Domestic Roofwater Harvesting
Research Programme

THE OPTIMUM SIZING OF GUTTERS FOR DOMESTIC ROOFWATER HARVESTING

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December 2002

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ABSTRACT

Guttering, in a roofwater harvesting system, has the purpose of intercepting the roof run-off and conveying it to a downpipe (which in turn carries it to a store). The two phases of 'interception' and 'conveyance' make different and sometimes conflicting demands upon a guttering design. Their respective failures (overshoot and overflow) occur under similar circumstances, namely intense rain, and for most analytic purposes it is appropriate to consider as total water loss just the higher of the overshoot loss and the overflow loss, rather than their sum. A good gutter design must satisfy many criteria including durability, cheapness and ease of fixing. In this paper on gutter sizing, the primary approach is to find that gutter size and shape that maximises the ratio of water benefit to system cost. The work was motivated by field observation of evidently over-sized gutters and the absence of any published 'informed' guidance on sizing. The study entailed theoretical analysis, laboratory experimentation and some field studies. The findings are that:

(i) 'U' or trapezoidal-section gutters give the best economy,

(ii) roof area is the primary determinant of gutter size and

(iii) a 'U'-shaped or trapezoidal section gutter of width only 70 mm will be sufficient for most house roofs in the tropics.

The optimum gutter location and fixing trajectory are also explored to produce recommendations.

CONTENTS

PREFACE

This Working Paper summarises research performed over a period of 5 years by Warwick University's Development Technology Unit. Some of it is mathematically analytical or entails computer simulations, however all the more complex maths has been removed to the Appendices of the Paper. Readers who only seek the findings, rather than the route by which they were reached, are recommended to read just the Introduction and the Conclusions.

Several people have been involved in the work besides the two named authors. Inputs have come from engineering students at Warwick University, from members of Palm Foundation (Nuwara Eliya, Sri Lanka) and Uganda Rural Development & Training (Kagadi) and (under the aegis of a research contract from DFID, UK Govt) from a Research Associate at Warwick and subcontractors in Sri Lanka (LRWHF) and Uganda (ACORD). The authors wish to acknowledge financial support from DFID, the European Union and the Nuffield Foundation.

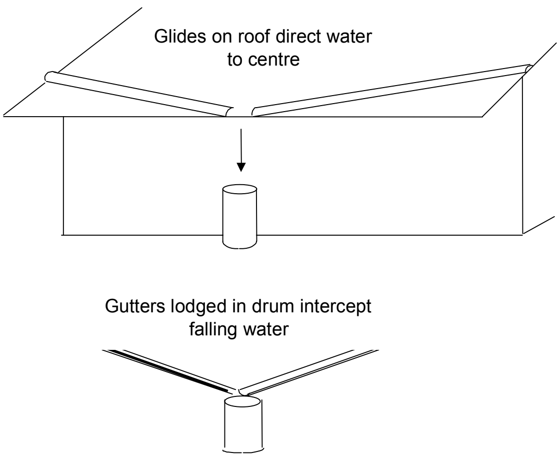
Gutter behaviour is very complex to analyse, yet RWH guttering design is not of such great economic importance that it justifies huge efforts to codify. The Paper exposes that complexity but then employs 'reasonable approximation' to reduce it to the point where simple design rules can be generated.

1 INTRODUCTION

Gutters are an almost essential but relatively cheap part of a roof-water harvesting (RWH) system. It *is* possible to collect roofwater without them by using instead glides or ground level troughs (Gould & Nissen-Petersen, 1999; Qiang & Fuxue, 1995) and some house geometries concentrate run-off from adjacent roofs into gulleys/valleys.

However the great majority of roof-water collection systems contain gutters to intercept run-off from the roof edge and convey it laterally to a downpipe leading to a tank

Figure 1.1: Alternatives to Roof-edge guttering



In temperate countries at latitudes above about 40°, roof overhangs are often very small, so gutters are commonly installed to prevent rainwater running down the house walls and damaging them. In countries closer to the equator, the higher temperatures and higher sun angles make it attractive to project roofs 60cm or more beyond house walls to provide shading. Such large overhangs throw most roof run-off water clear of the walls, especially in single-storey buildings, and therefore guttering is not needed for wall protection. Any guttering that is installed must therefore be financially justified wholly by its contribution to water harvesting.

In addition to the prevalence of big roof overhangs, and sometimes of poorly aligned roof edges, the *humid* tropics are characterised by three features that impinge upon gutter design, namely:

- rainfall can be intense,
- the dry season is not long,
- household incomes are low.

Intense rainfall requires guttering of relatively high flow capacity: a design norm equivalent to rainfall intensities of say 1.5 to 2 mm per minute. The short dry season permits use of relatively small and cheap tanks: this in turn raises the fraction of RWH system cost attributable to guttering. Finally, low household incomes require low-cost RWH systems. These three factors result in the need to pay more attention to minimising guttering costs in the humid tropics than elsewhere.

Any observation of existing tropical RWH systems reveals many inadequacies in guttering (Gould & Nissen-Petersen, 1999), often resulting in the loss of over 50% of potential water yield. Gutter slopes may be inadequate or even negative; joints may leak; serious blockage by debris is common, as is twisting of gutter sections (resulting in spillage over their sides). In institutional systems, lack of clear management responsibility results in damaged or stolen guttering not being replaced, often leading to total failure of water delivery.

A ‘failure’ of a different kind is that both gutters and downpipes are often seriously oversized in domestic RWH systems. This may be due to the unrealistic choice of 100% as the design criterion for run-off capture. To intercept *all* run-off from the poorly aligned edge of a small house’s roof may indeed require 100mm or even 150mm gutters, whereas to collect 96% of the run-off can be achieved with guttering of half the cost. Furthermore it is uncommon to find guttering economy given any attention when decisions are being made about tank location or tank height, so often gutters have to be designed for unnecessarily difficult conditions.

In some cultures it seems that aesthetics favour the selection of particularly conspicuous (large) gutters and pipes: in other cultures every attempt is made to hide them.

Finally guttering has a ‘health’ dimension, in that gutters can be a breeding ground for mosquitoes and in that gutters full of debris impart extra bacteria into the water they convey.

Ideally, guttering should be cheap to produce, efficient in capturing run-off water, easy to align and install, resistant to damage and (if not completely self-cleaning) simple to clean. The worldwide trend towards multi-storey housing increases the difficulty and even danger of installing and cleaning gutters, so that designs and attitudes adequate for RWH in rural homesteads in the past are unlikely to suffice for urban or rural housing in the future.

There has of course been some past research into guttering, but there is rather little one can refer to with respect to either the theory of its performance or to its performance in practice. Gutter manufacturers have undertaken tests of their own products and sponsored some research by others (for example into ‘downpipes for very large buildings). There are some standards (BS6367, 1983) and web pages. However very little of the published literature refers to conditions in poor tropical communities, to the specific context of roof-water collection or matches the information needs of promoters of RWH. The research reported in this Paper was therefore undertaken to extend existing guttering knowledge to better cover domestic tropical RWH, to fill gaps in that knowledge and to give certain aspects of gutter design a more scientific basis. Finally we have tried to translate our findings into ‘rules of thumb’ simple enough to be transmitted to RWH practitioners.

In the sections that follow we have concentrated on gutters proper, giving only brief attention to downpipes and avoiding any consideration of first-flush diverters or other devices sometimes incorporated into downpipes. Moreover our limited resources have led us to concentrate research upon gutter performance and sizing, rather than the equally important issues of gutter manufacture, design and durability.

The format of the paper is as follows. Sizing gutters for firstly water conveyance and then run-off interception are considered in isolation, giving some bounds on gutter size. Following this, modelling of gutter performance is conducted considering both these mechanisms acting together. Conclusions are given following analysis of the results.

2 SIZING A GUTTER TO CONVEY WATER

2.1 Capacity to convey water

Before examining the interaction of the conveyance and interception functions, we first fairly crudely examine conveyance on its own. We do this in order;

(a) to short-list configurations that are efficient at conveyance,

(b) to develop the conveyance model later to be used in combination with an interception model to produce an overall performance forecast and

(c) to be able to optimise gutters in situations where interception can be assumed to be near complete (e.g. where roofs are not corrugated and winds are generally gentle).

In this section we will consider sizing a gutter just to convey water from its entry into the gutter to the downpipe. The findings from the work are summarised in Appendix 1, which gives a more detailed explanation of the data used and analysis performed.

Sizing a gutter for conveyance involves modelling the flow within the gutter. The flow changes along the gutter, extra water coming in from the roof; so we are dealing with an example of spatially varying flow. There are difficulties with modelling this form of flow. Obtaining a full algebraic solution is not practical. So we developed instead a numerical model of this situation, and validated it via an experimental test rig. Further work yielded an asymptotic non-dimensional solution to the flow equation. [This was however only a second order solution, i.e. it was not exactly the solution of the original equation, but a very close approximation.] In this solution, the most significant term was equivalent to applying the long-established Manning formula:

$$Q = \frac{1}{n} a r_h^{2/3} \sqrt{S} \qquad \text{Equation 2.1}$$

Flow (Q) thus depends on the roughness of the gutter material (n), gutter cross-section area (a), hydraulic radius (r_h) and gutter slope (S). The roof area efficiently drainable by a gutter is proportional to Q.

However to this Manning term has to be applied a correction based on the aspect ratio of the gutter; namely the ratio of the gutter's length to its width. This correction gets smaller as the aspect ratio increases: i.e. as the gutter increases in length, the flow within it approximates more and more closely to that predicted by the Manning equation. As gutters in domestic applications nearly always have an aspect ratio higher than 100 (they are very narrow relative to their length), the correction to the Manning formula becomes sufficiently small that it can be neglected. The Manning formula alone may then be used to size gutters for water conveyance. Moreover, provided the roof area is not extremely squat (i.e. gutter length is not less than the slope-length of the roof perpendicular to the gutter), the gutter can be sized just according to the roof area, as is in section 4.7.

So we start by assuming all water falling on the roof also enters the gutter. If we now wish to minimise the system cost per litre captured, it can be shown (see Appendix 1) that a tropical gutter should be sized to match a rainfall intensity of around 2 mm/min of rainfall. (This intensity gives a gutter outlet flow of around 0.03 x A litres per second, where A is roof plan area.) As shown in Table 2.1, quite small gutters are adequate for rainwater conveyance from domestic roofs of representative areas.

Gutter trajectories where the slope varies along the gutter are also considered, leading to the conclusion that a gutter laid at a slope of α % at the outlet could be laid at $\alpha/2$ % for the first 2/3 of its length with no loss in conveyance capacity. This is covered in Section 2.3.

As we can achieve almost any flow capacity from a given gutter by making it steep enough, there is no meaning to ‘optimum size’ unless we first constrain the gutter slope. Moreover from just a conveyance point of view we would choose a deep gutter shape such as a square section or a deep-drawn ‘U’. (Later we will find that for economy, interception requires a shallow shape.) Table 2.1 lists the roof areas that different sizes of square gutter could optimally drain at various given slopes.

As a further point of interest, it would appear that many downpipes are oversized: calculations given in A1.5. These suggest that pipes with bores around 40mm should give adequate capacity for the flowrates of interest.

Table 2.1: Optimum roof areas drainable by square gutters (considering only conveyance)

Square gutters	Slope (%)			
	0.5	1	2	4
Gutter width	**Optimum roof area gutter will serve (m^2)**			
33 mm	10	14	20	28
50 mm	29	42	60	85
75 mm	88	125	177	250
100 mm	190	269	380	538

Note that (sheet) material width is 3 times gutter width for this square section.

2.2 Gutter shape and conveyance

The effect of gutter shape on conveyance can be examined assuming the Manning formula for capacity is valid. Where it is, capacity is proportional to:

$$A_g^{5/3}\ p_g^{-2/3} \qquad \text{Equation 2.2}$$

Where A_g is gutter cross-sectional area and p_g is the length of the wetted perimeter of the cross-section.

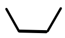
Changing from square section (as in Table 2.1) to other common shapes (semi-circular, trapezoidal and vee) requires us to decide what is to be fixed. Two important strategies are: -

(i) holding the amount of material in the gutter constant – in effect we hold the gutter perimeter p_g constant. – so that gutter cost is kept approximately constant

(ii) holding constant the gutter width (its aperture and therefore its ability to intercept roof run-off).

