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Guttering Design for Rainwater Harvesting

with special reference to conditions in Uganda

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Abstract

The way that rain runs off an unguttered roof is discussed and supported by findings from laboratory experiments. The purpose of and constraints upon guttering are identified. The principles of guttering design are developed and the trade-offs between cost, effectiveness in intercepting run-off, capacity to carry flow and architectural impact are discussed. Several low-cost guttering variants are identified, as are different ways of fixing gutters onto simple buildings. Initial field trials in Uganda are reported.

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Notes: This version of the Working Paper is provisional and it is hoped to replace it by a fuller version in 1998 after further experiments have been undertaken.

The Kagadi data was recorded by Mr Turyamureba Victor of URDT.

1 INTRODUCTION

The main components of a rainwater harvesting system fed by run-off from a roof are a tank and ‘guttering’, where ‘guttering’ includes both the actual gutters and the downpipe connecting gutters to tank. This paper examines the factors that control the design of good gutters. (Downpipes will be treated in the revision to this Working Paper planned for April 1998 following further fieldwork.) It reports work done within a programme to reduce the cost of the different components of domestic rainwater harvesting systems. Target costs of $50 and $200 have been chosen for respectively ‘wet season only’ and ‘all year’ water supply systems. Guttering represents about 30% of the cost of a ‘wet season only’ system, built to provide domestic water for about 8 months per year in Uganda, but only about 10% of the cost of an ‘all-year’ system in which the water storage capacity is large and expensive. Many gutters in Uganda perform badly and some are unsightly (for example large troughs made by cutting corrugated sheets). The majority of buildings are unguttered and need to be fitted if rainwater is to be harvested. For reasons not discussed in this paper, rainwater harvesting is likely to increase substantially in Uganda in the next few years.

Rain falling upon a sloping roof runs towards its lower edge and, if there are no gutters, from there falls to the ground. A little of the rain hitting the roof may evaporate at once from the roof surface, but typically over 95% will run off. By the time that the water reaches the edge of the roof it has acquired a velocity v parallel to the roof surface. This velocity increases with

a. the intensity I of the rainfall during the last few seconds (e.g. in millimetres per minute)
b. the length L of the roof, from ridge to edge in the direction of water flow
c. the slope of the roof S
d. the smoothness and shape of the roofing material.

During rain, even very heavy rain, the film of water on a roof is quite thin. On a plane roof it rarely exceeds 0.4 mm and in the furrows of a corrugated roof it rarely exceeds 1.5 mm. This shallow flow is subject to frictional drag as it moves down the roof. *If* there were no water-roof friction, quite high speeds would be reached - up to 5 meters per second on a typical roof. However there is friction and actual speeds are much lower than this, typically under 0.5 m/s. As rainwater flows down a roof from its top, being augmented as it goes, the film gets both deeper and faster. It usually has reached an ‘equilibrium’ speed at which the pull of gravity on the water is exactly balanced by the friction drag force on it. This equilibrium speed is about twice as high for a corrugated roof as for a plane or ribbed roof, and about 50% higher for a shiny metal roof than for a rough tiled one. (See Appendix B)

Because the runoff velocity at the bottom of the roof is not zero, the water does not fall vertically from the roof edge but instead follows a curved trajectory. Figure 1 shows such a trajectory. Under windless conditions, the no-wind outward ‘throw’ x increases with ‘drop’ y from the roof edge. For each run-off velocity v there will be a different curve: the higher the velocity, the greater the throw x.

It is common to experience strong winds during rainfall and these further disturb the stream of falling water, causing the actual throw x_w to vary continuously about its windless value x. For any particular roof therefore, the throw x_w for a given drop y varies predictably with rainfall intensity and unpredictably with wind. These variations make the design of guttering systems more difficult. It *may* be possible to obtain data about rainfall intensity - for example what fraction of annual rainfall occurs during storms exceeding a given intensity - and use this to aid guttering design. It is rarely possible to obtain relevant windspeed data or to use it in design, so it is desirable to undertake experiments to measure the statistical distribution of throw over a typical year before deciding guttering norms.

Where there are no gutters, water falls freely from roof edge to ground. There it may cause erosion of the soils and splashing of the bottom part of the building's walls. It is usual to make unguttered roofs overhang the walls by 300 to 600 mm to minimise damage to walls or foundations (and in hot climates also to shade the walls). Even so, it is common to find serious gully erosion around unguttered houses in tropical towns. In temperate climates almost all buildings are guttered and roof overhangs are often as little as 50 mm.

Gutters are fitted to roofs to channel the run-off into a drain or, in the case of rainwater harvesting, into a collecting vessel. (Water *can* be collected in wide-mouthed ground-level vessels even without using gutters but this process has several difficulties.) A gutter has essentially two functions

a. to intercept the run-off on its way from roof edge to the ground
b. to transport the intercepted water sideways towards some concentration point (usually to a downpipe).

For either of these functions the gutter may be less than 100% effective. If it is not wide enough some of the run-off may overshoot it and not be intercepted. If its carrying capacity is inadequate, it will overflow during heavy storms and lose some of the water that it has intercepted. Unfortunately, as will be shown later, some of the techniques for increasing capacity also reduce the fraction of water that is intercepted.

Because gutters have to be open-topped, they are not very suitable for conveying water downwards to the drain or collecting vessel. This task of vertical transport is usually performed by a closed 'downpipe'. To connect the gutter to the downpipe there may be a specially shaped junction called a 'gully'. Alternatives to the use of a downpipe are to let the water stream free-fall from the end of the gutter or to guide it by means of a rod or chain to which the water 'sticks' by surface tension.

