlet for a given flow rate.

A methodology for calculating the required water depth for a given flow rate, around an outlet with respect to its position within a gutter and the gutter sole width has been formualted and a worked example provided.

The work presented highlights a potential concern in respect of the pratice of grouping secondary outlets near to the ends of gutters. If, when using primary and secondary systems the grouping of outlets within the end of the gutter is unavoidable, then in order to accuratly determine the water profile within the gutter it would be advisable to place the primary system outlets at the ends and equi-space the secondary outlets along the gutter sole. As the work detailed in chapter 4 highlights when primary and secondary syphonic systems are installed in a common gutter, it is the secondary system that dominates the flow profile within the gutter therefore, by equally spacing the secondary outlets along the gutter sole will keep water depths to a minimum. Consequently, if the theory presented here were adopted the design of gutters would become more efficient and cost effective. It should be noted that the operational depth of water above the primary outlets should be calculated to ensure that it is shallower than the height of the upstand around the secondary outlets. However, the practice of grouping outlets should where ever possible be avoided as this may cause the gutter to over top at the mid point. A gutter needs to be designed accordingly if this philosophy of secondary outlets is to be used.

Based on the findings of this research, the designer of a gutter with primary and secondary outlets, need to appreciate the way in which the hydraulic regime is modified when the secondary outlets are primed ie when the secondary outlets dictate the flow regime.

Chapter Seven - Investigation into the effects that sub-atmospheric pressure has on the performance of a syphonic rainwater outlet

7.1 Aim of this study

The aim of this component of the study was to assess the impact that sub-atmospheric pressure within the piping system, has upon the depths of water within the gutter for any given rate of flow. It was therefore considered only necessary to investigate one design of outlet. Analysis of previous areas of study has highlighted the pressure regimes within a system and the relationship between each component with respect to pressure.

7.2 Sub atmospheric pressures within a syphonic system

Through the understanding of how depressurisation occurs within each element of a syphonic system, it can be shown that there may be a possibility of the translation of the effects of the depressurisation into a gutter.

7.3 The outlet

Slater (1998) noted that the depressurisation experienced between the inlet and tailpipe of a syphonic outlet was dependent upon the flow magnitude. Using a commercial CFD package he was able to show that at a flow rate of 6 l/s the pressure drop across the outlet was in the region of 0.0315 bar. Figures 7.1 and 7.2 highlight the work by Slater (1998) depicting the pressure regime within a syphonic outlet at flow rates of 6 l/s and 12 l/s.

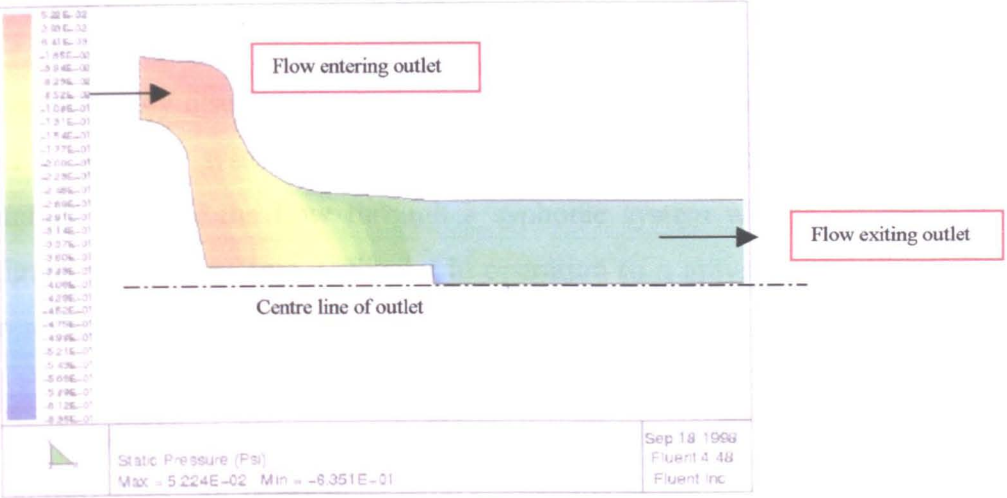


Figure 7.1 – Pressure distribution within an outlet at 6 l/s

Maximum pressure = 2.403×10^2 Pa

Minimum pressure = -2.913×10^3 Pa

Pressure drop across outlet $= 2.403 \times 10^2 - (-2.913 \times 10^3)$

$= 3.1533$ KPa

$= 0.0315$ bar

When the flow rate was increased to 12 l/s the pressure drop increased to 0.2788 bar. The pressure drop occurred over a relatively short distance as the length of the outlet is only 150mm

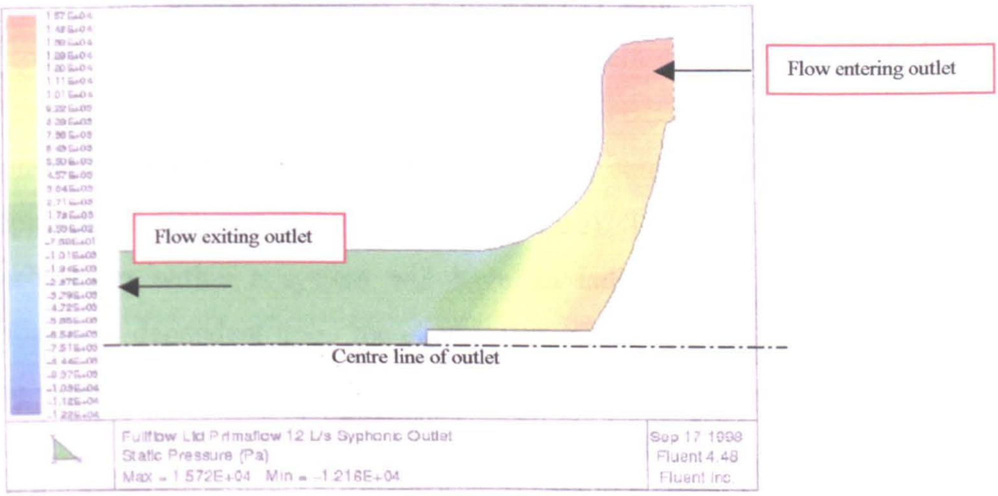


Figure 7.2 – Pressure distribution within an outlet at 12 l/s

7.4 The pipe work

As previously discussed in Chapter 1, the flow regime within the pipe work of a syphonic system develops through a cycle as the rainstorm events unfold. Initially, the flow through a syphonic system will be as shown in figure 1.3, flow pattern 1. Similar in operation to a gravitational system the resulting flow would partially fill the downpipe.

The gravitational flow will be transformed into full-bore flow as the storm intensity rises. Air is excluded from the system as the water level within the outlet approaches the anti-vortex plate. As this priming process progresses to the full bore flow condition, a depressurisation of the pipe work occurs, hence the quantity of water discharged from the roof or gutter, is increased.

May (1996) suggested that negative pressures generated within a syphonic system be considered for two reasons: 1. The possible buckling of the pipe through poor choice of pipe material 2. The avoidance of cavitation with the flow, therefore reducing a systems capacity and causing damage to pipe. The author hypothesised a possible third reason for the need to consider the negative pressures within a syphonic rainwater system. The possibility that the performance of a rainwater outlet maybe enhanced by negative pressures both in the outlet itself and the associated pipe work. As previously discussed, the use of commercial syphonic system design software provides a theoretical model based on the application of Bernoulli's energy equation combined with the Colebrook-White equation across a full flowing system (appendix 1 provides details of the software). The software predicts that each outlet within a system will have an individual flow capacity. This capacity is dependent upon the energy losses and available working head of the system. Typically, the outlets, which are located in the proximity of the downpipe, will have a higher capacity than others located along the length of the horizontal collector pipe. i.e. considering figure 7.4, generally, all outlets within the system would have a different maximum capacity, with outlet C having a higher capacity then outlets A & B.

The pressure distribution within the three-outlet system shown in figure 7.4 is highlighted within figure 7.5. Determined through the use of a vacuum pressure gauge at the maximum flow rate of the system, this chart indicates that the outlet position relative to the vertical stack and discharge point of the system has a considerable influence on the pressure distribution.

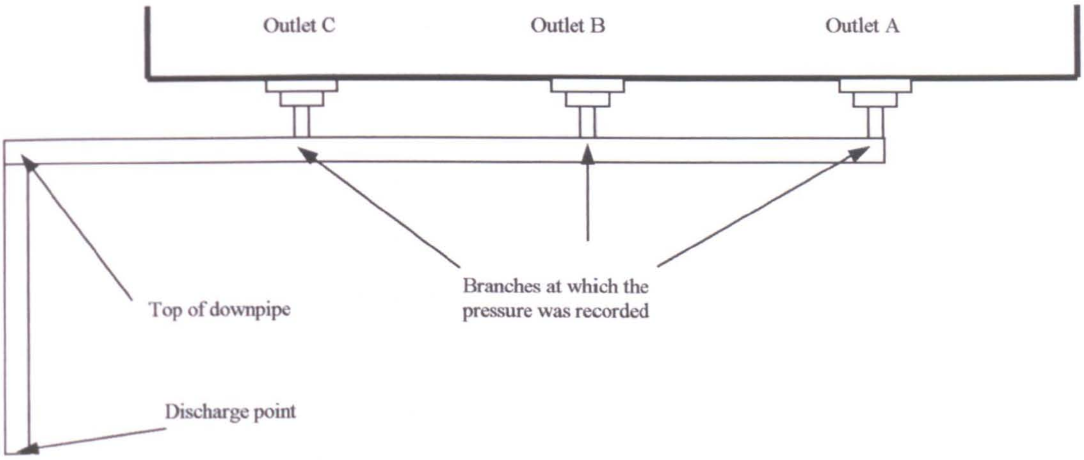


Figure 7.3 Three-outlet system – Indicating the points at which values of pressure were recorded.

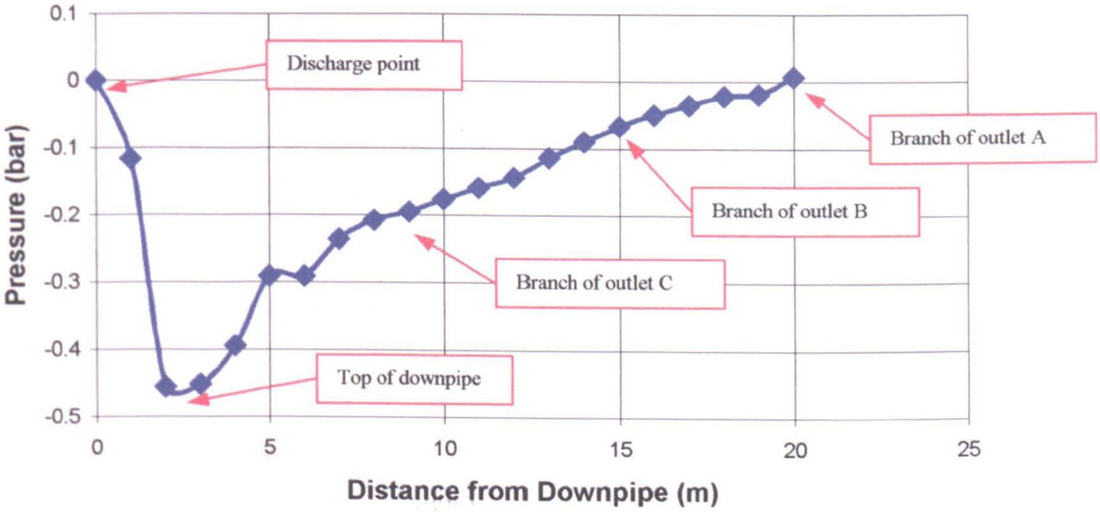


Figure 7.4 – Pressure distribution within a syphonic system

In an attempt to confirm the hypothesis a series of tests were performed, which compared the head of water around an outlet with the flow rate and localised pressure.

7.5 Experimental methodology

By utilising the test facility, an experiment was undertaken to determine how a negative pressure within the pipe work of a syphonic system influences the flow regime within the gutter. Previous investigations have concluded that, for a given steady state flow entering the gutter, and outlets located at the various positions along the sole of the gutter, the variation in the working head of water around the rim of each outlet was insignificant. Application of the conventional theoretical weir flow model suggests that the outlets accept the same flow rates due to the head of water above each outlet being comparable. However, this is a contradiction of the Bernoulli prediction that individual outlets have the capability of accepting varying flow rates. Therefore, if the working heads of water around each outlet rim are similar, but the flows different, then the negative pressure generated within the outlet and associated pipe work may have an affect upon the outlet's working head of water at each outlet.

A three outlet syphonic system was installed within the 35 metre long test facility with the distance between each outlet shown in figure 7.6. This was specifically set up to establish the relationship between flow rate through an outlet and negative pressure within the pipe work.

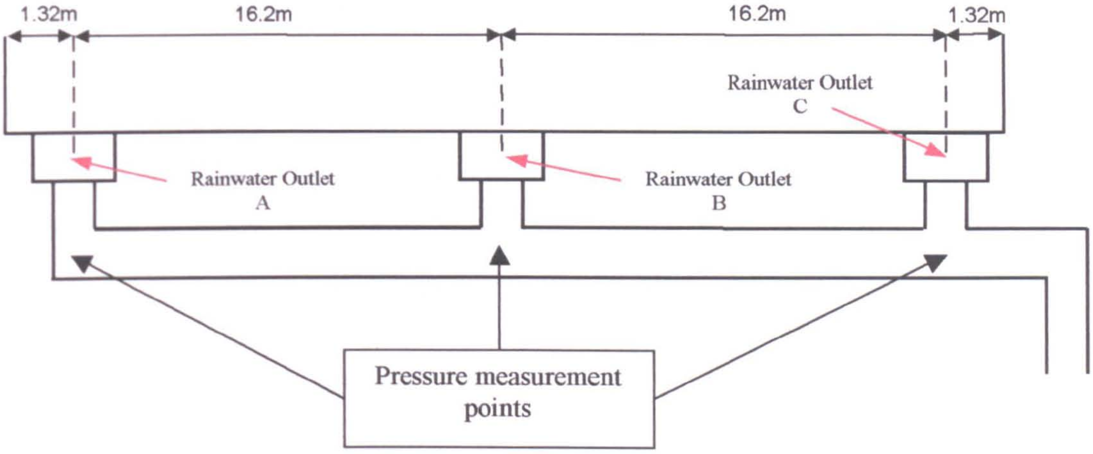


Figure 7.5 - Schematic diagram of a full-scale test facility

Steady state inflow rates to the gutter were measured through the use of pneumatically controlled valves. Depth measurements of the water within the gutter were recorded at two points around each outlet rim and at the upstream points of zero flow (i.e. the point at which the flow divides to flow between two outlets). Pressure readings were recorded along the main horizontal collector pipe at the branch junction of an outlet as shown in figure 7.6, by means of a Bourdon tube pressure gauge, manufactured by Wika, reading −1.0 bar to +1.5 bar full scale, with an accuracy of ±0.01 bar. Steady state inflow rates were measured against water depths and observations of flow patterns within the gutter taken.

7.6 Results and discussion.

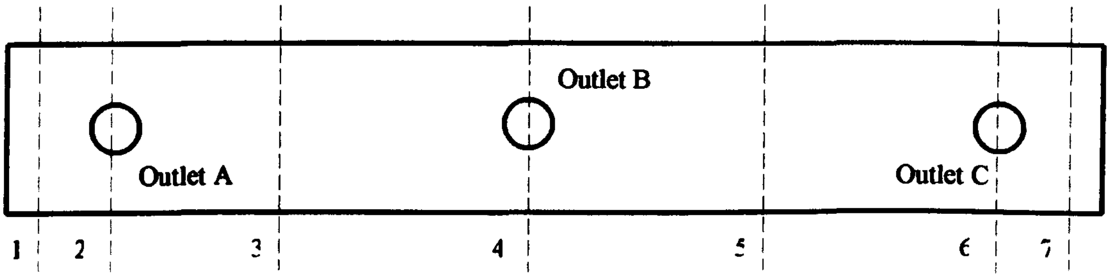
Three rainwater outlets were positioned along the sole of the gutter test facility and water depth measurements were retrieved at the positions indicated in figure 7.7. Figure 7.8 shows the relationship of flow against depth at each outlet and maximum depth position for various steady state flow rates.

Outlet C was located closest to the downpipe of the system, at point 6 indicated in figure 7.8. Two additional outlets were located at points 2 & 4, whilst points 3 and 5 were the position where the maximum depth of flow was recorded. As previous investigations have shown, and theoretical models predict, the upstream depth of water within the gutter is clearly definable from the working head of water around the outlet. Within the highlighted areas of figure 7.8 it may be seen that throughout the tests at varying inflow rates, the maximum difference between the water depths at points A & C is 7mm. In a conventional gravity system, through the application of the weir flow equation (Eq^n 5.5) similar variations in water depths between individual outlets would suggest that the outlets have the same flow capacity. However, through utilising the commercial syphonic system design software, which is based on the Bernoulli energy equation, in order to predict the capacity of outlets within the syphonic system, outlet C is predicted to accept in the region of 18.5% more flow than the outlet located at point A and 14.3% more flow than the outlet located at point B. This is shown in table 7.1. This is due to there being a differential energy loss within the pipework associated with individual outlets.

Outlet	Flow rate entering whole gutter = 40 l/s		
	Water depth mm	PrimaCalc Prediction l/s	Weir equation calculation l/s
A	58	12.02	15.2
B	75	13.74	22.3
C	65	14.24	18

Table 7.1 Comparison of predicted flow rates (PrimaCalc and weir equation) through individual outlets

Hence, it may be concluded that the location of an outlet, relative to the position of the downpipe, may have a significant influence on its flow capacity. This understanding that syphonic rainwater outlets sharing common pipework have differing flow capacities is fundamental to the design of systems and hence there is a need to improve the design philosophy of the system.



Plan section of gutter, total length 35m
Distances between outlets are identified in figure 7.6

Figure 7.7 – Indication of the positions of outlets and the location of water depth measurements used in this area of investigation.

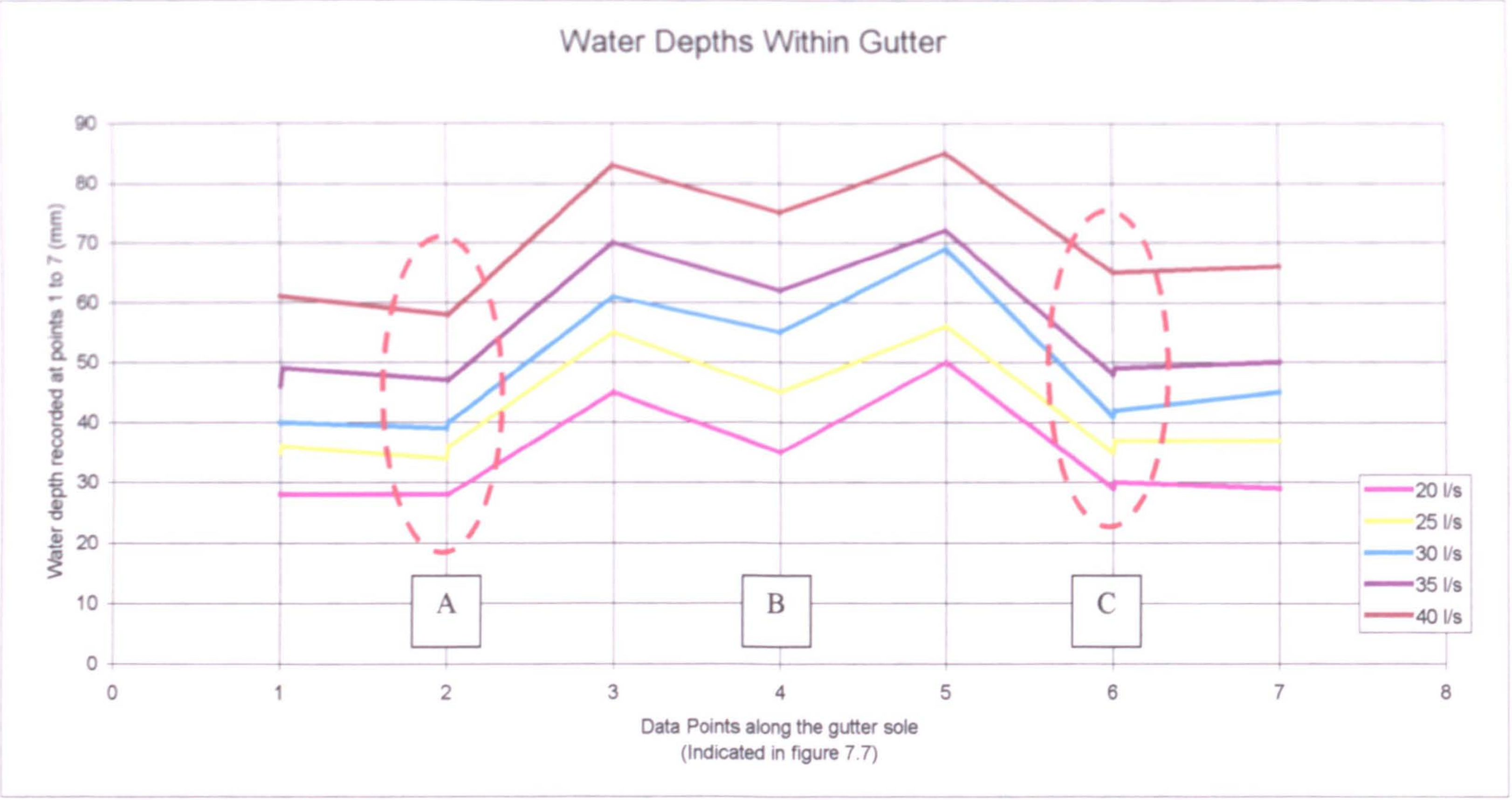


Figure 7.7 – Water depths within gutter (Standard error within the data ± 0.5mm)

Within the highlighted regions in figure 7.8, the fluctuations in water levels may be due to the priming action of the syphonic system pipework affecting the depth of water around the rim of the outlet. As discussed in section 7.4, during the early stages of priming a syphonic system fluctuates between syphonic and conventional operation, this may result in a 'pull down' effect around the outlet. In this investigation the range of fluctuation above the syphonic rainwater outlets was between 2 – 4 mm.

The predicted values of pressure, calculated through the use of commercial software, which utilises the Bernoulli energy equation and the Colebrook White equation and is further detailed in appendix 1, together with the pressures recorded at the junction of each outlet branch as it connects to the main collector pipe are shown in table 7.1. It may be seen that in both the actual and theoretical cases, the values of pressure are lower at the outlet situated nearest the vertical stack i.e. outlet C, figure 7.6

For example, the recorded pressure at the outlet furthest from the downpipe (outlet A) is atmospheric (zero) at a flow rate of 25 l/s. By comparison, at the same flow rate the pressure recorded at the outlet closest to the downpipe (outlet C) is –0.1 to 0.15 bar. This corresponds well to the pressure distribution previously determined and discussed in section 7.4, figure 7.5.

The two values of pressure recorded at the steady flow rate were due to the characteristic oscillation of the syphonic system during the priming phase. The effects of the oscillation were transmitted into the head of water around the outlet rim. Figure 7.7 identifies the fluctuations within the water depths at point 2 and 7. Observation of the water velocities within the gutter revealed the velocity around the two extreme outlets to be different. The highest velocities within the gutter were observed around the outlet located nearest to the vertical stack. As the water depths within the extreme ends of the gutter were comparable the increase in velocity suggest that the flow is also increased. The results of this particular test highlighted the need to measure the flow rates down individual outlets. Inflows to the gutter may be measured accurately through the use of control valves which were calibrated using measuring tanks and is discussed in chapter 3. However, this method of flow measurement does not indicate the proportion of the total flow being drained by individual outlets. A method of investigating the flow rate through an individual syphonic rainwater outlet was therefore designed. As there had been no previous work of this type a number of methods of flow measurement were considered and are discussed in Chapter 8.

Flow l/s	**Recorded Measurement (bar)**			**Theoretical Model predictions (bar)**		
	Outlet A	**Outlet B**	**Outlet C**	**Outlet A**	**Outlet B**	**Outlet C**
20	0	-0.025	-0.05 -0.1	0.03	-0.003	-0.065
25	0	-0.025 -0.05	-0.1 -0.15	0.022	-0.013	-0.19
30	-0.05	-0.05 -0.1	-0.15 -0.25	0.009	-0.028	-0.29
35	-0.05 -0.1	-0.075 -0.125	-0.25 -0.3	-0.0069	-0.045	-0.42
40		-0.15	-0.325		-0.114	-0.42

Table 7.2 – Measured and calculated pressures.
(Outlet locations relative to the downpipe position are shown in figure 7.6)

7.7 Summary

Areas of negative pressure within a syphonic system have been identified and investigated and a varying pressure distribution within a syphonic system was observed to occur.

In addition to the water depth measurements, observation of the varying velocities within the gutter suggest the outlet located nearest to the vertical stack of a system accepts more flow when compared to predictions using weir flow calculations. This may be due to the values of energy loss within pipework associated with individual outlets, or alternatively, the pressure distribution within the pipe work having an influence on an outlets capacity.

Pressure within a system has been recorded and compared with a typical theoretical model used by system manufacturers. It was shown in table 7.1, that the predicted values of pressure were not in close agreement with the recorded values. For example, at the flow rate of 35 l/s the predicted value of pressure at outlet C was – 0.42 bar, whilst the recorded value was in the region of – 0.25 to – 0.3 bar. The validity of the theoretical calculation therefore requires further investigation. As this was outside the aims and objectives of this study a recommendation for future work is discussed in Chapter 9.

Individual syphonic rainwater outlets within the same system invariably accept differing rates of flow. This is an important finding and there is a need to accommodate such changes in gutter design methodologies.

Chapter Eight - Flow measurement

8.1 Introduction

In chapter 7 it was shown that when a syphonic rainwater system consisting of 3 outlets was installed within a gutter and subjected to a constant inflow, the water depths around each of the outlets were comparable to each other. Through the application of the theoretical model detailed in appendix 1, each outlet has an individual capacity based upon the energy losses and resistance to flow in the associated pipe work. These results are in contradiction in that, if outlets were to accept differing flow rates at similar water depths around the rim, then there must be some other factor to influence the flow regime. One such factor could be the negative pressures within a system providing a pull down or suction effect on the water levels around the rim of an outlet. Conversely it may be hypothesised that the water levels within the gutter stabilised irrespective of the flow rate through individual rainwater outlets.

The current industry accepted British Standard for gravity drainage systems inside buildings applicable for the calculation of water depths within gutters. Within this standard, depths of water above a circular outlet for a given flow rate may be calculated using either a weir flow equation or an orifice flow equation.

Weir Flow.

(Valid where h = D/2 or less)

$$Q_w = \frac{K_o D h^{1.5}}{7500} \tag{8.1}$$

Where: Q_w = Flow rate (weir flow)

K_o = Outlet coefficient, taken as 1 for unobstructed outlets

h = head of water at the outlet

Orifice Flow

(Valid where h> D/2)

$$Q_o = \frac{K_o D^2 h^{0.5}}{15000} \qquad (8.2)$$

Where: Q_o = Flow rate (Orifice flow)

Ref: BS EN 12056-3:2000 Gravity drainage systems inside buildings Part 3 - Roof drainage, layout and calculation

The investigation discussed in chapter 4, highlighted that the water depths around the rims of individual outlets were comparable with each other. Applying formulae 8.1 & 8.2 to the results provided an indication that the 3 individual outlets within the common gutter were accepting equivalent rates of flow. In order to confirm that either this was the case, or that there was some other influencing factor affecting the flow through an outlet, it was considered necessary to accurately measure the flow rates through individual outlets. The background to the way in which this was completed is now discussed. Following a review of flow measuring meters, details of two types of meters, turbine meters and ultrasonic meters, are now discussed as these are considered the appropriate technology for application in a syphonic system in which the pipes flow full.

8.2 Turbine Flow Meters

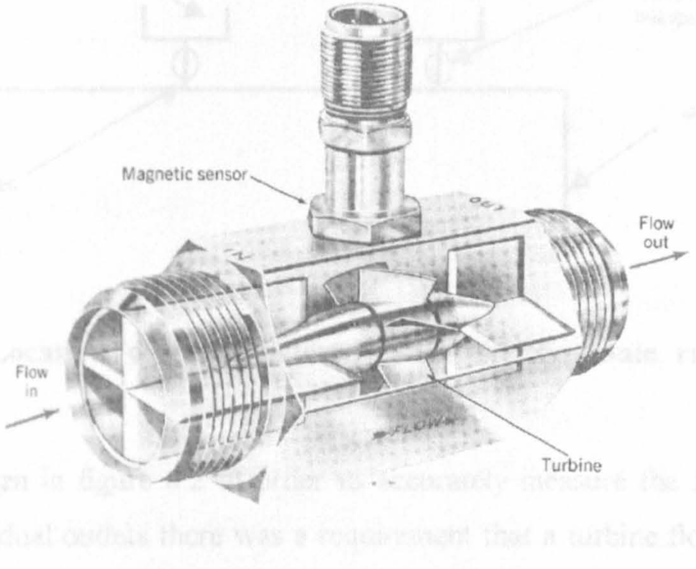


Figure 8.1 Principle components of a turbine flow meter.
Ref: Munson et al 1994

Turbine meters (figure 8.1) operate, as their name suggests, through a small freely rotating propeller or turbine within the meter housing rotating with an angular velocity that is a function of the average fluid velocity in the pipe. This angular velocity is detected magnetically and calibrated to provide a very accurate measure of the flow rate through the meter. In order for this particular type of meter to operate accurately and efficiently the pipe has to flow full. If this is not the case then spurious readings of flow may be recorded. Manufacturers of this type of meter publish tables of energy loss through the meter, which allows pipeline designers to account for the unit within their design.

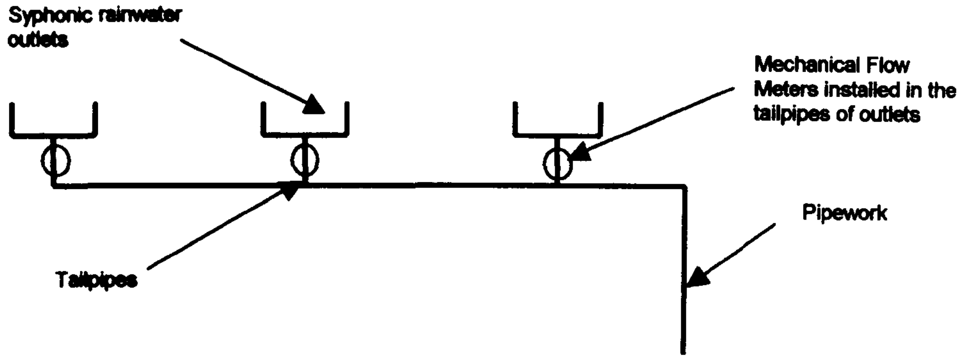


Figure 8.2 Location of flow meters within the syphonic rainwater system

As may be seen in figure 8.2 in order to accurately measure the flow rate through individual outlets there was a requirement that a turbine flow meter would need to be installed within each tailpipe associated with an outlet.

The turbine meter as a method of flow measurement was rejected due to the requirement for full flowing pipes and the restriction to flow, which would either affect the operation of the siphon or provide unstable readings due to the nature of the flow:

In addition to increasing the energy losses within individual outlet tailpipes, which were not accommodated during the design of the system, the inclusion of mechanical meters within the pipework would increase the resistance to flow and therefore affect the operation and performance of the syphon. It was also unclear from manufacturers what effect the negative pressures within the system would have on the internal workings of the meters.

The flow within the tailpipe consists of a certain amount of entrained air, which is unavoidable due to the aerated way that water enters the gutter from the roof section of the rig.

A conclusion from the consideration of the turbine flow meter was that as this method of flow measurement was inappropriate for this application, an alternative method of measurement was required, which did not involve intrusion into the pipe, therefore directly affecting the performance of the syphonic system.

8.3 Ultrasonic Flow Meters

The ultrasonic meter can measure fluids, which are ultrasonically conductive and have a reasonably well-formed flow. Clamp-on ultrasonic flow meters measure flow through the pipe without any contact with the process media, ensuring that corrosion and other effects from the fluid will not affect the workings of the sensors or electronics.

The ultrasonic transducers can be mounted in one of two modes. The upstream and downstream ultrasonic transducers can be installed on opposite sides of the pipe (diagonal mode) or on the same side (reflect mode) figure 8.3.

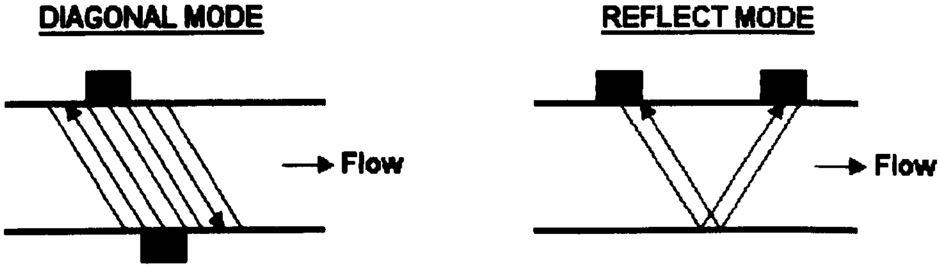


Figure 8.3: Two modes of signal measurement within an ultrasonic flow meter.

The control unit measures the time it takes for signals to transmit from one transducer to another. At zero flow, there is effectively no difference in time, but when flow is introduced the time for the transmission of signal from the downstream transducer to the upstream transducer will take longer than the upstream to downstream. Therefore producing a time differential, which may subsequently be used to calculate the velocity of the fluid being measured. Knowing the internal diameter of the pipe, it is possible to calculate a volumetric flow for the liquid.

It is important when installing an ultrasonic transit time flow meter to select a location where the flow profile is uniform i.e. in a straight length of pipe and away from bends. A rule of thumb in the industry is to give at least 10 diameter lengths upstream and 5 lengths downstream (Essiflo 2004)

As with the mechanical flow meters, figure 8.1, sonic meters would be required within each tailpipe of the system.

Although the use of this type of meter does not require any significant intrusion into the pipe that will have a detrimental affect on the flow regime, this method of measurement was rejected, predominantly due to the inability to measure flow in part filled pipes

As these methods of flow measurement proved to be unsuitable, mainly due to them either affecting the flow regime within the pipes or that the pipe flowed part full, alternative methods of flow measurement were required. Measurement of the flow rate within the connecting pipework downstream of the syphonic system would provide data with regard to the flow through the entire system. This would give no indication as to how the flow was apportioned between individual outlets. Therefore, the focus of the area at which the flow was measured was redirected upon the gutter. There would be no effect on the performance of the syphon, if the flow approaching an outlet could be accurately measured. Weirs within the gutter were considered and subsequently discounted. This was due to the unknown effects that the increased velocity and water depths associated with these constructions would have on the performance of the outlet and gutter.

8.4 Velocity Profile.

An effective method of measuring the velocity of flow within an open channel such as a gutter is through the use of a velocity probe (figure 8.4). One component of the probe is an 11.5 mm diameter propeller, which when placed in the gutter is driven by the flow of the water. This action creates a signal that is displayed to the user as a frequency with the value read in Hz. In order to establish a velocity the reading is then converted to m/s through the use of charts provided by the probe manufacturers.

To achieve an accurate flow rate measurement, it was necessary to record the mean velocity from around the outlet in addition to the cross sectional area of flow. The simple measurement of water depths around the outlet along with the gutter profile, provided the data from which to calculate the cross sectional area. However, due to the complex flow regime around an outlet, the retrieval of velocity measurements required a more considered approach. In order to achieve a consistent value of velocity, the probe was held at predetermined distances from both the sole of the gutter and from the outlet.

Consistency in data recording was accomplished through the development of a framework and carriage arrangement, which was fitted to the upper edge of the gutter. This framework and carriage allowed the probe to be positioned in 3 axes around the area of the outlet. Figure 8.5 shows a schematic view of how this was completed.

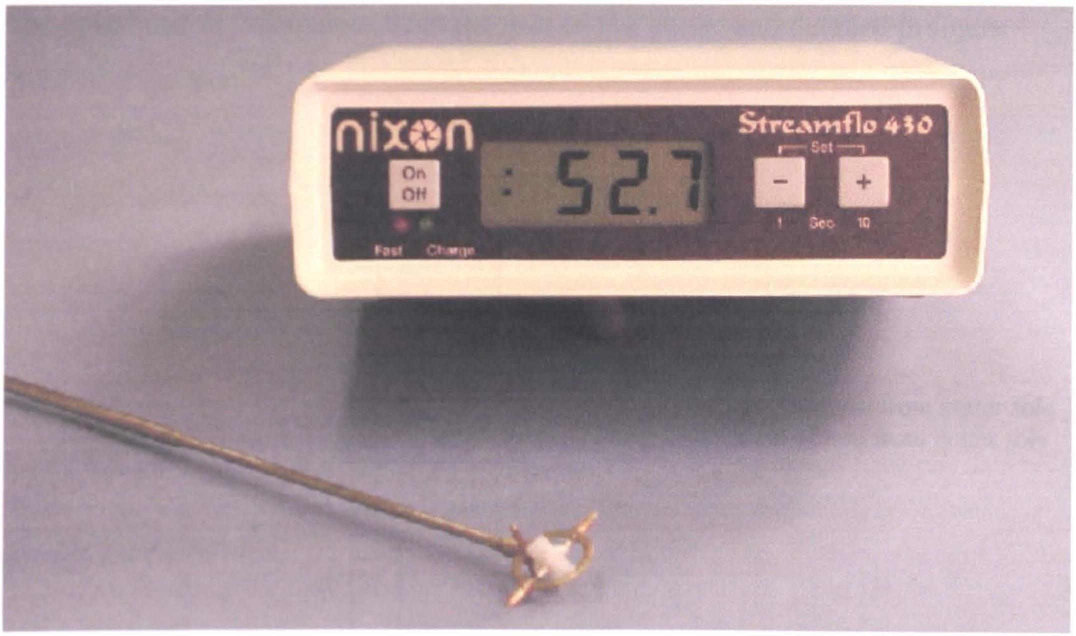


Figure 8.4 Nixon Streamflow miniature propeller meter.