Routine calculations then give us Table 2.2

Table 2.2: Roof areas drainable by gutters of different shapes (assuming square gutter is sized to drain 100 m^2)

Shape	square	semicircular	trapezoidal	vee (90°)
				
w / p_r	0.33	0.64	0.67	0.71
Strategy	**Roof area gutter drains (m^2)**			
(i) const p_r material	100	182	250	122
(ii) const *w* width	100	33	39	16

Thus on the criterion of flow capacity (and therefore roof area drainable) alone, for a given gutter *width* a square section is much superior to other shapes, while for a given gutter *cost* the square section is inferior. This switch reflects the low width-to-perimeter (w/p_r) ratio of the square shape. The trapezoidal shape is probably the best shape overall – the one used in these calculations has ‘wings’ set at 30° to the vertical and of the same size as the base.

2.3 Gutter trajectory (varying the gutter slope)

Hanging a gutter at a constant slope is easier than trying to follow a more complex trajectory. However this is not an efficient way of using a gutter of constant section: at rainfall intensities causing the lower (i.e. discharge) end of the gutter to overflow, the upper part of the gutter does not run full and is therefore ‘oversized’. One option would be to steadily increase a gutter’s *size* as one progressed from its top to its bottom end. This is not usually practical and a constant gutter section must be accepted. A second option would be to steadily increase the gutter’s *slope* along its length. Here we explore the theoretical benefits of such a procedure to see if they might justify the extra complexity it introduces into gutter hanging.

At *constant slope*:

local slope is: $S(x) = S_o$, where x is distance from the top end and S_o is maximum slope,

local drop is

$y(x) = S_o\, x$ Equation 2.3

maximum drop is

$y_o = L\, S_o$ Equation 2.4

mean drop is

$y_m = L\, S_o /2$ Equation 2.5

However the most efficient profile for a gutter would be the one whereby (at the design rainfall intensity) the gutter was running just full at every point along its length. Manning's flow formula indicates that the local slope of such an 'ideal' gutter would need to be not constant but according to

$S(x) = S_o\, (x/L)^2$, where L is the gutter length.

At this *ideal slope*:-

local drop is

$y(x) = x^3\, S_o / 3\, L^2$ Equation 2.6

maximum drop is

$y_o = L\, S_o /3$ Equation 2.7

mean drop is

$y_m = L\, S_o /12$ Equation 2.8

Thus compared with constant slope, by using an ideal profile we have achieved a 6-fold reduction in the mean drop, giving thereby a probably substantial improvement in run-off interception. Alternatively we could have kept the same interception (same mean drop y_m) and have increased the maximum slope S_o by a factor of 6, thereby increasing gutter flow capacity by factor 2.45. A further option would be to commute this extra capacity into a smaller gutter size, thereby allowing use of a 29% smaller gutter (as $2.45^{-3/8} = 0.71$). These are significant benefits.

Hanging a gutter to such an ideal cubic trajectory is unlikely to become common practice. Gutters are not made to bend easily in a vertical plane. Moreover to avoid mosquito breeding we require all parts of a gutter to drain down after a storm has ended. So we avoid flat gutter sections and can contemplate changes in slope only at the joints between gutter sections. One simple compromise is the 'dual-slope' gutter whose upper end (length L_u) is laid at a low slope S_u and whose lower end (length $L\text{-}L_u$) is laid at full slope S_o. Using the Manning formula one can find by inspection that to minimise mean drop y_m the *best dual slope* arrangement is for

$L_u/L = 0.5$ and $S_u/S_o = 0.25$ giving a mean drop of $y_m = 0.22\, L\, S_0$

Comparing with the *uniform slope* gutter, this *best dual slope* represents, for constant mean drop, a flow capacity gain factor of 1.51 (which is significant) or a size reduction factor of 0.86 (not very significant).

In recommending dual slope to practitioners, we have to describe it in a simple and easily memorable form. It may be that

> *"Use a quarter slope for the upper half of the gutter length and full slope for the rest"*

is too complex, or requires too fine a level of slope measurement. For that reason we have also investigated a less efficient but more memorable dual-slope configuration, which uses "half slope" ($S_u = 0.5\, S_o$) and "full slope". A near-optimum and readily memorable form of this we may call *simple dual slope*

> *"Use a half slope for the first 2/3 of the gutter length and full slope for the rest"*

The numerical results of comparing *constant slope, ideal slope, best dual slope* and *simple dual-slope* gutters are given in Table 2.3. There we see that substituting *best dual-slope* or *simple dual slope* for constant-slope guttering is likely to yield significant improvement in run-off interception (via halving the mean gutter drop) and that for very long large gutters it may even be worth adopting a complex trajectory close to *ideal slope* to reduce gutter size.

Table 2.3: Comparison of gutter-slope options

Gutter slope		Max drop	Mean drop	Capacity* enhanced by
		y_o/S_oL	$y_m/2S_oL$	$(S_mL/y_o)^{0.5}$
Constant	$S=S_o$	1.00	1.00	1.00
Ideal	$S_o(x/L)^2$	0.33	0.17	2.45
Best Dual	$S=S_o/4$ & $S=S_o$	0.63	0.44	1.51
Simple Dual	$S=S_o/2$ & $S=S_o$	0.67	0.56	1.36

* Flow capacity subject to a fixed mean gutter drop y_m

2.4 Conclusions concerning conveyance alone

Because gutter length-to-width aspect ratio is so high, gutter flow can be calculated using the steady flow Manning's formula. This formula shows that for a given amount of material and given slope, square gutters convey less water than other common shapes. A trapezoidal shape is recommended.

Using such a shape, laid at a slope of 1% at its discharge end, a gutter width of 67mm (material width of 100 mm) should suffice to carry the water running off one side of a domestic roof. The gutter size giving best economy is one that overflows when rainfall intensity reaches about 2 mm/minute. A dual-slope (0.5% & 1.0%) trajectory will not compromise capacity but will approximately halve the mean drop along the gutter compared with a constant slope trajectory. its use is therefore recommended. Even bigger advantages would accrue if gutters could be laid to a $y = k x^3$ trajectory.

3 SIZING A GUTTER TO INTERCEPT RUN-OFF FROM A ROOF

We now move to consider the interception aspect of guttering, which in this section is treated in isolation, i.e. assuming that all water that is intercepted will be conveyed without spillage. In this case the only gutter dimension of interest is its 'aperture' *w*, namely the width of the opening at the top of the gutter.

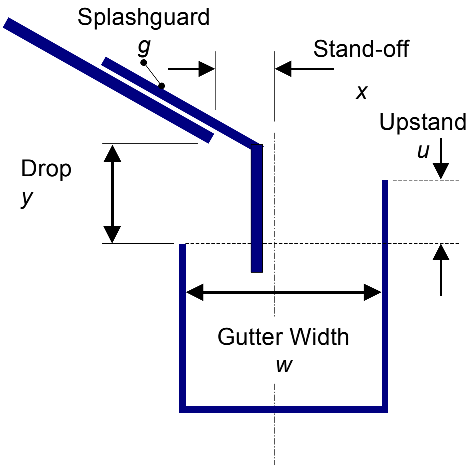
3.1 Characterising roof run-off

Water leaving a roof may collect at the edge and then fall in droplets, or it may leave in such a form as to give directed jets of water. This latter is particularly the case with corrugated roofs, where the corrugations act to concentrate the flow into channels, thereby increasing their flow velocity. By contrast, with tiled roofs the water is spread to such a fine layer that it rarely leaves the roof with a significant horizontal component to its velocity.

The performance of the gutter will vary from minute to minute, due to the ever-varying rainfall intensity. However the gutter designer needs an overall figure such as mean annual performance.

The interception performance of a gutter will depend primarily upon the dimensions labeled in Figure 3.1

Figure 3.1: Gutter Dimensions affecting Run-off Interception



These dimensions are, in declining order of influence,

i. Gutter aperture size (width *w*). The width of the opening at the top of the gutter will clearly affect its performance at collecting water leaving the roof. From the conveyance work in the previous section, we have in mind values around *w*=50 mm to *w*=100 mm; (2" to 4" gutters).

ii. Gutter drop *y,* measured from the discharge point on the roof to the top surface (level of water at overflow) of the gutter; spot values of 10mm and 100mm should cover the range of normal use.

iii. Gutter stand-off *x,* whose value is zero when the *centerline* of the gutter is directly below the edge of the roof.

iv. Gutter upstand *u* above its overflow surface. For symmetrical gutters this will be zero. For gutters with a raised outside edge this will be positive.

v. The presence or absence of a splash-guard on the roof edge directing water into the gutter: *g*=0 *or g*=1.

However besides the gutter dimensions many other factors affect interception performance, including:

i. Rainfall intensity.

ii. Wind strength.

iii. Backing – i.e. the presence or absence of a fascia board preventing wind passing across the gutter. Note that to be effective in controlling wind, such a board needs to be very close to the back of the gutter.

iv. Roof type – furrowed roofing gives a more strongly bunched and directed runoff than tile roofing.

v. Roof length *l* perpendicular to the gutter. For poor housing we might use *l*=2500 mm and *l*=3000mm, the latter being the length of a full GI sheet.

vi. Roof area draining into the gutter.

vii. Roof slope, which in the tropics typically lies in the band 15^o (S=0.26) to 30^o (S=0.5).

viii. Straightness of the roof edge (in plan) and the roof environment (e.g. overhanging trees).

It may be that a gutter sized to give sufficient flow capacity would not intercept sufficient water leaving the roof to make use of this capacity. Alternatively, sizing a gutter for interception alone would lead to an extremely wide, shallow gutter, which might lack the flow capacity to convey the water intercepted.

From observations by several fieldworkers, it would appear that except during the most intense rainfalls, water leaving the roof collects at the roof edge and then drips vertically, i.e. with negligible horizontal velocity. Such drips are strongly affected by wind around the gutter. Wind in turn is moderated by the presence of a fascia board. However it is intense rain that interests us most, because it generates such strong flows in the furrows of the roof that small jets are formed at the roof edge. These jets are more resistant to wind deviation but their velocity has a horizontal component that may carry them past the gutter's outside edge, resulting in loss through overshoot.

3.2 Gutter positioning in the absence of wind

Experimental work was conducted under laboratory conditions by two Warwick students, Boswell & Vispond, in 1997, simulating a range of rainfall intensities on corrugated roofs of varying length and slope. They found that the outward 'throw' of the run-off jets increases with roof slope, roof length and rainfall intensity, but that below certain levels of these parameters there was negligible throw.

For a representative roof (slope of 22^o), at rainfall intensities of 2 mm/min, the throw was found to be around 100mm at 100mm drop (slightly more for longer roofs). There is pulsation as the water leaves the roof, giving some variation in throw. The drop of 100mm was chosen, considering the previous work on conveyance, to be consistent with: a 1% gutter slope along a representative 10m roof edge.

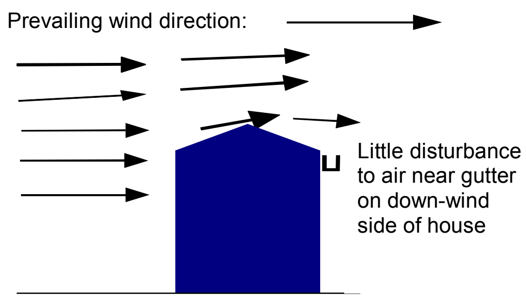
These results suggest that for likely gutter drops, to capture all the rainfall at intensities up to 2 mm/min requires a gutter stretching 100 mm outwards from the roof edge (requiring at least a w = 100 mm gutter aperture).

3.3 Effects of wind

Having obtained some data concerning the behaviour of water leaving the roof in calm conditions, it becomes necessary to consider the effects of wind. Wind is particularly important in the case of water dripping from the roof, as it will then be the only factor causing the water to deviate from a vertical path, and hence require a larger gutter.. However it is only wind perpendicular to the gutter that need concern us, since wind along the gutter can only generate a small end-loss.

One can argue that the wind is unlikely to be strong, and hence to have a significant effect on roof run-off, on the down-wind side of a house. Indeed wind below the roof edge on this lee side is probably an inwards-directed eddy rather than directed outwards. So we are primarily interested in wind influence on run-off on the *up*-wind side of a building. Here the effect of the wind is to reduce the outward throw, or in the case of 'dripping' run-off to impart a negative throw. This in turn requires the inside edge of the gutter to be set some distance *inside* the roof edge. Field observation suggests that provided the gutter inner edge is set about 20mm inside the roof edge, we need not worry unduly about wind effects.