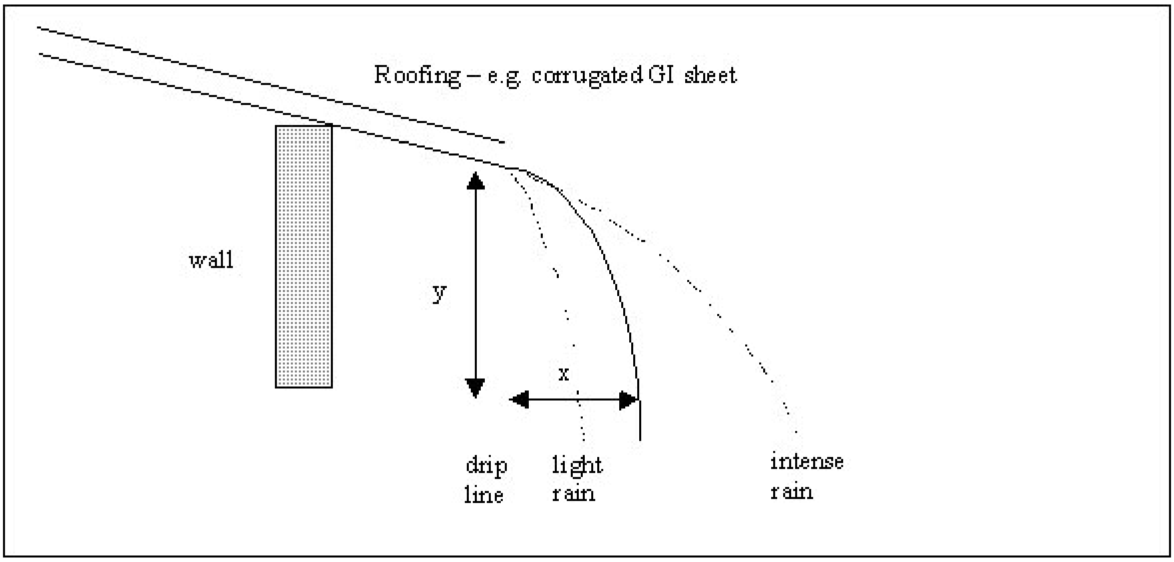

Figure 1 Trajectory of flow off an unguttered roof

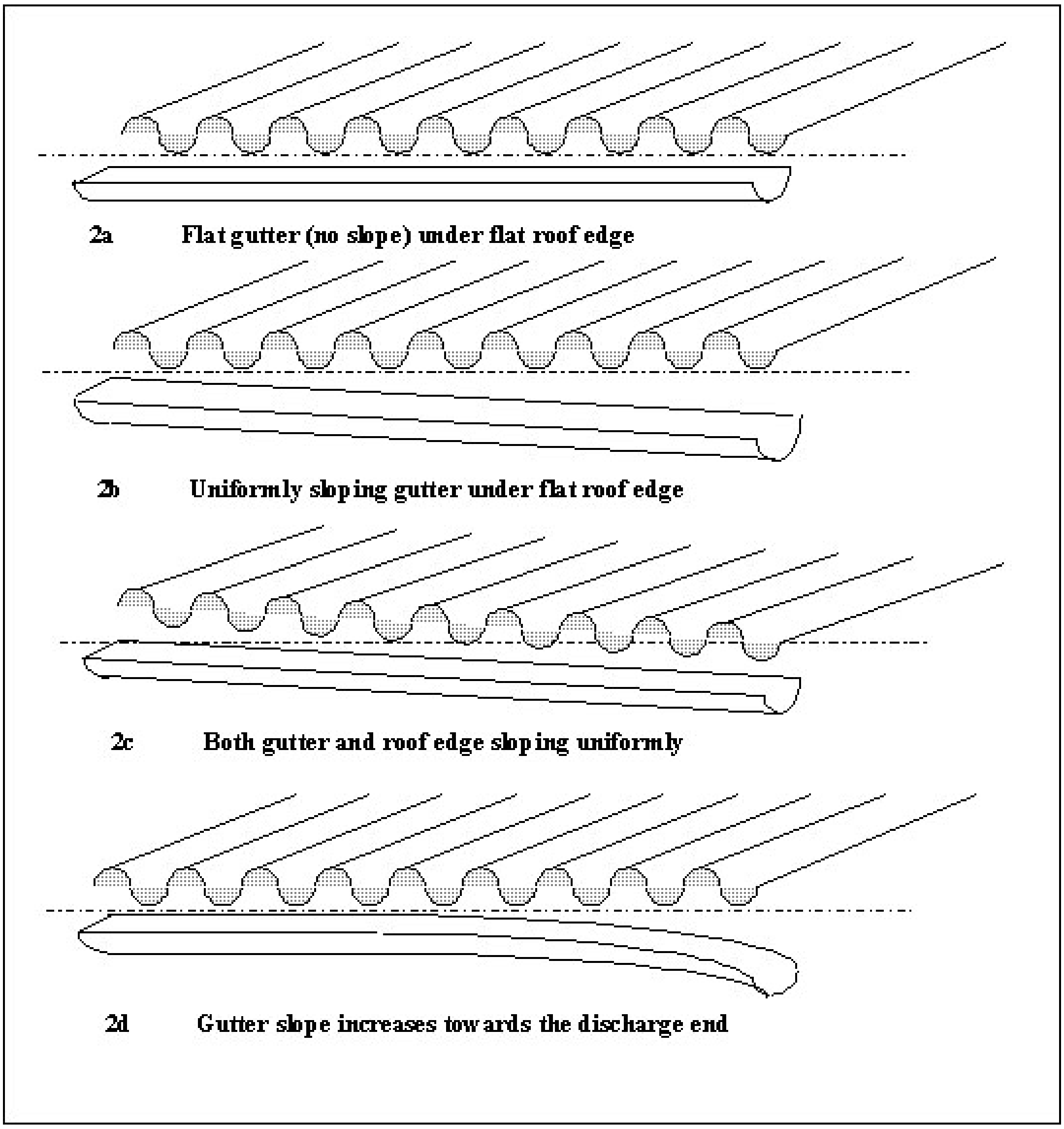

Figure 2 Gutter slope

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2 GUTTERING DESIGN

Our general design objective is to find the cheapest guttering arrangement that will achieve an agreed level of performance (such as to collect 95% of annual roof run-off). We need to select the slope, size, shape and material of the gutter.

2.1 Choosing the slope

The capacity of a gutter, i.e. the flow Q_C it can carry without over-topping, depends on several factors, especially:

a. its cross-sectional area *A*
b. its hydraulic radius *R=A/P*, where *P* is the length of the perimeter of the wetted cross-section when full, (for a square gutter *R* = 0.33 x width, for a semicircular gutter running full *R* = 0.25 x diameter, for a semi-circular gutter or roof furrow carrying a shallow flow *R* = 0.67 x depth of water)
c. its slope *S*

d. its roughness.