Ref: HR Wallingford web site 2004

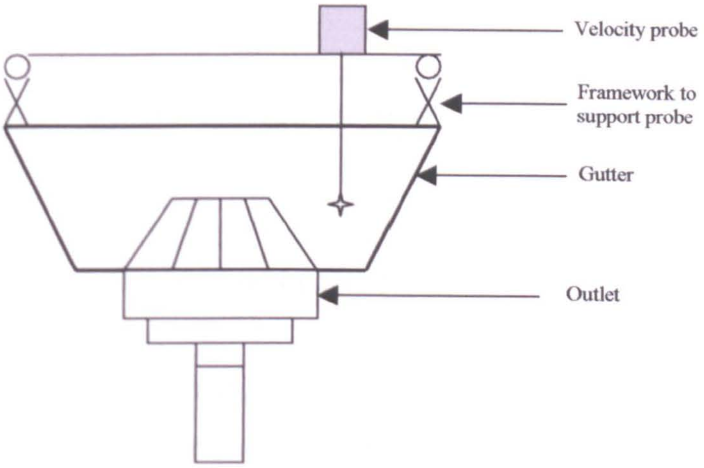


Figure 8.5 Schematic of velocity probe arrangement

It was hypothesised that the flow through the outlet could be determined through measurement of the mean velocity of the flow approaching the outlet and the cross sectional area of the flow profile. In order to assess these elements individual velocity readings were taken at 8 points around the outlet and at 2 distances from the sole of the gutter and detailed in figure 8.6.

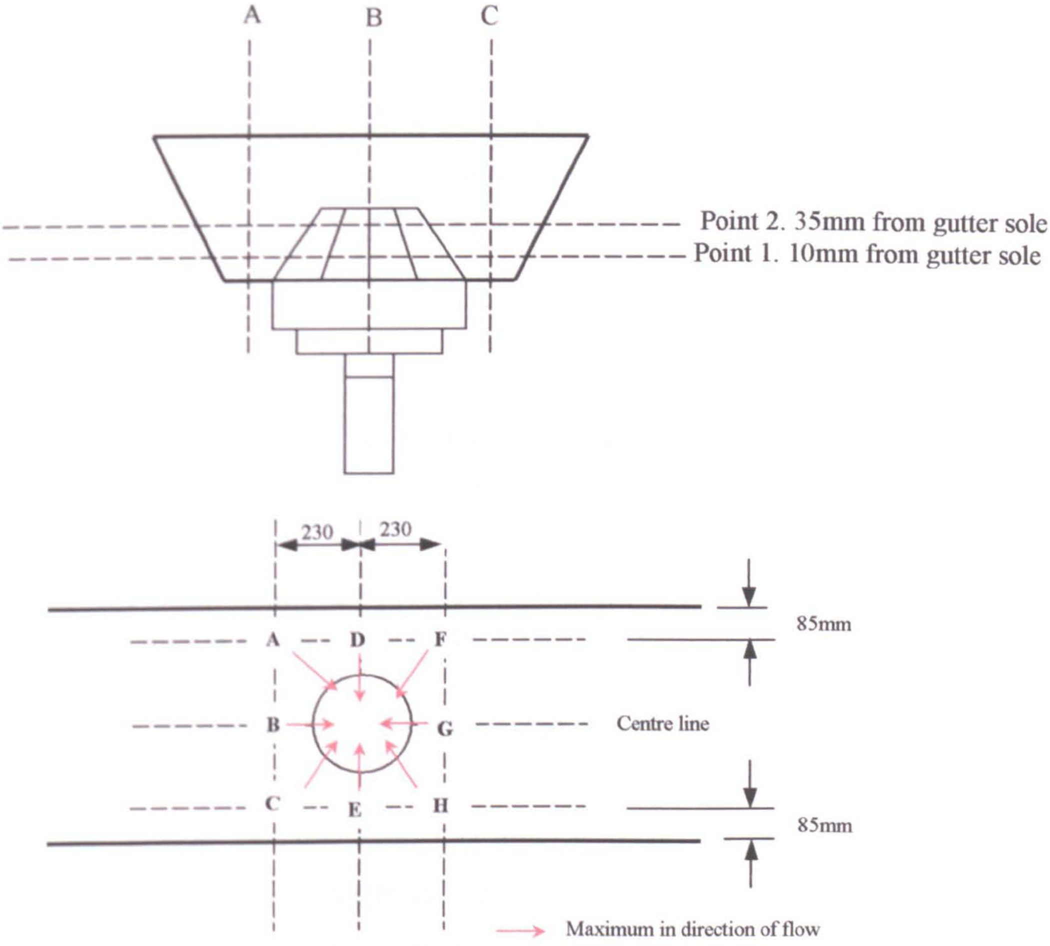


Figure 8.6 Velocity measurement positions

Over a period of 200 seconds, at steady state flow conditions, values of velocity were recorded individually at each of these points at time intervals of 20 seconds. The rotation of the propeller was adjusted so that the maximum velocity in the direction of flow to the outlet was the flow, which was recorded. Effectively this was at right angles to the circumference of the outlet as defined in figure 8.6. By recording over such a period any anomalies within the flow pattern created by the time required for water to reach the outlet would be highlighted. The results of a series of preliminary tests are recorded in appendix 6, tables A6.1, A6.2 and A6.3.

The water depths around an outlet across points A1 to H2, as identified in figure 8.6 were recorded. As the outlet was located 1 metre from the end of the gutter, the flow approached the outlet primarily from one direction. The profile of the gutter is trapezoidal in section with a sole of 600mm and walls angled at 20° from the vertical. Using this data the cross sectional area of flow was determined.

Using the cross sectional area of flow (established by recording the depth of flow at each point, see figure 8.4) and the measured mean velocities at each point the flow rate approaching the outlet was calculated. The calculated values are recorded in table 8.1.

Point	A	B	C	D	E	F	G	H
1	11.07	9.36	7.93	9.05	9.89	8.56	9.87	10.89
2	12.48	9.41	8.01	11.85	12.04	8.23	10.02	12.32

Table 8.1 Flow rates at predetermined locations around an outlet accepting flow from two directions

From these results the following conclusions were made:

The information obtained from this area of work has helped to gain an appreciation of the complexity of the flow profile around an outlet located within a gutter. These results suggest that although a syphonic rainwater outlet may have an individual flow capacity, which is dependent upon the associated pipework, this flow does not enter the outlet in a uniform manner.

The results have highlighted that due to the varying flow profile it is very difficult to determine the actual flow through the outlet, utilising the flow measurement methods discussed. Therefore, this particular method of flow calculation is unsuitable and unreliable for this application.

8.5 Fluorometry

Dye dilution techniques for flow measurement have in the past been utilised in rivers, streams, sewers and open drainage channels. In some situations this is the only method in which accurate data may be retrieved without determining the cross sectional area information.

When utilising this technique on relatively large-scale projects, the advantages, which may be gained, are:

Speed – Results are almost instantaneous without the need for expensive constructions such as weirs or flumes.
Simplicity – A dye at a known injection rate is introduced upstream within a river so that mixing is complete, by measuring the concentration downstream determines the flow as a ratio.

As the conditions of flow within a syphonic system (previously discussed in chapter 1, see figure 1.3), placed limitations on the flow measurement within the pipework. It was hypothesised that through adaptation of the existing fluorometry techniques, used to measure open channel flow, the measurement of flow through individual syphonic rainwater outlets may be achieved. The following adapted system was assembled.

An injection pump with a known flow rate injected dye, at a know concentration into the outlet furthest from the downpipe (outlet 1). The injection took place at three points located in the underside of the outlet bowl. The first sample point was downstream of outlet 1, at a point just prior to the pipe intersection of outlet 2. The choice of this point allowed the maximum time for the dye to mix with the water entering outlet 1. The turbulent nature of the flow through outlet 1 also encouraged the initial mixing of dye and water.

Similarly, sample point 2 was located at the furthest possible point downstream of outlet 2, as was outlet 3. The positioning of the sample points allowed maximum mixing. Figure 8.7 identifies the location of the outlets and sampling positions.

Dilution samples were retrieved from each point through the use of a number of adapted syringe arrangements, which were dedicated to each point and rinsed between samples. Once retrieved, the samples were placed in a clean sample tube. Clear identification of the sample tubes enabled the dye dilution to be analysed using the fluorometer with minimal risk of cross contamination.

The initial flow rate and concentration of dye was determined and is discussed in section 8.6. The following method of calculation was derived in order to determine how the flow entering the rig was apportioned to individual outlets.

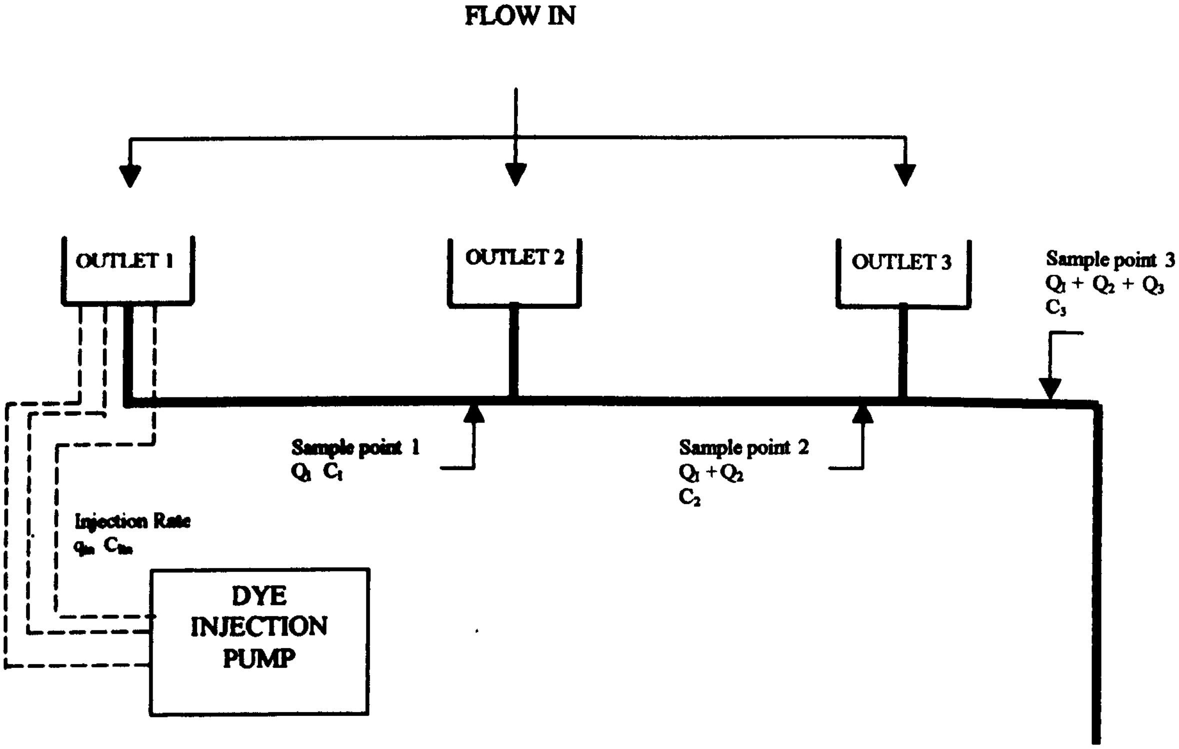


Figure 8.7 Schematic drawing of the fluorometry investigation of the syphonic system. Highlighting sample points and injection pump.

$$q_{In} C_{In} = Q_1 C_1$$

$$Q_1 = \frac{q_{In} C_{In}}{C_1} \tag{8.1}$$

$$q_{In} C_{In} = (Q_1 + Q_2) C_2$$

$$Q_2 = \frac{q_{In} C_{In}}{C_2} - Q_1 \tag{8.2}$$

Substituting 8.1 into 8.2

$$Q_2 = \frac{q_{In} C_{In}}{C_2} - \frac{q_{In} C_{In}}{C_1}$$

$$Q_2 = q_{In} C_{In} \left(\frac{1}{C_2} - \frac{1}{C_1} \right) \tag{8.3}$$

$$q_{In} C_{In} = (Q_1 + Q_2 + Q_3) C_3$$

$$Q_3 = \frac{q_{In} C_{In}}{C_3} - Q_2 - Q_1 \tag{8.4}$$

Substituting 8.1 and 8.3 into 8.4

$$Q_3 = q_{In} C_{In} \left(\frac{1}{C_3} - \frac{1}{C_2} + \frac{1}{C_1} - \frac{1}{C_1} \right)$$

$$Q_3 = q_{In} C_{In} \left(\frac{1}{C_3} - \frac{1}{C_2} \right) \tag{8.5}$$

Where:

C_b = Background dye concentration
C_{In} = Concentration of initial dye
C_1 = Concentration of dye at point 1
C_2 = Concentration of dye at point 2
C_3 = Concentration of dye at point 3
Q_1 = Flow rate through outlet 1
Q_2 = Flow rate through outlet 2
Q_3 = Flow rate through outlet 3
q_{In} = Injection flow rate of dye

Initially it was important that in order to operate within the range of the flourometer that the required concentration of dye was determined. This was achieved through experimentation involving differing concentrations of dye being analysed, the data recorded and calibration charts produced. Utilising these charts ensured that the correct dye concentration was used in order to determine the flow rate through individual rainwater outlets. The calibration charts are shown in figures 8.8, 8.9, 8.10 and 8.11.

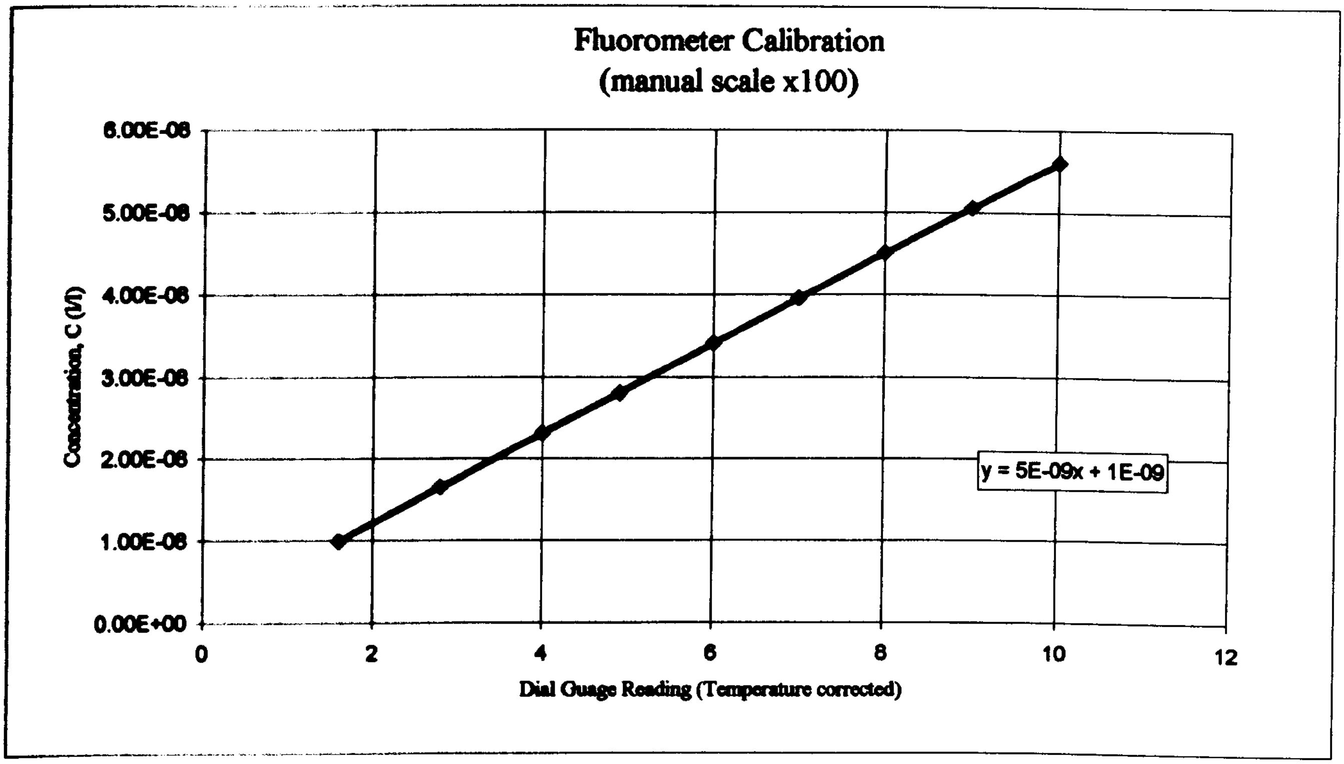


Figure 8.8 Fluorometer Calibration manual scale x 100

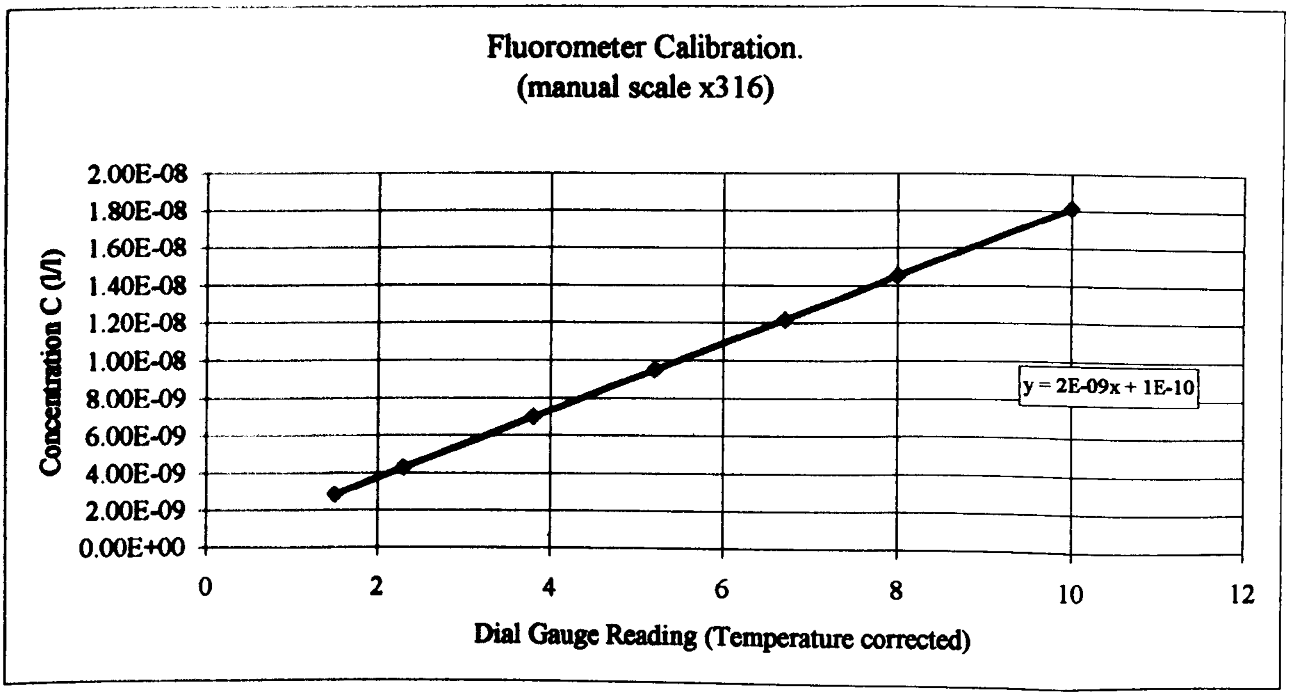


Figure 8.9 Fluorometer Calibration manual scale x 360

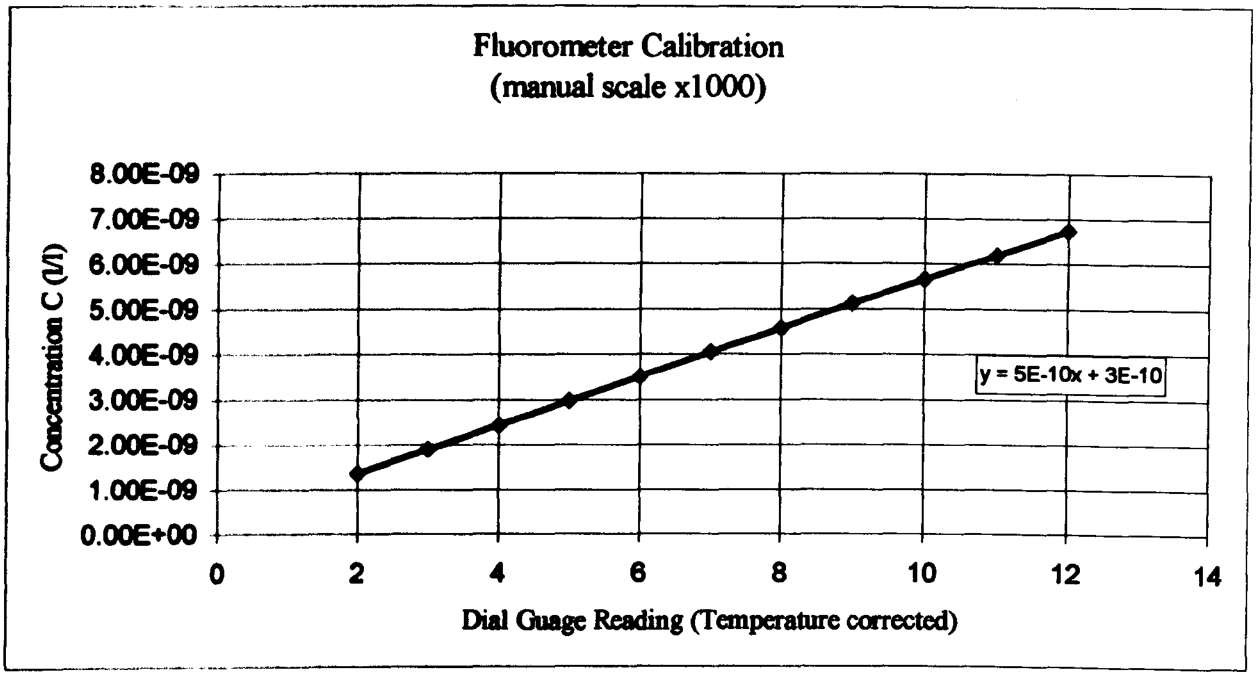


Figure 8.10 Fluorometer Calibration manual scale x 1000

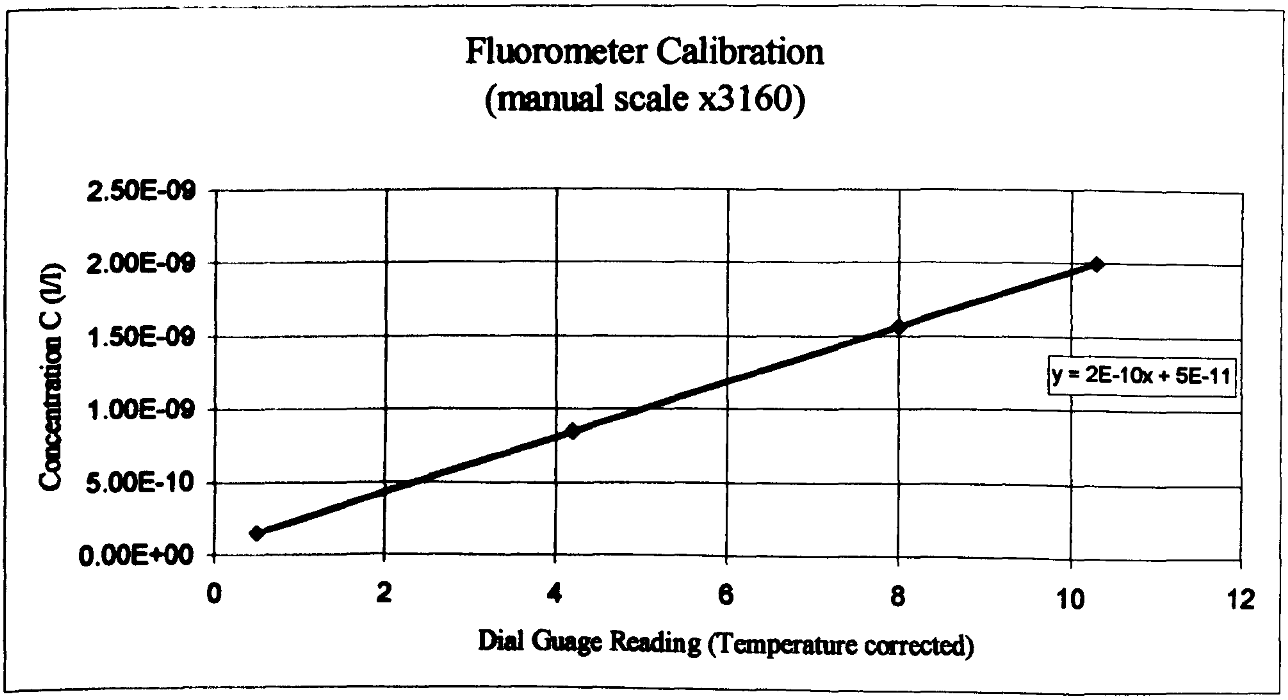


Figure 8.11 Fluorometer Calibration manual scale x 3160

It was determined that the range of the fluorometer was between $5.0\text{x}10^{-10}$ and $1.00\text{x}10^{-8}$. Calibration was achieved through the analysis of samples with a known dilution. Having calibrated and acquired the operating range of the fluorometer, it was now possible to undertake investigations to determine the flow rate of water through individual rainwater outlets. The total flow entering the rig was known as a result of the inlet control valves being calibrated previously (chapter 3). Also, at this time, theoretical values of how the total inflow was apportioned to individual outlets were determined through theoretical modelling of the pipework system.

8.6 Investigation

Assuming that a dye concentration of approximately $2\text{x}10^{-8}$ l/l is required at sample point 1 (figure 8.7), determine the required initial dye concentration. The dye is delivered at outlet 1, through 3 pipes, directly into the underside of the outlet bowl. The turbulent nature of the water flow at this point ensured that mixing of the dye and water was complete.

The pump used for the introduction of the dye has a delivery flow rate of 250 ml/min.

250 ml/min = 0.00417 l/s

Using commercially available software (appendix 1) the initial energy calculations, assume that outlet 1 has a flow rate of approximately 10 l/s.

$$C_{In} = \frac{q_{In} + Q_1 \ \text{x} \ C_1}{q_{In}} \tag{8.6}$$

$$C_{In} = \frac{(0.00417 + 10) \ 2 \ \text{x}10^{-8}}{0.00417}$$

$$C_{In} = 4.798 \ \text{x} \ 10^{-5} \ \text{l/l}$$

Therefore, an initial concentration of dye of 4.798 x 10^{-5} l/l is required in order to maintain the concentration throughout the investigation to within the limits of the fluorometer. As the water supply for the rig is used for all other investigation within the laboratory, within the initial concentration of dye there has to be an allowance made for any residual dye within the supply water.

Through the analysis of samples of the supply water, using methods described in section 8.5:

The background concentration of dye was found to be = 2.3794 x 10^{-10} l/l

Therefore, the initial concentration of dye = 4.798 x 10^{-5} - 2.3794 x 10^{-10}
= 4.797 x 10^{-5} l/l

The total in flow to the gutter was 36 l/s, this was controlled and measured through control valves installed within the inlet pipes and calibrated during the construction of the rig. The flow entered the gutter along one side of the 35m length via the pitched roof section.

The value of 36 l/s was selected as this value is close to the calculated theoretical maximum capacity of the syphonic system. As the commercial design software detailed in appendix A is based upon the application of Bernoulli's energy equation, the maximum capacity of the system is the only flow rate at which actual flow rates may be compared with the software predictions. At the point of maximum capacity the water depths above the rim of the system outlets would be constant and all recording would be at a steady state. A greater value of flow increased the risk of water depths within the gutter rising uncontrollably. 3 rainwater outlets were equi-spaced along the length of the gutter, in addition to flow rates, water depths above each outlet and at the mid outlet positions were recorded. In order to assess the possibility of negative pressures influencing the flow through the outlet, pressures were recorded through the use of a dial vacuum pressure gauge within the tail pipe of each outlet.

Over a number of test days, during which the background concentration of dye was periodically monitored through the method discussed in section 8.5, five samples were taken from each of the 3 sample points and an average concentration determined for each point. These values were then used within the calculation in order to determine the flow of water through individual outlets. Table 8.2 shows the values of dye concentration retrieved from each of the three sample points

Sample point	Test 1	Test 2	Test 3	Test 4	Test 5	Concentration Average Value
1	$2.1937\text{x}10^{-8}$	$2.1937\text{x}10^{-8}$	$2.1821\text{x}10^{-8}$	$2.1369\text{x}10^{-8}$	$2.1276\text{x}10^{-8}$	$2.1569\text{x}10^{-8}$
2	$8.5947\text{x}10^{-9}$	$8.6321\text{x}10^{-9}$	$8.6173\text{x}10^{-9}$	$8.5839\text{x}10^{-9}$	$8.6160\text{x}10^{-9}$	$8.6088\text{x}10^{-9}$
3	$5.6427\text{x}10^{-9}$	$5.6632\text{x}10^{-9}$	$5.6379\text{x}10^{-9}$	$5.6721\text{x}10^{-9}$	$5.5585\text{x}10^{-9}$	$5.6569\text{x}10^{-9}$

Table 8.2 Concentration of dye (l/l) retrieved from the points identified in figure 8.7.

Using equation 8.1 to determine Q_1

From 8.6, $q_{in} = 0.00417$ l/s and $C_{in} = 4.798\text{x}10^{-5}$

From table 8.5, average $C_1 = 2.1569\text{x}10^{-8}$

$$Q_1 = \frac{q_{In}\,C_{In}}{C_1}$$

$$Q_1 = \frac{0.00417 \text{ x } 4.798\text{x}10^{-5}}{2.1569\text{x}10^{-8}}$$

$$Q_1 = 9.28 \text{ l/s}$$

Using equation 8.3 to determine Q_2

$$Q_2 = q_{In}\,C_{In}\left(\frac{1}{C_2} - \frac{1}{C_1}\right)$$

$$Q_2 = 0.00417 \text{ x } 4.798\text{x}10^{-5}\left(\frac{1}{8.6088\text{x}10^{-9}} - \frac{1}{2.1569\text{x}10^{-8}}\right)$$

$$Q_2 = 2.0008\text{x}10^{-7} \text{ x } 6.9797\text{x}10^{7}$$

$$Q_2 = 13.965 \text{ l/s}$$

Using equation 8.5 to determine Q_3

$$Q_3 = 0.00417 \text{ x } 4.798\text{x}10^{-5} \left(\frac{1}{5.6569\text{x}10^{-9}} - \frac{1}{8.6088\text{x}10^{-9}} \right)$$

$$Q_3 = 2.0008\text{x}10^{-7} \left(1.7678\text{x}10^{8} - 1.1616\text{x}10^{8}\right)$$

$$Q_3 = 12.172 \text{ l/s}$$

8.7 Discussion of Results

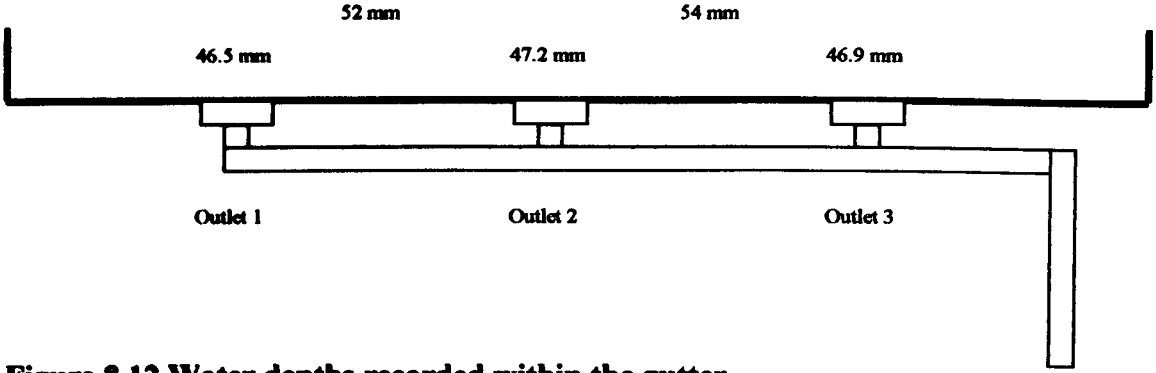


Figure 8.12 Water depths recorded within the gutter

The recorded values of water depth within the gutter are shown in figure 8.12. The measured flow rates through outlets and the pressure within the pipework were compared with the values calculated using the theoretical models identified within the current British Standard (see chapter 5 section 5.1) and commercially available design software, PrimaCalc (see appendix 1) A comparison of the results is shown in Table 8.3.

Flow Rate l/s			
	Outlet 1	**Outlet 2**	**Outlet 3**
Theoretical Model within BS EN 12056-3:2000. Based on an outlet effective diameter of 258mm	10.97 l/s	11.15 l/s	11.05 l/s
Theoretical model, commercial software.	9.86 l/s	16.65 l/s	11.68 l/s
Flourometry. Recorded values of flow	9.28 l/s	13.965 l/s	12.172 l/s
Percentage difference between the measured values and the BS theoretical model	10.6%	33%	5.4%
Percentage difference between the measured values and the values predicted by the commercial software	17.5%	20%	10%

Table 8.3 Comparison of recorded rates of flow with values predicted by BS 12056 and PrimaCalc commercial software

Pressure (Bar)			
	Outlet 1	**Outlet 2**	**Outlet 3**
Recorded Pressure	-0.01 bar	-0.116 bar	-0.372 bar
Calculated theoretical model	-0.007	-0.045	-0.42
Percentage difference within the software predicted values against the recorded values	6%	16%	4.2%

Table 8.4 Comparison of recorded pressure with values predicted by BS 12056 and PrimaCalc commercial software

The results of the comparison between the measured and predicted flow rate and pressure show an average difference of 16% for flow rate and 8.7% for pressure. The analysis of the flow rate measurements obtained through fluorometry closely matched the in flow to the gutter which was measured using the calibrated control valves detailed in chapter 3, section 3.8. This confirmed that the method adopted using fluorometry allowed a true representation of the flow capacities through individual outlets to be achieved. Through adaptation of fluorometry, flow rates through individual outlets were accurately determined without any detrimental affect upon the performance of the syphonic system.

Table 8.3 confirms the prediction of the theoretical model in that the syphonic rainwater outlets within the same system, discharge individual flow capacities. When compared with the theoretical models it may be seen that neither the method of calculating flow through an outlet based upon the weir equation nor the solution provided by the commercial software provides a true representation. For example, at outlet 2 the British Standard weir flow equation predicts that for a head of water of 47.2mm the outlet will accept a flow rate of 11.15 l/s. Alternatively, the commercial system design software predicts 16.65 l/s for the same outlet. However, through the use of fluorometry it was determined that the actual rate of flow was 13.97 l/s.

The flow rates predicted by commercially available software are expressly dependant upon the use of the correct values of energy loss, pipe diameter, pipe lengths and pipe direction. In reality it is not always possible to accurately define these input values for individual outlets. Consequently, an amount of uncertainty is associated with a system designed using any proprietary software. Designers should not become to reliant upon the results provided by such software and should proceed with a certain amount of caution. As this investigation used a test facility in which it was possible to accurately measure all the pipe parameters, the application of the software should therefore allow an accurate assessment of the predicted flowrates and pressures within the system. However, as the difference in the measured and predicted flow rate was 16% and for pressure 8.7% it is clear that based on the results of the experimental study that a factor of safety to accommodate the differences should be included within the software. Further validation of the need for such a factor of safety in the software should be completed to assess how the factor of safety changes for gutters and pipes of different size and position. This was considered to be beyond the scope of this thesis.

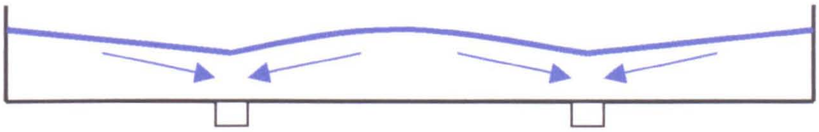
Analyses of the results within this investigation (table 8.3 & 8.4) have indicated that within the recorded values of percentage flow rate there is a standard error of 3.7% across the mean indicating that the values of flow predicted by the commercial software should incorporate a factor of safety in the region of 12% (i.e. mean % - standard error %).

The original hypothesis was that negative pressures within the tailpipes of individual outlets were having an influence on the water depth around an outlet for a given flow rate. However, the investigation has not provided any conclusive evidence that this is the case. Observations and recorded data have shown that water depths within the gutter become more constant and uniform as the syphonic rainwater system reaches the maximum flow capacity, with the redistribution of flow occurring within the gutter itself. This provides a solution to the questions raised in chapter 5 that when calculating upstream depths within a gutter, the factor of safety used within the theoretical model is reduced. This is as a result of the requirement for the redistribution of water within a gutter when installed with a syphonic system.

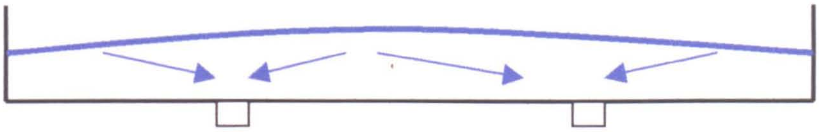
As detailed in figure 7.5, there is a decrease in pressure within the tailpipes of an outlet as its distance from the top of the downpipe decreases. This is to be expected, as calculations show and previous investigations have confirmed (Arthur and Swaffield 1999) that the point of least pressure within a system is generally the top of the downpipe. Table 8.3 highlights this expected reduction in pressure towards the downpipe recording pressures of –0.01 bar at outlet 1, -0.045 bar at outlet 2 and –0.372 bar at outlet 3. From figure 8.12 it may be seen that outlet 3 is closest to the downpipe. However, the flow rates through outlets 1, 2 and 3 are different with the highest value of flow rate. The position of the downpipe is also known to influence the magnitude of the negative pressure within the system, with the largest pressure at outlet 3. Hence, based on the hypothesis that negative pressures have an influence on water depths around an outlet rim, it would be expected that outlet 3 would discharge the largest flow rate.

However, the results obtained in table 8.3 highlight that this is not the case. Hence, it may be concluded that the capacity of individual outlets is dependent on other factors, for example, the resistance to flow within individual pipe sections, and that as a consequence there is a balancing out of the water profile within the gutter such that it becomes more uniform.

This balancing out of the water surface in a syphonic system does not occur in a conventional gutter downpipe system (figure 8.13). Hence, the factor of safety used within the British Standard, to calculate the upstream water depth is reduced due to the fact that the water is redistributed within the gutter in which a syphonic system is used. As already discussed, each outlet has an individual maximum capacity, and hence, in order to satisfy these flow rates, the water redistributes towards the outlet with the greatest capacity effectively producing a levelling off of the water profile.



Water profile within a gutter installed with a conventional system operating at design flow capacity.



Water profile within a gutter installed with a syphonic system operating at design flow capacity.

Figure 8.13 Comparison of water profiles within a gutter, when drainage systems are operating to maximum capacity

8.8 Summary

A method of obtaining flow measurements through individual outlets has been developed without compromising the performance of the system.

Two theoretical models have been compared with recorded values of pressure, flow and water depth.

The capacity of a syphonic rainwater outlet may not be directly determined through the application of weir flow or orifice flow equations given within the current British standard (BS EN 12056-3:2000).

