Sizing and optimally locating guttering for rainwater harvesting

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Abstract

Guttering is the most common method for conveying rainwater from the capture surface (normally a roof) to storage. The cost of such gutters is a relatively small fraction of the total system cost (typically under 20%) but guttering failure accounts for much loss in RWH system performance. The optimum gutter may be defined as that which minimises the system cost per litre of water captured. There are a series of gutter variables within the control of the installer, including: gutter shape, slope, width and position relative to the roof edge.

This paper focuses on an analysis of the sizing and positioning of gutters, based on several sources, including rainfall data from the humid tropics and experiments undertaken by the DTU at the University of Warwick and in Sri Lanka. For domestic RWH applications, it was found that relatively small gutters (around 5 to 8cm wide), if hung accurately, offer high performance. Typically an *economically optimum* gutter would intercept and convey only 90-95% of roof run-off to the cistern. Indeed, it appears that gutters are often oversized in practice. The use of a dual slope can improve the performance of guttering.

Having concluded the technical analysis, rules of thumb and tabulated recommendations are presented, suitable for application by rainwater harvesting practitioners.

Keywords: Guttering; economic; optimisation.

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1 Introduction

Gutters are the most common method for capturing water and conveying it to the storage container (normally via a downpipe). Whilst gutters constitute a relatively small fraction of the total system cost, the cost of their failure is significant, so there is clear motivation for ensuring adequate performance. Many gutters malperform because of poor fitting and RWH system designers often compensate for this by specifying very large gutters. Whilst gutter choice is also affected by considerations relating to durability, ease of hanging etc, the purpose of this paper is to explore how small a well-fitted gutter might be to achieve the most economic performance.

There is a wide range of factors determining gutter performance, some of which, such as weather patterns, are beyond the control of RWH users. Householders will however be able to influence gutter shape, slope, width and position relative to the roof edge, and this paper addresses choice of these parameters.

Different optimum gutters may be defined according to varying measures of performance: a gutter just of sufficient size to allow the capture of all precipitation would be larger than one chosen to ensure a base level of water supply. The optimum gutter here is defined as “that which minimises the cost per litre of water captured.”

Gutter performance is difficult to model. Models based on interception only (the ability of the gutter to capture water as it leaves the roof) and conveyance only (the ability of the gutter to transport water) are presented initially. These are followed by brief details of a numerical model developed to combine the effects of interception and conveyance.

This may be too detailed for some readers, for whom we recommend going straight to the findings in section 4. For those interested in a more detailed exploration of the problem, this is available as DTU working paper 56(Still & Thomas, 2002).

2 Approach and Initial Modelling

2.1 Gutter Losses

Gutters have two aspects to their action: they must *intercept* the water leaving the roof, and then *convey* that water to a storage container. These two impose conflicting demands on the shape and trajectory of the gutter: for interception a flat plate practically in contact with the roof edge would give an economy of material, whereas for conveyance a curved shape with relatively high slope would be optimal. Losses by either of the two mechanisms may also overlap: summing the losses expected from the two would give an underestimate of system performance.

2.2 Optimisation

The criteria adopted for assessment of gutter performance here is system cost per litre of water captured. The algebra for finding the optimum gutter width w_o is given in Appendix A .

2.3 Flow in Gutters

Gutters represent a particular category of open channel flow, namely spatially varying flow, in which the flow along the gutter is continually changing as more water enters it. An analytical solution to such flow is not possible, but a numerical model was developed and validated through empirical work (Still, 2001). Further work gave an asymptotic non-dimensional solution to the flow equation[1]. In this solution, the most significant term was equivalent to applying the long-established Manning formula:

$$Q = \frac{1}{n} A r_h^{2/3} \sqrt{S} \qquad (\textit{Equation 1})$$

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)[2].

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[1] 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.

[2] The roof area efficiently drainable by a gutter is proportional to Q.

A reduction should be applied to this Manning solution, based on the aspect ratio of the gutter (the ratio of the gutter's length to its width). However gutters in domestic applications nearly always have an aspect ratio higher than 100, the reduction becomes sufficiently small that it can be neglected. In this case, it can be shown that we may size gutters by roof area alone, rather than a combination of length and breadth terms. This is much more convenient for modelling; we have simplified two variables to one.

2.4 Conveyance Modelling

Having concluded that we may use the Manning formula, it is possible to optimise the gutter performance for conveyance alone. It can be shown that the sensitivity of water conveyed to gutter capacity, $s_{F,D}$ is:

$$s_{F,d} = \frac{I}{i_{mean}} P(I) \qquad (\textit{Equation 2})$$

Where I is the rainfall intensity at which the gutter overflows, i_{mean} is the mean rainfall intensity (taken over the entire year), and $P(I)$ the probability of intensity I being exceeded. The sensitivity of A to B ($S_{A,B}$) may be considered as the percentage change in A arising from a 1% change in B.