The standard formula is Manning's. Using the realistic value 0.01 for Manning's *n* gives:

Flow in m^3 per second, $Q_C = 100\, A\, R^{0.67}\, S^{0.5}$ [Eq.1]

(To convert Q_C to litres/minute, multiply the value given by this formula by 60 000.)

We can thus see that doubling the size of a gutter (for example its diameter) and hence increasing its area four-fold will multiply its capacity by 6.4 ($= 4 \times 2^{0.67}$). Doubling the slope *S* will only multiply it by 1.41 ($=\sqrt{2}$).

In an area subject to tropical rainfall, we might design gutters for rainfall intensities up to 4 mm per minute (i.e. to carry up to 4 litres per minute run-off per square meter of roof area). Some representative gutter capacities for comparison are

Gutter description	**Capacity in litres per minute at the specified slope (m^2 of roof that can be drained at rainfall of 4 mm/min is shown in brackets)**			
Slope =	1%	2%	3%	4%
semicircular, 50 mm ID	**32 (8)**	**45 (11)**	**55 (14)**	**64 (16)**
semicircular, 75 mm ID	**95 (24)**	**132 (34)**	**162 (41)**	**190 (48)**
semicircular, 100 mm ID	**201 (50)**	**285 (71)**	**349 (87)**	**403 (101)**
rectangular, 25mm x 50mm wide	**40 (10)**	**57 (14)**	**70 (18)**	**82 (21)**
square, 75 mm x 75 mm	**285 (71)**	**403 (101)**	**494 (124)**	**570 (143)**
square, 100 mm x 100 mm	**614 (151)**	**868 (217)**	**1076 (267)**	**1228 (307)**

Table 1 : Gutter capacity related to size, type and slope

From this table, and remembering that more than one gutter would normally be used, we can see that 75 mm width should be adequate for most domestic roofs and even only 50 mm might suffice.

Many gutters are laid almost level (with slope *S* less than 1%), close below the roof edge, as is shown in Figure 2a. In this position the drop *y* from furrow mouth to gutter is very small, perhaps only 20 mm, so both the mean throw (= no-wind throw *x*) and the variation in throw due to wind are small. Even a narrow gutter may be able to intercept all the run-off. However the small slope means that to achieve adequate carrying capacity the gutter must be large and costly. Architecturally this arrangement is neat: the gutter is unobtrusive and even where the eaves are low, the gutter can be kept above head height.

An alternative, as shown in Figure 2b, is to make the gutter steeper - say having a slope of 4% (for example a fall of 200 mm over a typical 5 m length). The formula above shows that for a given size the bigger slope increases capacity Q_C ; as we are designing for a particular capacity, using the bigger slope allows us to reduce the gutter size and hence its cost. Unfortunately the discharge end of a sloping gutter will be some way below the roof edge, and at this end may not intercept all the water coming off the roof. So we have the conflict that increasing the slope S will increase capacity but may reduce interception efficiency E_{Int} (= fraction of run-off that is intercepted).

There are three techniques for resolving this conflict so that steep slopes can be used safely. The first is to keep the gutter as short as possibly, by putting downpipes in the centre of a long gutter rather than at one end of it. This has the effect of creating two half-length gutters, each dropping towards the centre. Architecture may prevent the location of a downpipe exactly in the middle of a wall, but it is often possible to locate it somewhere near the middle. The custom of placing rainwater collection tanks at the corner of a building, or worse underneath the gable ends, means large gutters must be used. Moving the down-pipe from the gutter's end to a midway position means that for a given roof catchment the gutter can be about 32% smaller in diameter and therefore significantly cheaper.

The second technique is shown in Figure 2c. Here the purlin and hence the roof edge itself falls at a slope of several %, following the slope desired for the gutter. The gutter fits tightly under the roof edge all along its length, so there is no danger of failure to intercept run-off near its lower end. Of course this is against normal building practice, but it is easy to construct and not unsightly in simple buildings.

The third technique is to use a gutter slope that increases towards the discharge end, as shown in Figure 2d. As one moves along the gutter from its closed end to its discharge end (left to right in the figure) the flow increases, reaching a maximum at the discharge point. Ideally we should correspondingly increase either the slope or the size of the gutter as we approach that point. Generally it is not convenient to vary the gutter size along its length, but most gutters are sufficiently flexible that their slope can be varied. The most efficient curve for the gutter to follow is

$y_F = \mathrm{K}\, z^3$ [Eq.2]

where y_F is the fall of the gutter below the height of its closed end at a distance z from that end, and the constant K equals $S_{max} / 3L^2$. L is the length of the gutter and S_{max} is the slope needed to give enough capacity at the discharge end.

Comparing Figure 2d (where the gutter has this ideal varying slope) with Figure 2b (where the slope is fixed at $S = S_{max}$), we find that the fall at the discharge end is reduced by a factor of 3. For example we might compare a 6m gutter sloping uniformly (as Figure 2b) at 4% with a gutter made of 3 x 2m sections sloped at 0%, 1% and 4% respectively (which approximately follows the ideal curve). The first arrangement falls 24 cm along its length, the second falls only 9 cm, giving a substantial and useful reduction.

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2.2 Choosing the shape

The cost of a gutter is dominated by the amount of material in it. As gutters are generally made of material of constant thickness, this amount is usually proportional to the width of the strip from which it was formed. This width is the same as the 'perimeter' distance *P* used in the flow formula, Eq.1. We therefore seek to minimise *P* while maintaining the properties that we require, namely adequate capacity, high run-off interception and sufficient stiffness to allow the gutter supports to be widely spaced.

For good interception we require a big gutter aperture *W*. The run-off stream should also hit a gutter surface that is angled to reflect the stream into the gutter rather than outside it. Figure 3 shows some good and bad gutter shapes from these two points of view.

For high flow capacity the area *A* should be as large as possible, while for high stiffness D^3 should be maximised (*D* is depth). We can express the interception efficiency, flow capacity and stiffness obtainable in relation to the width *P* of guttering material by three dimensionless ratios. These are: area ratio = A/P^2 , aperture ratio = W/P and stiffness ratio = D^3/P^3 . They have the following values for the various shapes shown in Figure 3.