The design software utilised by syphonic drainage companies should encompass a factor of safety within the design to accommodate uncertainties in the routing of pipework, the positioning of outlets and the calculation of energy loss factors.

As a syphonic system reaches its maximum capacity the water is redistributed within the gutter in order to satisfy the capacity of the outlet. This redistribution causes uniformity within water depths, reducing the factor of safety written into the theoretical model. It is suggested that when designing syphonic systems using the British standard theoretical model an additional factor of safety is incorporated within the calculation of upstream depth.

9.0 Conclusions and recommendations for future research

9.1 Conclusions

9.1.1 Introduction

The present study began through the realisation of the fact that in general, the theoretical model for the design of gutters installed with conventional drainage, provided by BS 6367:1983 was being more frequently applied to syphonic roof drainage systems. Primary and secondary syphonic systems were also being installed within gutters on the assumption that the conventional model was applicable to the primary system and that the secondary system was an overflow requiring no analysis within the design of the gutter. In order to analyse the interaction of a primary and secondary system and to compare the performance of the syphonic system to the conventional theoretical model a full-scale experimental system was constructed and tested. Analysis of the information gained from a series of experiments has allowed for a greater understanding of the hydraulic performance of syphonic rainwater systems within gutters. Within chapter 6, a design methodology has been derived, which along with a series of recommendations that have been formulated and are discussed in chapters 6, 7 and 8 it is hoped, will influence the publication of a future British standard code of practice for the design of syphonic roof drainage systems.

9.1.2 The Superseding of the British Standard

The investigations within this programme of study have been based upon the information provided within BS 6367:1983, which at the time of the study was the recognised code of practice for the drainage of roofs and paved areas. Since the experimental stage of this work began, BS 6367:1983 has been superseded by a European standard BS EN 12056-3:2000.

A report entitled 'Manual for the design of roof drainage systems – A guide to the use of European standard BS EN 12056-3:2000', published by H.R.Wallingford (May 2003) states the following:

'Although the calculation procedures for gutter flow stated in BS EN 12056-3:2000 appear quite different from those in the superseded standard, they share a common theoretical basis and method of derivation'

Therefore, the work undertaken within this study which references BS 6367:1983 is still applicable to the revised standard.

9.1.3 Rainwater Outlets

It was concluded that BS EN 12056-3:2000 fails to adequately address the issue of the hydraulic design or performance of syphonic rainwater outlets. The recommended method of calculating the depth of water above an outlet for a given flow rate remains through the use of the same weir or orifice flow equations as stated with BS 6367:1983 together with a factor of safety, as recommended by May (2004). There is however a section within the new standard which recommends a procedure to test the performance of a syphonic rainwater outlet. This procedure is only appropriate to determine the depth against flow profile for a single outlet within a specific gutter or a flat roof. The research presented in this thesis has been to extend this approach such that the depth of flow may be calculated for any gutter width or position of outlet.

9.1.4 Test facility

The construction of the full-scale experimental system produced some inherent problems; typically levelling of the gutter sole, the attainment of a uniform flow along the weir edge which supplies the roof area and the routing of supply and return pipework. All problems were resolved and the final outcome was the construction of a research facility that has through experimentation, provided information that is of significant importance to the syphonic roof drainage industry.

9.1.5 Primary and secondary systems

The initial experiment was to determine the interaction between primary and secondary systems. When tested individually, primary and secondary systems have identical depth / flow characteristics. Contrary to the design of conventional systems, syphonic systems operate at, or close to their maximum capacity. Flow rates above this capacity result in a rapid increase in water depth within the gutter. It is therefore of great importance to understand the hydraulic performance of a system which is designed to operate so close to its maximum capacity. In this study the depth / flow profile of a secondary system was found to be comparable to that of the primary system with the addition of the upstand height. This is particularly important when consideration is given to climate change and the potential for increased rainfall intensities, as systems drain near to their hydraulic capacity there will be an increased potential for failure. However, the impact of climate change is as yet uncertain.

When primary and secondary systems operate within the same gutter, at water depths below the secondary outlet upstand it is the primary system that dictates the flow profile within the gutter. However, once the levels of water reach the level of the upstand, the findings in the thesis showed that the secondary system became the dominant system. Therefore, where primary and secondary systems are installed within the same gutter it is vital that the performance of both the primary and secondary outlets are considered and that the secondary outlet is not neglected as a type of additional overflow.

9.1.6 Upstream water depths

Through application of the equations in BS 6367:1983 to calculate the water depth upstream of an outlet, the theoretical value, which compensated for the 20% factor of safety provided within the standard, highlighted that the recorded upstream water depths were in excess of the predicted depths. This is a clear indication that when the conventional theoretical model is applied to syphonic rainwater outlets, the inherent factor of safety within the standard becomes inadequate. This is of critical importance. Consequently, when using the model to predict upstream water depths associated with syphonic systems it is recommended that in addition to the written in factor of safety of 20%, suggested by May (May 1982), an additional safety factor needs to be incorporated within the theoretical model when applied to syphonic rainwater outlets. In line with the findings reported on in chapter 5, a factor of 16% is therefore recommended.

When syphonic rainwater outlets are equally spaced along the sole of a gutter the theoretical model for weir flow is only applicable at low flow rates. The theoretical orifice flow equation is not applicable to syphonic rainwater outlets.

9.1.7 Outlet position

Flow rate through an outlet was observed to be a function of the position of the outlet within a gutter. Outlets placed at the extreme ends of a gutter were observed, in some cases to increase the flow depth by up to 47% to achieve the same flow rate when compared to the same outlet positioned to accept an equal flow from both sides.

The gutter sole width was shown to have an influence upon the water depth required around an outlet for a given flow rate. Flow depths were observed to increase as the gutter sole width was reduced

To improve knowledge of system performance, a series of charts have been produced (discussed in chapter 6) that identify the water depth required above an outlet within a flat roof or gutter of specifed width or given flow rates.

These charts are based on a new methodology for calculating the required water depth for a given flow rate, around an outlet with respect to its position within a gutter, and the gutter sole width. A worked example of how to use the methodology has been provided. Experiments have shown that the position of an outlet has no detrimental effect upon the performance of the syphonic system, providing all the design parameters (May 2004) of the pipework system are met.

The charts, detailed within chapter 6, have been established for two types of syphonic rainwater outlet, and it is recommended that the methodology may be subsequently applied to all other types of syphonic roof outlet.

A primary finding from the research is that the performance of the syphonic pipe system is independent of the position of the outlets within the system. What is important is the position of the outlet and the relationship between the resultant depth of flow in the gutter. When designing gutter profiles for buildings, it is vital that consideration is given to the outlets position prior to calculating the profile of the water within the gutter.

9.1.8 Flow measurement

A system of measurement using a dye dilution technique was developed to monitor the flow rate in tailpipes of each outlet. The research has shown that syphonic outlets within the same system do not accept equal amounts of flow, and that the upstream depth becomes deeper and the water redistributes along the gutters length towards the outlet with the greatest capacity. As already concluded, this additional depth requirement encompasses the factor of safety within the theoretical model and therefore additional safety factors, of a similar scale to the original should be incorporated when designing syphonic systems for use within gutters. This contrasts with the performance of a conventional system in which each outlet is generally designed to accept equal amounts of flow, therefore allowing the application of the theoretical model to calculate required depths of water at an outlet and upstream.

Alternatively, having determined the capacity of the syphonic rainwater outlets during the design of the system, the methodology may be adapted to space the outlets to accommodate the peak run off from a known roof area.

I.e. Using values of rainfall intensity (mm/h) and an effective roof area (m^2), the rainwater run off from a roof area may be determined. Through manipulation of the effective roof area, by adjustment of outlet spacings, the rainwater run off may be regulated in such a way that it corresponds to the capacity of an outlet. In the opinion of the author this is not a practical methodology and in practice, the author recommends that the design is completed such that the flow depth is allowed to balance out.

9.1.9 System design

Appendix A describes the theoretical representation of the equations used in the commercially available system design software and a review of this theory has highlighted that the performance predictions are expressly dependent upon the use of the correct values of energy loss, pipe diameter, pipe lengths and pipe direction. In reality it is not always possible to accurately predict these input values, specifically when the project is complex. Consequently, system designers should be aware of such limitations and treat the results of the software output with caution. In this study a test facility was used to accurately measure all the pipe parameters, which consequently allowed an accurate assessment of the software predictions. In chapter 9, it was concluded from the results of this investigation that an additional factor of safety, for the syphonic pipework system itself, should be incorporated into the software and a recommendation of a value in the region of 12% is advised. This is in addition to the increasing of the British Standard stated factor of safety by a further 16% recommended within chapter 5 (5.4.1) for the design of gutters.

9.1.10 Summary

In summary therefore, the thesis has concluded that the performance of syphonic systems is much more complex than conventional roof drainage systems. Specifically the thesis has concluded:

- The application of conventional theoretical models for the design of roof gutters, should not be transferred to syphonic systems. Additional factors of safety are required within the conventional theoretical model.
- The use of primary and secondary systems – the secondary system dominates the water depth profile within the gutter.
- It is recommended that additional information on the depth / flow relationship for individual designs of syphonic rainwater outlets, located within both a flat roof and gutter, needs to be determined through experimentation, such that the results for other roof and gutter arrangements may be interpolated.
- The results of the study have shown the sole width of a gutter has an affect upon the depth / flow relationship of an outlet. As the sole width is reduced the depth of flow an outlet increases.
- The proximity of the gutter end has an affect upon the depth / flow relationship of an outlet. The depth of flow at outlets positioned close to the gutter end require an increased flow depth to discharge the same flow rate as outlets located at mid position along the gutter length.
- A methodology to calculate the influence on water depth in any gutter and for any outlet position has been established and from this a methodology is recommended for design purposes.
- The flow depth in a gutter installed with a syphonic system is redistributed between outlets along the entire gutter length.
- A method to measure the actual flow rate through each outlet, of a syphonic system, using fluorometry was developed and it was shown that the flow rate through each outlet of the system was not the

same. This has important implications for design in that at the present time the design codes assume that the same flow rate is drained through each outlet. The results presented in the thesis have highlighted that an additional factor of safety should be used in design to accommodate for this flow between outlets.

- Negative pressures within the pipework of a syphonic system have no influence upon the performance of the syphonic rainwater outlet. The pressure regime within the pipework should be identified in order to:
    - A) Assess the ability of the pipe material to resist the buckling forces implied by the negative pressure.
    - B) Predict the formation of cavitation, which may have a detrimental effect upon the flow capacity of the syphonic system.

9.2 Recommendations for future work

9.2.1 Introduction

This study has provided users of syphonic rainwater outlets with new knowledge and understanding of the performance of systems installed within gutters. Although the study is comprehensive with the resulting methodology providing a new design methodology, defined in chapter 6, section 6.5, there are further areas of research work required in order to fully understand all aspects of the performance of syphonic systems.

9.2.2 Verification

In future, it is recommended that the results presented in this thesis be used to verify the accuracy of other existing or proposed numerical models.

9.2.3 Time varying flows

The work reported in this thesis has presented only steady flow results. Clearly, in practice, storms vary both spatially and temporally. For individual systems, in respect of syphonic action the spatial change may be repeated but the temporal change in the magnitude of the flow rate entering the outlet may influence the performance of the system. Further work is required to assess such changes in performance, particularly in the light of potential climate change scenarios.

9.2.4 Wind driven rain

Within the design of the full scale gutter test rig utilised within this study there is the facility to simulate wind driven rain. As this study has identified, the individual outlets within a syphonic rainwater system operate at various flow rates. Due to the fact that the flow entering the gutter will be non-uniform, the effects that wind driven rain have on syphonic outlets is not fully understood. The priming of syphonic outlets under such conditions may be influenced by the outlet allowing air to enter the system, particularly in outlets that have a low capacity within a gutter. It is therefore recommended that a programme of study be undertaken to assess the effect that high intense wind driven rainstorms have upon the priming of a syphonic rainwater system.

9.2.5 Negative pressure

From this study and the application of commercially available design software, it is evident that the calculation of negative pressure within these programmes does not provide a close relationship with recorded values. Further investigations are required in order to determine an accurate methodology of predicting the distribution of pressures within a syphonic system.

9.2.6 Rainwater harvesting

A syphonic system discharges through a single downpipe, therefore creating a single point discharge ideal for the collection of rainwater. Current rainwater harvesting systems are generally suited to interface to conventional roof drainage. The full bore flow, high flow rates and velocities experienced at the point of discharge of a syphonic system are not compatible with current harvesting practices. The inclusion of filters within the pipes provides additional issues with regard to the restriction of flow. Work is required to interface syphonic systems with rainwater harvesting technology.

9.2.7 Water redistribution

Compared with the relatively uniform flows achieved through the use of a conventional system, a significant conclusion of this thesis is the need for water redistribution when using syphonic systems within a gutter. As a result of the need for redistribution, the water depths are increased within the gutter and consequently factors of safety have been suggested in order to accommodate the additional depth requirement. It is recommended, that through validation using the results from the test facility, a numerical model of the flow regime within a gutter installed with syphonic rainwater outlets be developed for a variety of flow rates. Ultimately, such a tool may be used to provide a full analytical design of the syphonic systems and its interfacing components.

9.2.8 Interfaces

Previous work (Arthur and Swaffield 1999) has provided much needed understanding of the hydraulic performance of syphonic rainwater systems. However, as knowledge of these systems increases, what becomes more evident is the fact that syphonic systems should not be designed as stand alone systems. Syphonic systems are only one component part of a more complex rainwater drainage system, with the other components being the roof, gutter and sewer.

In order to ensure the integrity of the system and that full protection is given to a building, it is vital that the interface between these component parts is considered. As this thesis has provided design recommendations for syphonic systems within gutters, further investigations are required to assess the interface of sewer and syphonic system. This interface must consider the unique discharge conditions provided by the syphonic system, addressing such issues as full bore flow, high velocities and the breaking of the syphonic action. Currently the methodology used by system designers is based purely on theoretical practice and experience of failures, which requires additional verification.

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Appendix 1

PrimaCalc Analytical Design Software For the Design of Syphonic Rainwater Systems

CONTENTS

1. Introduction

PrimaCalc analytical software is a powerful design aid which will enable the designers of syphonic roof drainage systems to rapidly obtain an optimum solution to their drainage problem.

The parameters of the **Primaflow**™ patented self priming syphonic outlets have been embodied within the **PrimaCalc** analytical software. Without these special outlets the syphonic action cannot be created within the syphonic system.

PrimaCalc Analytical software has been written by Fullflow Ltd using Microsoft Visual Basic. The program is designed to run in a Microsoft Windows environment and originates from an earlier program developed by a consultant under contract to Fullflow Ltd. That program operated under the DOS environment and provided successful design solutions over a number of years.

2. Overview

The task that the syphonic roof drainage system designer faces is, to convey the rainfall collected by a roof during a storm which is considered to represent the worst occurrence during the life of the building, to the underground drainage system without risk of the rainwater entering the building. In effect to solve the fluid mechanics problem presented by the rainfall intensity and the height of the building.

PrimaCalc analytical software enables the roof drainage problem to be entered into the computer by creating the pipe system in three dimensions, starting at the discharge point and building up the pipework system towards each of the roof outlets. The design inflow value is then assigned to each of the roof outlets. Following the selection of a suitable piping system material the analytical software carries out a preliminary survey of the drainage problem to select initial pipe diameters from the available range, automatically selecting suitable connections and fittings throughout. The analytical software calculates and displays the water velocities, reserve head at each outlet, the hydraulic losses in each pipe and the system pressure at each node.

PrimaCalc uses mathematical techniques which allow these calculations to be executed rapidly. It also monitors a number of design criteria which need to be satisfied. It ensures for example that at the design flow rate, the water velocity is above 1m/s in all sections of the piping system to promote self cleaning; it checks that the operating pressure is within acceptable limits, that there is a positive pressure reserve at each syphonic outlet and that these reserves are all within a narrow band.

By observing the error messages displayed by **PrimaCalc** and then making corrective changes to the pipe sizes until the error messages disappear the syphonic system designer interacting with **PrimaCalc** optimises the design solution.

Pipework dimensions, flow velocities, operating pressure and reserves are then indicated for the final design. Embedded design limitations minimise the scope for error and assist in optimising the drainage systems design. The ability to simulate the surcharging of the system and to check the efficiency of the final design demonstrate the flexibility of the analysis and confirm confidence in the final solution.
Included within the analysis package is a bill of quantities section which enables the syphonic system designer to optimise for economy of construction by calculating the costs of alternative designs, which would equally satisfy the technical requirements.
Visual information provided by the analytical software includes:

1) A three-dimensional plot of the layout, which supports rotation, pan, zoom and data simplification, features for single and multiple downpipes.

2) Listings of pipe, incorporating velocity, dimensions, losses, operational pressures etc.

3) A list of the pressure reserves at each roof outlet.

4) A list of the location of each node.

5) A listing of the highest negative pressure at a particular node.

6) A graphical display of velocity throughout the piping system.

7) A graphical display of operational pressure throughout the piping system.

8) A graphical display of the piping sizes employed in the design.

9) A summary of the basic information used to produce the design.

10) A list of parts required. This is capable of amendment by the user to incorporate optional items.

Some of the options above are only available as part of a display. Hard copy of the listings is supported by the Reports menu.

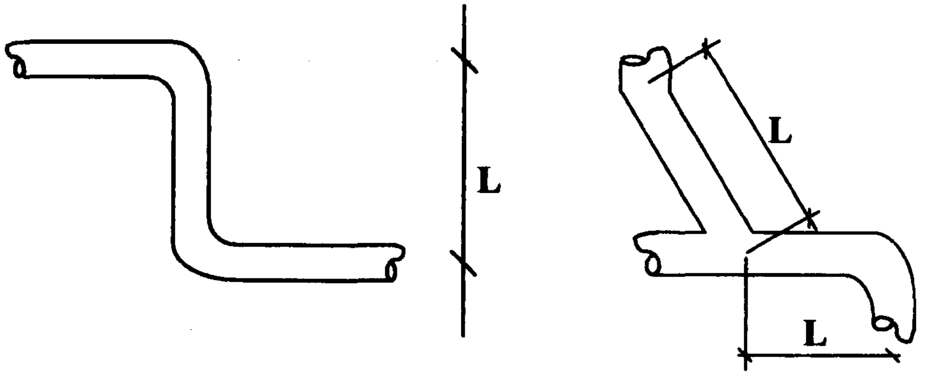
3. Defining The Syphonic Roof Drainage Problem

The basic design information required by the syphonic systems designer is; the detail of the roof layout including the preferred position of the syphonic roof outlets, the location of the connection to the underground drainage system, the design rainfall intensity and potential pipework routes from syphonic roof outlets to discharge.

The design inflow value is assigned to each individual syphonic roof outlet determined from the basic design information on catchment areas and rainfall intensity, in accordance with the principles of:

BS EN 12056-3:2000 Gravity Drainage Inside Buildings.

An isometric diagram of the proposed pipework layout and outlet position is then required to assist the designer in entering the roof drainage problem into PrimaCalc. This diagram should incorporate the desired inflow values and running lengths of pipework between bends and fittings. The lengths should be determined along the centreline of the pipework and from the intersection points of the associated centrelines.



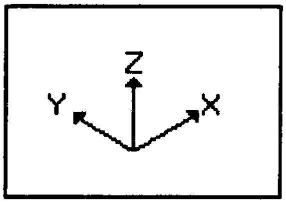
L = running length of pipework required by **PrimaCalc**

When preparing the isometric diagram it should be taken into consideration that **PrimaCalc** only supports the following range of pipe fittings: 45° and 90° bends, 'T' connections, 45° branch connections, concentric and eccentric reducers.

4. Entering The Syphonic Roof Drainage Problem Into PrimaCalc

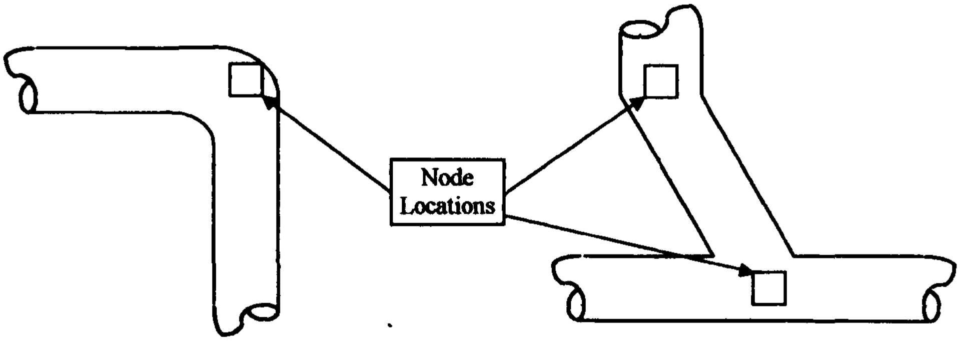
A three dimensional representation of the piping system, starting at the connection to the non syphonic underground drainage (discharge point) and building up the system towards each of the syphonic roof outlets, is introduced into the computer by selecting appropriate lengths and directions for the pipework. The analytical software recognises bends and fittings from the manner of introducing the pipework and will automatically incorporate node points (calculation stations) at bends, fittings and along straight runs of pipe at a maximum spacing of 6m.

PrimaCalc uses a three-dimensional Cartesian co-ordinate system (x, y, and z directions) conventionally with the positive z direction as vertical.



The method of defining the proposed piping network is to select first a direction and then apply a pipe length. The direction is determined by selection from a pre determined list which is complementary to the supported fittings.

The node points (Calculation Stations) are placed at the end of each defined pipe length and correspond to the intersection of each piping length centreline.



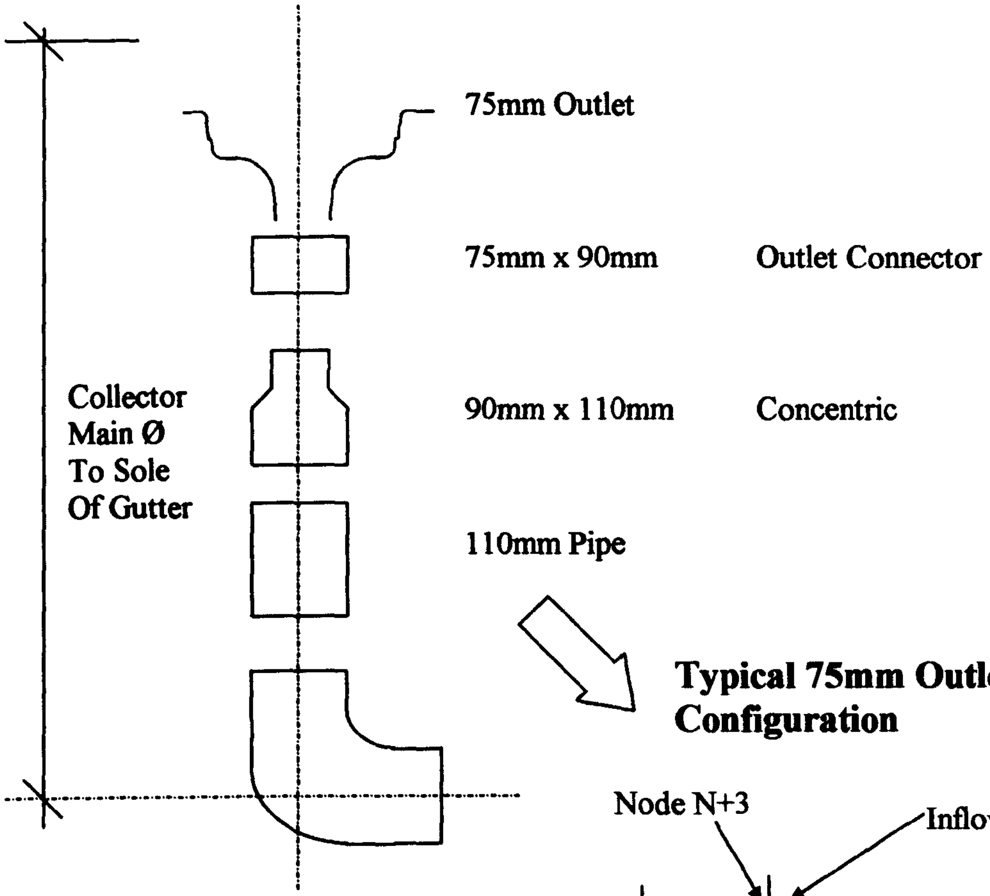
The piping network is progressively built up within **PrimaCalc** until the gutter level or roof level is reached.

The node at this location is then registered as a special type of node called an inflow node. The inflow node represents a **Primaflow**^{TM} self priming syphonic roof outlet and permits the quantity of rainwater entering the outlet and hence the roof drainage system to be specified.

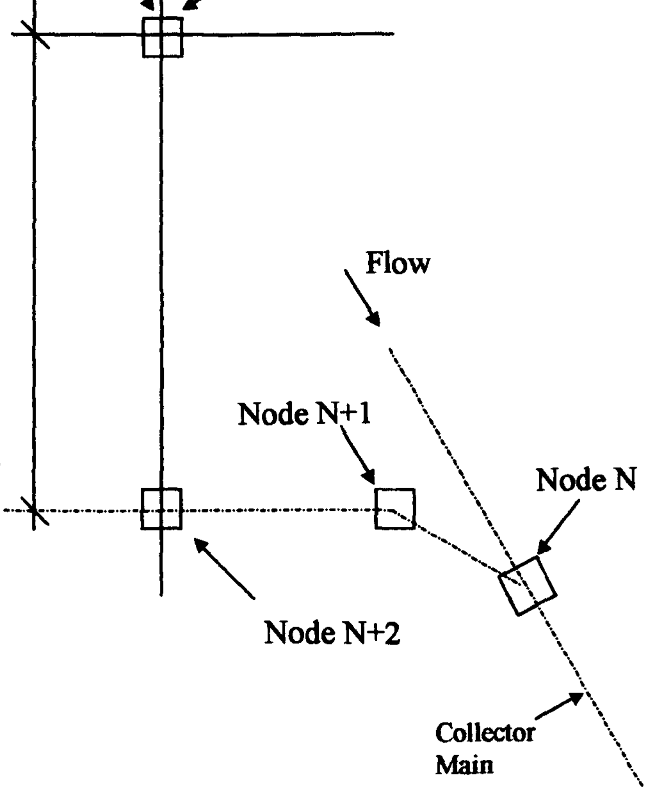
PrimaCalc automatically selects the appropriate sized outlet, outlet connector and reducers as required by the analysis.

A Typical physical and **PrimaCalc** configuration are shown for reference on the next page.

al 75mm Outlet Physical
iguration



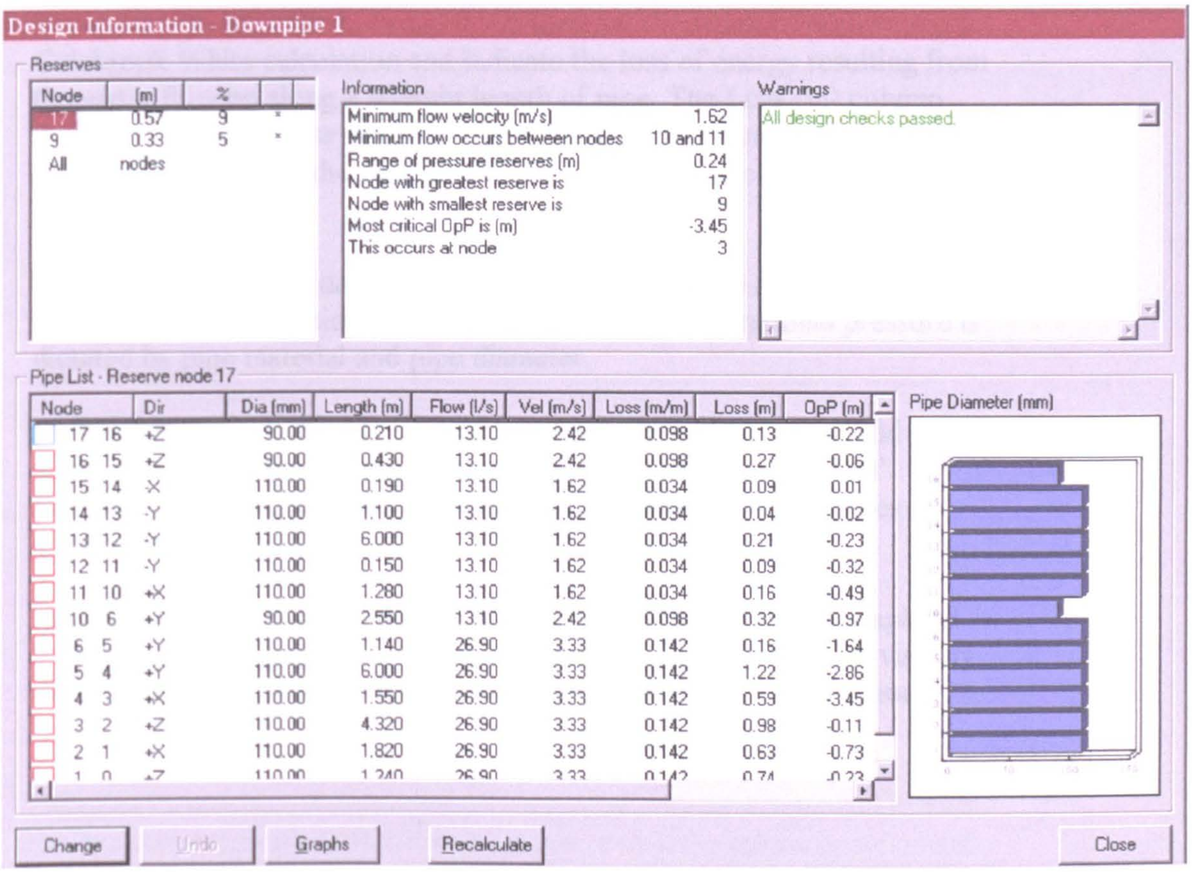
Typical 75mm Outlet Prima Calc Configuration



An initial (first size) automatic analysis provides an estimate of the required pipe sizes. From this initial estimate the syphonic system designer adjusts the piping diameters interactively until the design satisfies inbuilt acceptance criteria and the analytical software returns an 'All Design Checks Passed' message when a technically acceptable solution is obtained.

5. Results of the Analysis of the Syphonic Roof Drainage Problem

The results of the automatic 'first size' or subsequent recalculations are presented in tabular form on screen and are available as hard copy. A typical screen view is shown.



Design Information - Downpipe 1

Reserves

Node	(m)	%	
17	0.57	9	*
9	0.33	5	*
All	nodes		

Information

Minimum flow velocity (m/s)	1.62
Minimum flow occurs between nodes	10 and 11
Range of pressure reserves (m)	0.24
Node with greatest reserve is	17
Node with smallest reserve is	9
Most critical OpP is (m)	-3.45
This occurs at node	3

Warnings

All design checks passed.

Pipe List - Reserve node 17

Node	Dir	Dia (mm)	Length (m)	Flow (l/s)	Vel (m/s)	Loss (m/m)	Loss (m)	OpP (m)
☐ 17 16	+Z	90.00	0.210	13.10	2.42	0.098	0.13	-0.22
☐ 16 15	+Z	90.00	0.430	13.10	2.42	0.098	0.27	-0.06
☐ 15 14	-X	110.00	0.190	13.10	1.62	0.034	0.09	0.01
☐ 14 13	-Y	110.00	1.100	13.10	1.62	0.034	0.04	-0.02
☐ 13 12	-Y	110.00	6.000	13.10	1.62	0.034	0.21	-0.23
☐ 12 11	-Y	110.00	0.150	13.10	1.62	0.034	0.09	-0.32
☐ 11 10	+X	110.00	1.280	13.10	1.62	0.034	0.16	-0.49
☐ 10 6	+Y	90.00	2.550	13.10	2.42	0.098	0.32	-0.97
☐ 6 5	+Y	110.00	1.140	26.90	3.33	0.142	0.16	-1.64
☐ 5 4	+Y	110.00	6.000	26.90	3.33	0.142	1.22	-2.86
☐ 4 3	+X	110.00	1.550	26.90	3.33	0.142	0.59	-3.45
☐ 3 2	+Z	110.00	4.320	26.90	3.33	0.142	0.98	-0.11
☐ 2 1	+X	110.00	1.820	26.90	3.33	0.142	0.63	-0.73
☐ 1 0	+Z	110.00	1.240	26.90	3.33	0.142	0.74	-0.23

The reserve section of the screen (top left hand area) indicates the reserve value and % reserve for each inflow node. A highlight on the particular node will display in the pipe list area (bottom left hand area) all nodes and design information along the pipe network from the chosen inflow node to the discharge (A selection of 'All' in the reserve section will display all nodes in the downpipe network including all inflow nodes).

Other details on this screen indicate the warning status and general information on the design.

The presented pipe list is represented visually in the bottom right hand area by a graph indicating node number and pipe diameter.

The pipe list is important to the designer. Through this area the pipe diameters can be changed and recalculated as the design is refined.

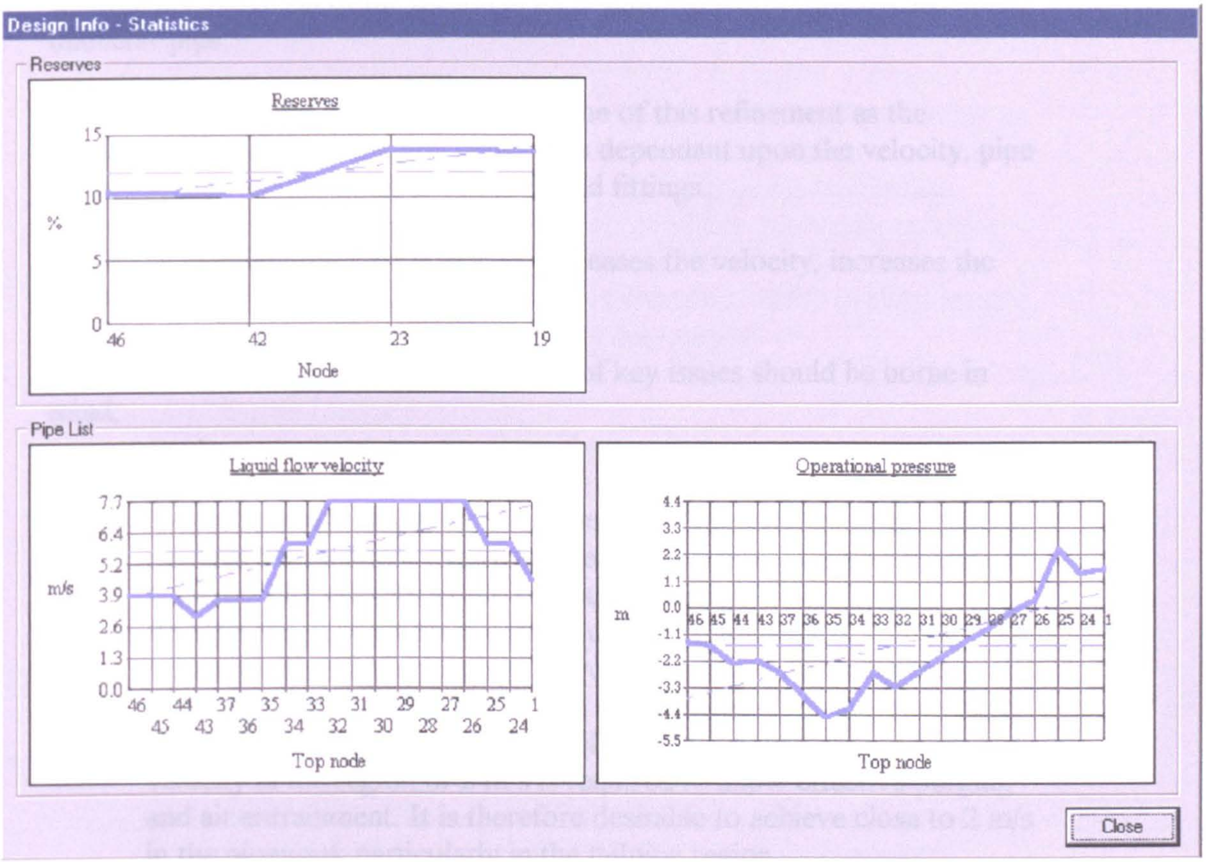
Within the pipe list each individual pipe run is indicated by the associated node at the top (furthest away from the discharge point node 0) and the bottom if the pipe run, a direction, a length and the flow rate. This information confirms that provided by the designer when entering the syphonic roof drainage problem. Additional information provided by the analysis is; an indication of the type of node (inflow nodes are shown as blue squares), the velocity, Loss (m/m), Loss (m) and the operating pressure (m).

The values given in the Loss (m/m) column are the result of performing the Colebrook White calculation and indicate the loss of energy resulting from the water flowing along a straight length of pipe. The Loss (m) column represents the total loss value for that particular pipe run and includes the Loss (m/m) value for the pipe length and any other losses incurred through bends, fittings etc.

The values of operational pressure indicate the pressure at the top node of the pipe run. A restriction on acceptable values for operational pressure is dictated by pipe material and pipe diameter.

By highlighting a particular top and bottom node in the pipe list and selecting **Change** the chosen pipe run diameter can be adjusted. If **Recalculate** is then selected the analysis is repeated and new values displayed.

The velocity, operational pressure and reserves are available in graphical form by selecting graphs on the pipe list screen. The graphs show visually the effect and limits of the three parameters against the node locations.



6. Refining the Solution to the Syphonic Drainage Problem

It is unlikely that the initial automatic analysis will provide a satisfactory solution. The design needs to be refined in an interactive manner by manipulation of piping diameters and recalculation until the analysis software returns an 'All design checks passed' message.

The options available when refining the design are; to increase or decrease the pipe diameter or to change the pipe length.

Efficient refinement of the design is developed only with experience. As a guide however, begin the refinement process with the inflow node located nearest to the downpipe. Modify the pipe diameters usually by choosing a smaller diameter, and observing the reserve value, continue changing pipe diameters until the reserve value approaches that of the inflow node remote from the downpipe. The process is subsequently repeated progressing from the inflow node nearest the downpipe to the inflow node remote from the downpipe.

The primary object of this exercise is to match as closely as possible the resistance to flow provided by the pipe network (from outlet to discharge) to the height of the building. A secondary objective is to produce the most cost effective design generally this entails minimising the pipe diameters by suitable manipulation of the design in an attempt to restrict the use of large diameter pipe.

A number of parameters affect the outcome of this refinement as the resistance provided by the pipe network is dependant upon the velocity, pipe diameter, pipe length, number of bends and fittings.

Generally reducing the pipe diameter; increases the velocity, increases the resistance and reduces the reserve value.