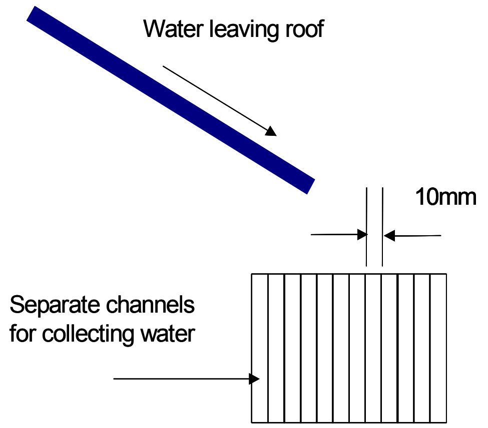
Figure 3.2: Wind flow past a building



3.4 Experimental evidence of gutter performance at intercepting run-off

Experimental work was conducted on GI roofing in Sri Lanka. Two roofs were used, one of 22° slope and one of only 6° slope. Both roofs were equipped with an experimental test rig that gave a distribution for the water leaving the roof to a resolution of 10mm:

Figure 3.3: Test rig for investigating roof run-off 'throw'



The distribution experiments were designed to allow the selection of an optimal gutter aperture, and give some indication of the trade-off, when increasing gutter slope, between increased flow capacity and reduced interception. To obtain an overall indication/measure of gutter performance, a number of rainfall events were sampled (more than 10).

Following collection of this data, it was observed that the rainfall leaving the 6° roof fell within a narrow spread, and was not significantly affected by drop (*y* in Figure 3.1). This, suggesting the water did not acquire a significant velocity whilst on the roof, and that dispersal was caused by wind action.

An analysis similar to that described in the Section 3 on conveyance was performed, in which the gutter size was optimised to give the lowest possible system cost per unit of water collected. This is described briefly in 6A6.1.

This indicated that for a drop of 100mm, the economical gutter width *w* would be about 115mm, whereas for a drop of 10mm the size would be only *ca* 45mm. These figures apply to a 22° roof angle and a 4 m long roof-slope. However the optima are not very sensitive to slope length. Both sets of results (6° and 22° slopes) indicated that water leaving the roof experienced a surface tension effect, causing it to curl back under the roof lip.

As the gutter itself will be at a slope, and hence the gutter drop *y* varies along its length, these values for respectively 100mm and 10mm drop may be taken as effectively maximum and minimum gutter sizes. Thus the optimum gutter width will fall within this range of 45mm to 105mm.

3.5 Summary of interception modelling

We have then performed two analyses, both assuming given values for roof-to-gutter drop. The first used rainfall simulations under laboratory conditions, and thereby showed the gutter aperture needed to intercept the same intensity of rainfall (2mm/min) as that already assumed for conveyance analysis. The second used data from fieldwork to optimise the aperture against a cost/unit water criterion.

Neither approach however generated an overall optimum gutter size, since neither determines the best slope of the gutter. Yet gutter slope generates the varying drop that causes the variation in performance along a gutter's length. We can however say, after placing an upper bound of 100mm on gutter drop *y*, that:

- the laboratory experiments place an upper bound of 120 mm on domestic gutter width,
- the fieldwork data places the optimum gutter width in the band 45 to 115 mm.

4 OPTIMISING SIZE & CONFIGURATION OF GUTTERS

4.1 Introduction to overall size optimisation

The previous sections have considered sizing gutters for interception or conveyance in isolation. This has been useful in giving some bounds to the size of gutter being considered, but cannot adequately simulate the interaction of the two in generating recommendations for gutter size and configuration.

Configuration is taken here to cover both the vertical trajectory of the gutter along the roof (the slope(s) it is hung at), and its horizontal position relative to the edge of the roof. To optimise guttering requires manipulation of these parameters in addition to gutter size. As mentioned before, changing the gutter slope will have opposite effects on the conveyance and interception performance. Both of these losses generally occur at the lower end of the gutter,[1] and so the smaller of the two will generally be subsumed in the larger when considering overall performance. Given the complexity of the interaction of these two phenomena, deriving a simple analytical model is not feasible.

So to obtain useful results, numerical simulation modelling was applied, which divided the gutter length into a series of small sections, and applied interception and conveyance criteria to determine the flow from one section to the next. Simulation was repeated over a full range of rainfall intensities, and, using information on actual tropical rainfall probabilities, the mean performance of the gutter was then calculated. Further details on the simulation are given in 6Appendix 6. Two simplifications are inherent in the model:

Firstly, the trajectory of the rainfall leaving the roof is assumed constant for a given rainfall intensity: pulsation effects are neglected. The losses from pulsation in one section would be opposed by gains in a separate section, so there is some justification for this.

Secondly, in the model each section as treated as having constant properties along its length. Maintaining a large number of section reduces inaccuracies arising from the use of such a numerical technique.

4.2 Gutter losses and overall losses

Gutters are part of a system that captures the rain falling on a roof and transfers it to a store. Not all the rainfall can be captured because of water-loss mechanisms. The four most important of these are:

i. Roof loss (due to splashing or absorption followed by evaporation): the latter is most prevalent during very light rainfall

ii. Gutter overshoot, due to inadequate gutter 'aperture', during intense rain or very strong winds: this is concentrated at the lower end of any gutter

iii. Gutter overflow during intense rain due to inadequate gutter capacity (itself a function of size, shape and slope): this normally takes place only at the lower end of each gutter

iv. Tank overflow occurring mainly when the rainfall in the say last 24-hours has been very high

These loss mechanisms interact, in that the same water cannot be lost more than once. Thus any process of calculating each loss independently and then adding them will seriously over-estimate the total loss. In the case of gutter losses (ii and iii), we should therefore calculate, for each rainfall intensity, both the overshoot fraction and an overflow fraction (assuming no overshoot), and then take the higher of the two to represent the loss

[1] The lower end of the gutter is the first place for interception losses to occur, and also for overspill from the gutter. With increasing rainfall intensity, overshoot will gradually occur further up the gutter, as will overflow. Overflow may also occur at the change in gradient if a dual-slope gutter has been used.

due to the two mechanisms acting together. This is equivalent to the operation performed by the numerical model.

It is well established that it is uneconomic to provide a tank so large that there is never any tank overflow (loss mechanism). Indeed an economically optimum tank design is likely to give tank overflow in the range 10% to 30% of annual roof run-off. Because gutters are cheaper than tanks, when considered in isolation an 'economically optimum gutter' is likely to lose only 3% to 6% of annual run-off. A question to be answered in any analysis of optimum gutter-size is therefore: "what fraction of gutter losses may be discounted because they have already been 'counted' in tank overflow?"

A full analysis of the interaction between gutter-loss and tank overflow is very complex and also requires extensive meteorological data (concerning the correlation between intense rainfall and high daily rainfall). Ideally one would use ten years' of rainfall data sampled at 1 minute intervals. Unfortunately such data is almost unobtainable even for temperate climate sites let alone for tropical ones. We might however crudely test three propositions (approximations). In order to illustrate the discussions we will take the particular case where gutter loss is around 5% and tank overflow loss (assuming perfect gutters) would be 10%; thus apparent gutter and tank efficiencies are 0.95 and 0.9 respectively.

(Proposition A) Gutter loss is *uncorrelated* with tank overflow; so gutter optimisation can be performed without consideration of tank losses other than to multiply the calculated raw gutter loss by tank efficiency (here = 0.9) to estimate water actually lost to the consumer due to gutter losses. The total system loss would therefore be 14.5%, namely 4.5% attributed to gutters + 10% attributed to tank overflow.

(Proposition B) Gutter losses are *totally correlated* with tank overflows so that we may simply take the higher of the gutter's annual loss fraction and the tank's annual loss fraction as representing their combined effect. In our example total loss is 10% and the gutter loss, being the lower of the two, doesn't matter.

(Proposition C) Intense rain giving gutter losses *occurs on different days from* tank overflow, so that there is *negative correlation* between the two. Total losses are now simply the sum of gutter and tank losses –e.g. 5% + 10% = 15%.

Although the total losses are not much different under the three assumptions, the gutter-loss component changes considerably and it is on this component alone that we choose gutter size.

Under Proposition A, a reduction in gutter losses (by *z*% of annual rainfall) would cause a reduction of 0.9 x *z*% in overall losses, corresponding to an increase of 0.9 x *z*% in the percentage of rain captured. Under (B), gutter losses don't contribute to overall losses, and could be increased up to 10% without any loss in system performance: in this case the gutter is oversized. Under (C), any reduction in gutter losses will have an equal effect on system losses.

Gutter losses depend only on very recent rainfall – it takes on average about 10 seconds between a raindrop striking a roof and its water content reaching the discharge end of that roof's gutter. By contrast tank overflow is likely to take place during the wet season (because then the tank is usually already partly full) when at least 20 mm of rain has fallen within the last two days. During the dry season the condition changes to 'when at least 30 mm has recently fallen'. With the large tanks used in semi-arid zones, all tank overflow, like almost all rainfall, will be in the wet season. However with the smaller tanks appropriate to a humid zone, a fraction of both tank overflow and rainfall occurs in the drier season, when captured water is particularly scarce and valuable.

We therefore have a number of scenarios, given in Table 4.1:

Table 4.1: RWH Scenarios

Tank Size	Climate & Conditions	Comments
Large	Semi-arid, dry year	No overflow, so assumption (C) holds, and all gutter losses should be counted
Large	Semi-arid, wet year	Some overflow, hence assumption (A) or (B) holds, and around say 50% of gutter losses should be counted.
Small	Humid zone, wet season	Considerable overflow, so assumption (B) holds, and only an (unlikely) excess of gutter loss over tank loss should be counted.
Small	Humid zone, dryer season	Some overflow, so assumption (A) holds, and around say 90% of gutter losses should be counted.
Small	Humid zone, whole year	Mostly assumption (B) holds, but (A) is representative for some of the time, so count say 60% of losses.

For a semi-arid zone and a large tank, we worry most about 'drier than average' years so assumption (A) can be accepted and as a 'rule of thumb' 90% to 100% of gutter losses should be counted. For a humid-zone small-tank system we might count only 60% of gutter losses in realistically accounting for the impact of gutter overshoot or overflow, the other 40% being included within the usually larger tank losses.

4.3 Overspill/overshoot tradeoffs

As we have seen from Section 3, sizing for interception gives a larger optimum gutter size as the drop from the roof increases. Gutter performance would be improved if the mean drop along the gutter length could be reduced whilst maintaining the gutter's flow capacity. We therefore need to choose a trajectory that best trades off overshoot losses with overspill ones.

Other trade-offs include those involved with gutter shape. Some of these relate to the gutter performance in use, and others to manufacture. The optimum shape for interception is a flat plate, which will clearly have a useless conveyance performance. There is a difference in ease of manufacture as well. If the gutter is being made from sheet metal, each fold will require additional forming, while folding metal will be simpler than trying to produce a specified curvature.

4.4 Typical roof situation

Given the large number of possible roof configurations, an exhaustive search for optimum guttering in every case would be time-consuming. The approach taken was to consider some typical values and ranges, and see which variables or combinations of variables could be eliminated or simplified. Some parameters were fixed, namely:

Roof Material Corrugated GI roofing was chosen, for several reasons: It is a common roofing material in developing countries, and is becoming more widespread in its use. The corrugations act to concentrate the flow, increasing the velocity at which it leaves the roof. This then acts as a worst-case material; a predicted performance from corrugated guttering should be equalled or exceeded by other roof materials.

Roof Slope A slope of 22^o was chosen as representative. Roof slope variation is dealt with further in Section 4.8.

4.5 Gutter shape

We may take gutter cost as being mainly dependent on the quantity of material used to produce it, which for sheet material is proportional to the perimeter p_g of the gutter cross-section. In the preceding sections it was observe that 'deep' shapes are desirable for water conveyance, wide (and therefore shallow) shapes are good for runoff interception. Here then is another conveyance *v* interception trade-off. Figure 4.1 shows the results of simulations for different gutter shapes placed at the dual slope (0.5% - 1.0%) already found to be optimum.