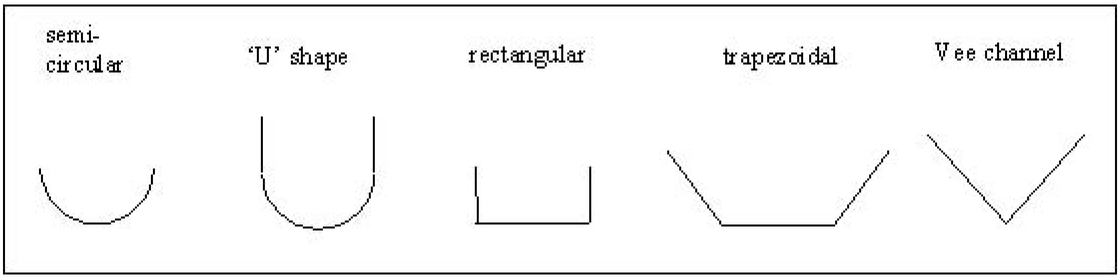

Figure 3 Shapes for gutters

	area ratio	apeture ratio	stiffness ratio
Semicircular trough	$A/P^2 = 0.159$	W/P = 0.64	$D^3/P^3 = 0.032$
'U' whose height equals its width	$A/P^2 = 0.135$	W/P = 0.39	$D^3/P^3 = 0.059$
Rectangular channel (h=1/2w)	$A/P^2 = 0.125$	W/P = 0.50	$D^3/P^3 = 0.016$
45 deg. trapezoidal channel with sides equal to base	$A/P^2 = 0.134$	W/P = 0.80	$D^3/P^3 = 0.013$
90 deg. 'V' channel	$A/P^2 = 0.124$	W/P = 0.71	$D^3/P^3 = 0.044$

Table 2 : Shape factors for gutters (the higher the values, the better**)**

Resistance to twisting is poor for any open section. For a given perimeter *P* it does not vary with gutter shape. Resistance to bending is determined by the second moment of area about a horizontal axis, which is approximately proportional to the cube of the gutter depth.

Thus the *semicircular trough* has about the best combination of properties, moreover it is fairly easy to make in metal and in plastic may be obtained by slicing a pipe in half. The resistance to vertical bending can be improved if periodic spacers are used to maintain the semi-circular shape against the tendency to flatten during bending.

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2.3 Guttering Materials

Modern materials are generally expensive in Uganda and are difficult to obtain outside Kampala or Jinja. Even substantial towns lack steel or plastic stockists although corrugated GI sheeting and plastic mouldings like bowls are available even in tiny trading posts.

Temporary gutters are often made of banana stems or bamboo. More permanent materials are extruded PVC, galvanised iron sheet, aluminium sheet and wood.

Wooden gutters need much skill or machinery to make watertight and are prone to warping and cracking as humidity changes. Moreover planks thinner than 25 mm are not available in most parts of the country, so wooden gutters are also heavy. They are not commonly found.

Aluminium sheet is more expensive and much less widely available than steel. Its workability is similar to steel and its resistance to corrosion is higher than galvanised iron (galvanised mild steel). Ugandan industry does not have the capacity to extrude aluminium sections, nor are many imported.

PVC is the standard guttering material in temperate countries but has a shorter life under tropical levels of ultra-violet radiation. Extruded purpose-made gutters are not yet widely available in Uganda, so slit PVC piping has to be used (which lacks desirable thickening at the edges and sealable joints). PVC costs about twice as much as galvanised steel. If rainwater harvesting becomes more common, Ugandan manufacturers of extruded plastic products may add gutters and associated fittings to their range. Meanwhile PVC and (more flexible and durable) HDPE tubing is suitable for downpipes, while gutter-downpipe junctions can be fabricated from plastic containers such as 3 litre oil cans.

At least in the short term GI sheeting (preferably not already corrugated) is the most suitable material for gutter construction. It requires folding at the edges to reduce sharpness. Such doubling increases torsional stiffness and may aid location in supports; it does however complicate jointing and the sealing of blind ends. Both rectangular and curved GI guttering is available on the market (at about $2 per meter for semicircular guttering of 80 mm diameter) being produced by very small enterprises by folding or rolling. All fittings must be made by the installer. Soldered or crimped GI tubes are widely used for downpipes but they are often crudely made, leak at elbows, fail to fit well and are more prone to rusting than GI gutters.

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2.4 Fixing Gutters

The fixing of gutters has to permit them to be given the appropriate slope and centreline location. Fixings have to resist wind forces, the weight of water, forces due to arresting the fall of the water stream and miscellaneous forces such as being stood on by someone mounting the roof. This last force is usually the largest and it is prudent to support gutters such that a 70 kg weight could be momentarily hung on any part without causing permanent displacement. For gutters up to 100 mm diameter, the weight of water and of momentum transfer is unlikely to exceed 10 kg per meter run.

Figure 4a shows a roof-edge detail typical of Ugandan houses with corrugated iron (CI) roofs. (Almost all buildings are single storey with CI or grass roofs). Few buildings have fascia boards, however where one is present the gutter can be nailed directly to it as shown in Figure 4c. The simplest fixing uses a nail longer than the gutter width driven through the gutter into the fascia. To prevent the gutter collapsing, a sleeve of metal pipe or plastic conduit should surround the nail where it crosses from one side of the gutter to the other. The best support comes where the fascia is backed by a rafter end. Vertical adjustment has to be done before the nails are driven. The fascia board may have to be packed out to the right position behind the roof edge. In the absence of a fascia, gutters have to be supported from one of the following:

a) the purlin - usually a 80 mm x 50 mm timber, see Figure 4d (bracket wired to purlin or put through a hole drilled in the purlin)

b) the rafter ends, see Figure 4e

c) the roof sheets themselves, see Figure 4b

d) the wall, which is usually 300 mm to 600 mm behind the roof edge

e) the ground (typically 2.2m below the roof edge).

In practice a) and b) offer the only simple fixings. Hanging from the roof edge with wire encourages rusting at the hole made in the sheet and gives poor control against wind forces or gutter twisting. The wire soon rusts too.