During this refinement process a number of key issues should be borne in mind;

a) Velocity

PrimaCalc will return an error message if the velocity in any pipe run falls below 1 m/s. However there are no limitations on maximum velocity. The velocity of the rainwater passing through the piping system can affect the syphon action. A high velocity will assist in purging air from the pipework during the priming phase and enable effective entrainment of air into the water flow there by ensuring that the syphonic action is maintained. A velocity in the region of 2 m/s is required to allow effective purging and air entrainment. It is therefore desirable to achieve close to 2 m/s in the pipework particularly in the tailpipe region.

At high velocities (approaching 8 m/s) cavitation is likely to occur within syphonic systems. This is a spontaneous release of dissolved gasses within the water. The inevitable collapse of the gas bubbles produced can have a detrimental effect on the pipework resulting ultimately in failure through leakage. Therefore maximum velocities should be limited to around 8 m/s.

The flow of rainwater discharged to the underground drainage system or from any secondary syphonic system will possess energy relating to its velocity. This energy is dissipated at the discharge. A high velocity jet of water issuing from the discharge of a syphonic system can therefore have a detrimental effect on any manhole or area the jet contacts. It is desirable to restrict the discharge velocity to a value of the order of 3 m/s to minimise this adverse effect.

b) Reserve

The reserve values returned by the analysis for each inflow node (syphonic outlet location) are a measure of how well the resistance presented by the piping network has been matched to the height of the building. It is also an indication of how much extra rainwater can be introduced into the system as designed. For multiple outlet installations it is important that the spread of reserve values are restricted to a small value typically less than 1m. In achieving the 'balance' of the system in this way (all inflow reserve values are approximately equal) ensures that the multiple outlets will operate simultaneously during service. In effect all outlets will prime at the same time rather than some outlets priming whilst others are still admitting air.

The target for the reserve values are less than 10% and preferably as close to zero as possible and a spread of reserves not to exceed 1m. This target cannot always be achieved owing to the limitations placed by the range of pipe diameters available. Generally reducing pipe diameters reduces the reserve values. A common solution to reducing the reserve values is to incorporate a choke (a short length of smaller diameter pipe) within the downpipe.

c) Operational Pressure

Syphonic systems can generate vacuum (below atmospheric or negative) pressures during operation. The analysis presents values of operational pressure for each node point on the piping network. The pipework and jointing methods used must be capable of accommodating the variations in operational pressures (positive and vacuum) which occur in service.

The stress analysis of each case (positive or vacuum) presents substantially different results. A pipe which will withstand an internal positive pressure of 4 bar will not withstand a vacuum pressure of 4 bar. Generally the vacuum case is the more concerning in that smaller values are permissible. The common pipework materials employed on syphonic systems have positive pressure capabilities which exceed the operational duty. The vacuum capability is determined by wall thickness and pipe diameter. Acceptable vacuum limits are as follows:-

PIPE MATERIAL	PIPE DIAMETER	ALLOWABLE VACUUM PRESSURE
HDPE	160mm and below	8mWc
HDPE	200mm and above	4mWc
HPPE	200mm and above	8mWc
B M Stainless	50, 75, 110mm	8mWc*
B M Stainless	160mm	5mWc
Cast Iron		8mWc

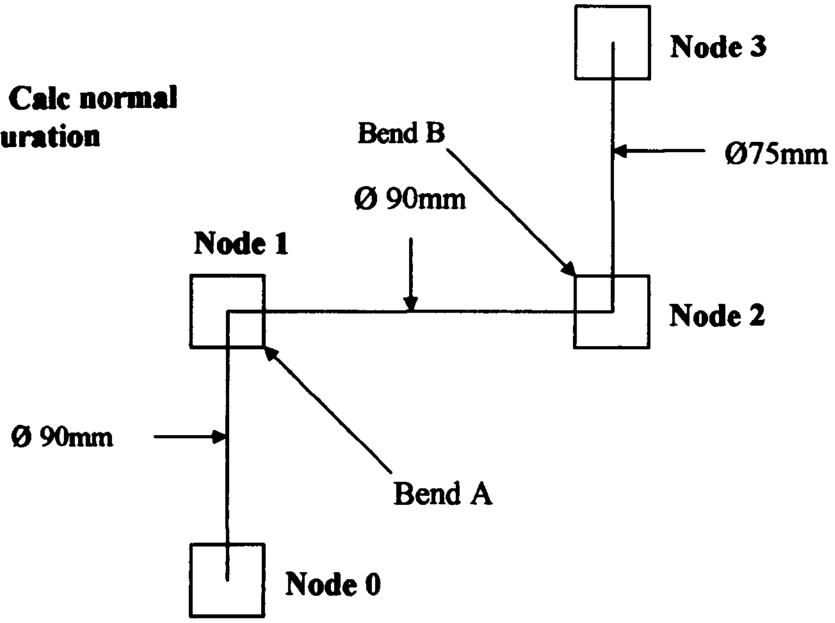
*When used with special 'O' Ring Seals to the joints.

Reducing certain pipe diameters particularly those close to the top of the downpipe will have the effect of increasing the value of vacuum pressure (say by changing from -6mWc to -8mWc). Placing the downpipe choke too close to the top of the downpipe will have a similar effect.

When refining the design in the region of bends it is important to understand how PrimaCalc visualises the pipe network and the effect of velocity on the resistance of bends.

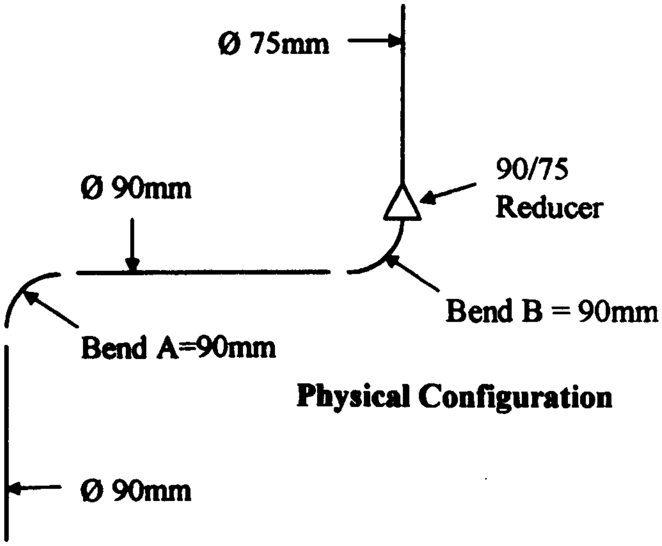
The resistance to flow through a bend is proportioned to the velocity (high velocity high loss) thus a 75mm 90° bend will have a greater resistance to the same flow rate than a 90mm 90° bend.

Considering a pipe network building up from the discharge (Node 0) consisting of a vertical pipe then a 90° bend (Bend A) then a horizontal pipe then a 90° bend (Bend B) and finally a vertical pipe as shown.



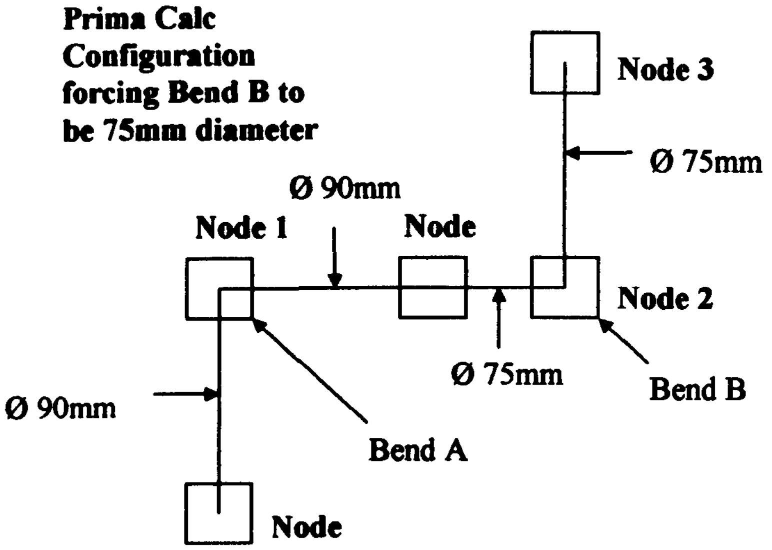
Prima Calc normal configuration

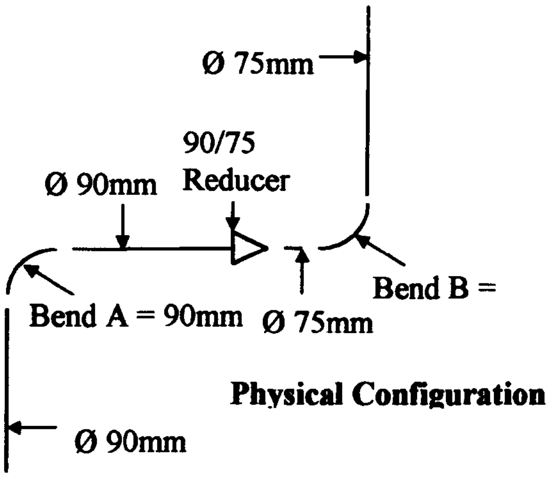
If the first size calculates a 90mm pipe for the vertical and horizontal pipes and a 75mm pipe for the final vertical pipe PrimaCalc will assume that bend A is 90mm and bend B is 90mm followed by a reducer to accept the 75mm pipe.



Physical Configuration

To increase the loss through this pipe network it may be required to 'force' **PrimaCalc** to consider bend B as 75mm diameter. In order to do this a short length (50mm or so) of 75mm diameter pipework has to be introduced into the system prior to Bend B.


Prima Calc Configuration forcing Bend B to be 75mm diameter


Physical Configuration

This then would increase the losses through the network by increasing the loss at bend B owing to the increase in velocity. This activity also has the effect of reducing the reserve values and may alter the operational pressure values at bend A.

7. Acceptance Criteria

The sizes of pipes are altered by the syphonic system designer and the analysis repeated until an acceptable layout is achieved and the analysis package returns the 'All design checks passed' message.

To satisfy all design checks the following must be obtained:-

a) Minimum Velocity ≥ 1 m/s

b) Operational pressure at any point > -8 mWC (i.e. > 0.2 bar absolute)

This is a general value based on the properties of water however, when designing syphonic roof drainage systems using the preferred piping system, HDPE, the value is modified as follows:-

-8 mWC for pipe sizes up to and including 160mm diameter.
-8 mWC for pipe sizes 200mm diameter and above.

c) Difference between Maximum and Minimum Pressure Reserve < 1mWC

d) Value of % Reserve Capacity should be in single figures and close to zero.

An ultimate flow (Q ultimate) calculation must be executed prior to printing out reports. This feature performs further interations by incrementing the inflow by a small amount and recalculating the system values until; a) the range of Pressure Reserve converges or b) the iteration limit set by the designer is exceeded. This condition of ultimate flow represents the maximum capacity of the system design and represents the most severe operating condition.

8. Calculations Incorporated Within PrimaCalc

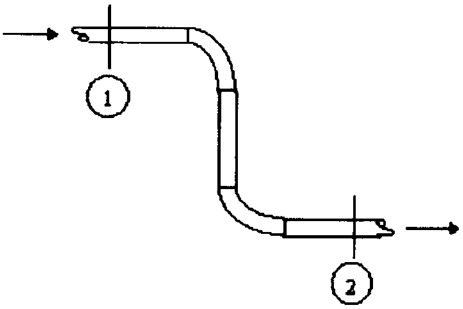
The basic fluid mechanics formulae embodied within **PrimaCalc** are Bernoullis's energy equation and the Colebrook-White equation (sometimes referred to as Prandtl - Colebrook).These equations are evaluated at each node in the computer piping network and the results presented in the appropriate reports within **PrimaCalc**.

Validity Of Formulae

The Colebrook-White formula is almost an 'industry standard'. Further evidence in support of the choice can be obtained by reference to the proposed European standard for Gravity Drainage Systems Inside Buildings Part 3: Roof Drainage, Layout and Calculations: prEN 10256-3: 1995 which defines in section 3.6 "Syphonic Drainage Systems: Drainage system in which the outlets and pipework enable the system to flow completely full under design conditions and make use of the total head available between the outlets and any established hydraulic equation........in cases of dispute the Prandtl -Colebrook equation shall be used."

The primary activity is involved in determining the energy losses associated with the flow of water through the piping network. Bernoulli's energy equation uses the loss values obtained to predict the other parameters such as operational pressure. The Colebrook-White formula is used to determine the loss factor for flow through the piping network. This formula is solved using iterative techniques embedded in the analysis program to establish the loss for each section of pipe. The losses through fittings are calculated by means of a loss factor applied to the kinetic energy of the flow through the fitting, a conventional pipework design technique.

Bernoulli's energy equation is used to determine the change in flow conditions between two points in the system and is conveniently expressed as:

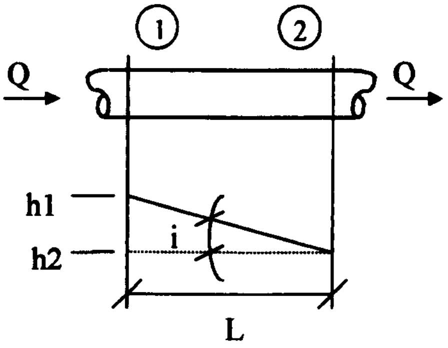


$$(h_1 - h_2) + (z_1 - z_2) + \frac{Q^2}{2g}\left\{\frac{1}{(A_1)^2} - \frac{1}{(A_2)^2}\right\} = K_{1,2}\frac{Q^2}{2g(A_2)^2}$$

The terms on the left hand side of the equation indicate the changes in the total energy of the flow, attributable to the pressure energy (h_1 - h_2), potential energy (z_1 - z_2) and the kinetic energy corresponding to the velocity of the flow.

The two terms on the right hand side of the equation determine the loss of total energy between point 1 and the downstream point 2. The first term is an expression of the losses at bends, fittings and changes in cross-sectional area. The remaining term accounts for the frictional losses of the length of pipe $L_{1,2}$ between the two points. Evaluation of the energy gradient $i_{1,2}$ (head loss in m per m length of pipe) is commonly obtained from the Colebrook-White formula:

$$i = \frac{Q^2}{8gA^2D}\left\{\log_{10}\left(\frac{ks}{3.7D} + \frac{2.51\nu}{D\sqrt{2gDi}}\right)\right\}^{-2}$$



This equation involves factors including the pipe diameter, surface roughness and viscosity of the liquid
and the formula is solved using iterative techniques embedded in the analysis program to establish the loss for each section of pipe.

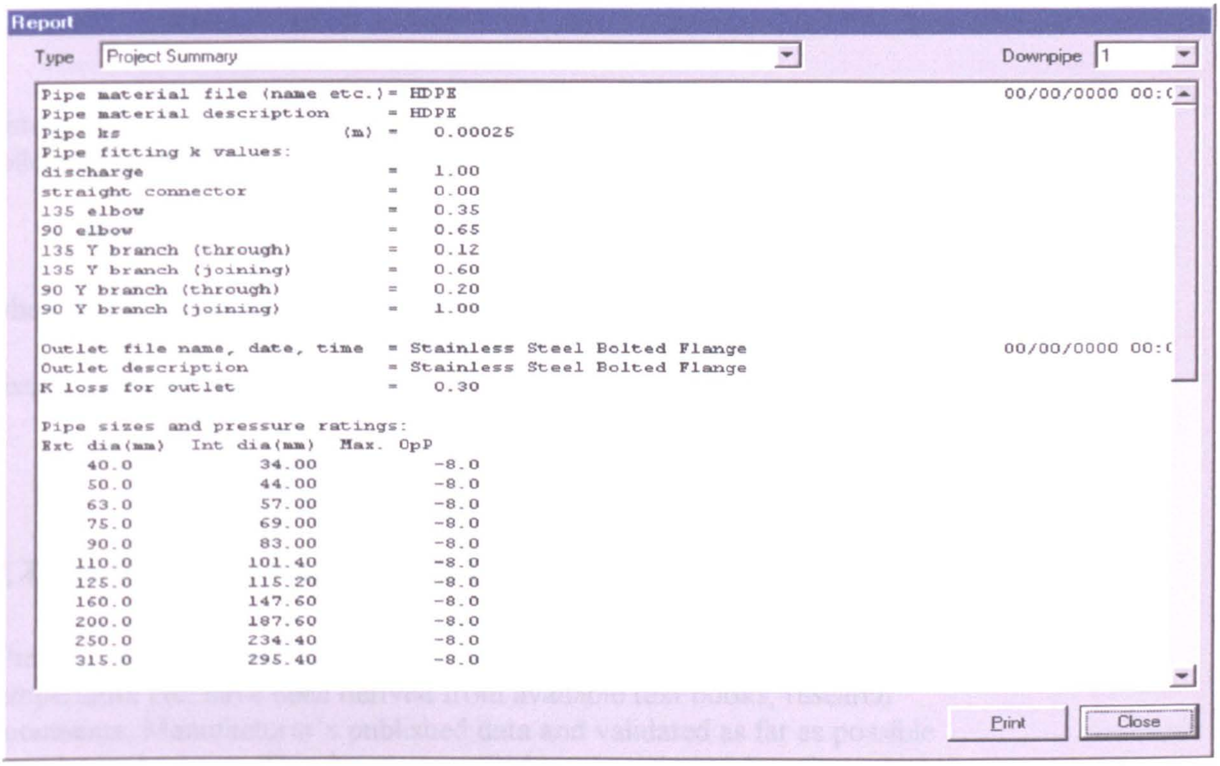
Pressure losses at each restriction to flow (inlet, outlet, reducer, bend, branch etc) are calculated in relation to the velocity term of the Bernoulli equation as follows:-

$$\text{Pressure loss} = \frac{Kv^2}{2g}$$

where: K = the loss factor for the component under consideration
v = the velocity
g = gravitational constant

The values for the loss factor are dependent upon the geometry of each component and may also vary on the severity of the change in velocity or direction. Loss factors have been derived from available text books, research documents, manufacturer's published data and validated as far as possible on text rigs.

Analysis factors are available to the analytical software in the form of data files and by use of multiple files various alternative pipework materials and systems can be accommodated. The factors used by a particular design are printed out on the project summary report.



```
Pipe material file (name etc.)= HDPE                                    00/00/0000 00:
Pipe material description      = HDPE
Pipe ks                   (m) =    0.00025
Pipe fitting k values:
discharge                      =    1.00
straight connector             =    0.00
135 elbow                      =    0.35
90 elbow                       =    0.65
135 Y branch (through)         =    0.12
135 Y branch (joining)         =    0.60
90 Y branch (through)          =    0.20
90 Y branch (joining)          =    1.00

Outlet file name, date, time   = Stainless Steel Bolted Flange          00/00/0000 00:
Outlet description             = Stainless Steel Bolted Flange
K loss for outlet              =    0.30

Pipe sizes and pressure ratings:
Ext dia(mm)  Int dia(mm)  Max. OpP
    40.0         34.00        -8.0
    50.0         44.00        -8.0
    63.0         57.00        -8.0
    75.0         69.00        -8.0
    90.0         83.00        -8.0
   110.0        101.40        -8.0
   125.0        115.20        -8.0
   160.0        147.60        -8.0
   200.0        187.60        -8.0
   250.0        234.40        -8.0
   315.0        295.40        -8.0
```

First sizing of the syphonic system determines an appropriate piping diameter by using the flow rate in the pipe, a maximum velocity of 10 m/s and the smallest pipe diameter available which would satisfy that condition. The pressure loss in each pipe run is then calculated by assuming an initial value and iterating until a suitable fit is obtained based on velocity and pipe dimensions. A value for the total loss for each pipe run is then determined by combining the loss for the pipe with losses attributable to fittings, bends etc.

The operational pressure is then determined for each node from the following calculation;

$$P_k = (O_h - N_h) - \Sigma P_L (o_N c_N) - \frac{v^2}{2g}$$

where P_k = Operational pressure
O_h = Outlet head (dimension in z direction)
N_h = Node head (dimension in z direction)
P_L = Pipe loss between Outlet Node (o_N) and current Node (c_N)
v = Velocity (at the current Node)
g = gravitational constant

Finally the pressure reserve for all outlet nodes is determined from the following equations:-

$$\text{Pressure Reserve} = R_T - L$$

where R_T = (Height of Outlet - Height of Discharge Point)
L = Σ (All losses between Outlet and Discharge including the discharge loss)

$$\%\ \text{Reserve Capacity} = \left(1 - \frac{L}{R_T}\right) x100$$

9. Data Files Associated With PrimaCalc

The analysis factors associated with the surface roughness, fittings loss, temperature etc. have been derived from available text books, research documents, Manufacturer's published data and validated as far as possible on in house test rigs. This data is compiled into a series of data files which are used by Prima Calc in the design of the system. The appropriate data files are selected as part of the Project Options setup.

In addition to calculating information the data files contain lists of part numbers, permissible fittings and fittings combination pricing and fabrication times. Normally the data files are transparent from a Prima Calc users viewpoint.

Appendix 2

A2.0 History of the Development of Syphonic Rainwater Systems

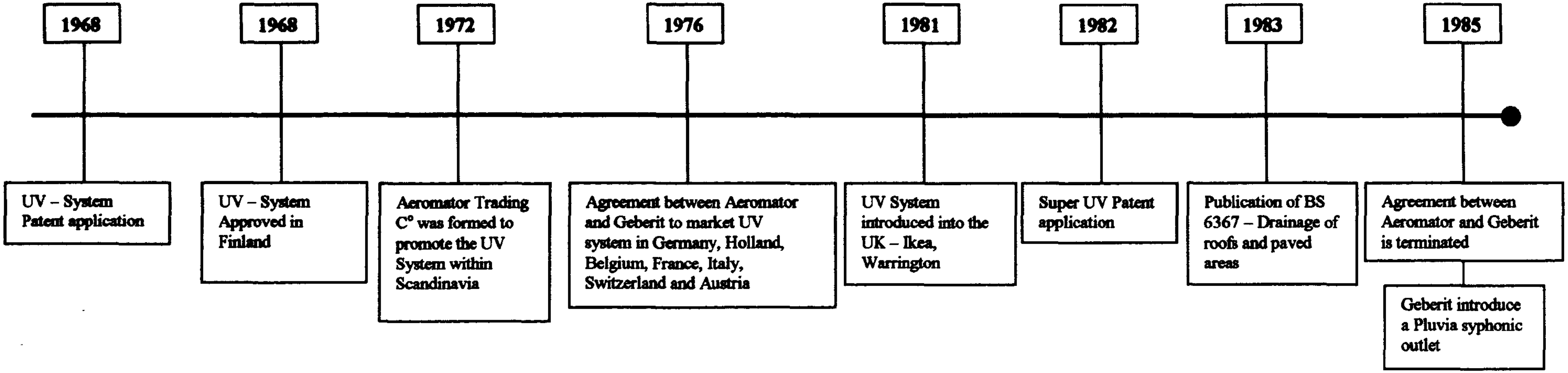


Figure A2.1 History of Syphonic System Development 1968 - 1985

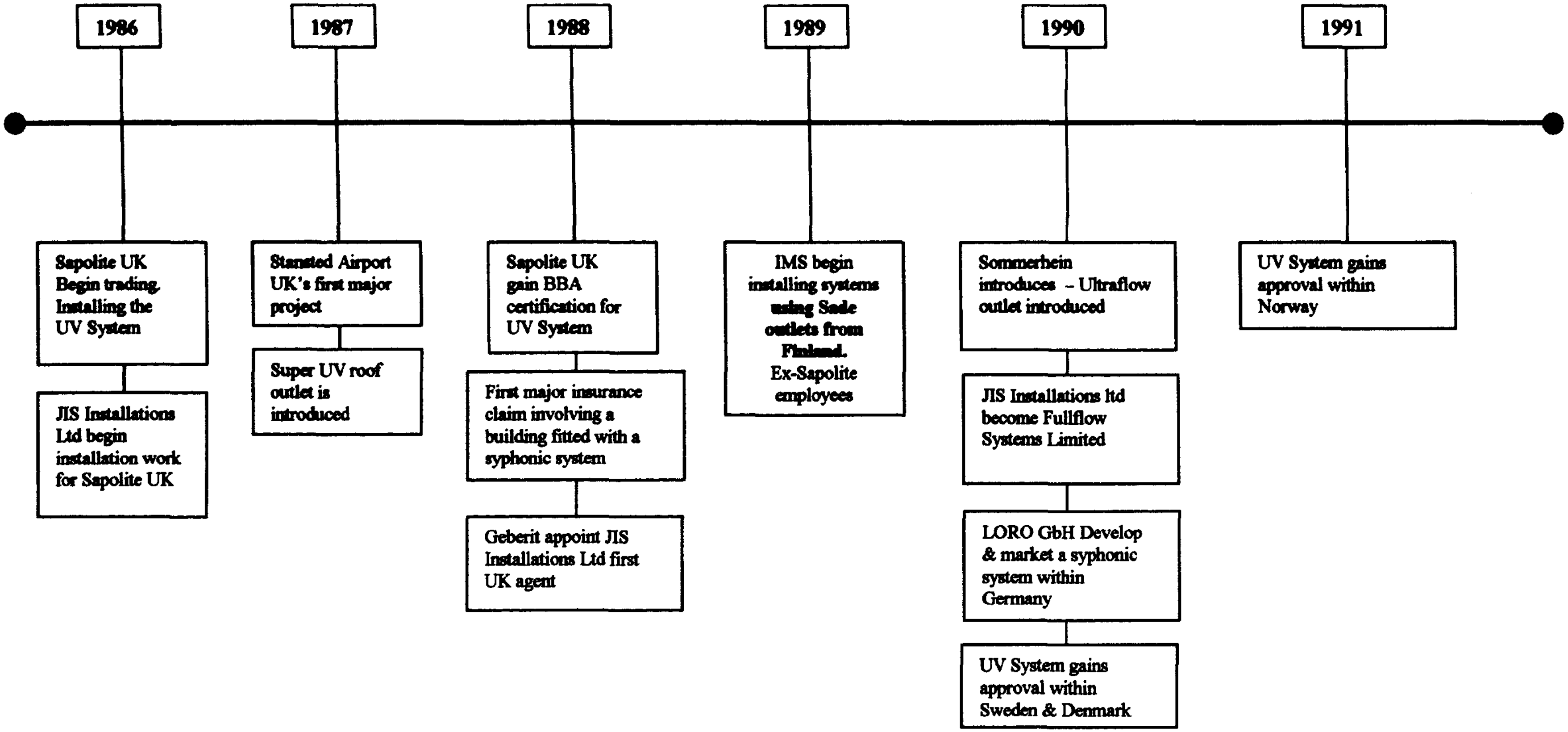


Figure A2.2 History of Syphonic System Development 1986 - 1991

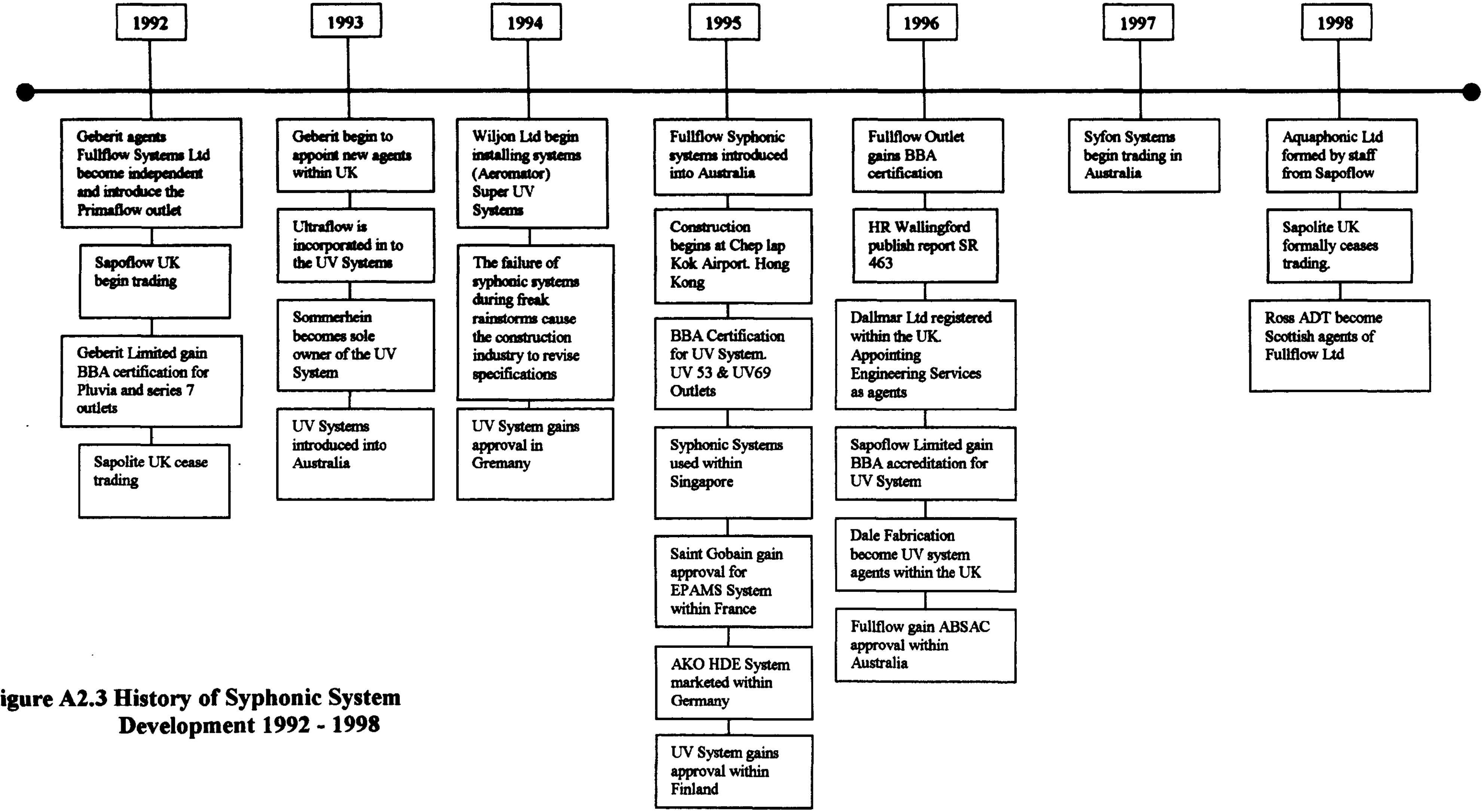
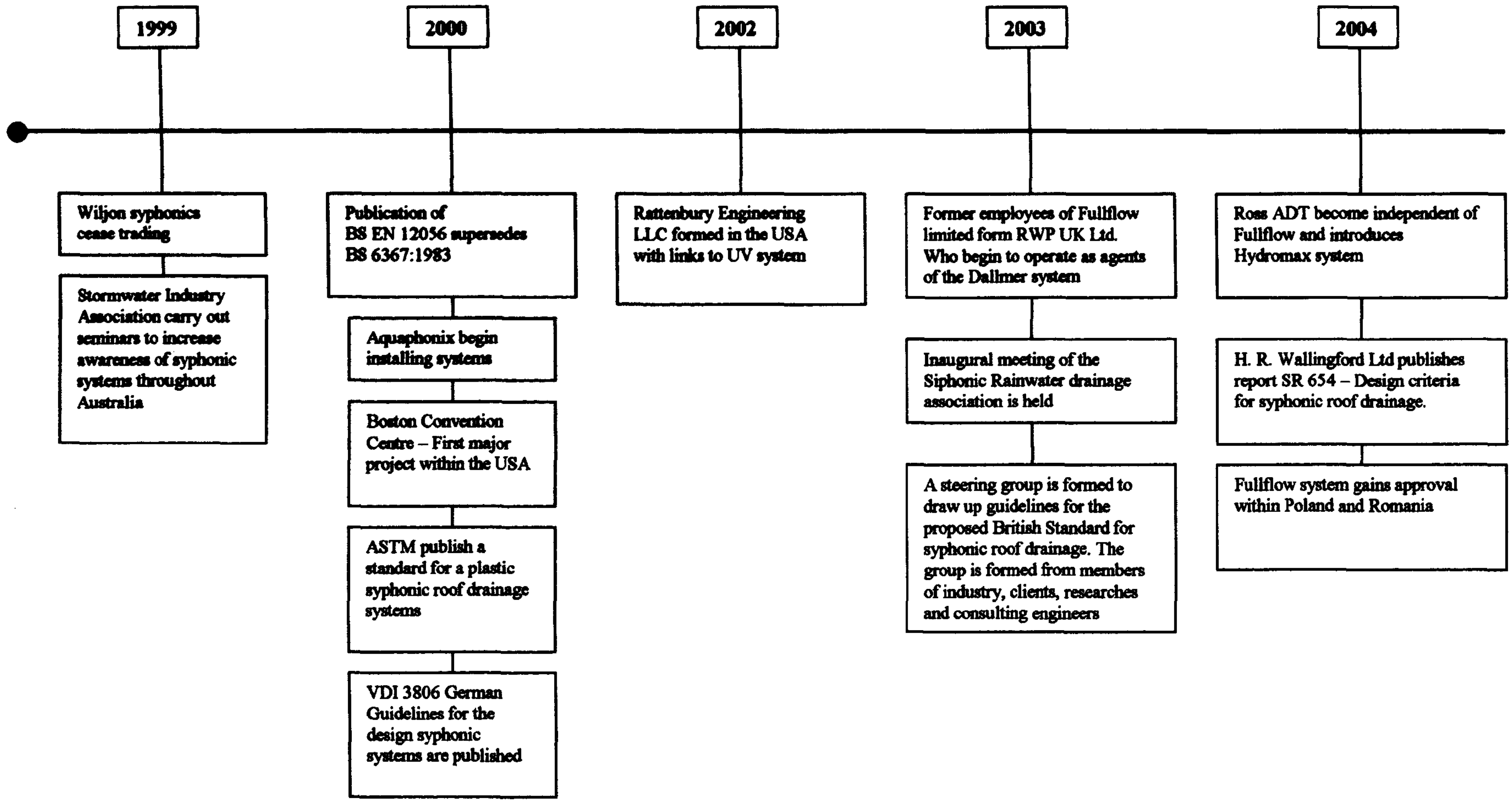


Figure A2.3 History of Syphonic System Development 1992 - 1998



1999

Wiljon syphonics cease trading

Stormwater Industry Association carry out seminars to increase awareness of syphonic systems throughout Australia

2000

Publication of BS EN 12056 supersedes BS 6367:1983

Aquaphonix begin installing systems

Boston Convention Centre – First major project within the USA

ASTM publish a standard for a plastic syphonic roof drainage systems

VDI 3806 German Guidelines for the design syphonic systems are published

2002

Rattenbury Engineering LLC formed in the USA with links to UV system

2003

Former employees of Fullflow limited form RWP UK Ltd. Who begin to operate as agents of the Dallmer system

Inaugural meeting of the Siphonic Rainwater drainage association is held

A steering group is formed to draw up guidelines for the proposed British Standard for syphonic roof drainage. The group is formed from members of industry, clients, researches and consulting engineers

2004

Ross ADT become independent of Fullflow and introduces Hydromax system

H. R. Wallingford Ltd publishes report SR 654 – Design criteria for syphonic roof drainage.

Fullflow system gains approval within Poland and Romania

Figure A2.4 History of Syphonic System Development 1999 - Present

A2.1 History of syphonic rainwater systems

A summary of the historical development of syphonic roof drainage systems is shown in figures A2.1 – A2.4.

The concept and design of syphonic rainwater drainage systems was initiated through the work of Scandinavian engineers Ove Ebling and Risto Lunden, in 1968, they patented their roof drainage outlet in the United Kingdom. Ebling began working closely with a consulting engineer Dr Per Sommerheim in order to further develop his original concept. As a result of this collaboration the UV system was introduced. To promote the use of this system, originally within Scandinavia, the Aeromator trading Company was formed in 1972.

Plate A2.1 Ebling & Sommerhein (UV 50) outlet 1973 - 1989
Photo supplied courtesy of Sommerhein AB

In 1976, an agreement between Aerometor and Swiss plumbing giants, Gerberit was drawn up, in order that Geberit could market the system within a number of European countries including: Holland, Germany, Italy and Switzerland. Within the United Kingdom, a Danish company, Sapolite

Limited, introduced the UV system under a licence agreement. The first project of the new company was the installation of a syphonic system within a building at Warrington, owned and operated IKEA. In 1982, the super UV rainwater outlet was granted its UK patent.

British Standard Code of Practice for the drainage for roofs and paved areas was published in 1983. The introduction of this standard had a significant influence on the effectiveness of syphonic systems, in that it allowed the designer to select an appropriate rainfall intensity. In 1985 the agreement between Aeromator and Gerberit was terminated, as Geberit introduced its own Pluvia syphonic rainwater outlet

The following year, Sapolite began installing the new UV system primarily through the use of sub contractors. One of these contractors was a company named JIS Installations who later became Fullflow Systems Limited.

Norman Foster Associates and Ove Arup Engineers chose the 'new' syphonic system to drain the airport terminal at Standsted Airport during 1987. The following year the British Board of Agrement issued their first certification of a syphonic system to Sapolite UK Ltd. Also, during 1988 Gerberit began to appoint UK Agents, one of who was JIS Installations Ltd, formally a Sapoflow sub contracting company. It was around 1988 that insurance companies received the first report of serious flooding of a building installed with a syphonic system.

The Scandinavian systems, some of which had 15 years of trouble free operation, began to gain popularity within the UK to such an extent that individuals who were employed by the UK agents of the Scandinavian systems began to form their own manufacturing and installation companies. Many installers had little experience and consequently, the number of problems associated with installation began to rise. Many 'specialist' companies were formed, for example, IMS Ltd was formed in 1989 by staff formally employed by Sapolite UK Ltd. They supplied and installed the Scandinavian outlets.

During this time Dr Per Sommerheim had continued to gain further understanding of the operation of syphonic systems and introduced his latest outlet, Ultraflow in 1990.

Plate A2.2 Sommerhein Outlet (Sweden circa 1989)
Photo supplied courtesy of Sommerhein AB

This year also saw JIS Installations become Fullflow Systems Limited.
1992 was an eventful year for the UK syphonic industry.

Plate A2.3 Geberit Series 7 Outlet
Graphic supplied courtesy of Geberit Limited

Gerberit Ltd gained British Board of Agrement certification for the Pluvia and series 7 outlets (Plate A2.3) whilst Fullflow Systems terminated their agreement with the introduction of the Primaflow outlet (Plate A2.4). This outlet was developed with partial financial assistance of the Department of Trade and Industry. Sapolite UK Ltd ceased trading with their business being taken over by Sapoflow Ltd.