Figure 4.1: Overall performance of differently-shaped gutters

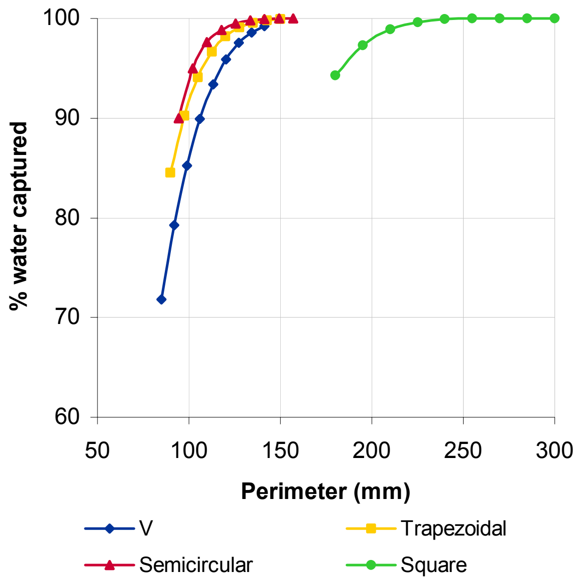


Figure 4.1 is illustrative of the situation for a range of gutter sizes. There is a distinct extra cost to using a square cross-section, because it has only a small aperture. There is however little difference between the remaining three gutter cross-sections, semi-circular, trapezoidal and vee: all have similar performance for equal material quantities. This is not surprising since both the aperture-to-perimeter ratios (w/p) of the three sections and their √area-to-perimeter ratios are similar as the following table shows.

Table 4.2: Properties of different gutter shapes

Cross-section	Ratio (√area)/p	Ratio *w/p*
Semicircular	0.40	0.64
Trapezoidal	0.41	0.67
Vee	0.35	0.71
Square	**0.33**	**0.33**

At this point the analysis simplifies, as from now on we may consider only one section, We reject the square section and choose as our norm for analysis the trapezoidal section (with wings set at 30° to the vertical). We know that substituting either semi-circular or vee shaped gutters would give very similar economic performance.

4.6 Gutter slope and trajectory

In the context just of conveyance, different gutter trajectories were discussed in Section 2.3. That discussion identified an 'ideal' but impractical trajectory of constantly-varying slope and a more practical 'simple dual-slope' trajectory that performed better than a fixed slope one. We can now examine the overall (interception plus conveyance) performance of a few promising trajectories. We have selected two candidates for the shape of the trajectory, namely uniform slope and simple dual slope., and we combine these with different mean slopes to give six rival configurations. These six, listed in Table 4.3, were tested in the overall model and their gutter efficiencies plotted against gutter width for a variety of roof lengths. (A rainfall intensity distribution representative of the humid tropics was used in combination with a trapezoidal gutter shape – see Appendix 6 – and the mean annual gutter losses were calculated.).

Table 4.3: Six gutter-slope configurations

Config No	Description	Slope of gutter (%)		
		First 2/3	Last 1/3	Mean
C1	low dual slope	0.25	0.50	0.33
C2	**medium dual slope**	**0.50**	**1.00**	**0.66**
C3	high dual slope	1.00	2.00	1.33
C4	low constant slope	0.50	0.50	0.50
C5	medium, constant slope	1.00	1.00	1.00
C6	high constant slope	2.00	2.00	2.00

The most efficient configuration (highest water capture for given roof and gutter material) was found to be C2, shown bold in the table above (Dual-slope: 0.5% & 1%). The two high slope configurations, C3 and C6 performed poorly. The remaining configurations, C1, C4 and C5, were a little inferior to C2. We therefore carry C2 forward as a recommended norm.

4.7 Roof area and shape

For a given roof area, increasing the gutter length will reduce the roof-slope length perpendicular to the gutter. The lower roof length will reduce the exit velocity of the water, but the longer gutter will develop a larger drop at its discharge end. So there are opposing effects acting on the interception performance. To test the proposition that roof area determines gutter performance independent of the shape of that area, several configurations were considered in which the aspect ratio of the roof area (gutter length / roof-slope length)was varied from 1 to 4:

Table 4.4: Various roofs used in modelling

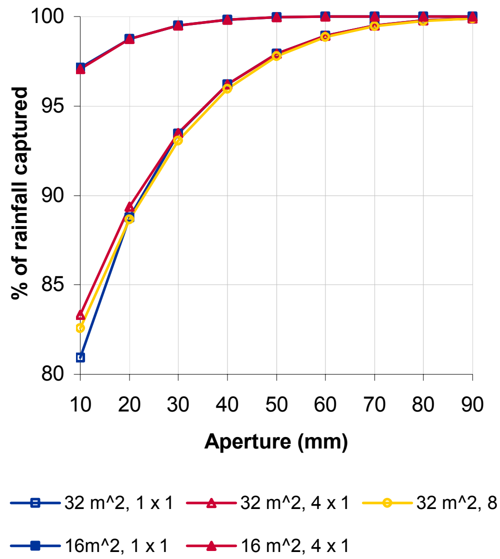
Roof-plan area* (m^2)	Gutter length (m)	Roof-slope length (m)	Aspect ratio
16	4.2	4.2	1
16	5.9	3.0	2
16	8.4	2.1	4
32	5.9	5.9	1
32	8.3	4.2	2
32	11.8	3.0	4

Note that roof plan area is smaller than roof length times depth, as the roof is not horizontal.

The performance of these configurations is shown in Figure 4.2.

As would be expected, for a given gutter size a higher fraction of yearly rainfall is captured on the smaller roof area. The more interesting feature of the efficiency plot however is the similarity in performance for the different roof shapes (aspect ratios from 1 to 4). This suggests that the effects of reduced mean drop and increased exit velocity (from using a low roof aspect ratio and hence a short gutter) largely cancel within our region of interest. Thus *we may size gutters according to the roof area*, rather than according to gutter length and roof-slope length considered separately

Figure 4.2: Gutter efficiency v roof size and shape



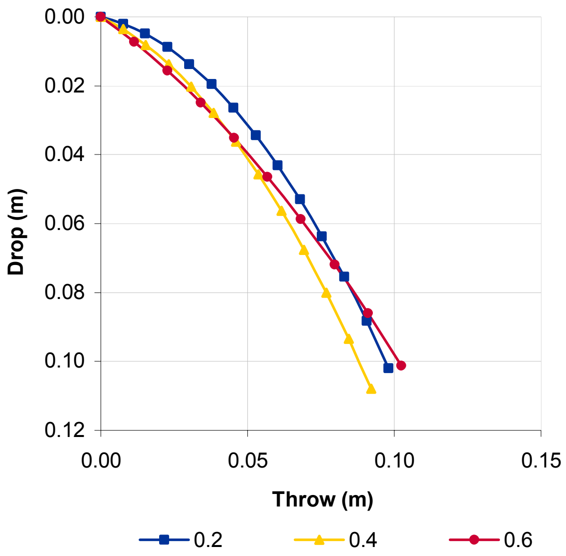
4.8 Roof slope

We might expect variation in the roof slope to alter the trajectory of the water leaving it. Analysis of the laboratory work conducted certainly shows that an increase in roof slope also increases the exit velocity of the water. Figure 4.3 shows jet trajectories leaving 4.2m-long roofs of 11°, 22° and 31° for rainfall intensities of 1 & 2 mm/min. In the region of interest (drops from 0 to 10cm), the throw from the 22 and 31° roofs are very similar. In addition to this, the throw from the 22° roof is larger initially, and there is then a cross-over point. For the lower rainfall intensity, the trajectory from the roof is greater for the lower slope.

The small variation with slope, and crossover within the area of interest indicate that gutter sizing is not very sensitive to variation in roof slope within the region of interest. For the normally-found roof slopes we may safely size gutters without taking actual slope into account.

The data from Sri Lanka and experimental work suggest that at untypically low roof slopes (less than 10°) the water leaving the roof has little velocity, so at this point there is some risk of gutter over-sizing.

Figure 4.3: Effect of roof slope on run-off trajectories



4.9 Reducing the number of variables

In Section 3.1, fourteen variables were listed as affecting 'interception', itself only one aspect of gutter performance. Such complexity is not acceptable in selecting an appropriate gutter size. However in the preceding sections we have considered many of these variables. For each we have identified a suitable 'good' value or we have shown that its influence on gutter performance is negligible. Thus we have reached the point of recommending:

i. a dual-slope gutter (with a slope in the region of 0.5% for 2/3 of its length, 1.0% for the remaining 1/3 of its length);

ii. a trapezoidal or semi-circular gutter shape;

iii. that the inside edge of the gutter be 20mm inside the roof edge;

iv. that roof *shape* can be ignored and only roof area considered;

v. that gutters correctly sized for a roof slope of 22° will also be good for common roof slopes from 15° to over 30°, thus we do not need to know roof slope;

vi. that within the humid tropics exact location and climate are not critical and we may assume a representative rainfall intensity distribution;

vii. that (common) corrugated iron roofs represent a worst case – gutters sized for CI will be adequate for other roofing types.

We are therefore now ready to explore optimum gutter size with only one variable left, namely roof area.

4.10 Economic gutter optimisation

We can define the optimum size ($w=w_0$) of a gutter as being the value that maximises the ratio of annual water captured Q to system cost and readily show (see Appendix 7) by standard calculus that this condition is met when:

$$S_{Q,w} = \frac{dQ/dw}{Q/w} = a \,.\, \lambda \qquad \text{Equation 4.1}$$

Where

$S_{Q,w}$ is the sensitivity of annual gutter discharge (Q) to gutter size (w)

a is the sensitivity of gutter cost to gutter size (typically 0.6) and

λ is the fraction of total system cost caused by the gutter cost (typically 0.15 in small systems).

The sensitivity $S_{Q,w}$ varies not only with gutter size but also with the site's rainfall intensity pattern, roof size, shape and type, gutter shape and location relative to the roof edge. However we can choose single representative values for all these variables except roof area. A_g. For each value of A_g, that leaves $S_{Q,w}$ as only a function of gutter size w.

For very small gutters, the annual captured flow Q will be low but the sensitivity S high. As we make the gutter steadily larger, Q will rise and S will drop, until at $w = w_0$ the equation above is satisfied. In practice therefore we plot S against w and note where the locus crosses the value aλ. Under some circumstances, discussed in section 4.2, only a fraction μ of the gutter losses should be counted, since some gutter losses only serve to reduce tank overflow rather than reduce water capture. For small-tank systems in the humid tropics it was argued that we might adopt the value μ=0.6. Under these circumstances our criterion for optimum gutter size changes to:

$$S_{Q,,w} = a\lambda/\mu \qquad \text{Equation 4.2}$$

typically 0.15.

Table 4.5 shows the application of this formula to find the optimum gutter width for a roof area of 16 square meters. This is a typical area for one side (and therefore one gutter) of the roof of a small rural home.

Table 4.5: Gutter optimisation for trapezoidal gutter, humid tropics, roof area A_g=30 m^2 and $a\lambda/\mu$=0.15

Gutter width *(w)* mm	Gutter annual efficiency (%)	$S_{Q,,w}$
60	84.5	0.81
65	90.3	0.55
70	94.1	0.38
75	96.6	0.24
80	**98.2**	**0.15**
85	99.1	0.08
90	99.6	0.04
95	99.8	0.02

Note: Optimum size ($w = w_o$, when $S_{Q,,w} = a\lambda/\mu$) is shown in bold.

The process used in this table was then repeated for other roof areas to generate Table 4.5, which therefore constitutes the basic output of this Working Paper. From the figure we can also deduce that the sensitivity of ideal gutter width to roof area is around 0.35.

Moreover we may use the economic optimisation model to confirm some of the assumptions listed in Section 4.9.

In particular it was found that the variation of optimum gutter width across the three locations (climates) Lae, Kampala and Surabaya was only ±3% about the value obtained using a rainfall intensity distribution averaged over all three sites. So it seems reasonable to suggest that the results found may be generalised across the humid tropics.

5 CONCLUSIONS

Having examined by field observations, laboratory experiments and computer simulations the situation of gutter size and position for roofwater harvesting in humid tropics, the following gutter widths are recommended

Table 5.1: Recommended gutter widths for use in the humid tropics

Gutter width (mm)	Roof area in (m^2) served by 1 gutter
55	13
60	17
65	21
70	25
75	29
80	34
85	40
90	46
95	54
100	66

These figures are smaller than common guttering sizes used in the tropics and indicate there are opportunities for cost-savings. Thus even a quite large house, roof 10m x 6m, requires only a 75 mm (3”) gutter on each side.

Variations in roof slope between around 20^o and 30^o have negligible effect on gutter size requirements. When the roof slope drops to around 10^o there is a significant drop in the velocity of water leaving the roof and slightly smaller gutters might be used.