Many buildings are only approximately horizontal so it is not easy to install gutters with a specified slope. Purlins offer greater scope for achieving suitable support spacing, rafter ends allow easier vertical adjustment. Notice with both Figures 4d and 4e that the bar or strip is bent back at its outer end to restrain the gutter. A suitable material is 6 mm reinforcing bar and this may easily be hammered into the right shape; to attach bar to a rafter it may be locally flattened and pierced by a blacksmith or it may be held with staples. With both 4d and 4e fixings, adjusting the vertical height of the gutter is likely to result in some rotation. Clearly the ideal is for the outer edge of the gutter to be as high as (or even higher than) its inner edge. In the position shown in Figure 4d, the purlin bar has inadequate vertical support. There are several options for locating it more rigidly. The first is to wire it tightly to the purlin. The second is to drill a (6 mm?) hole through the purlin, pass the bar through this hole and then bend the inwards end of the bar down behind it. The third is to give the bar a long tail that lies along the underside of a corrugation. Since both rafters and purlins vary considerably in size and location, some adjustment of the fixings by the installer will almost certainly be required to achieve the right gutter slope, distance out from the roof edge and rotation. This is an area of weakness since few installers are conscious of guttering design or possess tools like levels or hand drills. There is not yet in Uganda the custom of selling building products with installation advice notes, but such a practice may prove necessary for gutters.

In addition to facilitating slope adjustment, the fixing should resist the likely forces (including upwards wind forces), be durable, available and cheap, and should help the gutter retain its optimum shape. Mass-produced fixings are not available on the Ugandan market, so fixings are usually improvised by house-holders or builders with the aid of very the simple hand-tools.

Gutters are often made of several sections joined together. With mass-produced PVC guttering these joints are made with special injection-moulded connectors. With rural guttering in Africa, joints are made without such fittings. Successive gutter sections are overlapped, with the upstream section lying inside the downstream section. An overlap of 150 mm is common. The overlapped section should ideally be over a support. To hold the sections together they may be bound with rubber strip, or in the case of metal gutters they may be riveted. The upstream end of a gutter needs to be blocked to ensure all water flows to the downstream (outlet) end. A wooden disc that just fills the trough (held in position with a rubber strip) can be used to block the end of plastic guttering. For guttering made from sheet metal it is usually easier to make an end stop by folding up the metal.

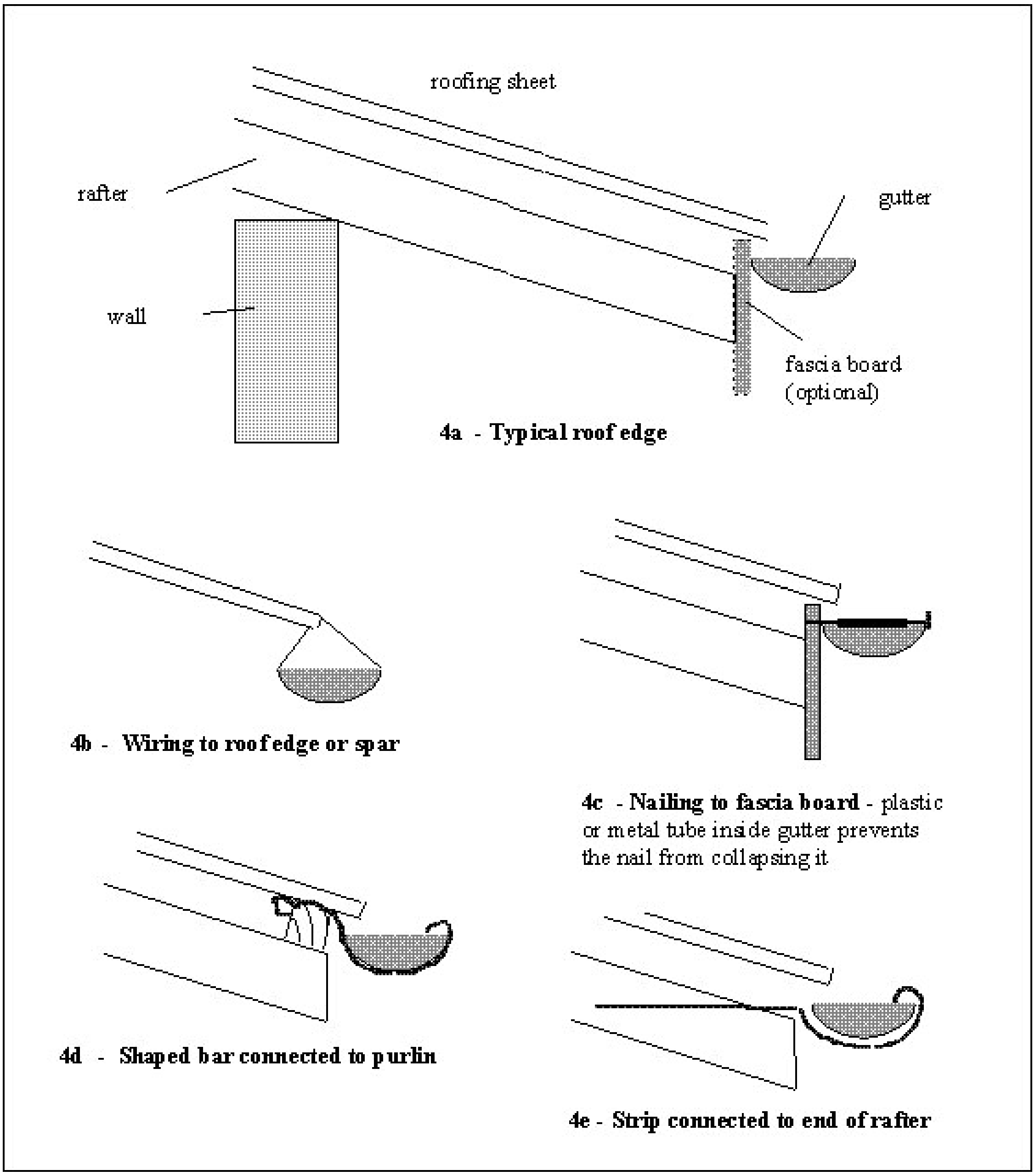

Figure 4 Roof-edge details and some gutter supports

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3 LABORATORY EXPERIMENTS

3.1 Experimental arrangments and results

In the laboratory it is possible to set the ‘rainfall’ fairly carefully and to observe the resultant run-off behaviour. However it is not easy to mimic the effects of wind. The laboratory data reported below therefore relates to the ‘no wind’ trajectory of the water leaving a roof. Corrugated galvanised iron roofing was used (furrow pitch = 80 mm).