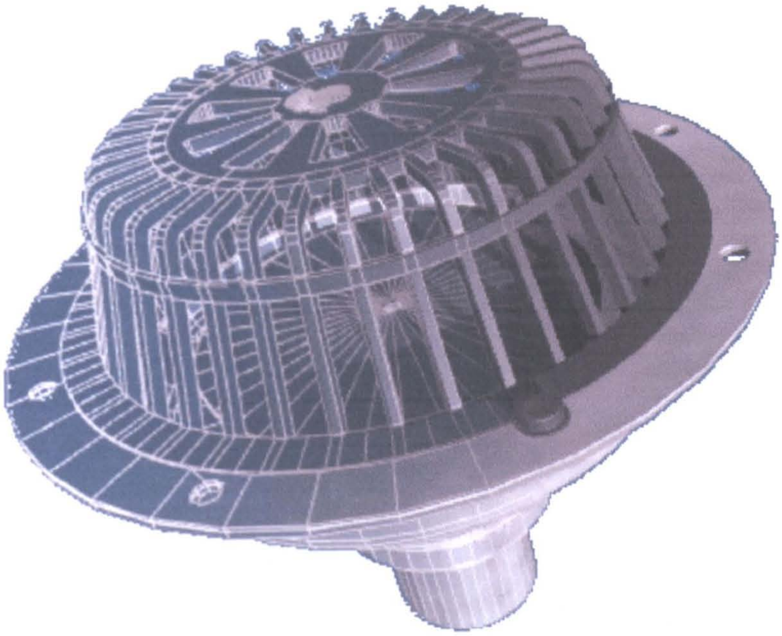
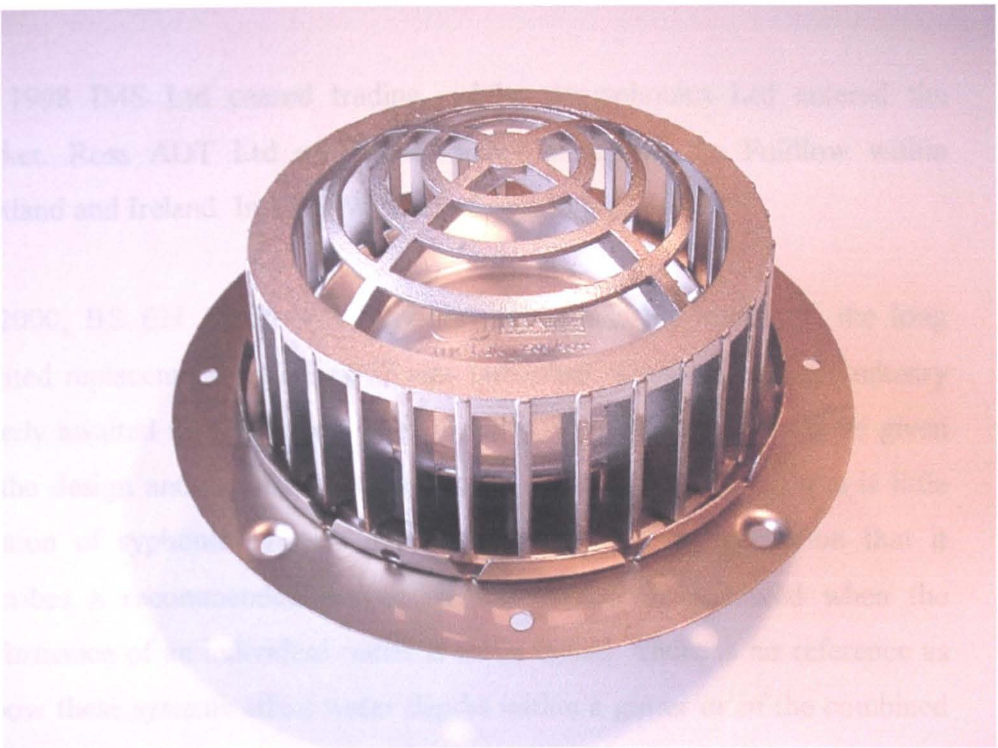


Plate A2.4 Fullflow Primaflow Outlet (UK circa 1992)
Supplied courtesy of Fullflow Group Limited

Hence, in 1993, the UK market now consisted of 4 major companies for the supply of syphonic systems. Gerberit, IMS, Sapoflow and Fullflow Systems. Between these companies there were approximately 7 different types of syphonic roof outlet.

Wiljon Limited was formed in 1994 and they designed and installed aeromator super UV systems. It was during this year that a freak storm incident resulted in the flooding of numerous large warehouse buildings on a business park in the Midlands. The resulting insurance claim eventually became a catalyst from which a greater understanding of the holistic design of syphonic systems developed. The construction industry began to revise the specifications with regard to rainwater systems, especially the choice of design rainfall intensity and the use of primary and secondary syphonic systems.

The UV system with UV53 and UV69 outlets received BBA certification in 1995.



PlateA2.5 Sommerhein (UV69) outlet 1993 to present
Photo supplied courtesy of Sommerhein AB

In 1996 the Department of Trade and Industry received an increasing number of reports of water ingress into buildings installed with syphonic roof drainage systems. This caused concern that resulted in the DTI funding a programme of investigation to determine the accuracy of the manufacturers design software. The resulting report produced by H. R. Wallingford (May and Escarameia 1996) was to become the authoritative independent publication on the performance of syphonic systems within gutters. However, although the title suggests that the water depths within a gutter would be the main consideration, a minimal amount of results of depth vs. flow within a gutter were presented and discussed within the report (see literature review).

A further two syphonic companies namely, Sapoflow and Fullflow, gained BBA accreditation during 1996, whilst a German company, Dallmer Limited appointed Engineering Services Limited as it's first UK agent.

By 1998 IMS Ltd ceased trading, whilst Aquaphonics Ltd entered the market. Ross ADT Ltd of Dundee acted as agents for Fullflow within Scotland and Ireland. In 1999 Wiljon Ltd ceased trading.

In 2000, BS EN 12056 – 3. Gravity drainage inside buildings, the long awaited replacement for BS 6367 was published. The construction industry eagerly awaited this document with the hope that guidance would be given on the design and installation of syphonic systems. However, there is little mention of syphonic systems in the standard with the exception that it describes a recommended procedure that should be followed when the performance of an individual outlet is to be tested. There is no reference as to how these systems affect water depths within a gutter or of the combined performance of primary and secondary systems within the same gutter.

In 2000 the UK syphonic drainage industry comprised of 5 major system producers and as a consequence the industry became extremely competitive.

In 2003 the syphonic roof drainage association was formed with a DTI funded steering group. It was hoped that the guidelines produced by this group would form the basis of a future British Standard for the design and installation of syphonic roof drainage.

In 2004 Ross ADT introduced the Hydromax syphonic outlet and hence at the present time the syphonic roof drainage industry within the UK consists of 6 main companies each with its own individual design of syphonic outlet.

H. R. Wallingford published the guidelines drawn up by the DTI steering group during 2003 in report SR654 (May 2004). There is currently no indication of when a British standard will be available. However, it is an appropriate time for the findings of this particular series of investigations to influence the development of the future standard. The outputs of this thesis, which examines the performance of two designs of syphonic roof outlet, propose to influence the development of such a future standard.

In summary therefore, as stated earlier, the sequence of development of the syphonic roof drainage industry is summarised in figures A2.1 – A2.4.

Appendix 3

A3.0 Standard Error Within Experimental Data - Discussed in Chapter 4.

Definition of terms utilised within the calculation of error within the recorded data

The Mean

$$Mean = \frac{\sum_{i=1}^{i=n} x_i}{n}$$

Where:
x_i = Individual water depth recordings
n = number of samples

For example, considering table A3.1.1

At a flow rate of 10 l/s the mean depth of water recorded:-

$$Mean = \sum_{i=1}^{i=n} x_i = x_1 + x_2 + x_3 + \ldots\ldots\ldots\ldots x_8$$

$$Mean = \frac{(26 + 21 + 26.5 + 21 + 26.5 + 21.5 + 26.5 + 21)}{8}$$

$$Mean = 23.8mm$$

The Standard Deviation

$$\sigma = \left[\frac{\Sigma(x_i - mean)^2}{n}\right]^{0.5}$$

Where:
x_i = Individual water depth recordings
n = number of samples
σ = Standard deviation

For example, considering the data shown in table A3.1.1, page 210 and extracted below

x_i (water depth)	x_i - mean	$(x_i - \text{mean})^2$
26.0	2.25	5.0625
21.0	-2.75	7.5625
26.5	2.75	7.5625
21.0	-2.75	7.5632
26.5	2.75	7.5625
21.5	-2.25	5.0625
26.5	2.75	7.5625
21.0	-2.75	7.5625
Σ	0.5	55.5

Therefore, the standard deviation within the recorded data detailed in table A3.1.1 at a flow rate of 10 l/s

$$\sigma = \left[\frac{\Sigma(x_i - mean)^2}{n}\right]^{0.5}$$

$$\sigma = \left[\frac{55.5}{8}\right]^{0.5}$$

$$\sigma = 2.8$$

Standard Error of the Mean

$$\sigma_{mean} = \frac{\sigma}{\sqrt{n}}$$

$$\sigma_{mean} = \frac{2.8}{\sqrt{8}}$$

$$\sigma_{mean} = 1.0$$

A3.1 Primary System

		Water Depths at Outlet 1									
		Flow l/s									
		10	**12**	**14**	**16**	**18**	**20**	**22**	**24**	**26**	**28**
Data Points	1	26.0	28.0	32.5	35.5	38.0	40.5	41.5	44.0	46.0	61.5
	2	21.0	23.0	27.0	31.0	33.5	37.0	37.0	40.0	42.5	58.5
	3	26.5	29.0	33.0	36.0	38.0	40.0	42.0	43.5	45.0	59.0
	4	21.0	23.0	27.0	30.0	31.0	34.5	36.0	38.0	40.5	60.0
	1	26.5	27.5	33.0	35.5	38.0	40.0	41.0	44.0	45.5	59.5
	2	21.5	23.0	27.5	31.5	33.0	36.5	37.0	41.0	42.0	57.0
	3	26.5	28.5	33.0	36.0	38.0	40.0	41.5	43.0	45.0	59.0
	4	21.0	21.5	27.0	31.0	31.5	35.0	37.0	39.0	41.0	56.5
Number of Samples		8	8	8	8	8	8	8	8	8	8
Mean (mm)		23.8	25.4	30.0	33.3	35.1	37.9	39.1	41.6	43.4	58.9
Standard Deviation (mm)		2.8	3.1	3.1	2.6	3.2	2.5	2.6	2.4	2.2	1.6
Standard Error (mm)		1.00	1.09	1.09	0.94	1.12	0.87	0.91	0.84	0.77	0.56
Average standard error within the data = 0.9mm											

Table A3.1.1: Water depths recorded at the rim of a syphonic rainwater outlet 1, identifying the standard error within the data.

		Water Depths at Outlet 2									
		Flow l/s									
		10	**12**	**14**	**16**	**18**	**20**	**22**	**24**	**26**	**28**
Data Points	1	25.5	28.0	33.0	35.0	37.5	40.0	41.5	44.5	45.0	62.0
	2	21.5	24.0	26.5	30.0	33.5	36.5	37.0	40.5	42.0	59.0
	3	26.5	28.5	33.0	36.5	37.0	39.0	41.0	43.5	44.0	61.0
	4	20.5	22.5	26.0	29.0	31.0	33.0	35.0	37.0	39.0	57.0
	1	24.0	28.5	32.5	34.0	37.0	41.0	42.0	43.5	46.0	61.0
	2	21.0	23.5	26.0	31.0	33.0	36.0	36.0	39.5	41.5	59.0
	3	25.5	27.0	33.0	37.0	38.0	40.0	42.0	44.0	43.0	60.0
	4	21.5	22.0	26.0	28.5	32.0	34.0	37.0	38.0	40.0	58.0
Number of Samples		8	8	8	8	8	8	8	8	8	8
Mean (mm)		23.3	25.5	29.5	32.6	34.9	37.4	38.9	41.3	42.6	59.6
Standard Deviation (mm)		2.4	2.8	3.6	3.4	2.8	3.0	3.0	2.9	2.4	1.7
Standard Error (mm)		0.85	0.98	1.28	1.21	0.99	1.06	1.05	1.04	0.85	0.60
Average standard error within the data = 1.0 mm											

Table A3.1.2: Water depths recorded at the rim of a syphonic rainwater outlet 2, identifying the standard error within the data.

		Water Depths Upstream On B-B									
		Flow l/s									
		10	**12**	**14**	**16**	**18**	**20**	**22**	**24**	**26**	**28**
Data Points	1	31.5	36.0	39.5	43.5	45.5	49.0	51.5	55.0	59.5	75.0
	2	31.0	36.5	38.0	41.0	44.0	48.0	50.5	53.0	58.5	73.0
	3	31.5	34.5	39.5	43.0	45.5	48.5	50.5	54.0	59.0	73.5
	1	30.5	35.5	40.0	44.0	46.0	49.0	51.0	54.5	59.0	74.0
	2	31.0	36.0	38.0	41.0	44.0	47.5	50.0	54.0	59.0	73.5
	3	32.0	34.5	39.5	42.5	45.5	49.0	50.5	54.0	58.0	74.0
Number of Samples		6	6	6	6	6	6	6	6	6	6
Mean (mm)		31.3	35.5	39.1	42.5	45.1	48.5	50.7	54.1	58.8	73.8
Standard Deviation (mm)		0.5	0.8	0.9	1.3	0.9	0.6	0.5	0.7	0.5	0.7
Standard Error (mm)		0.21	0.34	0.35	0.52	0.35	0.26	0.21	0.27	0.21	0.28
Average standard error within the data = 0.3mm											

Table A3.1.3: Water depths recorded upstream of the primary syphonic rainwater outlets (location detailed in figure 4.3a), identifying the standard error within the data.

		Water Depths Upstream On C-C outlet 1 side									
		Flow l/s									
		10	**12**	**14**	**16**	**18**	**20**	**22**	**24**	**26**	**28**
Data Points	1	31.0	35.5	40.0	42.0	45.5	49.5	52.0	56.0	59.5	75.0
	2	31.0	35.0	39.5	41.0	45.5	49.5	52.5	56.0	60.0	75.5
	1	31.0	35.0	40.0	41.5	45.0	49.5	51.5	56.0	59.5	75.0
	2	31.5	36.0	40.5	41.5	46.0	50.0	52.0	56.5	59.5	75.0
Number of Samples		4	4	4	4	4	4	4	4	4	4
Mean (mm)		31.1	35.4	40.0	41.5	45.5	49.6	52.0	56.1	59.6	75.1
Standard Deviation (mm)		0.3	0.5	0.4	0.4	0.4	0.3	0.4	0.3	0.3	0.3
Standard Error (mm)		0.13	0.24	0.20	0.20	0.20	0.13	0.20	0.13	0.13	0.13
Average standard error within the data = 0.2mm											

Table A3.1.4: Water depths recorded upstream of the primary syphonic rainwater outlets (location detailed in figure 4.3a), identifying the standard error within the data.

		Water Depths Upstream On C-C outlet 2 side									
		Flow l/s									
		10	**12**	**14**	**16**	**18**	**20**	**22**	**24**	**26**	**28**
Data Points	1	31.5	35.0	40.0	42.5	45.5	49.5	52.5	56.5	60.0	75.0
	2	31.0	35.5	39.5	42.0	46.0	49.3	52.0	56.0	59.5	76.0
	1	31.0	35.5	40.5	41.5	45.0	49.5	52.0	56.5	59.5	75.0
	2	32.0	36.0	41.0	42.0	46.0	49.5	52.0	56.5	59.5	75.0
Number of Samples		4	4	4	4	4	4	4	4	4	4
Mean (mm)		31.4	35.5	40.3	42.0	45.6	49.5	52.1	56.4	59.6	75.3
Standard Deviation (mm)		0.5	0.4	0.6	0.4	0.5	0.1	0.3	0.3	0.3	0.5
Standard Error (mm)		0.24	0.20	0.32	0.20	0.24	0.05	0.13	0.13	0.13	0.25
Average standard error within the data = 0.2mm											

Table A3.1.5: Water depths recorded upstream of the primary syphonic rainwater outlets (location detailed in figure 4.3a), identifying the standard error within the data.

A3.2 Secondary System

Water depth measurements data retrieved during the investigation in to the operation of a secondary system described in chapter 4:

		Water Depths at Outlet						
		Flow l/s						
		24	**27**	**30**	**33**	**36**	**39**	**40.5**
Data Points	1	86.0	88.5	91.0	94.0	96.5	101.0	108.0
	2	75.5	77.5	81.0	84.0	87.0	92.5	100.0
	3	82.0	85.0	87.0	90.0	93.0	97.0	112.0
	4	75.5	78.0	81.0	84.0	86.5	93.0	108.0
	1	84.5	89.0	90.5	94.0	96.0	100.0	107.0
	2	76.0	79.0	81.0	84.5	87.5	93.0	112.0
	3	82.0	85.0	87.5	89.5	92.0	96.5	115.0
	4	76.0	78	82	85	87	94.5	117
Number of Samples		8	8	8	8	8	8	8
Mean (mm)		79.7	82.5	85.1	88.1	90.7	95.9	109.9
Standard Deviation (mm)		4.4	4.9	4.4	4.3	4.2	3.3	5.3
Standard Error (mm)		1.6	1.7	1.5	1.5	1.5	1.2	1.9
Average standard error within the data = 1.5mm								

Table A3.2.1: Water depths recorded at the rim of a syphonic rainwater outlet (location identified in fig 4.4a), identifying the standard error within the data.

		Upstream Water Depths at B1 - B1						
		Flow l/s						
		24	**27**	**30**	**33**	**36**	**39**	**40.5**
Data Points	1	85.5	88.5	89.5	94.0	97.0	103.5	118.0
	2	83.5	87.0	90.0	92.0	96.0	101.0	119.0
	3	85.5	88.0	91.0	94.0	97.0	103.0	118.0
	1	86.0	89.0	90.0	94.5	97.0	104.0	117.0
	2	84.0	87.5	90.5	92.0	96.5	102.0	119.0
	3	85.0	88.0	90.5	94.0	96.5	103.0	120.0
Number of Samples		6	6	6	6	6	6	6
Mean (mm)		84.9	88.0	90.3	93.4	96.7	102.8	118.5
Standard Deviation (mm)		1.0	0.7	0.5	1.1	0.4	1.1	1.0
Standard Error (mm)		0.4	0.3	0.2	0.5	0.2	0.4	0.4
Average standard error within the data = 0.3mm								

Table A3.2.2: Maximum water depths recorded upstream of the secondary syphonic rainwater outlets (location highlighted in fig 4.4a), identifying the standard error within the data

		Upstream Water Depths at B2 - B2						
		Flow l/s						
		24	**27**	**30**	**33**	**36**	**39**	**40.5**
Data Points	1	85.5	88.0	89.5	94.0	97.0	103.5	118.0
	2	84.5	86.5	89.5	93.0	96.0	102.0	119.5
	3	84.0	88.0	90.0	93.0	96.5	101.5	119.5
	1	85.0	87.5	89.5	93.5	96.5	103.0	119.0
	2	83.5	88.5	91.0	94.0	96.5	103.5	120.0
	3	84.0	88.0	91.5	93.5	96.5	103.5	120.5
Number of Samples		6	6	6	6	6	6	6
Mean (mm)		84.4	87.8	90.2	93.5	96.5	102.8	119.4
Standard Deviation (mm)		0.7	0.7	0.9	0.4	0.3	0.9	0.9
Standard Error (mm)		0.3	0.3	0.4	0.2	0.1	0.4	0.4
Average standard error within the data = 0.3mm								

Table A3.2.3: Maximum water depths recorded upstream of the secondary syphonic rainwater outlets (location highlighted in fig 4.4a), identifying the standard error within the data

A3.3 Primary & Secondary System in a Common Gutter

Water depth measurements data retrieved during the investigation in to the operation of a primary and secondary system located in a common gutter described in chapter 4:

		Water Depths at $A_1 - A_1$										
		Flow l/s										
		14	**18**	**22**	**24**	**26**	**30**	**40**	**50**	**60**	**62**	**64**
Data Points	1	35.0	40.0	42.0	43.5	48.5	60.5	73.0	83.5	96.0	100.0	115.0
	2	32.5	38.0	41.5	43.0	46.0	59.5	73.0	83.5	96.0	99.5	113.5
	3	31.0	38.5	41.5	44.0	47.0	60.5	73.0	84.5	96.0	100.5	113.5
	4	33.0	40.0	42.5	45.0	49.0	61.0	73.0	84.5	95.5	98.5	113.0
	1	34.5	38.0	41.5	44.0	46.0	59.0	73.0	83.5	96.0	100.0	114.0
	2	32.0	36.0	39.0	40.0	45.5	61.0	72.5	84.0	95.5	99.5	113.0
	3	31.0	38.0	42.0	43.5	47.0	60.5	73.0	84.0	96.0	100.0	113.5
	4	32.0	37.0	39.0	44.0	46.0	60.0	72.0	84.0	96.0	99.0	114.0
Number of Samples		8	8	8	8	8	8	8	8.0	8	8	8
Mean (mm)		32.6	38.2	41.1	43.4	46.9	60.3	72.8	83.9	95.9	99.6	113.7
Standard Deviation (mm)		1.5	1.4	1.4	1.5	1.3	0.7	0.4	0.4	0.2	0.6	0.7
Standard Error (mm)		0.5	0.5	0.5	0.5	0.5	0.3	0.1	0.1	0.1	0.2	0.2
Average standard error within the data = 0.35mm												

Table A3.3.1: Water depths recorded at a position within the gutter highlighted in figure 4.5a. Identifying the standard error within the data.

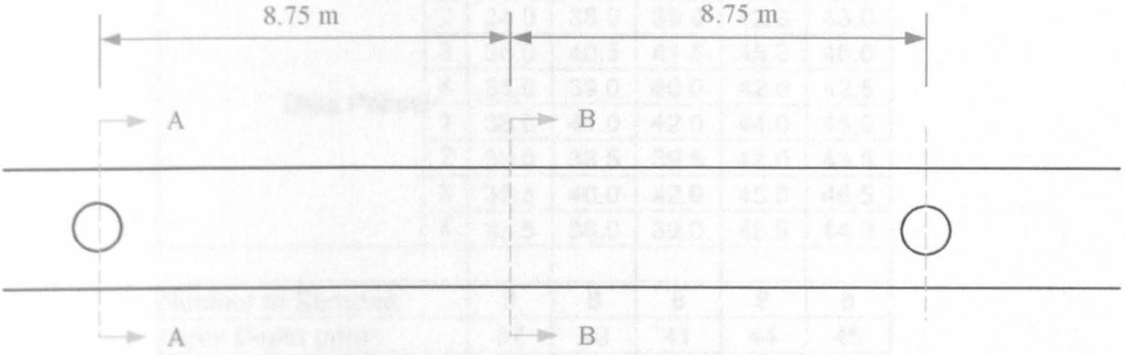
		Water Depths at B - B										
		Flow l/s										
		14	**18**	**22**	**24**	**26**	**30**	**40**	**50**	**60**	**62**	**64**
Data Points	5	40.0	46.0	51.0	55.0	59.5	66.5	77.0	86.0	98.0	101.0	117.0
	6	40.0	46.0	51.5	54.5	60.0	67.0	76.5	86.0	96.5	100.5	115.5
	7	40.0	46.5	51.0	54.0	59.0	67.0	75.0	85.0	97.0	98.5	114.5
	8	38.0	45.5	49.5	53.5	57.0	65.0	74.5	86.5	97.0	99.0	115.0
	5	39.0	45.5	51.0	55.0	59.0	66.0	76.0	85.5	98.0	101.0	116.0
	6	40.0	46.0	51.0	55.0	61.0	67.0	76.6	86.0	97.0	100.0	116.0
	7	40.0	45.5	50.5	53.5	60.0	66.0	76.0	85.0	96.5	99.0	115.0
	8	39.0	46.0	50.0	53.5	57.0	66.0	75.0	85.5	97.0	99.0	116.0
Number of Samples		8	8	8	8	8	8	8	8.0	8	8	8
Mean (mm)		39.5	45.9	50.7	54.3	59.1	66.3	75.8	85.7	97.1	99.8	115.6
Standard Deviation (mm)		0.8	0.4	0.7	0.7	1.4	0.7	0.9	0.5	0.6	1.0	0.8
Standard Error (mm)		0.3	0.1	0.2	0.3	0.5	0.2	0.3	0.2	0.2	0.4	0.3
Average standard error within the data = 0.3mm												

Table A3.3.2: Water depths recorded at a position within the gutter highlighted in figure 4.4a. Identifying the standard error within the data.

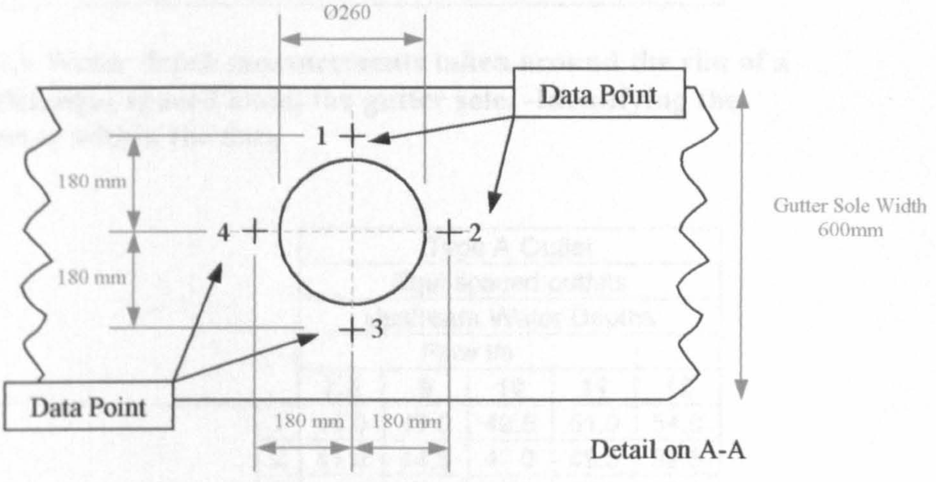
Appendix 4

A4.0 Standard Error Within Experimental Data – Discussed in Chapter 5

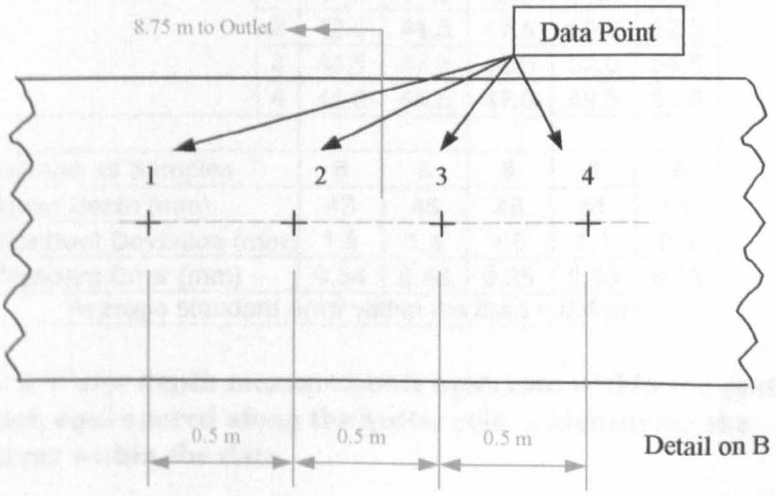
A4.1 Outlets equally spaced along the length of the gutter. Location of data collection points



Plan section of gutter, total length 35m



Detail on A-A



Detail on B - B

A4.2 Type A Outlets – Equally spaced along the sole of the gutter

		Type A Outlet				
		Equi spaced outlets				
		Water Depths at Outlet				
		Flow l/s				
		7.5	**9**	**10**	**11**	**12**
Data Points	1	38.5	41.0	42.0	44.5	45.5
	2	34.0	38.0	39.0	42.0	43.0
	3	38.0	40.5	41.5	45.0	46.0
	4	35.0	39.0	40.0	42.0	42.5
	1	38.0	41.0	42.0	44.0	45.0
	2	35.0	38.5	39.5	42.0	43.5
	3	38.5	40.0	42.0	45.0	46.5
	4	35.5	38.0	39.0	43.5	44.0
Number of Samples		8	8	8	8	8
Mean Depth (mm)		37	40	41	44	45
Standard Deviation (mm)		1.9	1.3	1.4	1.3	1.5
Standard Error (mm)		0.66	0.45	0.49	0.47	0.52
Average standard error within the data = 0.5m						

Table A4.2.1 Water depth measurements taken around the rim of a type A outlet, equi-spaced along the gutter sole. -Identifying the standard error within the data

		Type A Outlet				
		Equi spaced outlets				
		Upstream Water Depths				
		Flow l/s				
		7.5	**9**	**10**	**11**	**12**
Data Points	1	44.0	47.0	49.5	51.0	54.0
	2	41.0	44.5	47.0	49.5	52.5
	3	43.5	46.5	49.0	52.0	55.0
	4	41.5	44.0	47.5	50.0	53.0
	1	44.5	47.0	48.0	51.5	53.5
	2	42.0	44.5	47.5	50.0	52.5
	3	44.5	47.5	49.0	52.0	54.5
	4	41.0	45.5	47.0	49.5	53.0
Number of Samples		8	8	8	8	8
Mean Depth (mm)		43	46	48	51	54
Standard Deviation (mm)		1.5	1.4	1.0	1.1	0.9
Standard Error (mm)		0.54	0.48	0.35	0.38	0.33
Average standard error within the data = 0.4mm						

Table A4.2.2 Water depth measurements upstream within the gutter - type A outlet, equi-spaced along the gutter sole, – identifying the standard error within the data

	Type A Outlet				
	Equi spaced outlets				
	Calculated Upstream water depth				
	Flow l/s				
	7.5	**9**	**10**	**11**	**12**
Data Points	35.8	38.9	41	43.6	45.2

Table A4.2.3 Calculated water depths upstream within the gutter - type A outlet equi-spaced along the gutter sole.

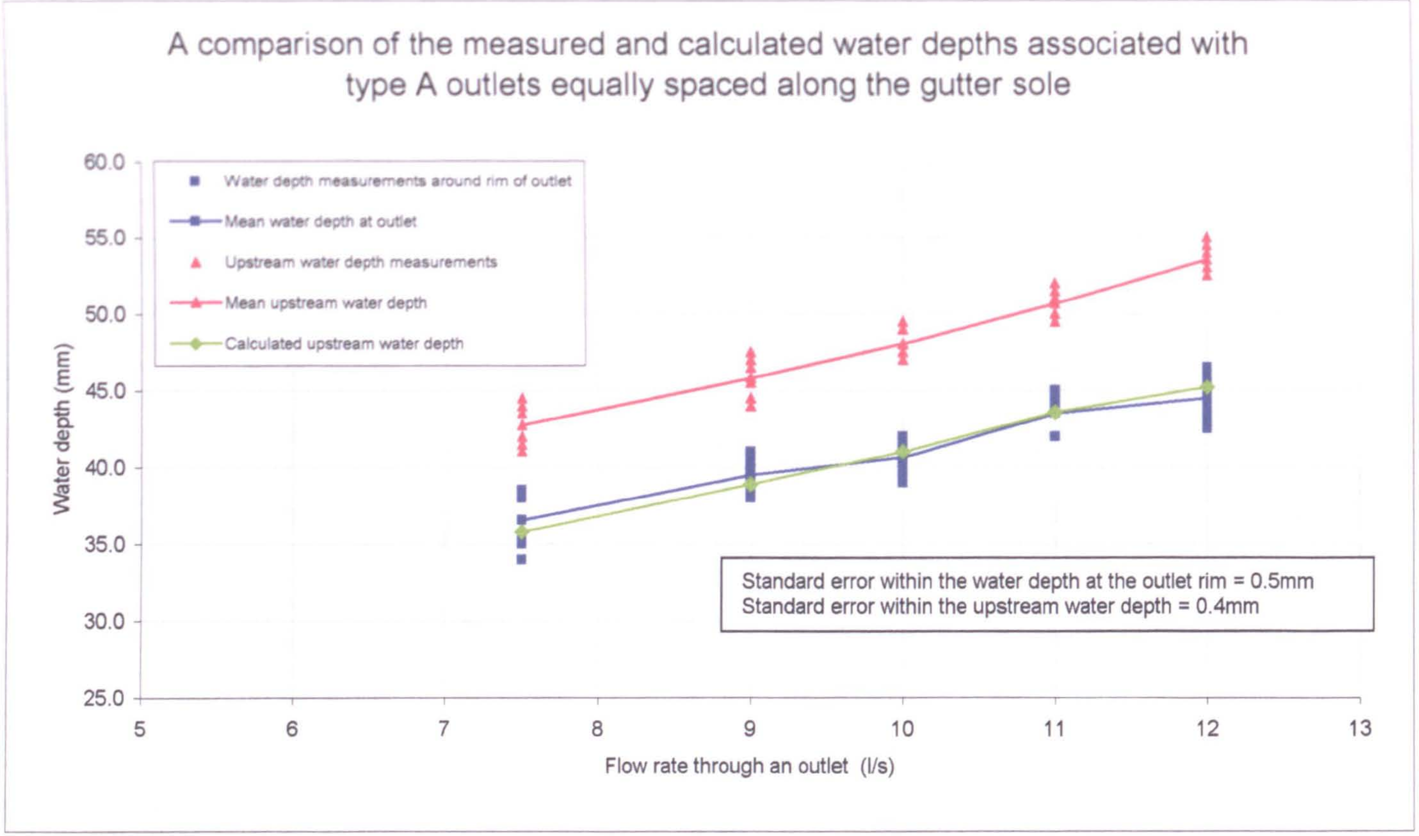


Figure A4.2.1 A graphical comparison of the measured and calculated water depths associated with type A outlets equally spaced along the gutter sole.

A4.3 Type B Outlets – Equally spaced along the sole of the gutter

		Type B Outlet				
		Equi spaced outlets				
		Water Depths at Outlet 1				
		Flow l/s				
		7.5	9	10	11	12
Data Points	1	38.0	41.5	44.0	47.5	51.0
	2	35.0	39.0	40.5	45.0	50.0
	3	38.5	42.0	43.0	47.0	50.5
	4	34.5	40.0	41.0	45.5	49.5
	1	37.5	42.0	44.5	48.0	51.0
	2	35.5	39.5	41.0	46.0	50.5
	3	38.0	42.5	44.0	47.5	50.0
	4	35.0	40.0	42.0	46.0	49.5
Number of Samples		8	8	8	8	8
Mean Depth (mm)		37	41	43	47	50
Standard Deviation (mm)		1.6	1.3	1.6	1.1	0.6
Standard Error (mm)		0.58	0.47	0.56	0.38	0.21
Average standard error within the data = 0.5mm						

Table A4.3.1 Water depth measurements taken around the rim of a type B outlet, equi-spaced along the gutter sole. - Identifying the standard error within the data

		Type B Outlet				
		Equi spaced outlets				
		Upstream Water Depths				
		Flow l/s				
		7.5	9	10	11	12
Data Points	1	45.0	49.5	50.5	51.0	54.0
	2	42.0	47.5	48.0	49.5	52.5
	3	44.5	49.0	51.0	52.0	55.0
	4	41.5	47.0	49.0	50.5	53.0
	1	45.5	48.0	50.5	51.5	54.0
	2	42.5	47.5	48.5	50.0	53.0
	3	45.0	49.0	51.5	52.0	54.5
	4	42.0	47.0	49.5	49.5	53.0
Number of Samples		8	8	8	8	8
Mean Depth (mm)		44	48	50	51	54
Standard Deviation (mm)		1.6	1.0	1.3	1.0	0.9
Standard Error (mm)		0.58	0.35	0.44	0.37	0.31
Average standard error within the data = 0.4mm						

Table A4.3.2 Water depth measurements upstream within the gutter - type B outlet, equi-spaced along the gutter sole. – identifying the standard error within the data

	Type B Outlet				
	Equi spaced outlets				
	Calculated Upstream water depth				
	Flow l/s				
	7.5	**9**	**10**	**11**	**12**
Data Points	35.1	38.9	41.2	44.6	47.5

Table A4.3.3 Calculated water depths upstream within the gutter - type B outlet equi-spaced along the gutter sole.