For realistic roof shapes, gutters may be sized simply on the basis of the roof plan area each serves rather than via separate consideration of gutter length and roof-slope length.

Trapezoidal, semicircular and Vee-shaped gutters give somewhat similar economic performance in intercepting and conveying roof run-off water. Choice between them can therefore be made on the basis of ease of manufacture or self-cleaning properties (Vee shapes become blocked rather frequently). Rectangular gutters however do not make efficient use of material.

Gutter mean slopes should be small, normally under 1% - and there is a small advantage in giving a gutter a dual slope such as 0.5% for the first 2/3 of its length, 1.0% for the final 1/3 to the outlet point. No part of a gutter should however be laid flat in an area subject to mosquitoes. In cases where roofs are not accurately aligned, higher slopes may be needed or the gutter direction should be decided only after the roof-edge slope has been measured.

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APPENDICES

APPENDIX 1 CONVEYANCE ANALYSIS

Section A1.1 will examine the economics of sizing gutters for their capacity to convey the water entering them. This leads to the suggestion that gutters should be sized for rainfall intensities of around 2 mm/min.

In section A1.2, the theory and calculations for sizing gutters are covered. This is followed by brief details of experimental work conducted (section A1.4), and sizing tables for downpipes (section A1.5).

A1.1 Describing the flow distribution

A gutter that is 'too small' will, under very heavy rainfall, spill some of the water it is trying to carry. A gutter that is too big will cost too much.

The cost of spilling water may be just the value of the water not conveyed, or it may be higher (if overflow causes damage to the building) or lower (if the overflow would have been discarded anyway due to tank overflow or inadequate tank inflow capacity).

As mentioned earlier, in the context of rainwater harvesting in the humid tropics, most buildings will have a considerable roof overhang. In this case, the cost of letting water overflow is likely to be equal to or less than the value of the water not conveyed to a tank.

From the analysis that follows, it appears that it is generally economic to make gutters large - for example so large that only 1% of the roof runoff overflows the gutter system.

In any economically viable roofwater harvesting system, the amortised value of the water collected is greater than the capital cost of the system: in the ensuing analysis, however, we will assume a 'just-economic' RWH system in which the amortised value of the water *equals* the system cost. We will also assume:

(a) The value of water, per litre, is constant, so that a 1% increase in water harvested represents a 1% increase in user benefit.

(b) There is sufficient storage that increasing gutter output by 1% will increase water available for consumption by 1% too.

Clearly both these assumptions are debatable and could be altered: however that would introduce unwanted further complexity into the basic analysis below.

The cost of guttering can vary considerably from system to system, for example, in one $10m^3$ system the guttering was 12% of the system cost, whereas in a (600) system the figure was 30% (DTU Working paper 55). In this analysis a mid-range figure of 20% will be used. Therefore, under the assumptions just made, increasing gutter size in order to collect more water is always worthwhile, providing that the fractional increase in gutter cost does not exceed 5 times (100% / 20%) the fractional increase in water harvested. The analysis below refines this statement.

A1.2 Strategy for optimising gutter size for conveyance alone

A1.2.1 Formal modelling

At some representative sites, data can be obtained for the rainfall intensity i, giving a probability distribution $p_r(i)$. To find the gutter inflow Q_i we multiply the intensity by the roof area, a runoff coefficient C_r and an interception coefficient C_i. These may be treated as a constant, Ω, for a particular roof. Q_i is a flow rate, as is the gutter capacity Q_d. The conveyance coefficient (or 'efficiency'), C_c, is the fraction of Q_i that is conveyed by the gutter to the tank.

Knowing the gutter shape, and keeping other factors such as slope constant, increasing the gutter capacity Q_d by 1% will have a certain effect on the total cost of the system. From applying the Manning formula to the flow in gutters (the validity and specifics of this is discussed in section 3.3), the gutter size will require a 0.4% increase. This can then be adjusted to take account of the change in materials and manufacturing cost of the gutter, to give a say 0.36% increase in gutter cost. [2]

As previously mentioned, the cost of the gutter as a fraction of the system cost may be taken as 20%. This means that the 1% increase in gutter capacity will result in only a 0.072% increase in the system cost.

Increasing the gutter capacity by 1% will also increase the quantity of water captured by the system, as expressed as the capture coefficient C_c.

Within the context described, it is economically sound to continue mentally increasing the gutter size until the percentage increase in C_c falls to that of the increase in gutter cost, i.e. 0.072% for each 1% increase in gutter capacity. After this point, any further increase in gutter cost will further increase the quantity of water harvested, but will not give a superior performance measured by cost per litre of water captured.

For a particular rainfall intensity probability distribution $p_r(i)$, an exceedance function $P_r(i)$ may be defined, giving the fraction of time that the rainfall intensity exceeds any threshold i.

A given gutter arrangement will have a flow capacity Q_c at which it overflows. This can be expressed as a corresponding rainfall intensity I. It is also possible to calculate the fraction of water spilled by the gutter, $sp(I)$, and hence the gutter efficiency $\eta(I)$. These performances will be for an entire year of operation, not a single rainfall event. At this point we need to use the concept of sensitivity. For two variables A and B, $S_{A,B}$ is the sensitivity of A with respect to B. This may be thought of as the percentage change in A for a 1% change in B.

The conveyance coefficient (C_c) for a particular gutter is a complicated function of the gutter's flow capacity (Q_d), the rainfall intensity distribution $P_r(i)$, and Ω (the roof area multiplied by roof run-off coefficient). As the gutter inflow is proportional to the rainfall intensity (runoff and interception coefficients being known), the exceedance curves for gutter inflow Q_i and for rainfall intensity i are therefore simply related:

$$P_{Qi}(i\Omega) = P_r(i) \quad \text{Equation A1.1}$$

From the theory included in Appendix 2, the sensitivity of conveyance coefficient to gutter capacity is given by:

$$S_{Cc,Qd} = \frac{I}{i_{mean}} \frac{P_r(I)}{\eta(I)} \quad \text{Equation A1.2}$$

As the gutter efficiency tends towards 1, this simplifies to:

$$S_{Cc,Qd} = \frac{I}{i_{mean}} P_r(I) \quad \text{Equation A1.3}$$

Where i_{mean} is the mean rainfall intensity.[3]

[2] The sensitivity of gutter depth D to gutter cost C_g is typically about 1.1 for gutters of fixed proportions cut from constant thickness sheet, although it would be as low as 0.6 if gutter thickness were kept proportional to its depth. In this analysis it is taken as 1.1, so the sensitivity of gutter cost C_g to gutter depth D is 1/1.1.

[3] In the calculations performed, the efficiency of the system has been included.

We are interested in the case where $S_{Cc,Qd} = 0.07$, so we require $\frac{I}{i_{mean}} \frac{P_r(I)}{\eta(I)} = 0.07$

For high rainfall intensities, the following formula may be used for the exceedance function:

$$P_r(i) = ae^{-bi}$$ Equation A1.1

Our task now is to find what gutter size gives the required value to $S_{Cc,Qd}$. [4]

Data has been obtained for actual rainfall distributions for three locations in the humid tropics, namely Uganda (Kampala), New Guinea (Lae) and Indonesia (Surabaya), and is included in Appendix 3.

This leads to the suggestion that the gutter should be sized for rainfall intensities between 80 and 120mm/hour (1.3~2mm/min).[5]

A1.3 Theory of Flow in Gutters

Moving along the gutter towards the outlet at the downpipe junction, the amount of water flowing in the gutter increases, as more water is fed into it from the roof. This is an instance of what is termed spatially varying flow. In some cases, such as corrugated roofs, the water enters the gutter in discrete jets, one jet coming from each furrow. With other roofing materials the flow may approach a continuous sheet, although in most cases it will remain discrete.

Within the context of sizing the gutter, we will deal with the situation where the flow entering the gutter is known. It is relatively simple to calculate the quantity of water falling on the roof, taking account of roof dimensions and slope.

In this case, we wish to be able to choose gutter size, cross-section, slope and material (within limits set by the situation) to give a system that will convey all the water for a selected rainfall intensity from its entry to the gutter into the downpipe. The value of 2mm/min as a sensible maximum intensity is argued for in A1.2 and Appendix 3, and the design calculations have been performed assuming all water falling on the roof is intercepted. Although this will overestimate gutter size, there are arguments for the validity of making this assumption, including system degradation over time and probability of errors in configuring the gutter.

This system should be the cheapest possible, so quantities of materials should be reduced, as should complexity of manufacture. In some cases there may be considerable flexibility in gutter size possible, particularly if the gutter is being made locally by artisans. There will be other situations however where guttering is more readily available in standard sizes, from industrial manufacturers. The local situation will dictate which is more economically attractive-if an oversized extruded PVC gutter is cheaper than a smaller locally-made gutter, then clearly the former should be used.

A1.3.1 Parameters

The following factors will influence the flow in the gutter, and should therefore be considered when designing the guttering system:

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[4] Interestingly, European standards for gutter capacities (where damage from overflow is the main concern, not rainwater harvesting) are set extremely high, corresponding to rainfall intensities I which are exceeded for less than 1 minute per year ($P_r(I) = 2\text{x}10^{-6}$)

[5] Logically the capacity Q_f of any tank inlet filters should be made to match the gutter capacity Q_d.

A1.3.1.1 Gutter material

This will affect the frictional force opposing the flow (quantified by the Manning roughness factor). The rougher the surface, the greater the resistance the water will experience, and hence the lower the gutter capacity.

This will be examined in greater depth later in section A1.3.2.1.

A1.3.1.2 Gutter cross-section

Different shapes and sizes of gutter will have different performances in otherwise identical situations. For example, a flat, wide gutter will have a greater resistance to flow when full than a semi-circular gutter of the same cross-sectional area.

There are likely to be local limitations on dimension (for example, standard sizes if mass-produced guttering is being bought/made from piping).

There are a series of common sizes of guttering used in industrialised countries. Obviously some of these shapes are more complex than can be reasonably treated by this paper, including the standard 'K' shape. It is hoped that the shapes considered will be best suited to the developing countries context. The most commonly used shapes are: semi-circular, rectangular, v-section and trapezoidal.

Standard sizes tend to be based upon gutter aperture: the width w of the top of the gutter. Common sizes range from 50 to 100mm.

A1.3.1.3 Roof dimensions

The edge-length, slope and roof-slope length (length of the roof perpendicular to the gutter) all influence the quantity of rainfall to be conveyed by the gutter. The edge-length clearly influences what gutter length will be required; the slope and roof-slope length will, (along with the rainfall intensity) fix the flow intensity leaving the roof.

A1.3.1.4 Maximum rainfall intensity to be accommodated

This has been discussed in section A1.2 and Appendix 3. Design and sizing recommendations produced are those to give a system that can convey all the water from a 2mm/min rainfall event, using coefficients for runoff and interception of 1.

A1.3.1.5 Gutter slope

Maximum permissible gutter drop will be influenced by both the throw from the roof (considered in section 1) and the gutter attachment methods to be used, both in terms of materials required, performance of fixings, and limits set by features such as fascia board dimensions. The maximum drop limits the mean slope of the gutter. For domestic roofwater harvesting, a slope of 4% is felt to be a reasonable maximum[6].

A1.3.1.6 Gutter outlet conditions

This will have some effect on the depth profile of the gutter flow. With a gutter unblocked at its lower end, the water flowing out is accelerating in the region of the outlet, hence reducing the depth of flow there for a given rainfall intensity.

An identical effect can be found when the flow from the gutter enters a downpipe that is not running full.

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[6] Such a slope would give a drop of 100mm in 2.5m of guttering. Larger drops than this would cause difficulties in mounting the gutter (from limited fascia board depth etc), and would suffer from poor interception performance.

In both cases, this "draw-down" effect is beneficial, as it reduces the maximum depth of the water in the gutter for a given rainfall intensity. Hence a gutter experiencing this effect would have a greater capacity than one that was not.

However, experimental work suggests that this effect is not sufficiently significant to be worth considering in the design procedure.

In this case, it is sufficient to ensure that the outlet will not run full and increase the depth of flow within the gutter. The sizing of downpipes is covered briefly in section A1.5.