Using representative tropical rainfall distributions (averaged data from sites in Uganda, Papua New Guinea and Indonesia) and roof sizes, assuming 1% gutter slope and applying the methodology in Appendix A we found that for "conveyance" the optimum gutter widths are 50 to 75mm. Gutters of these widths would overflow at rainfall intensities exceeding 80 to 120mm/hr.

2.5 Gutter Trajectory

For a given RWH situation, increasing the slope will improve conveyance, allowing the use of smaller gutters. Reducing the mean drop from roof edge to gutter will improve interception performance, allowing the use of a smaller gutter. There is a relation between these two: half the mean slope multiplied by the gutter length will give the mean drop. This point is the central trade-off in guttering, exchanging improvements in interception for decreases in conveyance.

Considering the gutter trajectory (the slope moving along the gutter), it is desirable to minimise the mean drop, to improve the interception performance of the gutter. From the Manning expression the optimum slope (that which minimises the drop for a given capacity) will follow a cubic profile ($y=kx^3$, where y is drop, x is distance along gutter, and k is a constant). This is not practicable, but a dual slope can be achieved. Given the practical constraints, a dual slope arrangement of the first 2/3 of the gutter length at 0.5% slope and the remaining 1/3 of the slope at 1% is recommended. Though it would be more efficient to lay the first half of the gutter at a quarter of the slope of the remaining half, for the case of 1% slope over the final section, this would require extremely accurate positioning of the gutter, so the initial slope choice given above will be kept.

2.6 Interception Analysis

Turning to analysis on the basis of interception only, information is available from:

- Laboratory work at Warwick University
- Experimental work in Sri Lanka
- Fieldworkers experience

The laboratory work was conducted on a corrugated roof at varying slopes and furrow length to simulate rainfalls of intensities from 0.5 to 4mm/min. The trajectory of the water leaving the corrugated roof was recorded.

Experimental work in Sri Lanka was conducted over a series of rainfalls, recording amount of rain falling at different horizontal displacements from the edge of a corrugated roof. The principal difference between field and lab conditions is the presence of wind in the former. Rainfall intensity analysis in the tropics (undertaken by experimenters with microwave transmissions)(Adimula et al.,) show that a negligible fraction of annual rainfall occurs at intensities exceeding 3mm/min.

- From the lab data (for a representative roof), with a drop of 100mm, a gutter of 120mm would capture all water falling at and below 4mm/min (more than 99.5% of yearly rainfall).
- The fieldwork data places the optimum gutter width at:
  - 45mm for a gap of 1cm between roof and gutter.
  - 115mm for a gap of 10cm between roof and gutter.
- All data sources show some throw of water towards the building for low rainfall intensities, suggesting the gutter lip be positioned around 20mm closer to the house than the roof edge.

3 Combined Interception & Conveyance Model

3.1 Workings of numerical scheme

Following the production of models for each of the two losses in isolation, a method of quantifying gutter performance given the interaction of these two was required.

From the laboratory work conducted in the DTU, the velocity of water as it left the roof for a variety of rainfall intensities, roof slopes and furrow lengths was obtained. Lookup tables were constructed from this information.

The data on tropical rainfall intensities was used to produce another set of lookup tables, listing rainfall intensity and fraction of water falling at each intensity band.

To utilise this information a numerical scheme was produced. This followed the steps indicated in Figure 1 More details are given in Appendix B

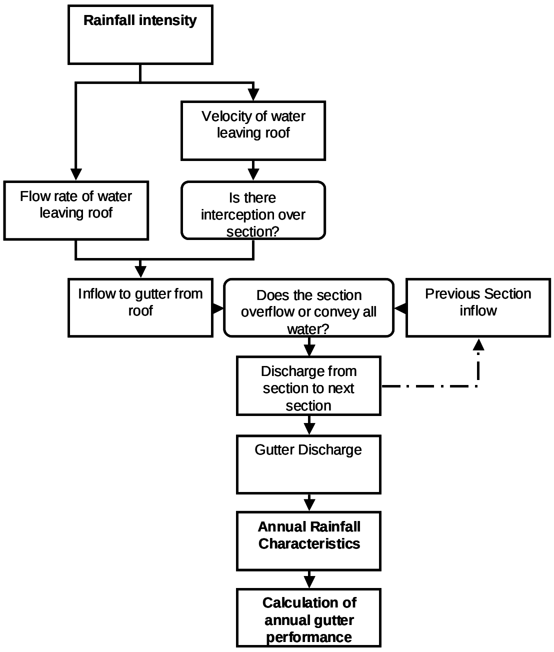

Figure 1: Conveyance and Interception Model

The numerical model was used to test for a variety of situations. The methodology employed was to use the model to eliminate as many factors as could be reasonably discarded or subsumed within other variables.