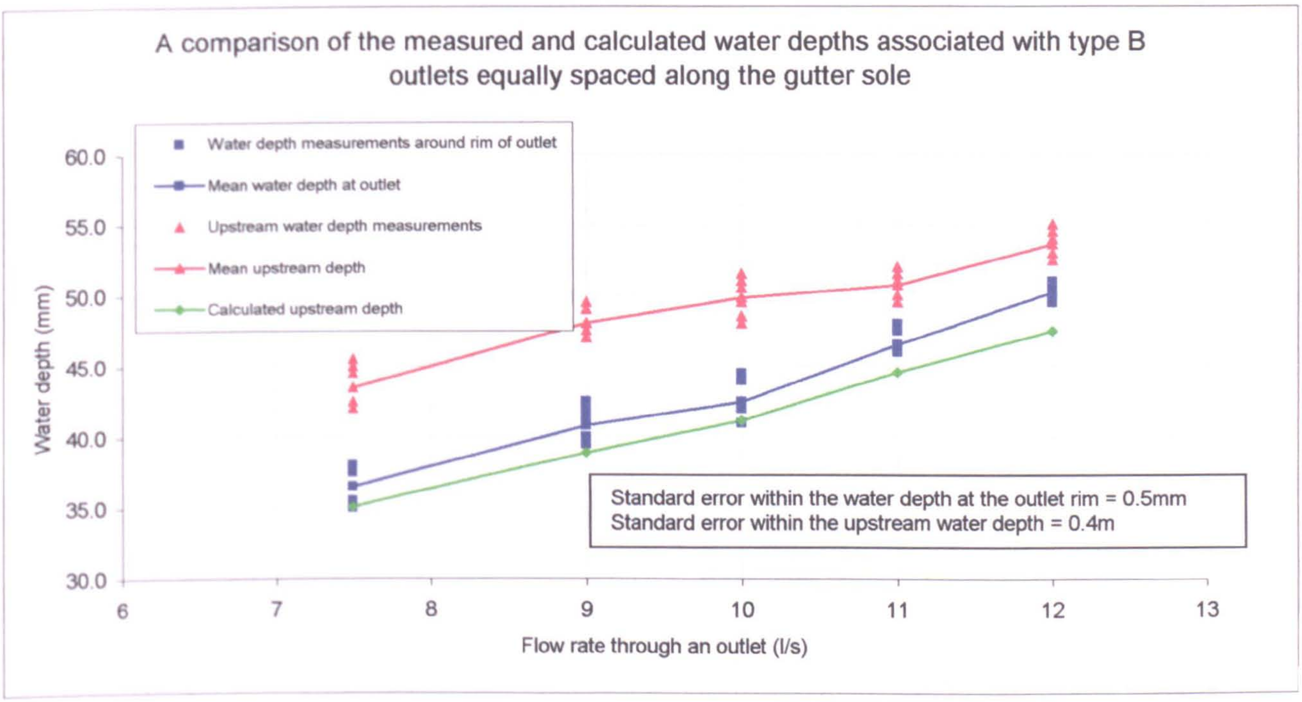
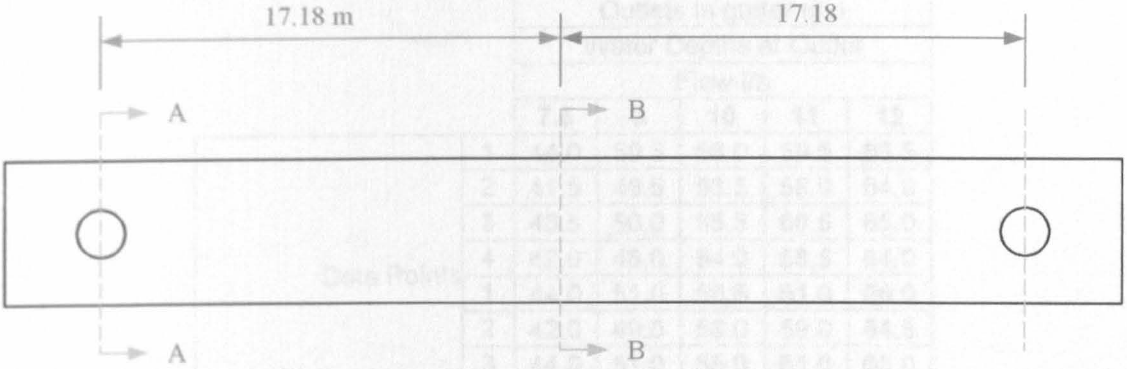
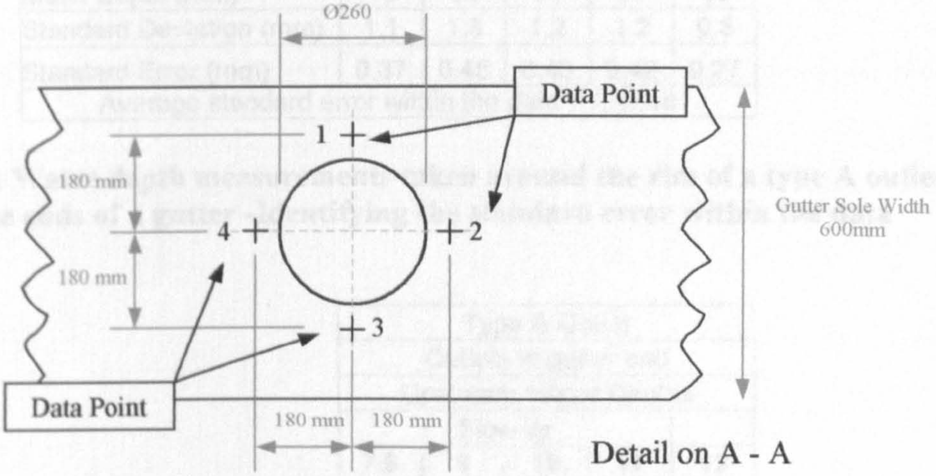


Figure A4.3.1 A graphical comparison of the measured and calculated water depths associated with type B outlets equally spaced along the gutter sole.

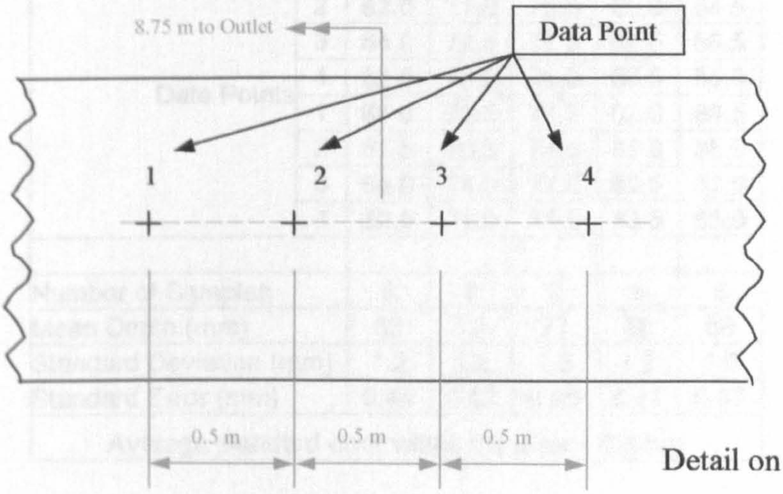
A4.4 Outlets located at the ends of the gutter – Location of data collection points



Plan section of gutter, total length 35m



Detail on A - A



Detail on B-B

A4.4.1Type A Outlets

		Type A Outlet				
		Outlets in gutter end				
		Water Depths at Outlet				
		Flow l/s				
		7.5	9	10	11	12
Data Points	1	44.0	50.5	56.0	59.5	65.5
	2	41.5	48.5	53.5	58.0	64.0
	3	43.5	50.0	55.5	60.5	65.0
	4	42.0	48.0	54.0	58.5	64.0
	1	44.0	51.0	56.5	61.0	66.0
	2	42.0	49.0	53.0	59.0	64.5
	3	44.0	51.0	55.0	61.0	65.0
	4	42.5	48.0	54.5	58.5	64.0
Number of Samples		8	8	8	8	8
Mean Depth (mm)		43	50	55	60	65
Standard Deviation (mm)		1.1	1.3	1.2	1.2	0.8
Standard Error (mm)		0.37	0.45	0.43	0.42	0.27
Average standard error within the data = 0.4mm						

Table A4.4.1 Water depth measurements taken around the rim of a type A outlet located at the ends of a gutter -Identifying the standard error within the data

		Type A Outlet				
		Outlets in gutter end				
		Upstream Water Depths				
		Flow l/s				
		7.5	9	10	11	12
Data Points	1	63.5	73.0	78.0	82.0	87.0
	2	62.0	71.0	75.5	80.0	84.5
	3	64.0	72.5	77.5	82.5	86.5
	4	62.5	72.0	76.0	80.5	85.0
	1	64.0	72.5	77.5	82.0	86.5
	2	61.5	70.5	74.5	81.0	85.0
	3	65.0	74.0	77.5	82.5	87.0
	4	62.0	71.0	75.5	83.5	85.0
Number of Samples		8	8	8	8	8
Mean Depth (mm)		63	72	77	82	86
Standard Deviation (mm)		1.2	1.2	1.3	1.2	1.0
Standard Error (mm)		0.44	0.42	0.45	0.41	0.37
Average standard error within the data = 0.4mm						

Table A4.4.2 Water depth measurements upstream within the gutter - type A outlet located at the ends of a gutter – identifying the standard error within the data

	Type A Outlet				
	Outlets in gutter end				
	Calculated Upstream water depth				
	Flow l/s				
	7.5	**9**	**10**	**11**	**12**
Data Points	53	59	63.8	68.4	73.1

Table A4.4.3 Calculated water depths upstream within the gutter - type A outlet located at the ends of a gutter.

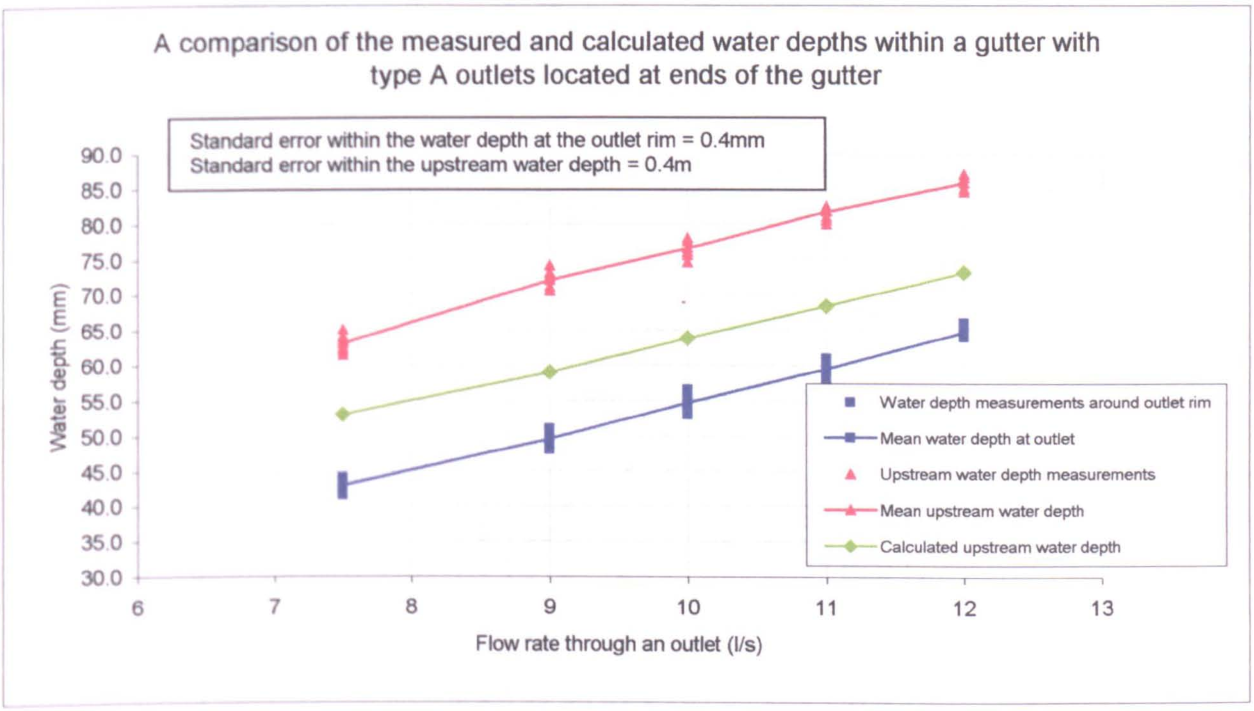


Figure A4.4.1 A graphical comparison of the measured and calculated water depths associated with type A outlets spaced at the ends of the gutter.

A4.5 Type B Outlets

		Type B Outlet				
		Outlets in gutter end				
		Water Depths at Outlet				
		Flow l/s				
		7.5	9	10	11	12
Data Points	1	43.0	48.0	50.5	58.5	62.0
	2	42.0	46.5	48.5	55.5	60.0
	3	42.5	49.0	50.0	58.5	63.5
	4	41.5	46.0	48.0	56.0	60.5
	1	43.5	48.5	51.0	60.0	63.0
	2	42.5	46.0	49.0	56.0	61.0
	3	43.0	48.5	51.0	59.0	63.5
	4	41.0	46.0	48.0	57.0	62.0
Number of Samples		8	8	8	8	8
Mean Depth (mm)		42	47	50	58	62
Standard Deviation (mm)		0.8	1.3	1.3	1.7	1.3
Standard Error (mm)		0.30	0.46	0.45	0.59	0.48
Average standard error within the data = 0.4mm						

Table A4.5.1 Water depth measurements taken around the rim of a type B outlet located at the ends of a gutter - Identifying the standard error within the data

		Type B Outlet				
		Outlets in gutter end				
		Upstream Water Depths				
		Flow l/s				
		7.5	9	10	11	12
Data Points	1	62.0	69.5	74.0	80.5	85.0
	2	60.0	67.0	72.0	80.0	84.0
	3	64.0	72.0	75.0	81.0	86.0
	4	61.5	68.5	73.0	79.5	84.5
	1	62.0	70.0	74.0	81.0	86.0
	2	61.0	69.0	73.5	79.0	83.5
	3	63.5	71.0	75.0	81.5	86.0
	4	62.0	69.0	73.0	79.0	84.0
Number of Samples		8	8	8	8	8
Mean Depth (mm)		62	70	74	80	85
Standard Deviation (mm)		1.3	1.5	1.0	1.0	1.0
Standard Error (mm)		0.45	0.54	0.37	0.34	0.36
Average standard error within the data = 0.4mm						

Table A4.5.2 Water depth measurements upstream within the gutter - type B outlet, located at the ends of a gutter – identifying the standard error within the data

	Type B Outlet				
	Outlets in gutter end				
	Calculated Upstream water depth				
	Flow l/s				
	7.5	**9**	**10**	**11**	**12**
Data Points	51	58	60.6	68.7	70

Table A4.5.3 Calculated water depths upstream within the gutter - type B outlet located at the ends of a gutter.

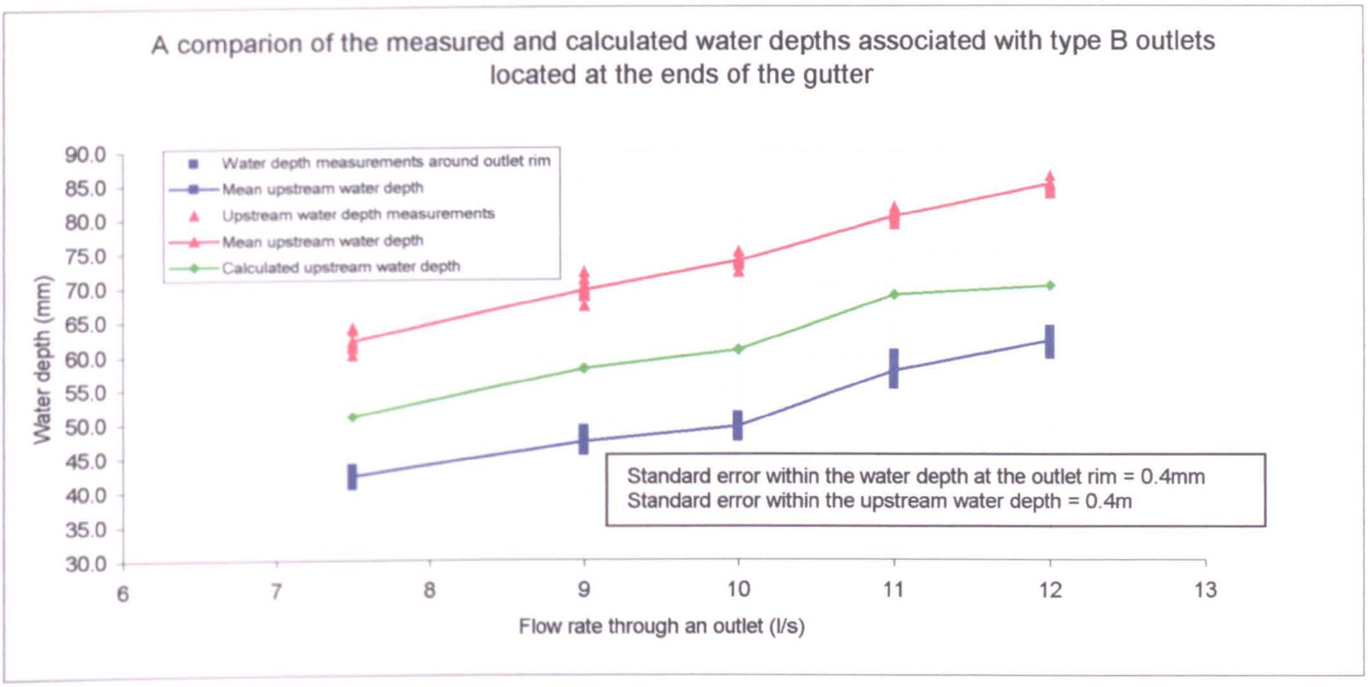
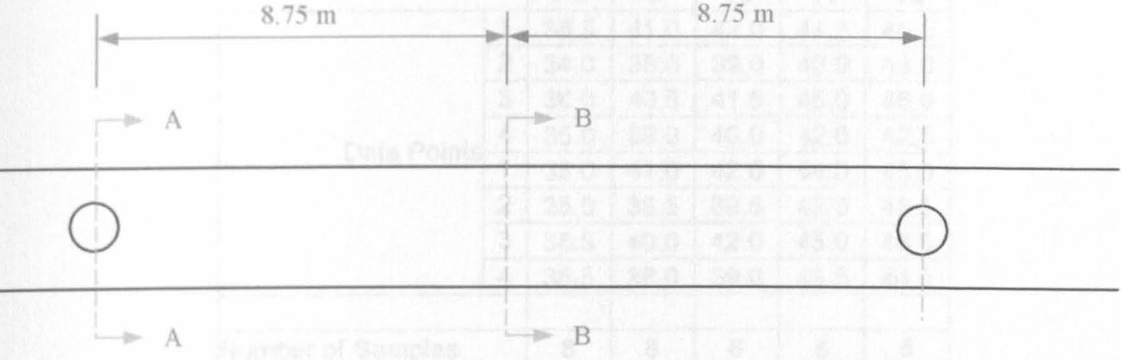


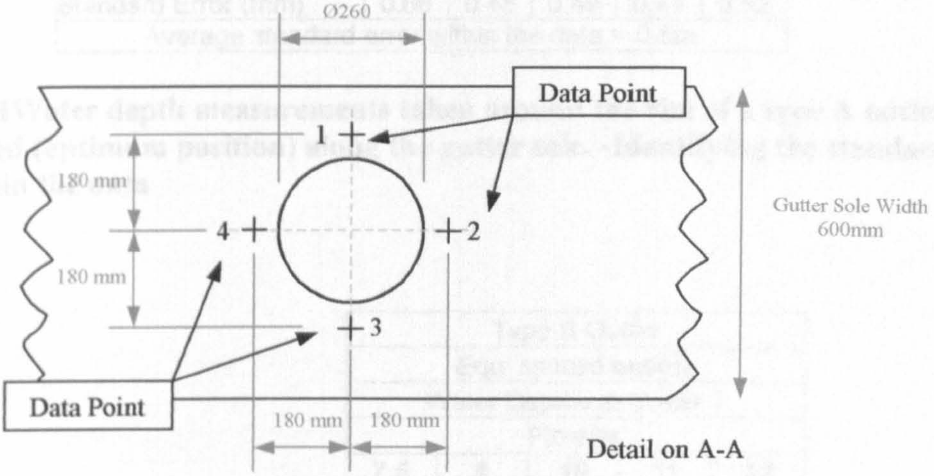
Figure A4.5.1 A graphical comparison of the measured and calculated water depths associated with type B outlets spaced at the ends of the gutter.

Appendix 5

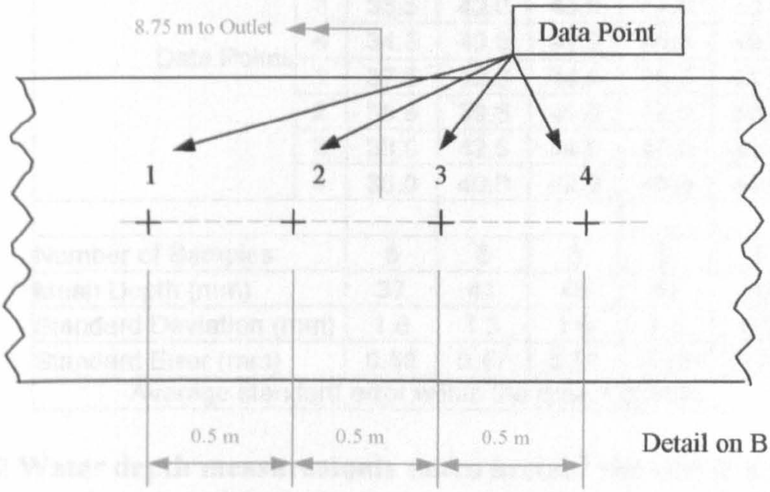
A5.1 Outlets equally spaced along the length of the gutter. Location of data collection points



Plan section of gutter, total length 35m



Detail on A-A



Detail on B - B

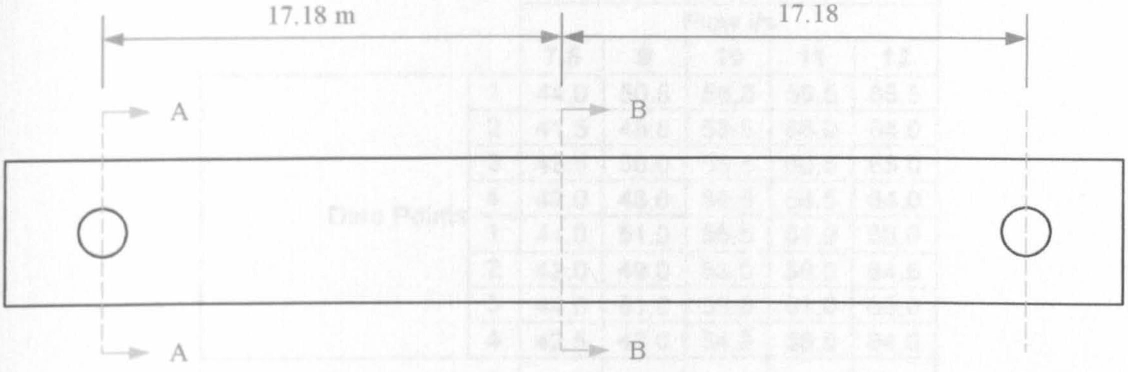
		Type A Outlet				
		Equi spaced outlets				
		Water Depths at Outlet				
		Flow l/s				
		7.5	**9**	**10**	**11**	**12**
Data Points	1	38.5	41.0	42.0	44.5	45.5
	2	34.0	38.0	39.0	42.0	43.0
	3	38.0	40.5	41.5	45.0	46.0
	4	35.0	39.0	40.0	42.0	42.5
	1	38.0	41.0	42.0	44.0	45.0
	2	35.0	38.5	39.5	42.0	43.5
	3	38.5	40.0	42.0	45.0	46.5
	4	35.5	38.0	39.0	43.5	44.0
Number of Samples		8	8	8	8	8
Mean Depth (mm)		37	40	41	44	45
Standard Deviation (mm)		1.9	1.3	1.4	1.3	1.5
Standard Error (mm)		0.66	0.45	0.49	0.47	0.52
Average standard error within the data = 0.5m						

Table A5.1Water depth measurements taken around the rim of a type A outlet, equi-spaced (optimum position) along the gutter sole. -Identifying the standard error within the data

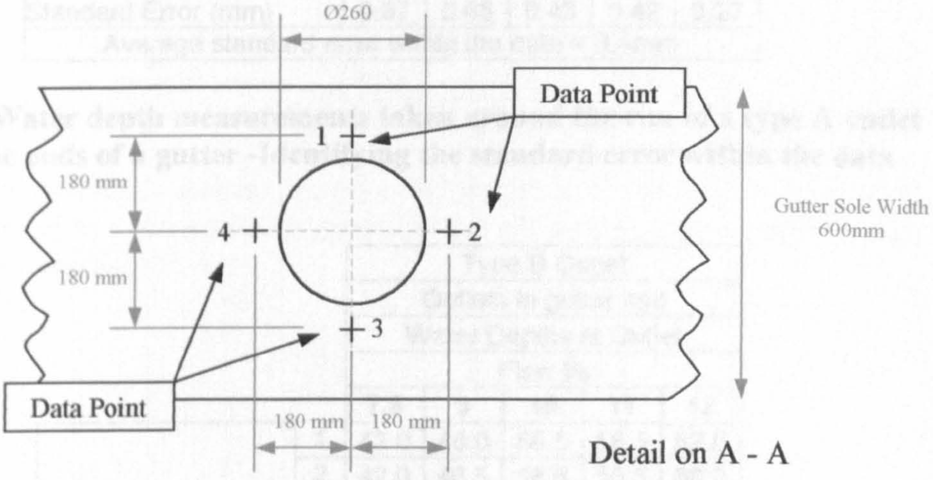
		Type B Outlet				
		Equi spaced outlets				
		Water Depths at Outlet 1				
		Flow l/s				
		7.5	**9**	**10**	**11**	**12**
Data Points	1	38.0	41.5	44.0	47.5	51.0
	2	35.0	39.0	40.5	45.0	50.0
	3	38.5	42.0	43.0	47.0	50.5
	4	34.5	40.0	41.0	45.5	49.5
	1	37.5	42.0	44.5	48.0	51.0
	2	35.5	39.5	41.0	46.0	50.5
	3	38.0	42.5	44.0	47.5	50.0
	4	35.0	40.0	42.0	46.0	49.5
Number of Samples		8	8	8	8	8
Mean Depth (mm)		37	41	43	47	50
Standard Deviation (mm)		1.6	1.3	1.6	1.1	0.6
Standard Error (mm)		0.58	0.47	0.56	0.38	0.21
Average standard error within the data = 0.5mm						

Table A5.2 Water depth measurements taken around the rim of a type B outlet, equi-spaced (optimum position) along the gutter sole. - Identifying the standard error within the data

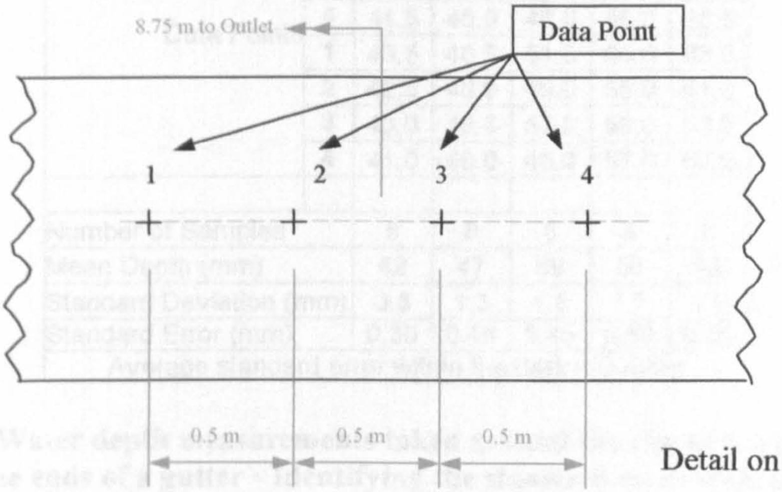
A5.2 Outlets located at the ends of the gutter – Location of data collection points



Plan section of gutter, total length 35m



Detail on A - A



Detail on B-B

		Type A Outlet				
		Outlets in gutter end				
		Water Depths at Outlet				
		Flow l/s				
		7.5	**9**	**10**	**11**	**12**
Data Points	1	44.0	50.5	56.0	59.5	65.5
	2	41.5	48.5	53.5	58.0	64.0
	3	43.5	50.0	55.5	60.5	65.0
	4	42.0	48.0	54.0	58.5	64.0
	1	44.0	51.0	56.5	61.0	66.0
	2	42.0	49.0	53.0	59.0	64.5
	3	44.0	51.0	55.0	61.0	65.0
	4	42.5	48.0	54.5	58.5	64.0
Number of Samples		8	8	8	8	8
Mean Depth (mm)		43	50	55	60	65
Standard Deviation (mm)		1.1	1.3	1.2	1.2	0.8
Standard Error (mm)		0.37	0.45	0.43	0.42	0.27
Average standard error within the data = 0.4mm						

Table A5.3 Water depth measurements taken around the rim of a type A outlet located at the ends of a gutter -Identifying the standard error within the data

		Type B Outlet				
		Outlets in gutter end				
		Water Depths at Outlet				
		Flow l/s				
		7.5	**9**	**10**	**11**	**12**
Data Points	1	43.0	48.0	50.5	58.5	62.0
	2	42.0	46.5	48.5	55.5	60.0
	3	42.5	49.0	50.0	58.5	63.5
	4	41.5	46.0	48.0	56.0	60.5
	1	43.5	48.5	51.0	60.0	63.0
	2	42.5	46.0	49.0	56.0	61.0
	3	43.0	48.5	51.0	59.0	63.5
	4	41.0	46.0	48.0	57.0	62.0
Number of Samples		8	8	8	8	8
Mean Depth (mm)		42	47	50	58	62
Standard Deviation (mm)		0.8	1.3	1.3	1.7	1.3
Standard Error (mm)		0.30	0.46	0.45	0.59	0.48
Average standard error within the data = 0.4mm						

Table A5.4 Water depth measurements taken around the rim of a type B outlet located at the ends of a gutter - Identifying the standard error within the data.

A5.3 Outlets located mid way between the optimum position and the end of gutter position.

		Type A Outlet				
		Water Depths at Outlet				
		Flow l/s				
		7.5	**9**	**10**	**11**	**12**
Data Points	1	40.0	46.0	50.0	55.0	59.0
	2	36.0	43.0	48.0	53.0	57.0
	3	40.5	44.0	51.0	55.0	58.5
	4	37.0	45.0	48.5	53.5	56.0
	1	40.5	46.5	49.5	56.0	59.5
	2	36.0	43.5	48.0	54.5	58.0
	3	41.0	45.0	51.5	55.0	59.0
	4	38.0	46.0	49.0	54.0	57.0
Number of Samples		8	8	8	8	8
Mean Depth (mm)		39	45	49	55	58
Standard Deviation (mm)		2.1	1.3	1.3	1.0	1.2
Standard Error (mm)		0.75	0.45	0.47	0.34	0.43
Average standard error within the data = 0.5mm						

Table A5.5 Water depth measurements taken around the rim of a type A outlet located mid way between optimum position and the gutter end -Identifying the standard error within the data

		Type B Outlet				
		Water Depths at Outlet				
		Flow l/s				
		7.5	**9**	**10**	**11**	**12**
Data Points	1	40.5	48.0	50.0	55.5	70.0
	2	36.5	44.0	48.0	54.5	68.5
	3	41.0	46.5	50.5	57.0	71.0
	4	37.0	43.5	48.5	54.5	67.0
	1	40.5	47.5	50.0	56.0	70.5
	2	37.0	44.0	48.0	54.5	68.0
	3	41.0	47.0	51.5	57.5	70.5
	4	39.0	44.0	49.0	55.0	67.0
Number of Samples		8	8	8	8	8
Mean Depth (mm)		39	46	49	56	69
Standard Deviation (mm)		2.0	1.9	1.3	1.3	1.6
Standard Error (mm)		0.69	0.66	0.45	0.44	0.58
Average standard error within the data = 0.5mm						

Table A5.6 Water depth measurements taken around the rim of a type B outlet located mid way between optimum position and the gutter end - Identifying the standard error within the data.

A5.4 Calculation of the constant value determined for the use within equation 6.1

Determination of the constant utilised within equation 6.1.

The linear equations derived for use within production of the chart detailed in figure 6.10 were obtained through a combination of the following sources of data:

a. The data for flat roofs and 350mm sole gutters obtained through experimentation by May (1996)
b. Interpolation by the author, of the data obtained by May.
c. Data obtained by the author during the investigation detailed in chapter 6.

Gutter Sole Width	Linear equation
350	$D_{sp} = 27.192\ R_D + D_f$
400	$D_{sp} = 26.404\ R_D + D_f$
600	$D_{sp} = 21.000\ R_D + D_f$
800	$D_{sp} = 18.956\ R_D + D_f$
Average Constant	$D_{sp} = 23.38\ R_D + D_f$

Where:

D_{sp} = Depth of flow around an outlet allowing for the gutter width and position of outlet along the gutter sole.

R_D = Distance ratio

D_f = Depth of flow above an outlet located in the optimum position

Table A5.7 Calculation of the linear constant used within equation 6.1

DETAILS OF GUTTER/OUTLETS		REMARKS
GUTTER SOLE WIDTH (mm)	800	Project specific dimension
INTERNAL ANGLE (right-hand side) (degrees)	20	Project specific dimension (measured from the vertical)
INTERNAL ANGLE (left-hand side) (degrees)	20	Project specific dimension (measured from the vertical)
FLOW/OUTLET (L/s)	10	BS 6367: Appendix A, rainfall intensity. Section 7, run off. Flow / outlet = run off / number of outlets required.
DEPTH OF WATER AT OUTLET (mm)	36	From Fullflow water depth charts. Based upon H. R. Wallingford report SR463 and SR473
Bo (surface width of flow) (mm)	826.21	BS 6367: Section 8 & Appendix B.2
Ao (cross sectional area of flow) (mm2)	29271.71	BS 6367: Section 8 & Appendix B.2
FROUDE NUMBER	0.29	BS 6367: Appendix B.2. The value of flow used in this calculation is half the flow per outlet
Bs/Bo	0.97	BS 6367: Appendix B.2.2
ENTER VALUE OF Yu/Yo	1.18	BS 6367: Appendix B.2.2 & figure 23
UPSTREAM DEPTH (P1) (mm)	42.48	BS 6367: Appendix B.2.2
MINIMUM OVERALL GUTTER DEPTH REQUIRED INCLUDING FREEBOARD (mm)	59	Calculated in accordance with BS 6367 Appendix B.2. The value of upstream depth used is either: S2 + P2 or S2 + Height of upstand, whichever gives the largest value.

Table A5.8 Calculation of required gutter depth in accordance with BS 6367:1983, with no allowance for the position of the outlet within a gutter – See worked example 6.5

DETAILS OF GUTTER/OUTLETS		REMARKS
GUTTER SOLE WIDTH (mm)	800	Project specific dimension
INTERNAL ANGLE (right-hand side) (degrees)	20	Project specific dimension (measured from the vertical)
INTERNAL ANGLE (left-hand side) (degrees)	20	Project specific dimension (measured from the vertical)
FLOW/OUTLET (L/s)	10	BS 6367: Appendix A, rainfall intensity. Section 7, run off. Flow / outlet = run off / number of outlets required.
DEPTH OF WATER AT OUTLET (mm)	53.5	From Fullflow water depth charts. Based upon H. R. Wallingford report SR463 and SR473
Bo (surface width of flow) (mm)	838.94	BS 6367: Section 8 & Appendix B.2
Ao (cross sectional area of flow) (mm2)	43841.77	BS 6367: Section 8 & Appendix B.2
FROUDE NUMBER	0.16	BS 6367: Appendix B.2. The value of flow used in this calculation is half the flow per outlet
Bs/Bo	0.95	BS 6367: Appendix B.2.2
ENTER VALUE OF Yu/Yo	1.07	BS 6367: Appendix B.2.2 & figure 23
UPSTREAM DEPTH (P1) (mm)	57.25	BS 6367: Appendix B.2.2

MINIMUM OVERALL GUTTER DEPTH REQUIRED INCLUDING FREEBOARD (mm)	80

Table A5.9 Calculation of required gutter depth in accordance with BS 6367:1983, with allowance for the position of the outlet within a gutter – See worked example 6.5

Appendix 6

Velocity Probe Reading												
Time (sec)	A				B				C			
	1		2		1		2		1		2	
	Hz	m/s	Hz	m/s	Hz	m/s	Hz	m/s	Hz	m/s	Hz	m/s
20	36.4	0.255	39.9	0.2581	28.8	0.2077	29.1	0.2096	25.2	0.1853	25.5	0.1872
40	35.2	0.248	39.4	0.2737	30.6	0.2189	29.0	0.2090	23.8	0.1766	25.0	0.1841
60	37.3	0.261	41.4	0.2861	30.2	0.2164	30.0	0.2152	24.8	0.1829	25.4	0.1866
80	37.6	0.263	42.2	0.2911	31.6	0.2252	29.4	0.2115	26.0	0.1903	23.5	0.1748
100	36.0	0.253	41.8	0.2886	31.1	0.2220	29.0	0.2090	24.9	0.1835	25.0	0.1841
120	36.0	0.253	42.1	0.2905	29.0	0.2090	31.9	0.2270	24.2	0.1791	24.6	0.1861
140	34.8	0.245	42.6	0.2936	30.5	0.2183	29.8	0.2140	21.9	0.1648	25.7	0.1885
160	35.9	0.252	43.1	0.2967	28.1	0.2034	29.9	0.2146	23.8	0.1766	24.2	0.1791
180	35.7	0.251	41.6	0.2874	29.5	0.2121	31.4	0.2239	25.0	0.1841	24.8	0.1829
200	35.6	0.250	41.5	0.2867	28.4	0.2052	30.2	0.2164	25.5	0.1872	24.6	0.1816
Mean Velocity		0.253		0.2852		0.2138		0.2150		0.1811		0.1816

Table A6.1 Velocity probe readings taken at points A, B and C in Hz then converted to m/s using manufacturers charts.

Velocity Probe Reading								
Time (sec)	D				E			
	1		2		1		2	
	Hz	m/s	Hz	m/s	Hz	m/s	Hz	m/s
20	27.3	0.1982	40.7	0.2819	33.0	0.2341	38.7	0.2693
40	26.8	0.1953	40.4	0.2798	34.1	0.2409	39.0	0.2714
60	28.0	0.2026	38.2	0.2659	30.5	0.2183	41.9	0.2892
80	33.7	0.2384	36.2	0.2536	31.8	0.2264	40.6	0.2811
100	29.2	0.2103	37.1	0.2594	30.1	0.2156	39.7	0.2753
120	27.7	0.2009	37.7	0.2633	33.9	0.2392	38.6	0.2689
140	26.6	0.1942	38.8	0.2701	32.4	0.2301	39.0	0.2713
160	25.8	0.1893	40.4	0.2796	30.4	0.2176	38.9	0.2706
180	29.8	0.2142	37.9	0.2643	31.8	0.2262	39.9	0.2768
200	31.4	0.2237	41.7	0.2881	29.3	0.2106	39.8	0.2761
Mean Velocity		0.2967		0.2706		0.2259		0.2750

Table A6.2 Velocity probe readings taken at points D and E in Hz then converted to m/s using manufacturers charts.

Velocity Probe Reading												
Time (sec)	F				G				H			
	1		2		1		2		1		2	
	Hz	m/s	Hz	m/s	Hz	m/s	Hz	m/s	Hz	m/s	Hz	m/s
20	26.0	0.1903	25.3	0.1862	31.9	0.2268	32.0	0.2276	33.9	0.2392	40.5	0.2804
40	26.7	0.1946	25.8	0.1893	31.6	0.2250	33.7	0.2381	34.0	0.2401	42.3	0.2919
60	27.2	0.1976	26.1	0.1908	30.7	0.2198	32.8	0.2326	35.6	0.2498	39.6	0.2751
80	26.8	0.1952	25.5	0.1872	32.5	0.2306	35.2	0.2476	36.2	0.2536	40.2	0.2784
100	27.4	0.1992	26.1	0.1912	30.6	0.2187	28.9	0.2082	35.6	0.2501	39.3	0.2732
120	27.7	0.2006	25.2	0.1854	32.5	0.2309	32.0	0.2275	36.0	0.2523	40.6	0.2812
140	25.8	0.1893	25.6	0.1881	30.3	0.2168	31.9	0.2273	36.4	0.2552	41.0	0.2839
160	26.6	0.1941	26.0	0.1904	32.5	0.2308	32.7	0.2321	36.2	0.2536	40.4	0.2796
180	27.2	0.1978	25.4	0.1868	30.7	0.2196	32.2	0.2287	35.1	0.2472	40.6	0.2811
200	27.0	0.1963	25.1	0.1846	33.2	0.2350	30.7	0.2193	34.9	0.2459	41.9	0.2892
Mean Velocity		0.1955		0.1880		0.2254		0.2289		0.2487		0.2814

Table A6.3 Velocity probe readings taken at points F, G and H in Hz then converted to m/s using manufacturers charts.