An apparatus was built which allowed the following roof parameters to be set:

roof slope (sin θ = rise/length) = 0.1 (v. shallow), 0.2, 0.4, 0.6 and 0.8 (v. steep)

roof length = 0.7, 1.4, 2.1, 2.8, 3.5 and 4.2 meters

rainfall intensity = 0.5 mm/minute (light), 1 (heavy), 2 (very heavy) and 4 (cloudburst)

For each combination of slope, length and rainfall intensity, the 'throw' *x* was measured at four different values (100 mm, 200 mm, 1000 mm and 2000 mm) of the drop *y*. The throw was measured relative to a vertical line descending from the lip of each corrugation ('furrow'). The rain was simulated by a calibrated (± 2%) 3-jet spray applied at the centre of each 0.7 meter length of furrow. At low rainfall intensities this spray spread over only a few cm of furrow. At maximum intensity it spread over the entire 0.7 meter length. It is not thought that this distribution has significantly distorted the data (compared with the ideal of a uniform distribution). The maximum rainfall intensity chosen (4 mm per minute) is likely to occur for only a few minutes a year even in the tropics. From a rainwater harvesting point of view, to be able to intercept run-off at all intensities up to 2 mm per minute would be quite good enough.

Spray bars were placed horizontally across the roofing so that the various 'furrow length' could be simulated by having a particular furrow fed from 1 or 2 or 3 etc. bars. Unfortunately this means that a different furrow is used for each 'length', so that the effect of any imperfections in the furrow lip falsely appear in the data as length effects. The rig also had an unintentional short section (0.3 m) of unsprayed roof immediately above the furrow lips. It might be thought that the water would accelerate down this section and give an upwards bias to the throw data. However the discharge velocities are found to be only about 10% of those calculated assuming no water friction in the furrows. This suggests that the flow reaches a velocity equilibrium almost immediately - within a few cm of the rain impact point. So no corrections have been made for this unintended dry section.

A futher small experiment was undertaken to check that the flow down a roof quickly reaches 'equilibrium'. A flow was generated by spraying various parts of a roof in such a way that the discharge from each furrow was held constant. It was found that if the rain was sprayed near the top of the roof (i.e. between about 3.2 m and 4.5 m from the roof edge) the discharge velocity was 10% to 15% higher than when it was sprayed near the bottom of the roof (i.e between about 0.4 m and 1.7 m from the roof edge). This suggests that it is strictly untrue to say that equilibrium velocities are almost instantly reached: the water is still accelerating when it reaches the roof edge. However for practical purposes we can use equilibrium theory to roughly estimate the thickness of the water film (observed above to be under 1 mm) and the effect of corrugations in increasing the discharge velocity (by a factor of from 1.5 to 2.5) over that observable with other roofing profiles.

Slope	**Length**	**Throw (mm) at a drop of 100 mm for the rainfall intensities below**			
arcsine	m	**0.5 mm/min**	**1.0 mm/min**	**2.0 mm/min**	**4.0 mm/min**

		min	max	ave	min	max	ave	min	max	ave	min	max	ave
0.1	1.05	0	0	0	0	2	*1	15	27	21	43	55	49
	2.45	0	0	0	5	38	22	57	67	62	68	82	75
	3.85	5	40	*22	37	50	43	75	90	82	77	91	84
0.2	1.05	0	0	0	0	2	*1	25	37	31	57	67	62
	2.45	0	15	*7	27	55	41	70	95	82	83	97	90
	3.85	7	45	*26	48	72	60	85	105	95	92	108	100
0.4	1.05	0	5	*2	0	14	*7	37	47	42	70	85	77
	2.45	12	37	*24	15	67	41	70	85	77	100	112	106
	3.85	27	55	41	42	82	62	75	95	85	100	117	113
0.6	1.05	0	10	*5	0	15	*7	45	53	49	60	80	70
	2.45	2	45	*23	20	72	46	75	95	85	82	95	88
	3.85	35	70	52	40	77	$^{+}$**58**	95	107	101	90	102	96
0.8	1.05	2	12	*7	0	17	*8	45	57	51	60	75	67
	2.45	10	35	*22	30	62	46	70	85	77	75	80	77
	3.85	20	75	47	35	67	51	80	92	86	80	87	84

Table 3 Compressed data from indoor experiments: 'Throw' at 100 mm below lip

Combination of measures for roof lengths (0.7 & 1.4), (2.1 & 2.8), (3.5 & 4.2)
For throws at 300 mm, 1000 mm and 2000 mm below lip multiply data by 1.7, 3.0 and 4.5 except data shown *, in which case use factors 1.2, 2.0 and 3.0.
The typical figure shown in bold ($^{+}$**58 mm**) corresponds to a water velocity of 0.70 m/s.

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3.2 Discussion of findings

Examination of this data indicates that *even in the absence of wind*, a gutter 100 mm below a roof edge (say with 4 m long furrows and a typical slope of 0.6) needs to be at least 100 mm wide to catch all the run-off at rainfall intensities from 0 to 2 mm/minute. At 300 mm below the roof edge a 150 mm gutter would be needed. A gutter or trough placed at ground level, say 2 m below the roof edge, correspondingly needs to be about 500 mm wide. The presence of wind would considerably increase these widths necessary for effective (say 98%) interception. Wind particularly effects lighter precipitation. Whilst this lighter rain may not constitute the major part of total annual precipitation in a tropical location, it may include particularly valuable supplies during drier months.