A1.3.2 The Manning Formula

The simplest theory to use within the context of flows in gutters is the Manning formula:

$$Q = A\frac{1}{n}R^{2/3}\sqrt{S}$$ Equation A. 1.4

Where Q= flow in channel (m^3/s)

A= cross-sectional area (m^2)

v= velocity of flow in channel (m/s)

n= Manning roughness coefficient

p_w= Wetted perimeter (m)

R= Hydraulic radius (m) ($R = \frac{A}{p_w}$)

S= Slope

There are some theoretical objections to the validity of applying this to the flow in gutters. The Manning formula is derived assuming a constant flow, and that the flow has reached an equilibrium. Neither of these is the case for the flow in gutters. The flow in gutters approaches the Manning solution as the gutter becomes longer, but does not reach the flow conditions described, hence the Manning formula will give an over-estimate of the performance of a set gutter.

A more appropriate area of fluid dynamics to apply to the flow in gutters is that of spatially varying flow. This was developed by Garcia (2000) and Still (2001) (in conjunction with Lucey). The details of the theory are unlikely to be of interest to all users, and so have not been included. Further information is available on the web at: http://www.eng.warwick.ac.uk/dtu/pubs/rn/rwh/ugp014_still.pdf

The spatially varying flow work allowed the generation of flow profiles-predicted depths of flow at varying points along the gutter. The approach taken to obtain these flow profiles for gutters was to use a non-dimensional asymptotic solution to the model developed. In essence this consisted of an initial solution which is equivalent to using the Manning formula, and corrective terms to account for the difference in the flow distribution. The corrective terms are based upon an aspect ratio, that is a ratio of gutter length to a cross-section dimension (width). As this increases, the deviation from the flow predicted by the Manning formula decreases. In the case of guttering, this aspect ratio is often of the order 100~1000, and so the corrections to the Manning formula become small enough to be neglected. In this case, analytic results can readily be obtained for different gutter cross-sections, slopes etc.

A1.3.2.1 Manning roughness coefficient

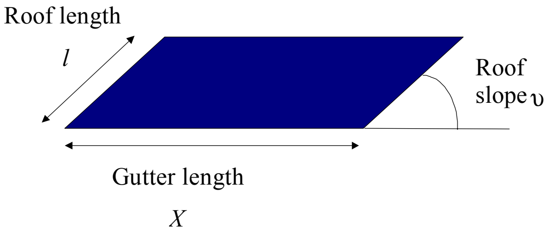
There are various possible values for this, according to the material being used in the gutter. For smooth PVC values of 0.009~0.011 are suggested. It is likely that in use some sediment will collect in the gutter, and that this will increase the frictional resistance to flow in the gutter.

One source suggests "for gutters with small slopes, where sediment may accumulate, increase [the Manning roughness coefficient] by 0.002." This would lead to a reduction in capacity of around 20%, which seems plausible. To take account of the effect of joints etc, a figure of 0.015 has been used in the sizing calculations.

A1.3.2.2 Using the Manning formula

Sizing calculations using the Manning formula are relatively simple (particularly compared to the spatially varying flow model).

Figure A. 1.1: Roof dimensions.



The assumption will be made that the gutter is being sized so that it is at the point of overflowing at the outlet end.

For this case, the flow within the gutter is expressed as a multiple of the rainfall intensity, *i* (mm/min), the gutter length, *X* (m), the roof length *l* (m), and the roof slope *θ*, as illustrated above in Figure A. 1.1. If the cross-sectional area and hydraulic radius are evaluated for the gutter running full, then the roof area at which the gutter will reach this stage can be calculated:

$$Roof\ area,\ A_{rg} = \frac{60\,000}{nI\cos\theta}\sqrt{S}R_H^{2/3}A$$
$$= \frac{60\,000}{nI\cos\theta}\sqrt{S}\,\frac{A^{5/3}}{\wp^{2/3}}$$

Some sensitivity analysis is possible from this:

$A_{rg} \propto \frac{1}{n}$: the roof area that can be covered by a gutter is inversely proportional to the manning roughness coefficient of the gutter material, so a 10% increase in the roughness value arising from gutter degradation over time, effects of joints etc will lead to a 10% decrease in the roof area the gutter can convey water from.

$A_{rg} \propto R_H^{2/3}A\,;\,R_H = \frac{A}{\wp},R^{2/3}A = \frac{A^{5/3}}{\wp^{2/3}}$: generally, $A \propto Cross - section\ dimension\ ^2$, and $\wp \propto Cross\text{ - }section\ dimension$, so

$\frac{A^{5/3}}{\wp^{2/3}} \propto \frac{(Dimension^2)^{5/3}}{Dimension^{2/3}} = Dimension^{8/3}$, so the roof area that can be covered is sensitive to a scaling in cross-section.

The hydraulic radius of cross-sections can be used as a measure of the efficiency of that shape for carrying water. The lower the hydraulic radius, the greater the wetted perimeter for a given cross-sectional area of water, and hence the poorer the performance for a given cross-sectional area and slope.

A1.4 Experimental evidence of gutter flow capacity

A test rig was to simulate water leaving a roof was constructed at Warwick University. This enabled measurement of the flow profile within the gutter for varying gutter cross-sections, slopes and simulated rainfall intensities. These profiles were compared with predicted profiles using the spatially varying flow theory and a numerical technique. A good match was found between the measured and the predicted profiles. This was taken as validation of the theory. Plots of the results may be seen on the website mentioned above.

A1.5 Downpipe Sizing

There are well-established procedures for estimating the maximum gravity-driven flow that will occur through a piping system - its so-called capacity Q_c. Unfortunately these procedures are too complex for general use in roofwater harvesting and need to be replaced by simpler 'rules of thumb' or design tables.

For a very long vertical pipe we can experimentally determine its capacity $Q_c = Q_m$. This will be the highest gravity flowrate we can get through a pipe of that size and is tabulated below. The term 'very long' indicates that secondary effects, like turbulence at entry or the presence of sharp bends, can be neglected and the flow obtainable only depends on the friction in the pipe itself. For any pipe, the *total head loss* h_L must equal the *actual drop* h_D (from the water surface at the top to the water surface at the bottom of the pipe run). For a vertical pipe this drop is the same as the pipe's length L. For non-vertical pipes, h_L still equals h_D but $h_D = S \times L$ where S is the effective slope of the pipe. The capacity of a long sloping pipe is naturally less than for a vertical one. The table below shows the capacity of long smooth pipes of various internal diameters. Capacity is roughly proportional to the square root of the slope S. Thus at a slope of only 10% ($S = 0.1$) the capacity is only about 30% that Q_m of a vertical pipe.

Table A1.1: Ideal flow capacities of smooth downpipes running full

Internal Diameter	Vertical, S = drop/length =1.0			or Drop/length= 0.5			or Drop/length= 0.25		
	Capacity Q_m	Velocity	Equiv to h_v	Capacity Q_m	Velocity	Equiv to h_v	Capacity Q_m	Velocity	Equiv to h_v
mm	l/min	m/s	m	l/min	m/s	m	l/min	m/s	m
25	160	5.4	1.48	104	3.5	0.62	70	2.4	0.28
32	295	6.1	1.77	200	4.1	0.86	135	2.8	0.39
40	540	7.2	2.56	360	4.8	1.14	250	3.3	0.55
50	1000	8.5	3.60	680	5.8	1.66	450	3.8	0.73
63	1800	9.6	4.63	1250	6.9	2.23	840	4.5	1.00
75	2900	10.9	5.98	2000	7.5	2.85	1400	5.3	1.39

[In the table the water velocity in the pipe is expressed both as a speed (m/s) and as an equivalent head h_v. This head is the head thrown away if the kinetic energy in the pipe discharge is not recovered by suitable pipe tapering. It also equals the height through which the water would have to free fall to reach the velocity v.]

If a pipe is not 'long', the effect of the three factors discussed in Appendix 4 will no longer be negligible. All these factors reduce the pipe's capacity.

For practical purposes we will be safe, even for quite short pipes, if we assume capacities of 50% of the tabulated figures.

In the analysis earlier, it was suggested that RWH systems be designed for a rainfall intensity of 2 mm/min (~120 mm/hour), which gives 200 litres/min for each 100 m^2 of roof area. Small domestic roofs are about 50 m^2 and therefore require a downpipe capacity of 100 litres/min. For this a 40 mm (internal diameter) downpipe would usually suffice and even a 32 or 25 mm pipe would often do. These are much smaller sizes than are commonly found in RWH systems. Even a large school building of 400 m^2 and an effective downpipe slope of only 0.25 does not need a pipe larger than 75 mm ID whereas 160 mm OD pipes are commonly used.

In some cases the downpipe may be replaced by a section of gutter running for the roof to the tank. In general, if this is made the same size as the gutter, and laid at a steeper slope, there should not be problems with overflow. Sudden changes in channel direction or constrictions should be avoided, as these will reduce the channel capacity, and may lead to overflow.

APPENDIX 2 RAINFALL INTENSITY FUNCTIONS

Records are available from which, for particular locations, rainfall intensity exceedence $P_r(i)$ or rainfall intensity probability density $p_r(i)$ can be derived. Rainfall intensity i is precipitation per unit time (e.g. mm per minute).

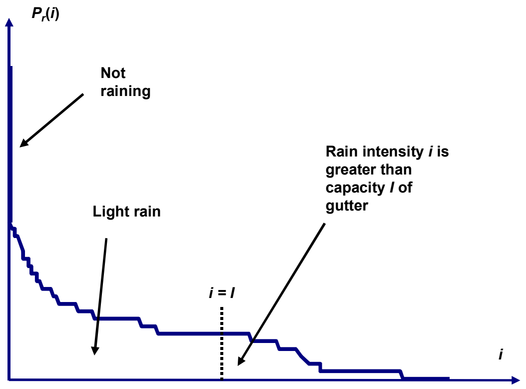
$P_r(i)$ and $p_r(i)$ are related by:

$$P_r(i) = \int_i^{\infty} p_r(i)di = 1 - \int_0^i p_r(i)di \text{ or } p_r(i) = -\frac{dP_r(i)}{di}.$$

We can note that:

1. The rainfall intensity is never infinite, so . $p_r(\infty) = 0$.
2. Hence the rainfall intensity can never exceed infinity $P_r(\infty) = 0$.
3. The rainfall intensity is never less than zero: "reverse raining" does not happen. $p_r(i) = 0$ for $i<0$

Figure A. 2.1: Rainfall intensity probability distribution



(There is some uncertainty about what happens at a rainfall intensity of i=0 since it only actually rains for about 1% of the time. Probability(i>0) is thus much less than Probability(i≥0) and therefore we might need to distinguish the former, $P_r(0^+)=0.01$ for example, from the latter $P_r(0^-)=1.0$. In practice this does not create a computational problem.)

The rainfall expected in unit time is $i_{mean} = \int_0^{\infty} i.p_r(i)di$

Substituting $p_r(i)di = -dP_r(i)$: $i_{mean} = -\int_0^{\infty} idP_r(i)$.

Integrating by parts gives $i_{mean} = -[i.P_r(i)]_0^{\infty} + \int_0^{\infty} P_r(i)di$

So $i_{mean} = \int_0^{\infty} P_r(i)di$, since $[i.P_r(i)]_0^{\infty} = 0$. Equation A2.1

Thus i_{mean} is equal to the area under the whole $P_r(i)$ versus i curve.

If however, we restrict our interest to rainfall whose intensity exceeds a threshold intensity I then the quantity $e(I)$ expected in unit time will fall to:

$$e(I) = \int_I^{\infty} i.p_r(i)di = -\int_I^{\infty} idP_r(i)$$
$$= -[i.P_r(i)]_I^{\infty} + \int_I^{\infty} P_r(i)di = I.P_r(I) + \int_I^{\infty} P_r(i)di$$

Where $\int_I^\infty P_r(i)di$ is the area under just the tail of the $P_r(i)$ versus i curve

The *fraction* of the rain that falls at these high intensities ($i>I$) equals $e(I)$ / i_{mean} .

A gutter designed for a maximum flowrate corresponding to rainfall intensity I will spill a fraction *sp(I)* of the flow entering it. The mean spill flow, which is this spill fraction times the mean inflow, equals the integral, for all intensities greater than gutter capacity, of the difference between rain intensity and gutter capacity (expressed as equivalent intensity) weighted by the relevant probability of that intensity occurring, thus:

$$sp(I).i_{mean} = \int_I^\infty (i-I)p_r(i)di = -\int_I^\infty (i-I)dP_r(i)$$
$$= I\int_I^\infty dP_r(i) - [i.P_r(i)]_I^\infty + \int_I^\infty P_r(i)di$$

Therefore

$sp(I).i_{mean} = \int_I^\infty P_r(i)di$ Since the other 2 terms cancel out .