Roof area and shape

As both the gutter length and roof depth could be varied, one proposition to be tested was; “The optimal gutter size may be defined by just roof area instead of roof length and depth.”

Three different configurations were used for each of two roof areas (16m^2 and 32m^2), as detailed in Table 1. The results are shown in Figure 2. For the smaller area it can be seen that the performance of different sized gutters for the three different configurations are indistinguishable (shown by the upper line). The same can be seen for the larger roof area, shown by the lower line in the figure. Thus there is no significant affect on gutter performance of different aspect ratios for a given roof area, and the proposition above is acceptable.

Table 1: Roof configurations

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

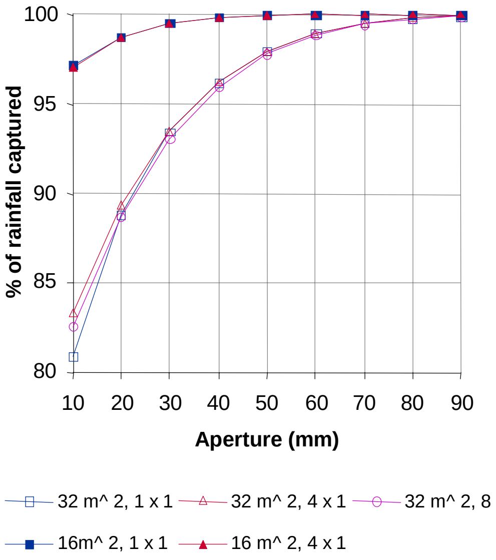

Figure 2: Gutter performance with varying roof shape

3.2 Gutter Shape

The performance of five gutter cross-section shapes was trialled with the chosen dual slope trajectory (2/3 at 0.5%, 1/3 at 1%). As gutter cost depends mainly on how much material is used, and this in turn is proportional to gutter "perimeter", so gutters of the same perimeter though different shapes should cost the same. The results (overall capture efficiency versus perimeter) indicated that semicircular, trapezoidal (with wings set at 30^o to vertical) and v-section gutters are comparable. The poorly-performing square section gutters are rejected. Rectangular sections with a width twice their height were also tested, and showed an inferior performance, though not as poor as that of square sections.

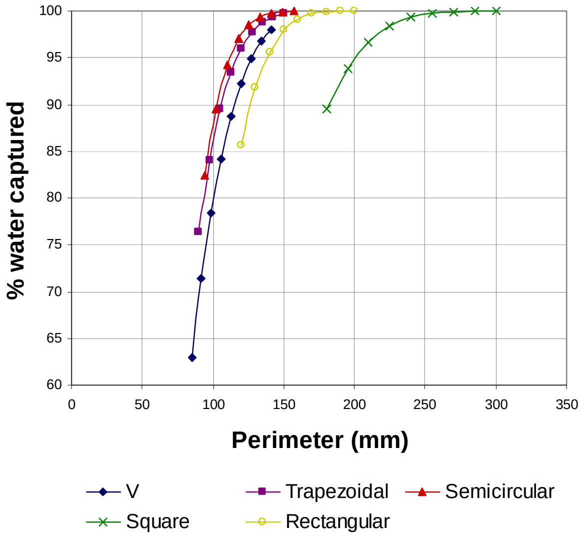

Figure 3: Gutter shape comparison

In this case we may recommend trapezoidal or semi-circular gutters, with v-section gutters being possible, but practical experience has shown they are more prone to blockages, and they are slightly less efficient than either of the other two shapes, and rectangular sections possible but not as effective.

3.3 Gutter slope

The 6 slope configurations shown in Table 2 were tested. It was found that configuration C2 gave the highest water capture efficiency. The high slope configurations (C3 and C6) performed poorly, whilst the remaining configurations (C1, C4 and C5) were a little inferior. C2 is thus carried forward as the recommended form.