The flow observed from the roof edge showed some instability, especially at low flow rates when surface tension may cause the jet to adhere to the lip of the furrow and leave it with negligible horizontal velocity (and therefore negligible throw). The flowrate at which this surface tension adhesion is first broken depends upon the fine detail of the lip and upon the roof slope. For a shallow roof with standard 80 mm pitch corrugations it is about 0.15 litres per minute per furrow, corresponding to a medium rainfall intensity of say 0.7 mm/minute (40 mm/hour) falling on a 3-meter roof. Thus for much of a typical rainfall event we can treat the water as dropping vertically from the edge of a *shallow* roof unless it is displaced by wind. Figure 6 shows the phenomenon. For steeper roofs the break-away occurs at lower flows.

Another form of flow-instability visible in roof furrows is pulsation. The water travels down a furrow in waves and in consequence the jet leaving its lip is pulsating. The throw for any given drop therefore varies cyclically between a maximum value and a minimum one whose ratio exceeds 2:1 for all but the heaviest flows. Often the minimum throw is zero due to surface-tension adhesion even when the maximum throw is quite large. In all the following discussion, the data we will use is the mean of these pulsation minima and maxima.

The trajectory followed by the falling spout is not the exact parabola we should expect in the absence of air friction. Friction has the effect of reducing the throw at long drops. For example if we compare the throws at drops of 2000 mm and at 100 mm (which in the absence of friction would be in the ratio of $\sqrt{(2000/100)} = 4.5$) we find an actual throw ratio varying from 3.0 at very low discharges to 4.5 for medium and high discharges.

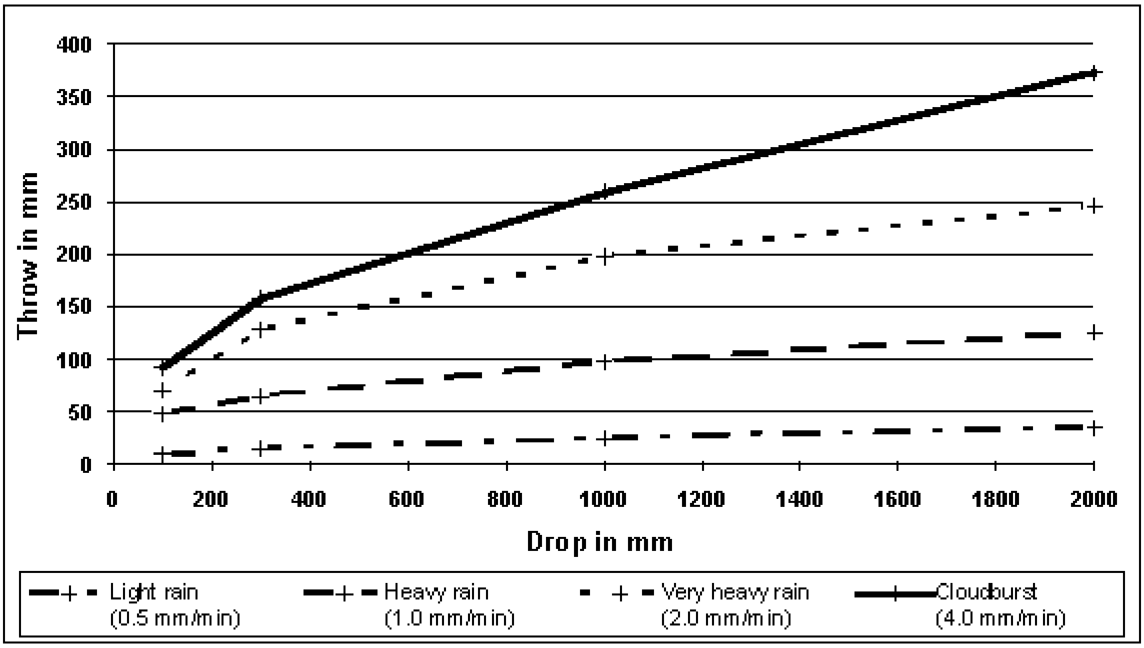

Figure 5 Trajectory of falling water : Throw in mm

(Roof is of length 2.8 m and of shallow slope sin θ = 0.2)

For a given roof slope, the mean throw at a given drop depends mainly on the flowrate discharging from the lip, and not so much upon the particular combination of rainfall intensity and furrow length producing that discharge. Table 4 below shows throw, at a given drop, for a fixed furrow discharge but for various intensity-furrow length combinations. (The individual table entries show much scatter due to lip variations). Interestingly the average throw reaches a maximum at a roof slope of about 60% ($\theta \cong 40^0$, a common roof slope) and declines as slope increases beyond this.

Rain Intensity	Furrow Length	Roof Slope			
mm/min	m	**0.2**	**0.4**	**0.6**	**0.8**
1	2.8	*86*	*120*	*113*	*105*
2	1.4	*68*	*53*	*113*	*73*
4	0.7	*65*	*78*	*115*	*78*
Average of the three throws above		*73*	*84*	*114*	*85*

Table 4 Throw (*mm*) at a drop of 300 mm and constant furrow discharge of 0.22 l/min

As long furrows collect more rain than short ones, we should expect throw to increase with furrow length. Indeed observing buildings whose roofs contain sheets of different lengths reveals a great dependence of throw upon furrow length. In the same storm, 3 meter furrows may only dribble whilst 5 meter ones gush. Graph 2 shows this effect as furrow initially lengthen, but then rather surprisingly the throw tends to a limit as the furrow lengthens further. This phenomena depends on furrow shape: the experimental data was obtained from sinusoidal furrows.