Note that the spill fraction $sp(I)$ is (much) less than the fraction ($e(I)/i_{mean}$) of rain falling faster than the gutter can carry, since even during intense rain the gutter captures some.

The gutter efficiency (fraction *not* spilled) is:

$$\eta_c(I) = 1 - sp(I) = 1 - \frac{\int_I^\infty P_r(i)di}{\int_0^\infty P_r(i)di}$$ Equation A2.2

(Since $i_{mean} = \int_0^\infty P_r(i)di$)

$$\eta(I) = 1 - \frac{\text{area under tail of distribution}}{\text{area under whole distribution}}.$$

A2.1 Special case

In the region in the tail of the intensity exceedence curve (namely where $i>>i_{mean}$) we may often approximate $P_r(i)$ by

$$P_r(i) = ae^{-bi}$$ Equation A2.3

This enables us to simplify Equation A2.2:

$$\eta(I) = 1 - \frac{\int_I^\infty ae^{-bi}di}{\int_0^\infty P_r(i)di},$$

and $\int_I^\infty ae^{-bi}di = \left[-\frac{a}{b}e^{-bi}\right]_I^\infty = \frac{1}{b}P_r(I)$

So $\eta(I) = 1 - \frac{P_r(I)}{b\int_0^\infty P_r(i)di}$ and hence the 'inefficiency' (fraction spilled) is

$$sp(I) = 1 - \eta(I) = P_r(I)/bi_{mean}$$ Equation A2.4

This enables the sensitivity of efficiency $\eta(I)$ to gutter capacity *(I)* to be expressed as

$$S_{\eta(I),I} = \frac{\left(\frac{d\eta(I)}{dI}\right)}{\left(\frac{\eta(I)}{I}\right)} = \frac{-\left(\frac{d\,sp(I)}{dI}\right)}{\left(\frac{\eta(I)}{I}\right)} = \frac{\left(\frac{b\,P_r(I)}{b\,i_{mean}}\right)}{\left(\frac{\eta(I)}{I}\right)}$$

$$= \frac{I}{i_{mean}}\frac{P_r(I)}{\eta(I)}$$

As $\eta(I)$ approaches 1, we can say

$$S_{\eta(I),I} \approx \frac{I}{i_{mean}} P_r(I)$$ Equation A2.5

Note that i_{mean} has the dimensions of rainfall intensity and b has the dimensions intensity^{-1}.

The sensitivity of *water harvested* to *gutter capacity* $S_{Qh,Qg}$ is equal to $S_{\eta(I),I}$

This quantity has been evaluated in Appendix 3 below (as a function of the rainfall intensity I that the gutters are just large enough to carry) for three locations in the humid tropics.

Setting $S_{Qh,Qg}$ = 0.03, as suggested above for gutters alone, gives I values in the range 120 to 150 mm/hr.

Setting $S_{Qh,Qg}$ = 0.1, as suggested above for gutters + filter, gives I in the lower range 80 to 90 mm/hr.

APPENDIX 3 CALCULATIONS FOR 3 LOCATIONS IN THE HUMID TROPICS

(At high rainfall intensities we use the approximation $P_r(i) = A\ e^{-bi}$)

Microwave telecommunications are interrupted by very heavy rainfall occurring along the path between transmitter and receiver. For this reason, detailed rainfall intensity data has been collected in many countries including some tropical ones. A telecomms engineer is primarily interested in the fraction of the time (in say minutes per average year) that rainfall is so intense that transmissions are affected. We can however use this same data to aid gutter design, provided we can convert it to express not the fraction of time but the fraction of total annual rainfall accounted for by very intense rain.

As we are primarily interested in *intense* rainfall, we can use a rainfall intensity model that is only valid at high intensities. Studies have shown that tropical rainfall derives from two main meteorological mechanisms and that the one that accounts for intense rain (say over 1 mm/minute) may be modelled by the probability density distribution

$$P_r(i) = A\ e^{-bi}$$

where i is rainfall intensity (e.g. in mm/min) and b is a constant (units of min/mm)

Moreover the annual rainfall R_a mm can also be expressed as a mean intensity

$$i_{mean} = R_a / (365 \times 24 \times 60)$$

Any particular gutter size, in the context of a particular roof and gutter drop, corresponds to a threshold I of rainfall intensity falling on that roof above which the gutter will overflow. At higher rainfall intensities $i>I$ the overflow fraction will be $(i-I)/i$.

By suitable algebraic manipulation of the quantities b, i_{mean} and I, we can estimate the fraction $sp(I)$ of annual rainfall that will spill and hence a conveyance efficiency. $\eta_c(I) = 1 - sp(I)$. Assuming for a moment that a constant fraction of water reaching the roof also reaches the gutter, annual water delivered by the gutter to the tank will be proportional to this conveyance efficiency η_c. Moreover we have shown earlier that the economically optimum size of gutter is that which gives a particular sensitivity of *water harvested* to *gutter size*. This criterion can be re-expressed as a particular value for the sensitivity of *conveyance efficiency* η_c to *design threshold rainfall intensity* I, namely to the measure $S_{\eta c,I.}$

We can also look directly at the values for spill fraction as a function of design intensity I to get an immediate feel for gutter sizing. For example we can decide that a conveyance efficiency $\eta_c = 0.95$ is appropriate and find the corresponding value for I.

If we extend this analysis to the *interception* of run-off by a gutter we must allow for important differences between 'overflow' and 'overshoot'. With conveyance a fraction $(i-I)/i$ of rainfall with intensity $i>I$ is spilled. With interception we assume ALL of the precipitation occurring at intensity $i>I$ is lost through overshoot. However for interception, unlike conveyance, the value of I corresponding to a particular gutter size varies along the gutter and cannot be defined for the gutter as a whole. One approach is to define I for midway along the gutter. If we define the fraction of annual rainfall intercepted as $\eta_i(I)$ we will find that $\eta_i(I)$ is often larger than $\eta_c(I)$. The corresponding sensitivity $S_{\eta i,I.}$ will also be different.

In the tables below we have listed values for these various measures (for representative values of I) for three tropical sites. There is some uncertainty about the notation used in the data source: $P_r(i)$ is assumed to be given in % rather than as a fraction. Otherwise the mean annual precipitation would be about 100 times higher than is likely for the locations given and one would have to assume that the probabilities given only applied to time when rain is actually falling. In the tables, I is defined as the rainfall intensity at which gutters are just full (or for interception analysis the rainfall intensity at which gutter overshoot commences).

To size a gutter we might use such conveyance criteria as

$$S_{\eta c,I} = 0.07$$

or $$\eta c(I) = 0.95$$

Applying all these criteria gives the range shown at the top of each page. For the three sites these criteria indicate one should size a gutter so that its flow capacity corresponds to about 1.7 mm per minute rainfall. Note that for no site would spill fraction exceed 2% if the gutter were sized for 2 mm/minute of rainfall.

The high intensity fraction for such a (I = 2 mm/min) gutter might however reach 8%. However analysis of overshoot (where loss from any small part of the gutter equals the high intensity fraction for that part) is more difficult to handle in this 'overall performance' way. So useful conveyance *v* interception comparisons cannot be made here.

Kampala, Uganda R_a = 1402 mm; b = 0.029 min/mm; i_{mean} = 0.00267 mm/min; I_{design} = 1.4 to 1.9 mm/minr					
Gutter design capacity expressed as rain intensity	I	0.67 mm/min	1.33 mm/min	2.00 mm/min	2.50 mm/min
Normalised Capacity	I/i_{mean}	246	491	737	921
Exceedence $P_r(I)$ i.e.	Prob $i>I$	0.00092	0.00027	0.000084	0.00003
Spill Fraction	$sp(I)$	0.197	0.062	0.019	0.008
Conveyance effic'ncy	$\eta_c(I) = 1-sp(I)$	0.803	0.943	0.981	0.992
High intensity fraction	$F_{hi}(I) = e(I)/i_{mean}$	0.43	0.21	0.087	0.044
Interception effic'ncy	$\eta_i(I) = 1-F_{hi}(I)$	0.57	0.79	0.91	0.96
Sensitivity: harvest to gutter capacity	$S_{\eta c,I}$	0.28	0.141	0.063	0.028

Lae, PNG R_a = 1875 mm/year; b = 0.048 ; i_{mean} = 0.00357; I_{design} = 1.6 to 1.8 mm/min					
Gutter design capacity expressed as rain intensity	I	**0.67 mm/min**	**1.33 mm/min**	**2.00 mm/min**	**2.50 mm/min**
Normalised Capacity	I/i_{mean}	187	374	561	700
Exceedence $P_r(I)$ i.e.	Prob $i>I$	0.0021	0.00038	0.00006	0.00001
Spill Fraction	$sp(I)$	0.146	0.022	0.003	0.001
Conveyance effic'ncy	$\eta_c(I) = 1-sp(I)$	0.854	0.979	0.997	0.999
High intensity fraction	$F_{hi}(I) = e(I)/i_{mean}$	0.692	0.168	0.034	0.007
Interception effic'ncy	$\eta_i(I) = 1-F_{hi}(I)$	0.31	0.83	0.97	0.99
Sensitivity: harvest to gutter capacity	$S_{\eta c,I}$	0.46	0.145	0.03	0.007

Surabaya, Indonesia R_a = 1445 mm/year; b = 0.040 min/mm; i_{mean} = *0.00275 mm/min*[1] I_{design} = 1.3 to 1.8 mm/min					
Gutter design capacity expressed as rain intensity	I	**0.67 mm/min**	**1.33 mm/min**	**2.00 mm/min**	**2.50 mm/min**
Normalised Capacity	I/i_{mean}	242	484	726	908
Exceedence $P_r(I)$ i.e.	Prob $i>I$	0.0013	0.00029	0.00006	0.00002
Spill Fraction	$sp(I)$	0.201	0.04	0.008	0.002
Conveyance effic'ncy	$\eta_c(I) = 1-sp(I)$	0.799	0.96	0.992	0.998
High intensity fraction	$F_{hi}(I) = e(I)/i_{mean}$	0.52	0.17	0.047	0.017
Interception effic'ncy	$\eta_i(I) = 1-F_{hi}(I)$	0.48	0.83	0.95	0.98
Sensitivity: harvest to gutter capacity	$S_{\eta c,I}$	0.39	0.15	0.043	0.018

Source: Adimula A, 1998, Rain-rate Distribution for Tropical Regions,

APPENDIX 4 CAPACITY OF 'SHORT' PIPES

The capacity of a smooth vertical downpipe running full (neglecting entry, exit and "bend" losses) woud be:

Table A4.1: Flow capacity of downpipes

Pipe OD (mm)	25	32	40	50	63	75
Capacity at 90° (l/s)	2.5	5.0	9.0	16	30	48
Capacity at 45° (l/s)	2.1	4.2	7.5	13	25	37
Capacity at 35° (l/s)	1.7	3.4	6.2	11	21	32
Capacity at 15° (l/s)	1.2	2.4	4.4	8	14	23

(The angle quoted is that between a line drawn from downpipe entry to downpipe exit and the horizontal.)

However, extra head losses at pipe entry and at bends, and unrecovered velocity head at pipe exit will reduce these capacities.

'Head-loss' (*h*) is the difference in water level between the two ends of a pipe necessary to drive the specified flow along that pipe. The four main phenomena causing head-loss in a flow are:

Pipewall friction

Causing loss $h_1 \approx k_1 Q^2$ where k_1 is proportional to pipe length L and roughly proportional to $1/D^5$. D is pipe internal diameter).

Entry headloss

$h_2 = k_2 Q^2$ where k_2 is not greater than $.025/A^2$ in suitable (MKS) units. A is the pipe's internal cross-sectional area. For a rounded rather than sharp-edged entry, h_2 can be neglected.

Exit headloss

(Kinetic energy not recovered), $h_3 = .05/A^2$ or less. This maximum value (i.e. no recovery) however commonly applies.

Bends

Cause an extra headloss which depends upon their sharpness: it is common to replace the effect of a bend by an equivalent increase in pipe length and hence pipewall friction of $6D$, so $h_4 = k_4 Q^2$ where $k_4 = k_1 \times 6D/L$

Taken together, total headloss = $h_1+h_2+h_3+h_4 = (k_1+k_2+k_3+k_4)\, Q^2$

The table 5.1 above effectively only allows for h_1 and not for the other effects, and we should like to know roughly how much to reduce the capacities in that table to account for them. Unfortunately each system is different, but we can at least calculate the necessary (downwards) correction for a couple of representative cases.