Appendix 7

EXAMINATION OF THE PERFORMANCE OF SYPHONIC RAINWATER OUTLETS

CIB-W62-1998 INTERNATIONAL SYMPOSIUM ON WATER SUPPLY AND DRAINAGE FOR BUILDINGS

by

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Abstract

As Engineers and Architects become more aware of the benefits of syphonic roof drainage there is a greater need for a better understanding of a systems hydraulic performance. This is particularly relevant to systems which are installed in gutters that are typical of large industrial and commercial buildings. In order to meet this demand for additional information The University of Sheffield together with Fullflow Limited has financed an extensive programme of research.

This paper describes the initial work carried out in this programme, concentrating upon the construction of a full-scale experimental system and the basic hydraulic performance of a primary and secondary (overflow) syphonic system, located within a gutter.

The system has been used to accurately measure the capacity of both the primary and secondary outlets and it has been shown that for the twin system it is the secondary outlet which governs the water depths in the gutter when the secondary system is in operation. The results also highlight the well-known fact that the syphonic outlets have a capacity that is some ten times greater than manufacturers specified capacity of conventional outlet systems.

Introduction

Historically, roof areas of large industrial and commercial buildings have been drained through the installation of rainwater outlets which are fundamentally nothing more than circular openings at the top of a downpipe. The rainwater flows through these holes into the downpipe due to the force of gravity acting upon the depth of the water around the outlet. Standard weir flow equations have been derived and these detail flow / depth relationship of any particular rainwater outlet.

In comparison, a syphonic rainwater system utilises the full height of a building in order to achieve a high flow rate through the piping network. This has the advantage of allowing a gutter to be drained more quickly than conventional systems would allow. As the syphonic outlet and the piping system are primed, a partial vacuum is created and the rainwater is literally "sucked" from the gutter into the downpipes. These latter pipes flow full without the presence of a central core of air hence it is possible to utilise smaller diameter pipes when compared to the conventional system (in which water and an air core are present).

Syphonic System Development

Syphonic systems were first developed and patented by Eberling and Lunden (1969) in Scandinavia, during the late 1960's. The early systems were designed for use on typical Scandinavian buildings, which were constructed with extensive areas of flat concrete roof. The basis of the operation of the early outlets required a head of water to build up above the outlet, in order for full syphonic action to occur. This often resulted in the flooding of the roof area.

More recently, through the work of Smith (1994) a new generation of syphonic rainwater outlets have been developed. The self-priming outlet enables the syphonic system to prime more rapidly without the need for a head of water above the outlet.

As Engineers and Architects became more aware of the benefits of syphonic systems, their use has extended to many European countries. One reason for this additional interest may be that there has been an increase in the number of localised violent storms, perhaps due to the global warming, in which large volumes of high intensity rainfall are released in extremely short periods of time. Modern buildings make frequent use of pitched roofs and gutters and hence the time of run-off of these high intensity storms is extremely low. The use of syphonic systems within gutters has produced a need for a better understanding of their hydraulic performance. May and Escarameia (1996) have highlighted how single syphonic systems performed when placed in gutters and were subjected to steady state flows.

As syphonic system technology is a developing technology research is required in order to gain a better understanding into the performance of such hi-tech systems. Of particular interest is the performance of twin pipe systems, primary and overflow, located within the same gutter and at time-varying flow rates. To meet this need for additional information The University of Sheffield and Fullflow Limited have financed a programme of research in which extensive use will be made of a 35 metre long full-scale system. The aim of the present study was to compare the hydraulic performance of primary and secondary outlets (figures 1 & 2).

Experimental System

The full-scale experimental system of length 35 metres and width 2.5 metres was constructed on a galvanised mild steel framework. The framework supports a 35 metre long section of 600mm trapezoidal gutter (plate 1), within which multiple outlets of the syphonic rainwater system may be placed. In this study a three outlet secondary or overflow system (plate 2) with a maximum flow capacity of 40 l/s, and a primary system comprising of two syphonic outlets with a maximum capacity of 27 l/s was used. A one metre wide section of roof which was pitched at an angle of 6° (plate 3) was supplied with water to a supply channel via three independently computer controlled submersible pumps each with an independent supply pipe. Together with computer software developed at The University of Sheffield the use of computer controlled pumps enables the experimental system to reproduce almost any rainfall hyetograph and run-off hydrograph, including flash floods and wind driven rain.

The pumps lift the water through a height of 16m, from a 2000m^3 sump in the basement of The University's Water Engineering Laboratory, up on to the roof of The Sir Frederick Mappin Building (plate 4). By utilising this elevated position there is a large head difference between the outlet position and the point of discharge. This ensures that not only is a syphonic action established within the pipework but the full-scale system has a large capacity system in which an extensive range of tests may be undertaken.

The flow rate which enters the system at the three points in the supply channel was monitored through the use of computer controlled valves which were calibrated by utilising volumetric measuring tanks. This calibration was confirmed by diverting the outflow from the syphonic system discharge back through the measuring tanks.

The aim of the present study was to establish the hydraulic performance of single and multi-part outlets. To do this it was necessary to determine the depth / head discharge relationship for each outlet. In order to establish depth / flow relationships a number of sight glasses were installed along the length of the gutter. These were located at the outlets and at midpoints between the outlets. In addition to this, a rail system which extended along the entire gutter length enabled a profile of the water surface to be measured with a Vernier gauge. As the programme of research develops further pressure tappings along the pipework and velocity measurements both within the gutter and the pipework will be made.
To ensure that constant and repeatable data was achieved fine adjustment of the gutter sole level was necessary and a knife-edged weir was installed at the front edge of the supply channel to ensure that, at low flow rates, the water flowed in a uniform manner onto the full length of the simulated roof area.

In addition to the system providing a closely controlled environment in which to study the performance of a syphonic system, much consideration was given to the design. This ensured that there was a close resemblance to systems currently being installed on the majority of large industrial and commercial buildings, particularly those overseas.

Performance of Syphonic Roof Outlets

A preliminary test procedure was devised in which the performance of the primary and secondary outlets within the gutter were initially determined independently of each other. Further to this measurements of the combined systems "performance" were undertaken.

Test 1

The primary system consisted of two syphonic rainwater outlets located within the gutter sole and spaced at 17.5 metre centres. The flow rate into the system was uniform along the length of the gutter. The flow rate to the outlets was increased in small increments and depth measurements were taken at the positions shown in figure 3. The secondary outlets located within the gutter were sealed off and therefore had no detrimental effect upon the performance of the primary system.

The syphonic system pipework configuration was designed using the Fullflow Primacalc software.

Test 2

Test 2 followed the same procedure as test 1 with the additional factor that the secondary system was fitted with three syphonic rainwater outlets spaced at 15 metres and 17 metres between centres (figure 4)

Once again the pipework was designed using Primacalc analytical software and the primary system outlets were sealed.

Test 3

The test procedure was repeated for the final test with both systems fully operational. Figure 5 shows the configuration and the points at which measurements were taken.

Test Results

The results for the flow / depth relationship of the primary system (Test 1) are shown in figure. 6. The abscissa of the figure shows the total flow entering the gutter. It should be noted that within the gutter this flow rate was divided between the two primary outlets. Therefore, water depths are associated with approximately half the flow entering the system. It can be seen that as the flow rate increased there was an increase in water depth within the gutter. At a flow rate of 26 l/s there was a rapid increase in depth for a small increase in flow rate. At this flow rate the syphonic pipework system had reached its maximum flow capacity. Any extra flow rate entering the system above this value was taken up as an increase in flow depth within the gutter. Unlike a conventional roof drainage outlet, it is the pipework and available head difference of a syphonic system that determines the flow capacity.

The flow depth relationship of a secondary system (Test2) is shown in figure 7. This shows that, as expected, the flow depth curve had a similar form to that of the primary system. The water depths were greater due to the utilisation of a 50mm upstand around the secondary system outlet. (Plate 2). In this case the total flow entering the gutter was divided by the three outlets in order to obtain the flow associated with the actual depth of water in the gutter. The maximum capacity of the secondary system is 40 l/s.

Measurements from the testing of the combined primary and secondary system are shown in figure 8. It may be seen from this figure that it is the performance of the secondary system that determines the water depth within the gutter. The flow which enters the system is now discharged through a total of 5 syphonic rainwater outlets. Figure 8 also highlights that at a flow rate of 26 l/s, i.e. when the primary system has reached it's maximum capacity, the secondary system takes control of the water depth within the gutter.

A comparison of the measurements taken in the primary system test and the previous tests carried out by May and Escarameia (1996) is shown in Figure 9.

It is stressed that the work outlined above describes the results of the first phase of an extensive programme of full-scale testing which is ongoing. In addition to highlighting the capacity of each individual system it has been shown that the performance of twin primary and secondary outlets is governed by the secondary outlet.

Conclusion

The construction of the full-scale experimental system produced some inherent problems; typically levelling of the gutter sole and the attainment of a uniform flow along the weir edge which supplies the roof area. All problems were resolved and the final outcome has been the construction of a research facility that will benefit the syphonic industry. The analysis of the initial work has already produced a greater awareness of how primary and secondary (overflow) systems interact within a gutter. Accurate data on system capacity has also been established.

With the ability of the experimental system to produce rainfall hydrographs there is a large scope for future work. It is proposed that initially the work would be concentrated upon the relationship of primary and secondary systems with respect to their location within a gutter. There are currently a number of design philosophies being adapted by syphonic system manufacturers which require a fuller investigation. The system developed has the advantage that it is possible to carry out an extensive programme of tests with time varying inflows and wind-driven effects.

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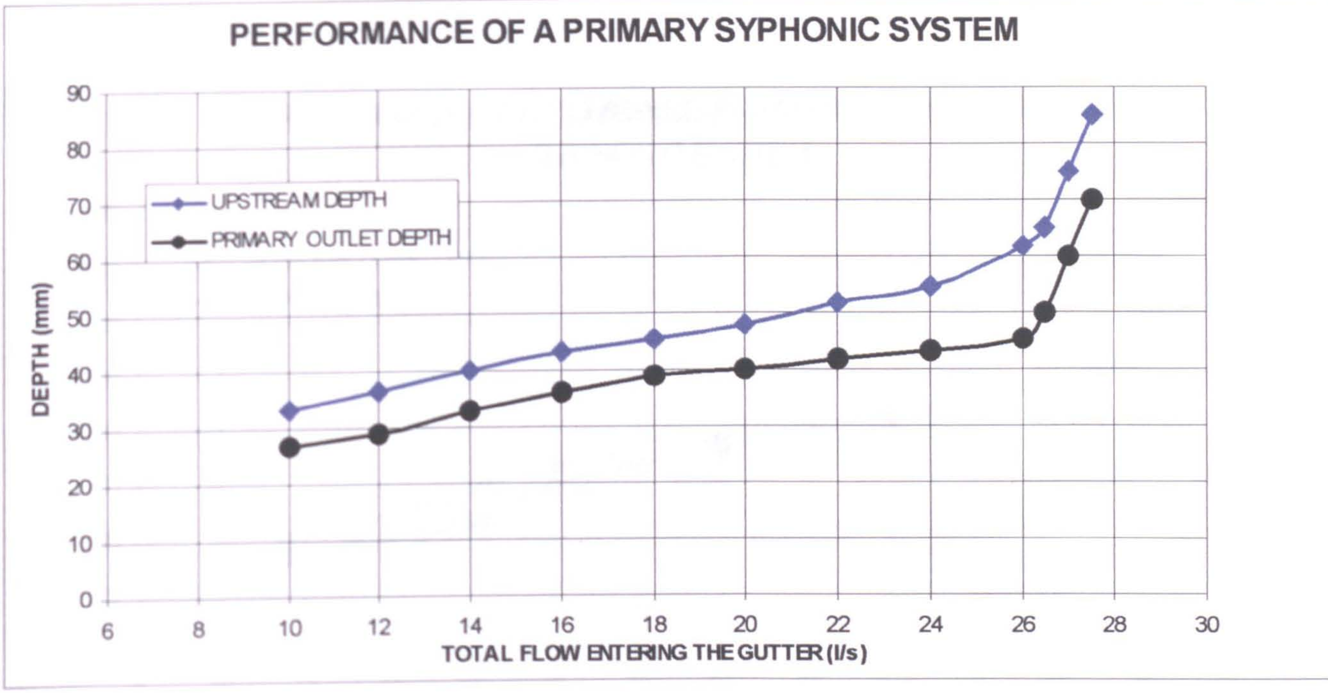

FIGURE 6

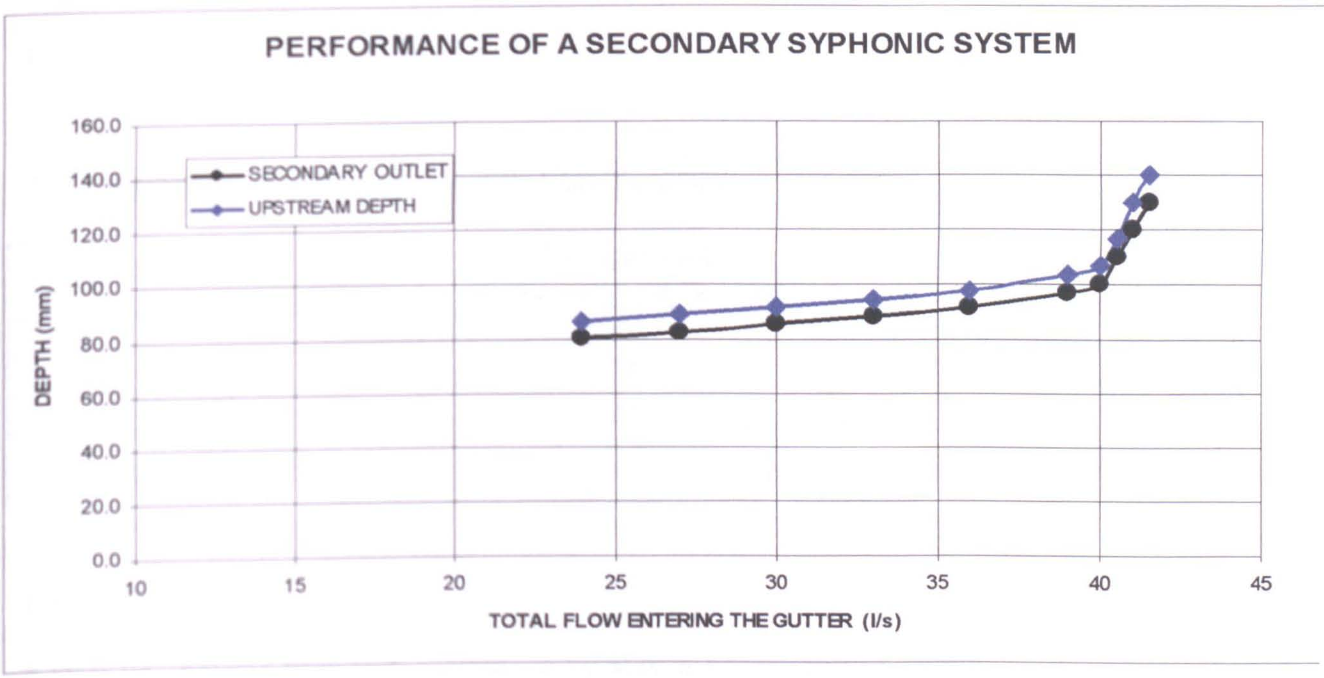

FIGURE 7

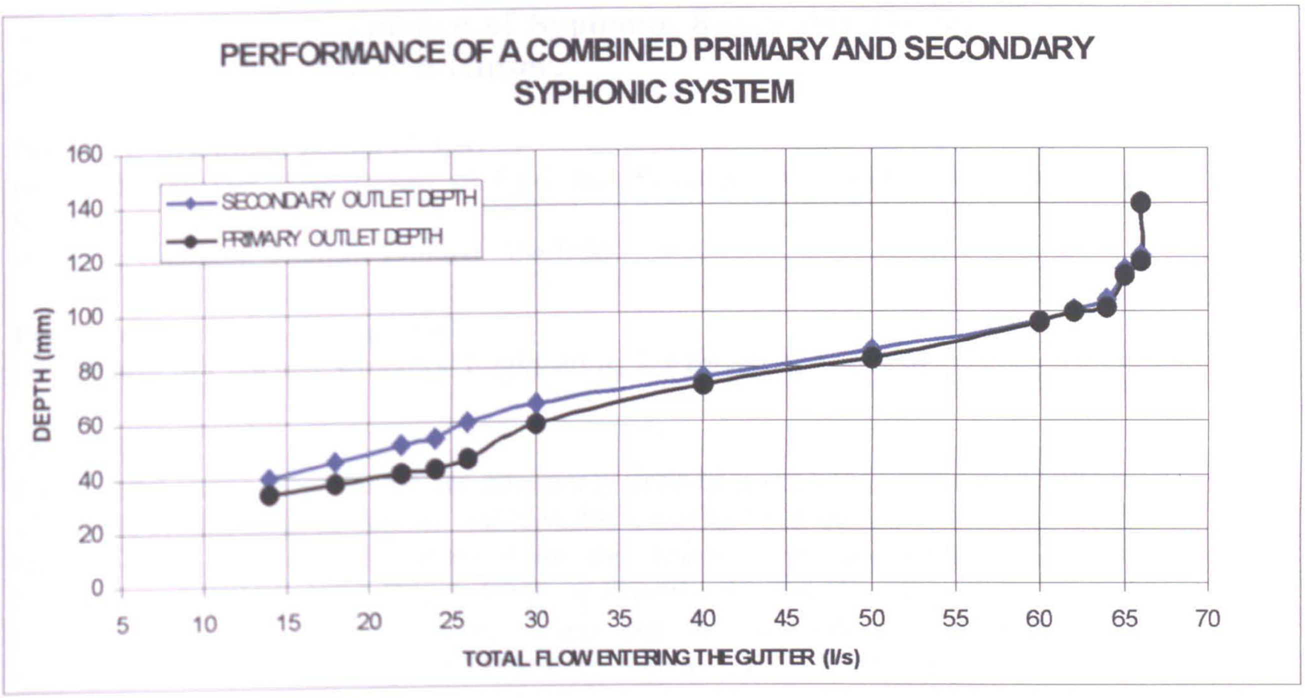

FIGURE 8

A Comparison of Primary System Performance

Flow (l/s)	*Previous Tests. Outlet water depth (mm)	Current Test Outlet water depth (mm)
5	29	27
7	36	33
9	42	38
11	49	42
13	58	45

FIGURE 9

* Data interpolated from tests carried out by May and Escarameia (1996)

The Hydraulic Performance of Syphonic Rainwater Outlets Relative to Their Location Within a Gutter.

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ABSTRACT

Throughout Europe, roof areas are commonly drained using valley and eaves gutters. These are usually large in volume and have the capacity to discharge rainwater at high rates of flow. The definitive method for the design of gutters within the United Kingdom is BS6367: 1983 British Code of Practice for the Drainage of Roofs and Paved Areas. This publication clearly sets out the methodology to predict the hydraulic performance of a gutter. However, within the Code no design criteria for syphonic rainwater systems are outlined.

The location of rainwater outlets within a gutter determines the overall hydraulic performance of the system. The distance from the gutter wall and stop end at which the outlets are placed has a significant influence on the flow depth within the gutter. In turn, this flow depth is a function of the head discharge relationship for the particular outlet. To reduce costs it is thought desirable to place rainwater outlets at ever increasing intervals and if necessary at the ends of gutters; this obviously has a detrimental effect upon the upstream depth within the gutter. This practice will cause an increase in the depth of flow within the upstream gutter, which if overtopping occurs may have a catastrophic consequence for the building and its contents.

Syphonic roof drainage systems may be preferred to conventional systems where high intensity rainfall results in large volumes of run-off which have to be quickly and safely drained from roof systems. This paper describes the examination the influence of the position of two outlets within the gutter. The results have been compared to previous work carried out, and it has been found that it is vitally important to take account of any restrictions to the flow through the outlet, as this results in an increased depth of flow within the gutter.

INTRODUCTION

As the understanding of the hydraulic operation of syphonic rainwater drainage systems increases, so does the popularity of their use, especially in areas of high intensity rainfall. Recent studies investigating the priming time of a syphonic system(1) and the performance of outlets located within gutters(2&3) have highlighted issues that must be addressed in order that the optimum performance of a system is achieved.

In the modern economic climate, developers and specifiers are being placed under increasing pressure to ensure that a project is completed within the allowed budget. Each aspect of the construction has its own potential for cost saving, non-more so than the roof drainage system of a building. One method of reducing the cost of the roof drainage is to install an overflow (secondary) rainwater system within the gutter. This effectively divides the rainwater collected during the design rainstorm in to two independent rainwater systems serving the same gutter. One advantage of utilising this design philosophy is that in certain cases there is a significant reduction of pipe sizes within the syphonic rainwater system design. This in turn reduces the cost of the total drainage system, as large diameter pipes are disproportionately more expensive than the lesser diameter pipes. It has been identified that the cost of a capable secondary system may be similar to that of the main rainwater system(4).

In an attempt to further reduce the cost of a system it is becoming increasingly popular with specifiers, to group secondary rainwater outlets at the extreme end of long gutter runs. This practice significantly reduces the amount of pipe work required and consequently the cost of the total system. In the authors experience it has often been suggested that 5 or 6 outlets are grouped together within the end 2 or 3 meters of a gutter. 'This type of configuration has only a limited effect on preventing overtopping near the middle of the gutter'(4).

EXPERIMENTAL SYSTEM AND SECONDARY FLOW

A full scale experimental system has been established on the roof of the Department of Civil and Structural Engineering, The University of Sheffield, and is outlined elsewhere, Bramhall and Saul(2). Schematic drawings of the system outlined in figures 1 and 2 clearly show the system configuration.

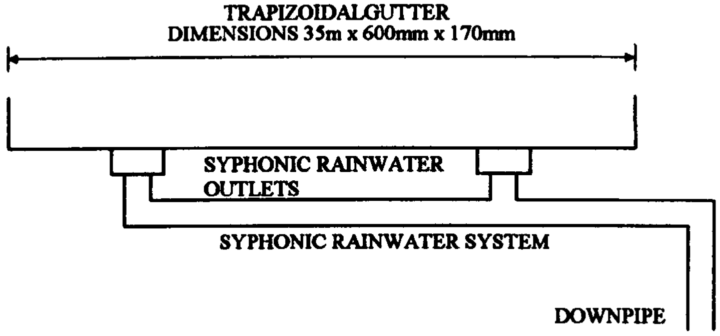

Figure 1 Schematic detail of experimental system (front view)

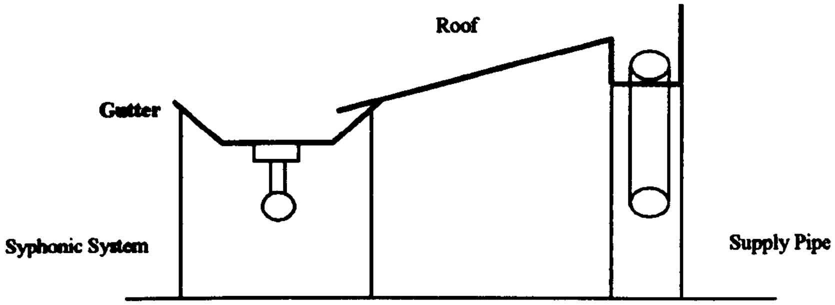

Figure 2 Schematic detail of experimental system (Side view)

The British Standard BS 6367:1983. 'Drainage for roofs and Paved Areas'(5) identifies that it is the location of rainwater outlets within a gutter which dictates the hydraulic performance of the gutter. Additionally, when a syphonic system is installed within a gutter the associated pipework may also have an effect upon the hydraulic performance of the gutter. This paper describes a series of evaluations and comparisons, which investigated the effect the gutter side walls and gutter stop ends impart onto a rainwater outlet. The work is a progression from previous work which identified that when a primary and secondary syphonic system is located within the same gutter, then it is the secondary system flow profile which dictates the hydraulic performance of the gutter(2).

The aim of the current study was to:

- Establish through the examination of previous work(3&6) the effect a gutter side wall imparts on an outlets performance. Extrapolated data along with experimental data retrieved from the current study was utilised for this purpose.
- Using a point of optimum flow for an outlet within a gutter as a datum (i.e. receiving equal flow from both directions), identification of the reduction in flow capacity for a given head of water due to the position of the outlet with respect to the gutter end was investigated.

EXPERIMENTAL METHODOLOGY

The results of previous work(3&6) presented in table 1, carried out by May and May and Escarameia, showed that for a given flow rate, the recorded depths of water were significantly greater within a gutter with syphonic outlets, than those produced on a simulated flat roof (also with syphonic outlets) for an equivalent flow rate. In these experiments a gutter test rig with a sole width of 350 mm was utilised, along with syphonic outlets located within a simulated flat roof.

It may be argued that this work forms the two extremes in which rainwater outlets are most likely to be situated. i.e. the narrowest gutter sole, restricting flow into an outlet and a flat roof obtaining complete radial flow around an outlet.

	Syphonic Outlets Within a gutter (May 1996)	Syphonic Outlets Within a Flat Roof (May & Escarameia 1996)
Flow (l/s)	Depth (mm)	Depth (mm)
7.5	40.5	27.5
9	45	31
10	47	33.5
11	50	35.5
12	54	36.5
12.5	56	37.5

Table 1 : A Comparison of Water Depths Around an Outlet.

Within the British Standard 6367:1983, it is recommended that water depths of up to 30 mm may be acceptable on a flat roof if it is confined to a relatively small area around an outlet. In an attempt to conform to this section of the standard, manufacturers of syphonic rainwater systems claim that a 30 mm head of water above a syphonic outlet will allow a flow rate of 12 l/s.

As the standard suggests these water depths are based upon a flat roof scenario. When outlets are located within gutters, the head of water above an outlet increases for an equivalent flow rate. This increase in water depth is due to the effect the gutter wall has on restricting flow to outlet.

Unlike conventional drainage systems, it is the pipework of a syphonic system that dictates the flow capacity not the syphonic rainwater outlet. Correctly designed pipe work may in some cases allow an outlet to accept flow rates as high as 30 l/s, providing that the gutter is designed accordingly.

It is hypothesised by the authors that it is possible to extrapolate this data to determine theoretical values for the head of water required above an outlet at any given flow rate in a gutter of any sole width.

Figure 3 highlights the theoretical water depths extrapolated (by the authors) from the data in table 1 for an array of gutter sole widths, ranging from the flat roof to the 350 mm gutter sole. This chart clearly demonstrates the effect that the gutter wall has on increasing the head above an outlet for any given flow.

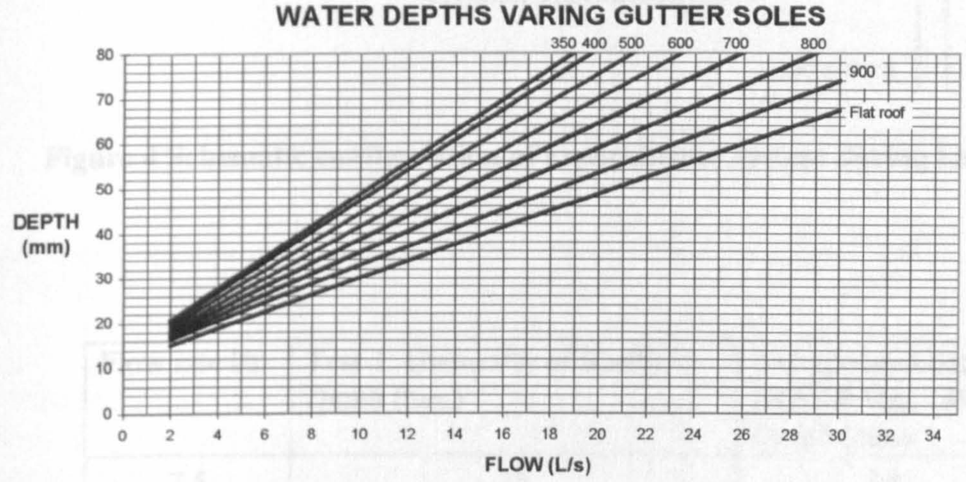

Figure 3 The Effect on Flow Depth Within Gutters of Varying Width

To confirm the validity of the hypothesis the authors carried out a series of tests using syphonic rainwater outlets spaced equi-distant along the length of the experimental system at the University of Sheffield. This was considered as the position in which the outlets would achieve the optimum flow condition. In addition to the gutter sole width, the only difference between the two systems was that the Sheffield rig had a trapezoidal gutter, whereas the Wallingford rig had a gutter with vertical walls.

Water depth measurements were recorded at each outlet and the results are presented in Table 2. This Table also includes the theoretical figures obtained in figure 3 for a gutter with a 600 mm sole width.

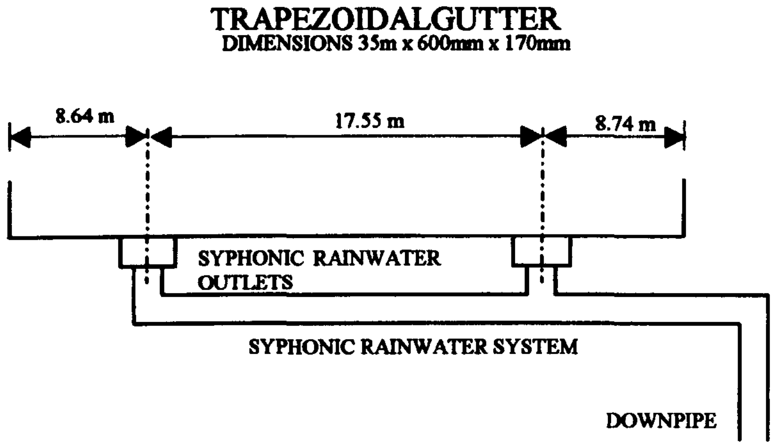

Figure 4 Schematic configuration of experimental system during test 1

Flow rate l/s	Test 1: University of Sheffield. Depth (mm)	Extrapolated data: (R.W.P May 1996) Depth (mm)
7.5	35	34
9	38	39.6
10	40	41.8
11	42.5	44.4
12	44	47.5

Table 2: Comparison of experimental and extrapolated data

Good agreement is observed with the small differences attributable to the difference in cross sectional shape of the gutter. Having established that the proximity of the gutter wall will restrict the flow rate through an outlet for a given head of water, the next stage of the study was to transfer this knowledge to the effects a gutter stop end may have upon an outlets flow capacity.

The outlets were repositioned within the experimental system (figure 5) and the tests undertaken in the first part of the study were repeated. Water depth measurements were again recorded at each outlet.

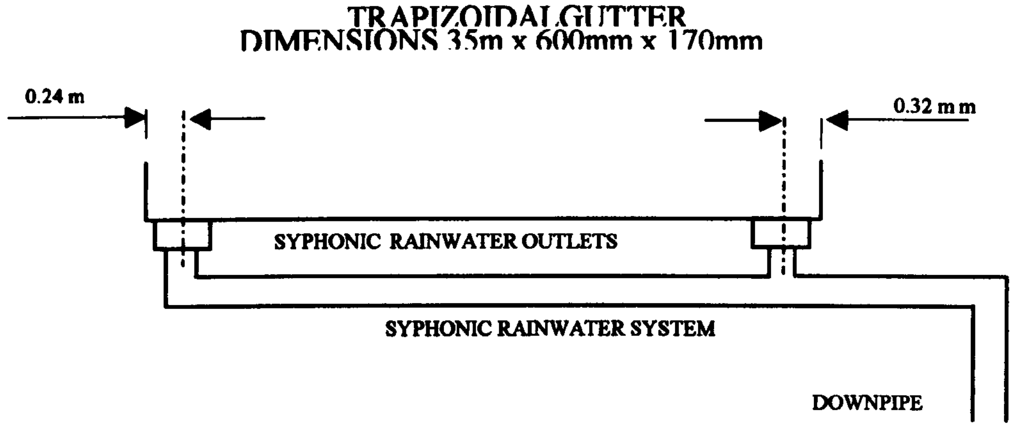

Figure 5 Schematic configuration of experimental system during test 2

In a similar manner the authors hypothesised that based on the results of the tests with a free discharge from either side ie the optimum position (concidered zero value) and from data with the outlets located at the gutter stop ends (considered a value of 1) that the theortical values for outlets located at points D x 0.25, D x 0.50 and D x 0.75 of optimum flow, where D = the distance of the outlet from the gutter end at optimum flow, may be extrapolated from the two sets of experimental results. Actual and extrapolated values are shown in table 3.

Flow (l/s)	Optimum flow (test 1) D = 0.00	Gutter end (test 2) D = 1.00	**Extrapolated Values**		
			D x 0.25	D x 0.5	D x 0.75
7.5	35	43	37	39	41
9	38	50	41	44	47
10	40	55	43.75	47.5	51.25
11	42.5	60	46.89	51.25	55.62
12	44	65	49.25	54.5	59.75

Table 3 Recorded and Theoretical Values of Water depth at Varying Outlet Positions Relative to a Gutter Stop End.

To confirm this hypothesis a final series of experiments was undertaken in order to verify the theroretical values derived in table 3. The rainwater outlets were located at the mid point of the previous experiments. Water depths were recorded at the outlets. Comparisons of the recorded depths and the theoretical values are shown in table 4

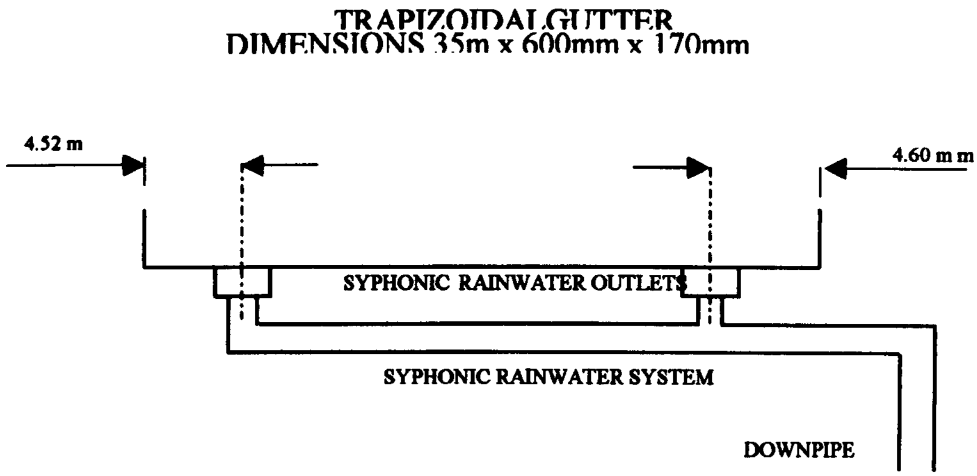

Figure 6 Schematic configuration of experimental system during test 3

Flow (l/s)	Recorded data (depth mm)	Extrapolated data (depth mm)
7.5	39	39
9	45	44
10	49	47.5
11	55	51.25
12	58	54.5

Table 4: Comparison of Recorded and Extrapolated values

Clearly at the higher flow rates there is some discrepancy between the actual depth and that obtained by extrapolation.

Examination of the data recorded in previous tests and from the current series have shown that there is a restriction to the flow through an outlet due to the proximity of the gutter walls. This close proximity has the effect of reducing the effective diameter of a rainwater outlet. This effect on weir diameter needs to be addressed when using the weir formulae described in the British Standard BS 6367.

As an aid to determining the restricting effect a gutter places upon the flow rate of an outlet, a chart has been derived for a flow rate of 12 l/s and is shown in figure 7. The data used in this chart, which is one of a family, has been recorded throughout this series of experiments. Data has been extrapolated and shown as a percentage increase in water depth above an outlet for a given flow rate, in various gutter sole widths. The chart identifies how the head of water above an outlet increases as the gutter sole width decreases. In addition there is an obvious inrease in water depth due to the outlets proximity to the gutter end. Within the chart the optimum position for an outlet is shown as D = 0, where D is the distance from the outlet to the gutter end. D = 1 is an outlet located at the gutter end.

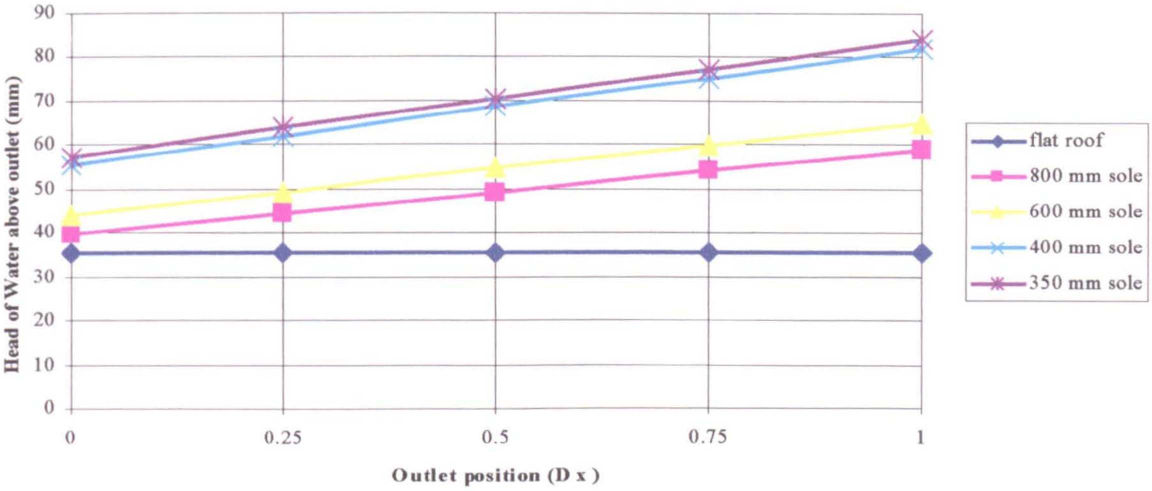

Figure 7 : Increase in head above an outlet due to its position within a gutter

This chart may therefore be used to establish the actual depth in a gutter due to the position of the outlet relative to the gutter end. A similar chart has been established for each flow rate in the range 7.5 to 12 litres/second.

CONCLUSIONS

- Flow rate through an outlet is affected by the outlets position within a gutter.
- Outlets placed at the extreme ends of a gutter may in some cases require an increase of 47% in the head of water to achieve the same flow when compared to the same outlet positioned at its optimum point (equal flow from both sides).
- As secondary systems dictate the water profile within a gutter, engineers and specifiers must become more aware of the restriction to flow that gutter dimensions may impart on an outlet.
- The work presented in the paper highlights a potential concern in respect of grouping secondary outlets within the ends of gutters. This may cause the gutter to over top at the mid point. A gutter needs to be designed accordingly if this philosophy of secondary outlets is to be used.
- An holistic approach is required which combines both gutter design and the rainwater drainage system design.

FURTHER WORK

There is a need to identify a common factor within the effect of the gutter walls, which will assist in determining a simplified method of calculation. Experiments using conventional rainwater outlets would help to confirm the flow reduction effect a gutter wall has on an outlet.