Table 2: Gutter slope configurations

Config No	**Description**	**Slope of gutter (%)**			**Gutter performance (%)**[3]
		First 2/3	**Last 1/3**	**Mean**	
C1	low dual slope	0.25	0.50	0.33	92
C2	**medium dual slope**	**0.50**	**1.00**	**0.66**	**97**
C3	high dual slope	1.00	2.00	1.33	85
C4	low constant slope	0.50	0.50	0.50	92
C5	medium constant slope	1.00	1.00	1.00	88
C6	high constant slope	2.00	2.00	2.00	61

3.4 Roof Slope

Figure 4 shows jet trajectories leaving 4.2m-long roofs of 11°, 22° and 31° for rainfall intensity of 2 mm/min.

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 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 atypically 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 (Still & Thomas, 2002).

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[3] The figures shown were those from a large roof with 75mm semi-circular gutters

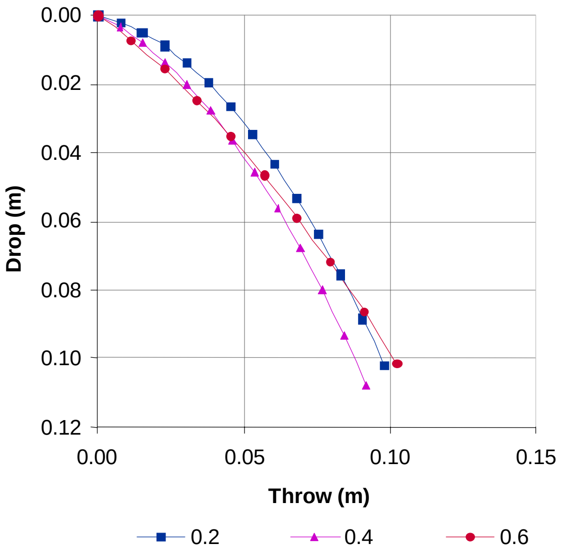

Figure 4: Throw trajectory

4 Conclusions

4.1.1 Simplifying Gutter Sizing

From the previous sections, we have reached the point of recommending:

1. 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);
2. A trapezoidal or semi-circular gutter shape;
3. That the inside edge of the gutter be 20mm inside the roof edge;
4. That gutters correctly sized for a roof slope of 22^o will also be good for common roof slopes from 15^o to over 30^o, thus we do not need to know roof slope;
5. That within the humid tropics exact location and climate are not critical and we may assume a representative rainfall intensity distribution;
6. That (common) corrugated iron roofs represent a worst case – gutters sized for CI will be adequate for other roofing types;

7. That roof *shape* can be ignored and only roof area considered.

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

4.2 Gutter size optimisation

Implementing the recommendations from the previous section, the model was run to find the optimum gutter width for given roof plan areas. The output may be expressed in a variety of forms; the one chosen in Table 3 here is of recommended gutter width versus roof area.

Table 3: Recommended gutter widths for use in the humid tropics.

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

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Appendix A

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 wo.

$$Q = f(w) \qquad (\textit{Equation 3})$$

The ‘water captured’ we can treat just as ‘water intercepted’ when we are exploring the economically optimum gutter size just 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 just *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 $B\,w^a$):

$$C = A + Bw^a \qquad (\textit{Equation 4})$$

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

$$\frac{d\left(Q/C\right)}{dw} = 0 \qquad (\textit{Equation 5})$$

Giving

$$C\frac{dQ}{dw} - Q\frac{dC}{dw} = 0 \qquad (\textit{Equation 6})$$

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

(*Equation 7*)

Rearranging this last equation we get that w_o is the value that satisfies:

$$\left.\frac{dQ/dw}{Q/w}\right|_{w_o} = a\lambda \qquad (\textit{Equation 8})$$

Where $S_{Q,w}$ is the sensitivity of water capture to gutter width.

Appendix B

The steps involved in setting up the model were:

1. Fix the gutter length, size and trajectory.
2. Discretise the gutter, calculating the drop at each section midpoint.
3. Combining the roof data with midsection drops, use a conservative (no air resistance) model to calculate the maximum velocity at which water leaving the roof will overshoot the gutter.
4. From lookup tables find the corresponding rainfall intensity at which there will be no interception.
5. Calculate the conveyance capacity of each section.
6. Select a rainfall intensity.

7. Starting at the furthest upstream gutter section, a logical test was applied for interception, giving either full or zero interception over that section.
8. The flow entering from the roof was added to that from any upstream sections. This was subject to another logical test. If the water entering was greater than the conveyance capacity, the only the conveyance capacity was transferred to the next section, if less, then all the water entering was conveyed.
9. This was repeated until the discharge from the end of the gutter was found, and from this the gutter efficiency at this rainfall.
10. Repeating this procedure for a range of rainfall intensities, and combining it with rainfall probability data, the overall performance of the gutter was calculated.