Case (a) a 40mm downpipe has length 4m and drop 2m; there is also one bend.

4m of 40mm pipe has $k_1 = 49400$

1 bend is equivalent to an increase in length of 6 x .04 = .24m, $\therefore$ $k_4 = 3000$

$A = .000\ 126\ \text{m}^2$ so assume a sharp entry so that $k_2 = 15900$

and a sharp exit will give $k_3 = 31700$

Thus using $k_1+k_2+k_3+k_4$ instead of k_1 in a formula of type $h_L = k\, Q^2$ requires us to multiply Q by factor $(49400/100000)^{0.5}$ = **0.70** (i.e. a 30% reduction)

Applying this factor to the tabulated flow ($S = 0.5$) of 360 l/min gives a flow of 250 l/min and a velocity of 3.4 m/s (equivalent to 0.56 m).

Case (b) a 63mm downpipe has length 2m and drop 0.5m; there are 2 bends

4 m of 63 mm pipe has $k_1 = 4444$

2 bends are equivalent to an extra 0.25 m of length, giving $k_4 = 278$

$k_2 = 2572$ and $k_3 = 5146$

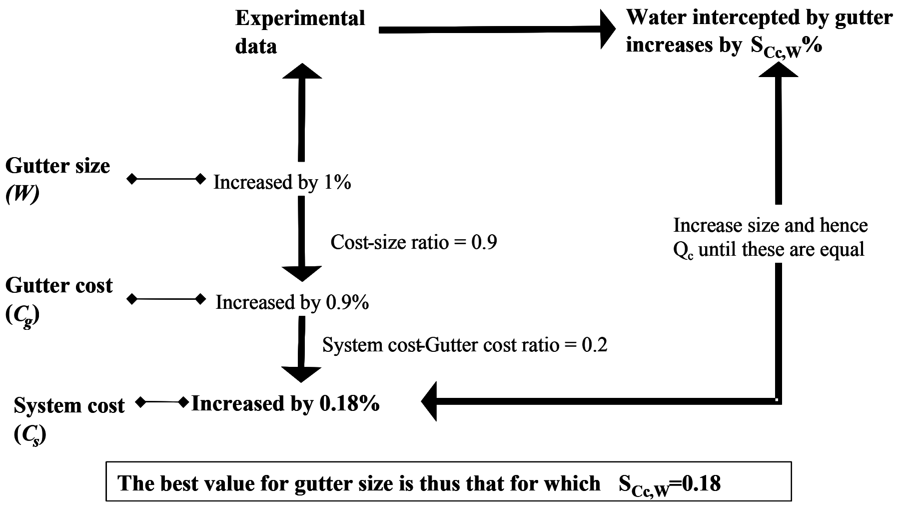
So correction factor for capacity is $(4444/12440)^{0.5}$ = **0.60** (i.e. a 40% reduction)

Applying this factor to the tabulated flow ($S = 0.25$) of 840 l/min gives a flow of 500 l/min and a velocity of 2.7 m/s (equivalent to 0.36 m)

APPENDIX 5 INTERCEPTION ANALYSIS

The basic approach used for Interception analysis is that set out in Appendix 7, namely to seek the gutter width *w* that gives the Interception-to-Width sensitivity corresponding to the maximising the system's benefit to cost ratio. This approach was applied to the interception performance of gutters with drops of respectively 10 mm and of 100 mm and a roof slope of 22°. Unlike conveyance, interception shows a sharp rather than gentle cut-off when a critical rainfall intensity is reached. If the run-off flowrate is high enough to overshoot the gutter, then we assume that none of it is intercepted. (With conveyance the gutter capacity flow is conveyed and only any excess is over this is spilled).

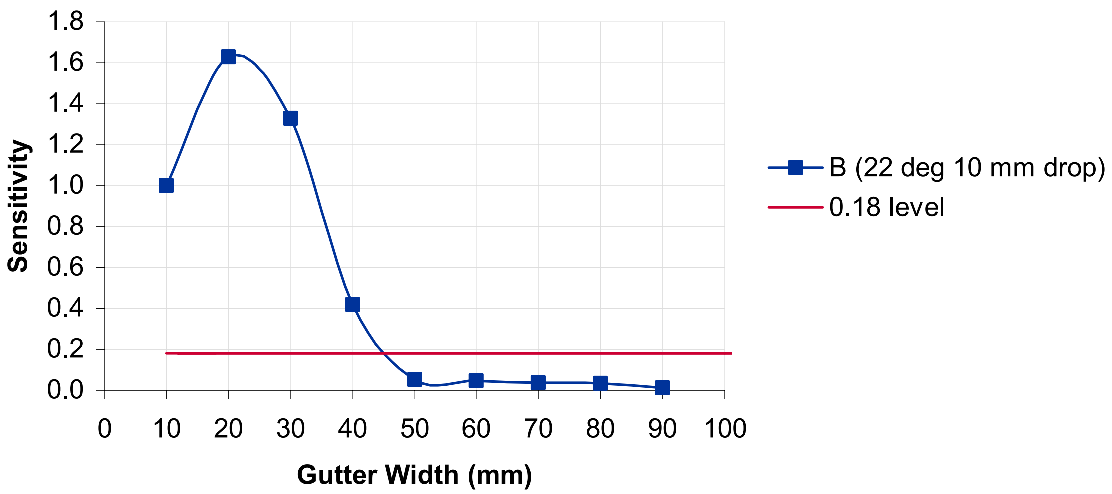
Figure A. 5.1



As can be seen, the gutter aperture is being increased until the sensitivity of water intercepted to gutter width equals that of system cost to gutter width. The diagram is slightly simpler than that used in the conveyance section, as the experimental data provides more direct information on the amount of water captured, without relying on further manipulation of rainfall data.

An example plot is given below:

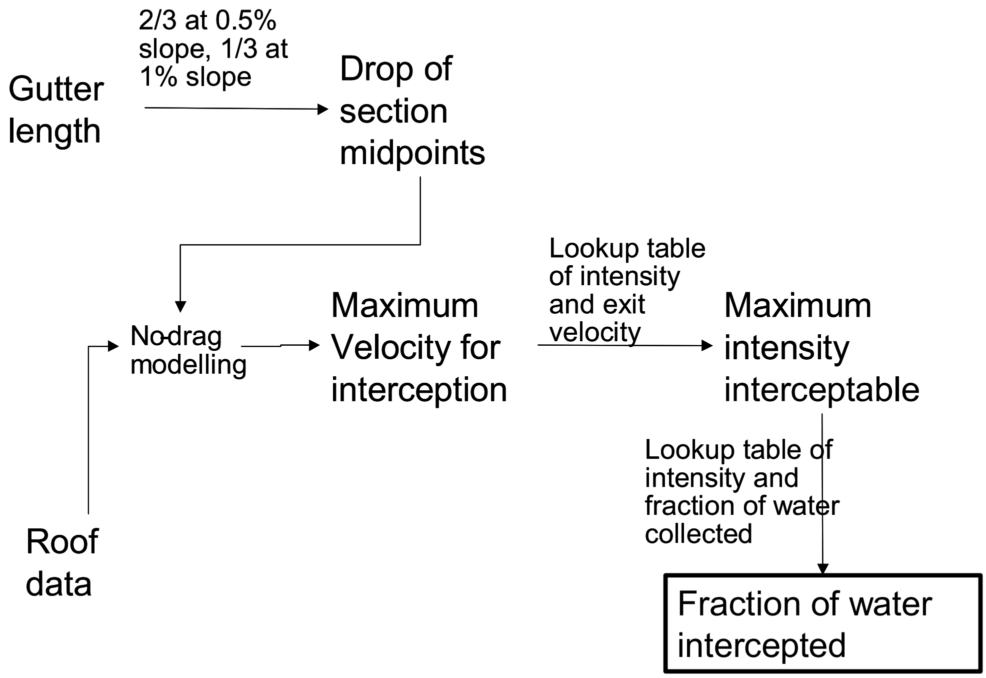
Figure A. 5.2: Sensitivity of water intercepted to gutter width (Sri Lanka data)



APPENDIX 6 COMBINED INTERCEPTION AND CONVEYANCE MODEL

A6.1 Explanation of interception data processing

As interception precedes conveyance, it was treated in isolation of the latter. Information from several sources was combined to model the interception performance of the gutter. This is summarised in the flow chart below:



The complexity in modelling interception performance arises from the slope of the gutter changing its performance along its length. To solve this problem several simplifications were required:

1. The gutter slope was specified at 0.5% for 2/3 of it's length, and 1% for the remaining 1/3.
2. The gutter is of a constant aperture along its length.
3. The jet leaving the roof was treated as following a single parabola with no spread. Although pulsation would exist, it was taken as causing benefits at some points and losses at others, and as such given no net effect.
4. The effects of wind were neglected on high rainfall intensities. To collect water from lower rainfall intensities the gutter inside lip was set 20mm inside the roof edge.

From experimentally-generated throw data, a simple calculation may be performed to predict the velocity of the water when leaving the roof edge in the absence of air resistance. By plotting this against drop, a regression may be performed to eliminate the effect of air resistance. A regression was then performed of exit velocities against rainfall intensity, and a lookup table produced of typical rainfall intensities and their respective roof exit velocities.

The gutter to be modelled was divided into a number of sections. For each section the drop at the midpoint was calculated. Given this drop and the throw (known from the gutter aperture and position relative to the roof edge), the exit velocity of water to just be caught by the gutter was calculated. The lookup table then gave the corresponding rainfall intensity at which this would occur.

The rainfall data from three locations used in the conveyance section was also processed here. For each site the exceedance probability at high rainfall intensities was plotted and a curve of the form $P(I) = Ae^{-bI}$ was fitted to the data. From this the amount of rainfall above intensity *I* per unit time was found, and thus the fraction of yearly rainfall falling below intensity *I* calculated. A second lookup table was produced giving rainfall intensity and fraction of rain falling below this intensity for each site. From this the performance of each section of the gutter was calculated, and these results aggregated to give an overall gutter performance.

A6.2 Interception and Conveyance Model

Following the production of the interception model, the discretisation approach was extended to model overall gutter performance. For a given configuration the capacity of each section of the gutter was determined. The gutter performance was modelled over a series of rainfall intensities, ranging from very high to moderate, for which latter condition the model predicted collection and conveyance of *all* water landing on the roof. For a given rainfall intensity, an algorithm determined how much (if any) run-off each section would intercept. The sum of this and water flowing from the previous section were compared to the capacity of the section. If the water entering the section were less than the capacity, all that water would be conveyed. If the water entering the section were greater than the capacity, the gutter would convey at a flow rate equal to its capacity, and the remaining water be spilled.

Using the probability data from tropical countries, it is possible to predict the quantity of rain falling in each small rainfall intensity band, and thus the overall efficiency of the gutter.

APPENDIX 7 OPTIMISATION OF SYSTEM PERFORMANCE

We wish to maximise the ratio of water captured (Q) to system cost (C) by optimising the gutter width (w): This optimum width we can denote as w_o.

$$Q = f(w)$$

The 'water captured' we can treat just as 'water intercepted' when we are exploring the economically optimum gutter size for run-off interception, subject to conditions such as pre-specified drop. Similarly we can treat it as 'water conveyed' (i.e. not spilled) when seeking the optimum size for conveyance. Normally however our interest is in optimising width for a system in which both interception and conveyance affect final water yield.

The system cost is the sum of tank cost (A) and gutter cost (assumed to be of form $B\,w^a$):

$$C = A + Bw^a$$

To maximise water captured: system cost, the following condition must be satisfied:

$$\frac{d\left(Q/C\right)}{dC} = 0 \qquad \text{giving} \qquad C\frac{dQ}{Dw} - Q\frac{dC}{dw} = 0$$

$$\therefore \frac{dQ}{dw} = \frac{Q}{C}\frac{dC}{dw} = \frac{Q}{C}aBw^{a-1} = a\left(\frac{Bw^a}{C}\right)\frac{Q}{w}$$

Rearranging this last equation yields

$$S_{Q,w} = \frac{dQ/dw}{Q/w} = a\lambda \qquad \text{Equation A. 7.1}$$

$\text{where}: \lambda = \frac{Bw^a}{C} = \text{fraction of total cost attributable to gutter}$ and $S_{Q,w}$ we call the 'sensitivity of water capture to gutter width'.

The economically optimum gutter width w_o is that which satisfies Equation A. 7.1.