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HYDRAULIC PERFORMANCE OF SYPHONIC RAINWATER OUTLETS.

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ABSTRACT

Syphonic roof drainage systems may be preferred to conventional systems where high intensity rainfall results in large volumes of run-off, which have to be quickly and safely drained from roof systems. This paper describes the development of a full-scale system to test the performance of such systems. The system has been used to examine the influence of the position of two outlets within the gutter: spaced equi-distant and at either end of the gutter run. The results have been compared to conventional design equations outlined in the British Code of Practice BS 6367. It has been found that the capacity of an outlet is governed by the negative pressure which is created in the pipework downstream of the outlet and that the water depth within the gutter is subsequently influenced by the position of the outlet.

KEYWORDS

Gutter, hydraulic performance, outlet, rainwater, syphonic roof drainage

INTRODUCTION

Syphonic roof drainage systems have strategic advantages over conventional systems, and particularly so in respect of their cost-effectiveness to quickly remove large volumes of rainwater safely and effectively. In addition, modern day attitudes are placing greater constraints on developers and constructors to achieve building completion within ever-decreasing target times and to tighter budgets. Consequently, a design and build contractor has to find the most cost-effective solution. This is true for all aspects of building construction, including the roof drainage. Unfortunately, in some cases the drainage of the roof area of a building does not receive the same level of consideration that many of the more prestigious aspects of the building receive e.g. attention to aesthetics. This maybe because the total cost of a rainwater system forms a small percentage of the overall cost of the building. If developers were more aware of the significant costs associated with system failure then more consideration would be given to the design of the rainwater disposal system.

In the past, this has resulted in systems being installed without due consideration to the accurate assessment of hydraulic performance. This is vitally important when the systems are installed within valley or eaves gutters. Checking engineers, although experts usually work only with the information that is supplied by the individual rainwater system component manufacturers. If such information is not correctly verified, for example through rigorous testing of the particular combination of gutter and rainwater system, it may prove difficult to accurately predict the hydraulic performance of the system.

This paper describes a series of performance evaluations of syphonic roof drainage system. Through the utilisation of this full-scale test facility, located on the roof of Department of Civil and Structural Engineering, The University of Sheffield. A schematic diagram of the system is shown in Figure 1.

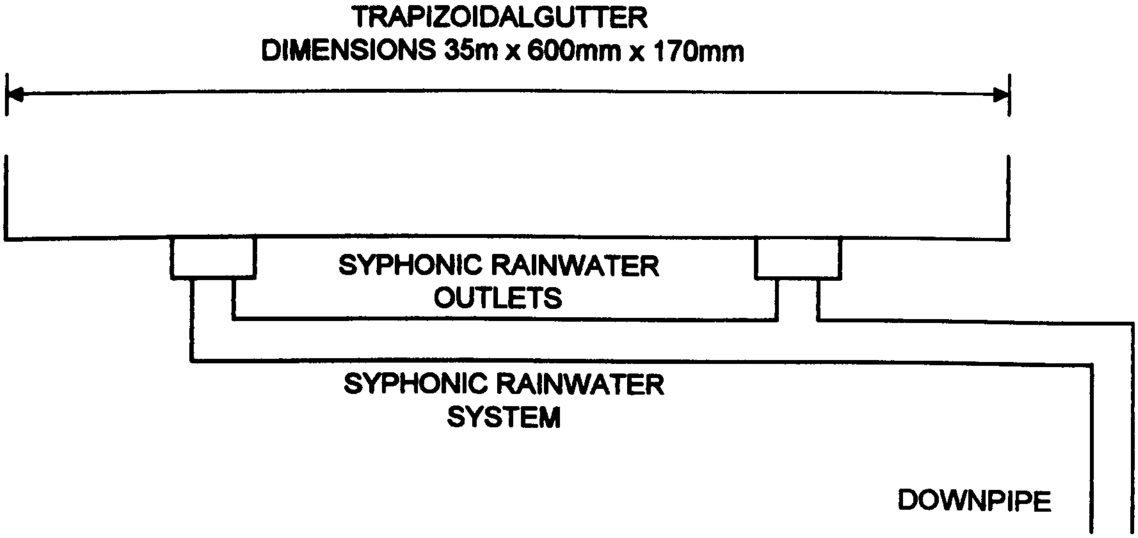

FIGURE 1 Test rig (schematic)

A full description of the system was outlined by Bramhall and Saul (1998). The system has been used to establish the hydraulic performance of a twin outlet syphonic system. The results of the experimental study have been compared with those formulae recommended for use by design engineers outlined in the British Standard Code of Practice BS 6367.

GUTTERS

Throughout Europe, roof areas are commonly drained using valley and eaves gutters. These are usually large in volume and have the capacity to discharge rainwater at high rates of flow. The definitive method for the design of gutters within the United Kingdom is BS6367: 1983 British Code of Practice for the Drainage of Roofs and Paved Areas. This publication clearly sets out the methodology to predict the hydraulic performance of a gutter. However, within the Code no design criteria for syphonic rainwater systems are outlined.

The location of rainwater outlets within a gutter determines the overall hydraulic performance of the system and the distance interval at which the outlets are placed has a significant influence on the flow depth within the gutter. In turn, this flow depth is a function of the head discharge relationship for the particular outlet. To reduce costs it is desirable to place rainwater outlets at ever increasing intervals; this obviously has a detrimental effect upon the upstream depth within the gutter. This practice maybe acceptable if the outlets are used in systems which drain a flat roof area or where a certain volume of storage is available. However, within a typical gutter, there is no allowable storage and consequently even a small rise in upstream depth could have a catastrophic consequence for the building and it's contents.

The objective of this study, in addition to the basic assessment of the hydraulic performance of a syphonic system with two outlets, was to examine the acceptability of the existing design Code for syphonic systems. The hydraulic performance of conventional systems is based on Equations 1-5.

$$F_o = \left(\frac{B_o \times Q}{g \times A_o} \right)^{\frac{1}{2}} \tag{1}$$

Where: F_o = Froude Number
B_o = Surface width of flow (mm)
Q = Flow (l/s)
g = gravitational constant (m/s^2)
A_o = Area of flow (mm^2)

To determine the upstream depth

$$Y_u = \left(1 + \left[0.4795 + \left(0.5205 \times \frac{B_s}{B_o}\right)\right] \times F_o^{1.4}\right) \times Y_o$$

(2)

Where: Y_u = Upstream depth of flow (mm)
B_s = Gutter sole width (mm)
Y_o = Depth of flow at the outlet rim (mm)

To make an allowance for the resistance to flow due to the length of the gutter, equation 3 may be used. The equation is based upon a Manning roughness coefficient of between n = 0.015 $m^{1/3}/s$ in small gutters, and n = 0.020 $m^{1/3}/s$ in large gutters.

$$x = 0.186 \times \left[1 - \left(1 - F_o^{2}\right)^{3.7}\right] \times \left[\frac{L_g}{Y_d}\right]^{0.75}$$

(3)

Where: x = Percentage increase in upstream depth of flow due to frictional resistance
L_g = Gutter length (mm)
Y_d = depth of flow at the downstream end (mm)

The overall upstream depth of flow, including the allowance for frictional resistance is calculated using equation

$$Y_{uf} = Y_u \times \left(1 + \frac{x}{100}\right)$$

(4)

Where: Y_{uf} = Upstream depth taking account for frictional resistance (mm)

The flow to the outlet may be expressed in the form of an equivalent weir equation

$$Q = \frac{D \times h^{1.5}}{7500}$$

(5)

Where: Q = Flow (l/s)
D = Effective diameter of the outlet (mm)
h = head of water above the outlet rim (mm)

The coefficient 7500 was derived from an extensive series of tests carried out by H. R. Wallingford and the British Hydromechanics Research Association (Wallingford Report IT 205).

EXPERIMENTAL METHODOLOGY

B) As already discussed, in order to accurately analyse the hydraulic performance of a gutter containing two syphonic rainwater outlets, extensive use was made of the full scale test facility constructed at The University of Sheffield. The aim of the tests was to compare the performance of two syphonic rainwater outlets when the outlets were positioned A) equi-spaced along the length of the gutter and B) when placed at the extreme ends of the gutter.

Figures 2 and 3 show the schematic outlet arrangement for each case.

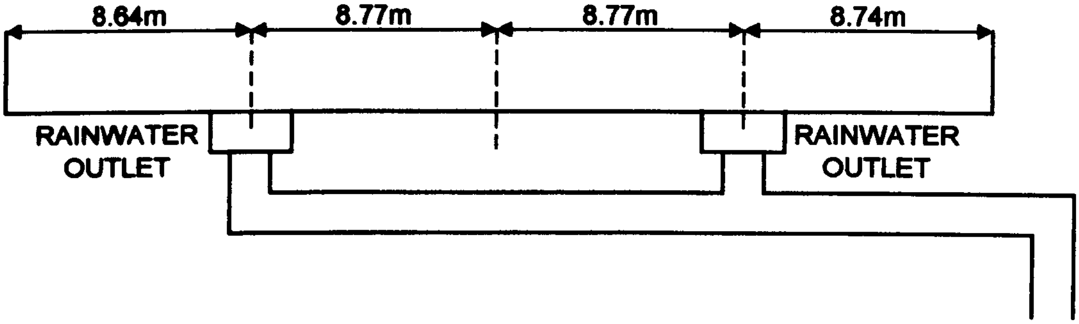

Figure 2 Outlets equidistant

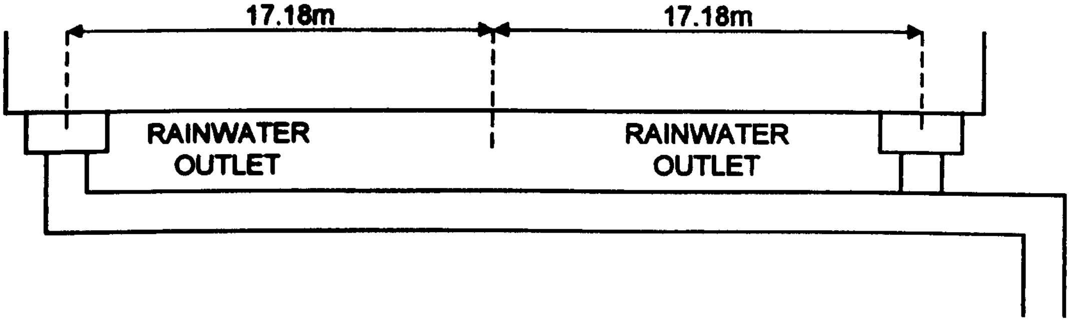

Figure 3 Outlets at either end of gutter

The pipe diameters were identical for both experiments, with a slight variance in overall pipe length in method B. Consequently; the flow capacity for each system was comparable. Various steady state flows were introduced into the gutter. Water depths were recorded using sight glasses connected to the gutter sole and located at both the outlet rim and mid way between the outlets i.e. the upstream point of zero flow.

RESULTS

Table 1 shows the results of the tests when the syphonic rainwater outlets were equi-spaced along the gutter sole, whilst the results outlined in table 2 correspond to the outlets located at the extremes of the gutter. Equations 1-4 were used to calculate the upstream depth.

Table 1: Measured and calculated water depths (outlets equi-spaced)

Flow through an outlet (l/s)	Measured depth at outlet rim (mm)	Measured depth upstream (mm)	Calculated upstream depth (BS6367) (mm)
7.5	37	43	43.00
9	40	46	46.70
10	41	48	49.10
11	44	51	52.31
12	45	53	54.27

Table 2: Measured and calculated water depths (outlets at extremes)

Flow through an outlet (l/s)	Measured depth at outlet rim (mm)	Measured depth upstream (mm)	Calculated upstream depth (BS6367) (mm)
7.5	43	63	63.40
9	50	72	71.33
10	55	77	76.52
11	60	82	82.03
12	65	86	87.75

In addition to the monitoring of flow depth, the pressure was recorded within each of the return pipes at each flow rate. This data, highlighted in Tables 3 and 4, was collected such that an examination could be made to establish whether the syphonic action within the pipework produced a 'pull down' effect on the water around the outlet rim. The measured water depths were compared the actual flow through the outlet with that estimated by equation 5.

Table 3: Flow rates through equally spaced outlets.

Measured water depth at outlet rim (mm)	Measured flow rate (l/s)	Calculated flow rate (l/s)	Negative pressure within the pipework (mWc)
37	7.5	7.7	3.11
40	9	8.70	4.27
41	10	9.03	4.90
44	11	10.04	5.44
45	12	10.38	6.17

Table 4: Flow rates through outlets placed at each end of the gutter

Measured water depth at outlet rim (mm)	Measured flow rate (l/s)	Calculated flow rate (l/s)	Negative pressure within the pipework (mWc)
43	7.5	9.6	3.11
50	9	12.16	4.13
55	10	14.03	4.87
60	11	15.98	5.44
65	12	18.03	6.13

DISCUSSION OF RESULTS

On inspection it can be seen from the data outlined in tables 1 and 2 that the calculated values of upstream depth from BS 6367 closely approximate to the actual measured depth. This finding initially indicates that the method of calculation of the flow depth in the gutter upstream of an outlet in a conventional system may be applied to a syphonic system. However the Code of Practice adopts a factor of safety and the experimental values were only approximately 80% of the theoretically derived values using the Standard. This suggests that either an increased estimate of the flow depth is required when a syphonic system is used or that the constants used in the equations do not take full account of all the parameters e.g. the sole width of the gutter. Future studies will attempt to address this issue. In the meantime, because the experimental values obtained from the syphonic system are in the same order as the theoretical ones, then BS 6367 may be considered as an accurate design tool when determining upstream depth with a gutter.

It is recommended however that in the interim a factor of safety is used in the design – say by increasing the predicted depth by 20%. However, to obtain an accurate estimate of the depth upstream of the outlet, the water depth at the outlet must first be obtained. When outlets are equally spaced along the length of the gutter this series of experiments has shown that the flow rate through the outlet corresponds with that calculated using the weir flow equation, but only at low flow rates. As the flow rate through the system increased the results from the experimental study suggest that the influence of the syphonic action created by the pipework is also increased. Consequently, the greater the flow rate through the outlet the more inaccurate the weir equation becomes. It is hypothesised that this is due to the negative pressures in the pipework which increase the suction force at the entry to the pipework. The recorded negative pressures, and a comparison between the measured and calculated flow rates are shown in Tables 3 and 4 for each series of experiments. The effect of the negative pressure is subsequently transmitted to the region of gutter flow in the vicinity of the outlet. Further experimentation is required to examine this hypothesis, but, if proven, then the accurate determination of upstream water depths within a gutter will be made all the more complex.

With regard to the location of the rainwater outlets along a gutter length, Table 4 shows that when an outlet is placed at the extreme ends of a gutter, and receives flow from only one direction, the effective weir diameter is greatly reduced. As a result of the position of the outlets there is a requirement for a much greater water depth around the outlet rim. In this particular series of experiments the outlets which were placed at the extremes of the gutter, were found to be 65% -77% less efficient. It should be noted that the outlet position only effected the water depths within the gutter. There was no detrimental effect upon the overall system performance due to the outlet's position. However it is argued that the water depth is a critical parameter, particularly in valley gutters, and hence due regard of this increased flow depth should be taken into account by the design engineers.

CONCLUSIONS

- The results of the study have shown that the position of the syphonic roof drainage outlet has a significant influence on the flow depth within the gutter.

- The equations outline in BS 6367 may, in the interim, be applied to predict the hydraulic performance of syphonic systems, as recorded depths of flow equate closely to the theoretical values derived using the standard.

- Further work is on-going to establish the influence on the hydraulic performance of the outlets due to the negative pressures in the downstream pipework and of the outlet geometry.

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An Investigation into the Effects of Negative Pressure Upon the Performance of a Syphonic Rainwater Outlet.

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Abstract

Through a number of recent research projects the understanding of the hydraulic performance of syphonic rainwater drainage systems has increased. This has resulted in these systems becoming more widely accepted within the construction industry, However, there is still a requirement for further knowledge, particularly with regard to the interface between the performance of a rainwater outlets and the flow conditions within the installed pipe work.

The operational pressures experienced within the pipe work of a syphonic rainwater drainage system are often sub atmospheric. Past studies have identified that there is pressure decay within a system downstream of the outlets, with the lowest pressure been experienced at a point located at the top of the greatest vertical drop. The performance of a syphonic rainwater drainage system located within a gutter may be affected by the pressure decay being translated back into the gutter via the rainwater outlet.

As part of the ongoing investigation into the performance of syphonic roof drainage systems a method of determining the flow rates through individual rainwater outlets has been developed. This paper describes the development of a dye concentration technique for the measurement of flow through individual outlets, without affecting the performance of the complete system. The results have been used to investigate the effects that the negative pressures within the pipe work have upon the performance of the symphonic rainwater outlet.

Keywords

Gutter, hydraulic performance, outlet, rainwater, syphonic roof drainage

1. Introduction

One strategic advantage of syphonic roof drainage system have over conventional systems, is the ability to rapidly remove large volumes of rainwater safely and effectively. This ultimately leads to significant cost savings with the building drainage. Additionally, current attitudes throughout the construction industry mean that developers and constructors operate under increasing constraints, in order to achieve targets both in time and monetary terms. This is true for all aspects of building construction, including the roof drainage. In some cases the drainage of the roof area of a building does not receive the same level of consideration that many of the more prestigious aspects of the building receive. This maybe due to the fact that the roof drainage only forms around 1% of the project budget. If developers were more aware of the significant costs associated with system failure, then more consideration would be given to the design of the rainwater disposal system.

In the past, this lack of consideration has resulted in systems being installed without due diligence to the accurate assessment of hydraulic performance. This is vitally important when the systems are installed within valley or eaves gutters. Checking engineers, although experts usually work only with the information that is supplied by the individual rainwater system component manufacturers. If such information is not correctly verified, for example through rigorous testing of the particular combination of gutter and rainwater system, it may prove difficult to accurately predict the hydraulic performance of the system.

This paper describes a series of performance evaluations of syphonic roof drainage system. Through the utilisation of this full-scale test facility, located on the roof of Department of Civil and Structural Engineering, The University of Sheffield. A schematic diagram of the system is shown in figure 1

A full description of the system was outlined by Bramhall and Saul (1998). The system has been used to establish the hydraulic performance of a twin outlet syphonic system.

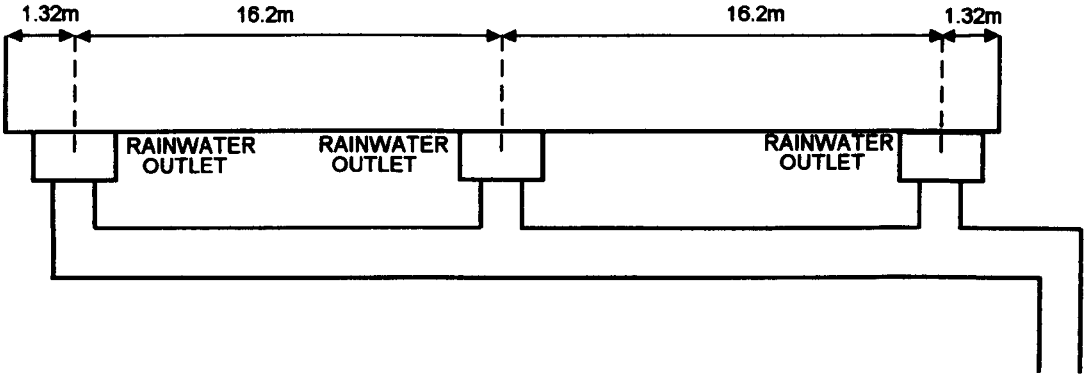


Figure 1 - Schematic diagram of a full scale test facility

2. Aim of This Study

The aim of this study was to assess the affect that sub-atmospheric pressure within the piping system, has upon the depths of water within the gutter for any given rate of flow. Analysis of previous areas of study has highlighted the pressure regimes within a system and the relationship between each component with respect to pressure. There has been highlighted a need for the development of a dye tracer technique in order to establish flow rates within any individual part of a system. This has been achieved with out compromising the effect intrusive flow measurement techniques may have had on the performance of the syphonic action within the system.

3. Sub Atmospheric Pressures within a Syphonic system

Through the understanding of how depressurisation occurs within each element of a syphonic system, it can be shown that there may be a possibility of the translation of the effects of the depressurisation in to a gutter.

The Outlet

Slater (1998) noted that the depressurisation experienced between the inlet and tailpipe of a syphonic outlet was dependant upon the flow. Using a commercial CFD package he was able to show that at a given flow rate of 6l/s the pressure drop across the outlet was in the region of 0.0315 bar

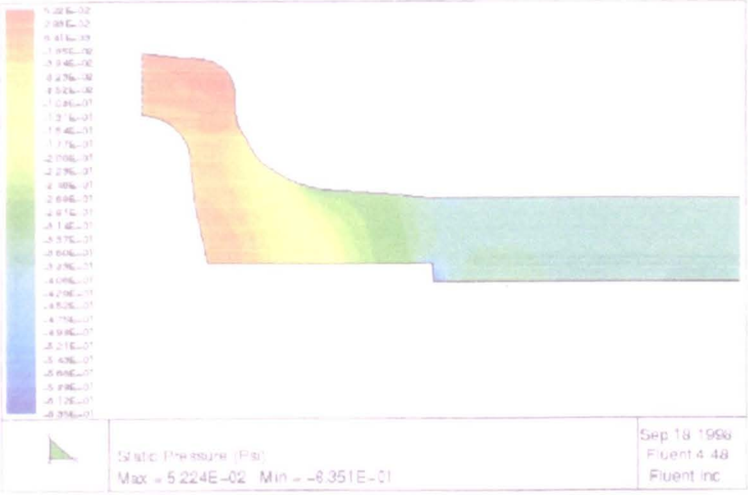


Figure 2 – Pressure distribution within an outlet at 6l/s

Maximum pressure = 2.403x102 Pa
Minimum pressure = – 2.913x103 Pa
Pressure drop across outlet = 2.403x102 – (-2.913x103)
= 3.1533 KPa
= 0.0315 bar

When the flow rate was increased to 12 l/s the pressure drop increased to 0.2788 bar. The pressure drop occurred over a relatively short distance as the length of the outlet is only 150mm

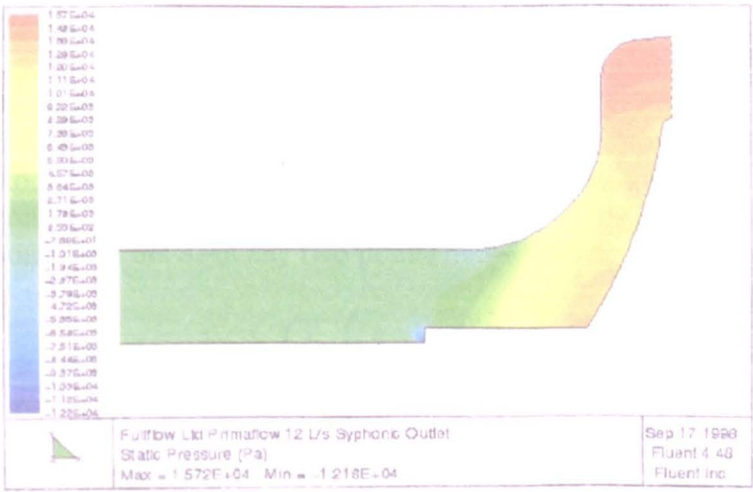
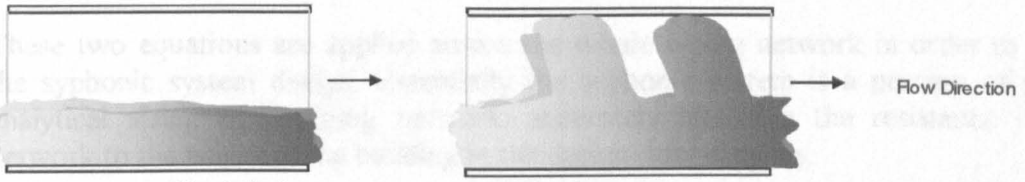


Figure 3 – Pressure distribution within an outlet at 12l/s

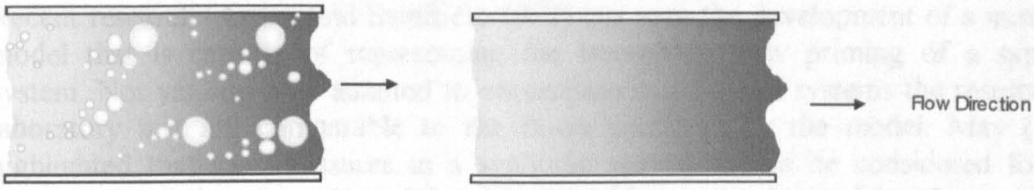
The pipe work

The flow regime within the pipe work of a syphonic system develops through a cycle as the rainstorm events unfold. Initially, the flow through a syphonic system will be as shown in flow pattern 1. Similar in operation to a gravitational system the resulting flow would partially fill the pipe.

The gravitational flow will be transformed into full-bore flow as the storm intensity rises. Air is excluded from the system as the water level within the outlet approaches the ant-vortex pate. Arthur and Swaffield (1999) described how the syphonic action is initiated within the pipe network as the rainstorm intensity and consequently the flow velocity increases.



Flow pattern 1 **(Gravity flow)** **Flow pattern 2** **(Plug flow)**



Flow pattern 3 **(Bubble flow)** **Flow pattern 4** **(Full bore flow)**

Figure 4 – Stages of priming of a syphonic system

As this priming process progresses to the full bore flow condition, a depressurisation of the pipe work occurs, hence the quantity of water discharged from the roof or gutter, is increased.

Bernoulli's Energy Equation

A Syphonic rainwater system designer has to solve the fluid mechanism problem presented by the height of the building and the quantity of rainwater generated by the storm event. Currently within the industry the pipe are considered to flow full and consequently Bernoulli's energy equation is used to determine the change in flow conditions between any two points in the system.

$$\left(h_1-h_2\right)+\left(z_1-z_2\right)+\frac{Q^2}{2g}\left\{\frac{1}{(A_1)^2}-\frac{1}{(A_2)^2}\right\}=K_{1,2}\frac{Q^2}{2g(A_2)^2}+i_{1,2}L_{1,2}$$

Bernoulli's energy equation

The terms on the left-hand side of the equation indicate the changes in the total energy of the flow, attributable to the pressure energy, (h1-h2), potential energy (z1-z2), and the corresponding kinetic energy.

The two terms on the right hand side of the equation determine the loss of total energy between the two points. The first term is an expression of the losses at bends, fittings and changes in the cross sectional area. The remaining term accounts for the frictional losses of the length of pipe between the two points.

Evaluation of the energy gradient is commonly obtained from the Colebrook-White formula shown.

$$i = \frac{Q^2}{2g(A_1)^2}\left\{\log_{10}\left(\frac{ks}{3.7D} + \frac{2.51v}{D\sqrt{2gDi}}\right)\right\}^{-2}$$

Colebrook-White formula

This equation involves factors including the pipe diameter, surface roughness and viscosity of the liquid.

These two equations are applied across the whole piping network in order to obtain the syphonic system design. Essentially the syphonic system is a process of careful analytical sizing of a piping network, accurately matching the resistance of that network to the height of the building at the design flow capacity.

Recent research (Arthur and Swaffield 1999) has seen the development of a numerical model that is capable of representing the two-phase flow priming of a syphonic system. Not yet currently adapted to encompass multi outlet systems the results from laboratory test are comparable to the flows predicted by the model. May (1996) highlighted that low pressures in a syphonic system should be considered for two reasons. One being the ability of the pipe material to resist the buckling forces implied by the negative pressure. This area of study has been reported upon by Bowler and Arthur (1999) who concluded that through the correct choice of pipe material the issue of pipe failure due to buckling should be eliminated. The phenomenon of cavitation was the second consideration of May (1996) who recommended that the cavitation index for pipes and fittings should be incorporated into the design analysis of a syphonic system.

Additional to the work undertaken by May, this author hypothesises a possible third reason for the consideration of negative pressures within a syphonic rainwater system. This reason concerns the performance of a rainwater outlet being enhanced by the negative pressures both in the outlet itself and the associated pipe work. The application of Bernoulli's energy equation combined with the Colebrook-White equation across a full flowing system predicts that typically the rainwater outlet located closest to the vertical stack will have a higher capacity than any other individual outlet. Furthermore, the pressure distribution chart for the system highlights that the position of the same outlet coincides with the area of least pressure. Figure 5 shows the typical pressure distribution relative to the vertical stack and the rainwater outlets. In an attempt to confirm the hypothesis a series of tests were performed. The first test compared the head of water around an outlet with the flow rate and localised pressure. The second test developed a dye tracing technique in order to establish the proportion of total flow attributed to individual outlets.

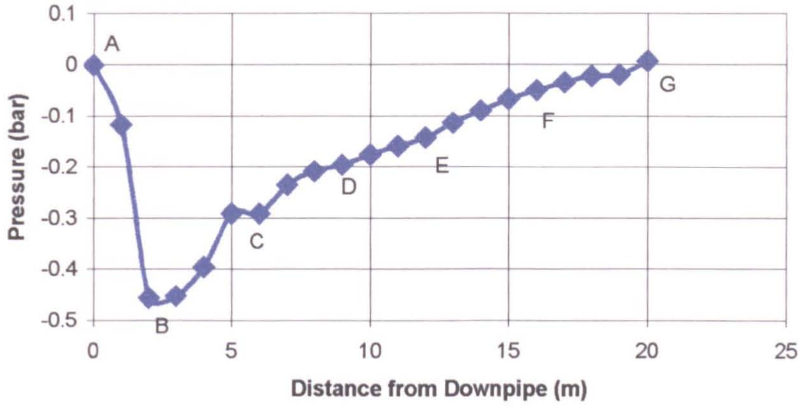


Figure 5 – Pressure Decay within a syphonic system

Point A = Discharge point
Point B = Top of vertical stack
Points C,D,E,F and G = outlet positions

4. Experimental Methodology

A description of a full-scale test facility located on the roof of the Department of Civil and Structural Engineering at the University of Sheffield, was outlined by Bramhall and Saul (1998). By utilising this facility through data collection and observation, an experiment was undertaken to determine how a negative pressure within the pipe work of a syphonic system affected the flow regime within the gutter. Previous test, Bramhall and Saul (1999), have concluded that for a given steady state flow entering the gutter, and two outlets being located at the extreme ends of the gutter, the variation in the working head of water around the rim of each outlet was insignificant. This would suggest that the outlets are accepting the same flow rates and contradicting the Bernoulli prediction that the outlet nearest the vertical stack has the capability of accepting greater flow rates than the other outlets. Therefore, if the working heads of water around each outlet rim are similar, but the flows different then the negative pressure generated within the outlet and associated pipe work maybe having an affect upon the outlets working head of water.

A three outlet syphonic system was installed within the 35 metre long test facility, the distance between each outlet is shown in figure 1. Steady state inflow rates to the gutter were measured through the use of pneumatically controlled valves. Depth measurements of the water within the gutter were recorded around each outlet rim and at the upstream points of zero flow (i.e. the point at which the flow divides to flow between two outlets). Pressure readings were recorded along the main horizontal collector pipe at the branch junction of an outlet, by means of a dial gauge. Steady state inflow rates were measured against water depths and observations of flow patterns within the gutter taken.

5. Discussion of Results

Figure 6 shows the relationship of flow against depth at various steady state flow rates. The three outlets were positioned between points 1 & 2, 4 & 5 and 7 & 8. Points 3 and 6 were the positions of zero flow (i.e. the point at which the flow divides to flow between two outlets). As previous studies have shown, and as relevant standards predict, the upstream depth of water within the gutter is clearly definable from the working head of water around the outlet. It should be noted that throughout the tests at varying inflow rates the variation in water depths around the two extreme outlets remains within 5mm. If this were a conventional gravity system the similar water depths would suggest that the outlets have the same flow capacity. However, when Bernoulli's energy equation is applied to the system, the outlet at point 7 is predicted to accept 18.5% more flow than the outlet at point 2.

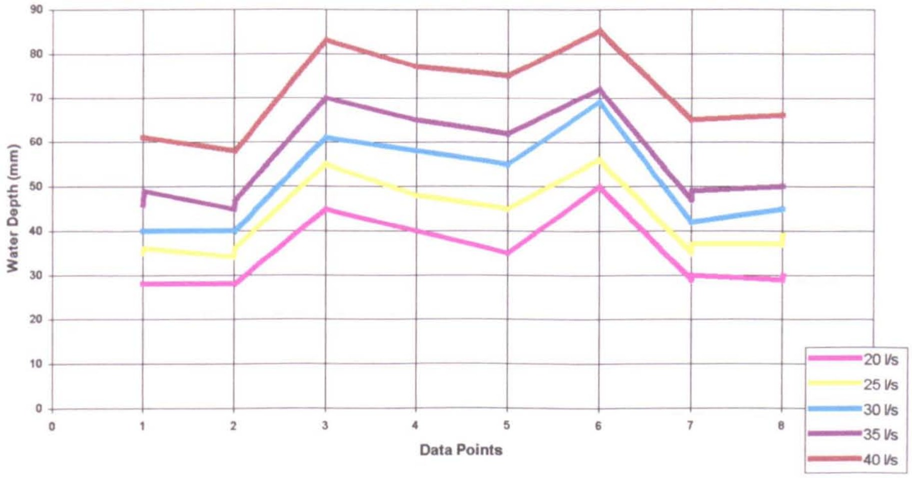


Figure 6 – Water depths within gutter

Alongside the Bernoulli's predicted values of pressure, table 1 shows the pressures recorded at the junction of each outlet branch as it connects to the main collector pipe. It may be seen that in both the actual and theoretical cases, the values of pressure are lower at the outlet situated nearest the vertical stack. I.e. point 7. The two values of pressure recorded at the steady flow rate were due to the characteristic oscillation of the syphonic system during the priming phase. The effects of the oscillation were transmitted into the head of water around the outlet rim. Figure 6 identifies the fluctuations within the water depths at point 2 and 7. Observation of the water velocities within the gutter revealed the velocity around the two extreme outlets to be different. The highest velocities within the gutter were observed around the outlet located nearest to the vertical stack. As the water depths within the extreme ends of the gutter were comparable the increase in velocity would suggest an increase in flow. The results of this particular test highlighted the need to assess the flow rates down individual outlets. Inflows to the gutter may be measured accurately through the use of control vales. However, this method of flow measurement does not indicate the proportion of the total flow being drained by individual outlets. A method of determining this individual flow without placing restriction within the pipe had to be found. The insertion of flow meters both mechanical and ultrasonic was considered but these were found to be unsuitable due to the pipes flow part full and the necessary restriction to flow.

Flow l/s	Recorded Measurement (bar)			Bernoulli's Calculation (bar)		
	Pt 1	Pt 4	Pt 7	Pt 1	Pt 4	Pt 7
20	0	-0.025	-0.05 -0.1	0.03	-0.003	-0.065
25	0	-0.025 -0.05	-0.1 -0.15	0.022	-0.013	-0.19
30	-0.05	-0.05 -0.1	-0.15 -0.25	0.009	-0.028	-0.29
35	-0.05 -0.1	-0.075 -0.125	-0.25 -0.3	-0.0069	-0.045	-0.42
40		-0.15	-0.325		-0.114	-0.42

Table 1 – Measured and calculated pressures

Fluorometry has been typically used in the measurement of flow within streams, rivers, partially filled sewers and open drainage canals. Adaptation of this tried and tested method of flow measurement into the roof drainage systems has been developed.

6. Development of a dye tracer technique for the calculation of flow

A dilution of dye is injected into the bowl of the rainwater outlet located furthest from the vertical stack. Injecting the dye in such a way enable the dilution to mix with the turbulent flow of water within the outlet. The flow rate of the dilution was controlled through the use of a variable speed pump. Figure 7 shows the configuration of the dye injection points and sample retrieval points.

By comparing the initial analysis of the dye concentration and the analysis of the samples retrieved from points 1 and 2 it is possible to calculate the rates of flow within individual rainwater outlets.

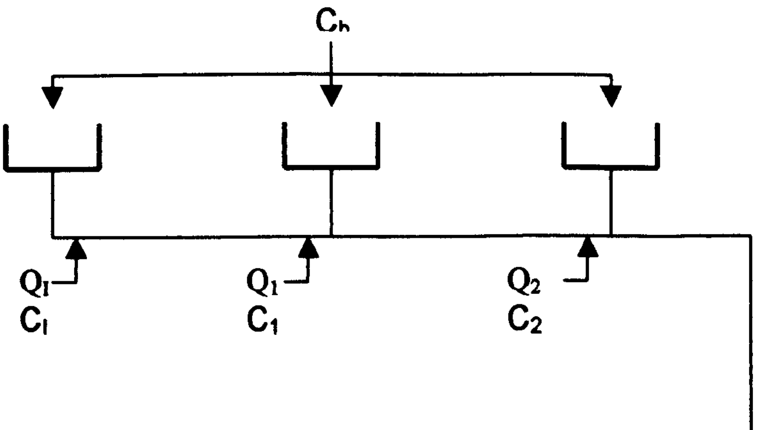


Figure 7 – Configuration of dye tracer technique

Q_I = Flow rate of initial dye water mix (l/s)
C_I = concentration of initial dye water mix (l/l)
Q_1 = Flow rate at point 1 (l/s)
C_1 = Concentration of dye at point 1 (l/l)
C_b = Background concentration (l/l)

7. Conclusion

- Areas of negative pressure within a syphonic system have been identified and investigated.
- Pressure decay within a syphonic system has been recorded.
- Previous area of study have been assessed and reported on
- A dye concentration technique has been developed for the measurement of flow through individual outlets.
- Observed velocities within the gutter suggest the outlet located nearest to the vertical stack of a system accepts more flow than weir flow calculations suggest

8. Further Work

By design, negative pressures are experienced within the pipe work of a syphonic system. The initial tests have indicated that due to the existence of the below atmospheric pressure within the associated pipe work, the hydraulic performance of an outlet may be enhanced.

It is the intention that future work will investigate the effects a negative pressure has upon an outlets capacity. This will be achieved by measuring the steady state flow rate through an outlet using the dilution technique developed within this study, and recording the depth of water above the outlet. Careful manipulation of tailpipe diameters to give different flow velocities and consequently the negative pressure within the pipe work, will enable comparisons to be made. Through a series of such tests, the effects of negative pressure upon an outlet will be determined. It is proposed that the tailpipe diameters will be changed on a maximum of two further occasions (one larger and one smaller than existing).

Once the full series of tests have been completed the tests will be repeated using alternative designs of syphonic rainwater outlets. In addition to confirming the accuracy of the numerical models, the change of outlets would also highlight the adaptability of such models and give credibility to the findings. Repeating the tests in this way would give confidence to all designers and help to ensure that the results are adopted through out the syphonic rainwater drainage industry with a high degree of confidence.

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