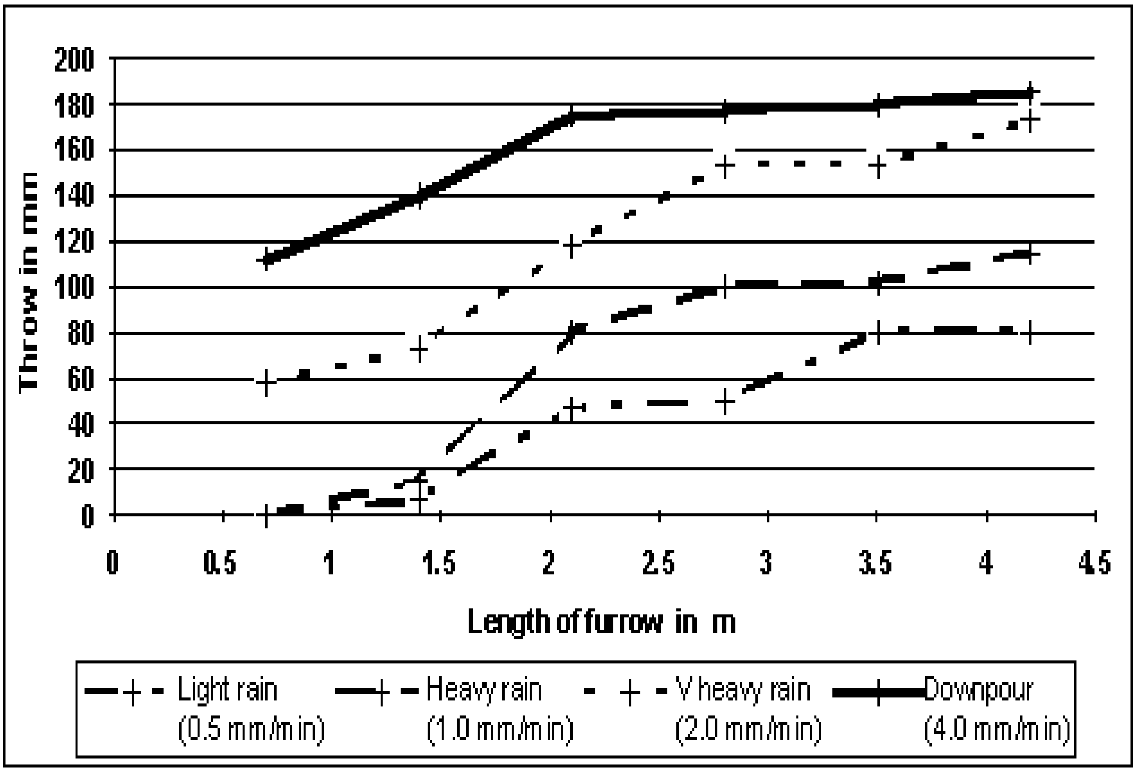

Figure 6 Effect of Roof length on 'Throw' in mm
(Roof slope is 0.6, Drop is 300 mm)

To summarise these laboratory findings:

1 even in the absence of wind, a wide gutter (over 75 mm wide) is needed to intercept intense rainfall if the drop from roof edge to gutter exceeds more than about 10 cm;

2 the jet leaving a furrow pulsates significantly;

3 the trajectory of the jet is nearly parabolic during intense rainfall, but is affected by air friction (throw is less than expected at large drops) during normal or light rainfall;

4 for a given roof slope and rain intensity, the jet velocity (and hence throw) increases with furrow length only up to a certain point then tends to a constant (*the theory*

presented in Appendix B suggests that throw might increase with furrow-length$^{1/4}$ *: this is broadly compatible with the shape of the curves in figure 6)*;

5 at low flows, the surface tension at the lip of the furrow prevents the jet from detaching from the lip except in a vertically downwards direction, thus at low flows there is no throw.

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4 RESULTS OF INITIAL FIELD EXPERIMENTS

The flow off a long shallow unguttered roof in Western Uganda was studied. (Roof-furrow length was 5.7 meters and the furrows sloped at $\sin\theta = 0.09$). The roof was supported by walls with full length unglazed openings immediately under the roof edge. This meant that wind could blow through these walls, a situation not representative of solid walls where wind can only blow parallel them. For this reason, the flow from roof edge to ground was highly affected by wind, sometimes blowing into the building (a chicken house).

Collecting vessels (plastic 3-litre vegetable oil containers, inverted and with an 75 mm x 80 mm aperture cut in their base) were placed in a row out from the wall. The aperture width corresponded to the width of the roofing corrugations, so each vessel intercepted flow from only one furrow. Seven such vessels were placed at various distances from the drip line from the roof edge. Relative to the drip line, the vessel centres were at the distances shown below. Thus vessel *B* was placed to receive any drips from the roof when no wind was blowing, vessel *A* was closer to the building, vessels *C* to *G* were progressively further out from the building.

Vessel		***A***	***B***	***C***	***D***	***E***	***F***	***G***	***ALL***
'Throw' at centre (mm)		***-75***	***0***	***+75***	***+150***	***+225***	***+300***	***+375***	
	Rainfall (mm)	***Percentage of expected run-off collected in vessel (*indicates vessel overflowed at 3 litres)***							
Rain event 1	***47.0***	5.3	8.7*	8.7*	8.7*	8.7*	1.8	3.4	**45***
Rain event 2	***12.5***	16,9	33.3*	33.3*	1.4	0.8	1.1	1.0	**88***
Rain event 3	***38.0***	5.4	10.9*	10.9*	8.1	3.3	1.5	1.2	**41***
Rain event 4	***8.5***	0.8	26.4	48.5*	28.0	3.1	2.3	0.1	**109**
Rain event 5	***16.0***	9.9	19.8	25.8*	5.4	1.7	0.8	0.8	**64**
Rain event 6	***3.5***	11.3	45.2	35.8	0	0.8	0	0	**93**
Rain event 7	***24.5***	5.7	13.5	13.5	2.3	3.0	1.5	1.6	**41**
Rain event 8	***26.0***	5.1	12.1	13.6	13.2	3.0	1.5	1.4	**50**

Rain event 9	***12.5***	1.4	2.5	28.0	2.1	1.6	1.6	1.6	**39**

Table 5 Throw from an actual roof, 300 mm below the roof edge

It is not easy to interpret this data, as it is much affected by overflow of the collecting vessels which should have been much larger. (During Rain event 1, for example, run-off per furrow exceeded 20 litres but under 15 litres was collected). Moreover during Rain event 5, despite some loss due to overflow, the total water collected exceeded that calculated from rainfall records to have fallen on the furrow. By contrast during Rain events 7, 8 and 9 where there was no overflow the total collected was less than half the calculated precipitation. This may be due to differences in storm intensity over the 100 meters that separated the rain guage from the roof or due to inadequate experimental design. It was not possible to measure minute-by-minute rainfall, but only the total precipitation in a 'Rainfall event' lasting up to six hours: it seems unlikely that instantaneous rainfall intensities ever exceeded 2 mm per minute.

We may however observe that a significant fraction (possibly over 30% during heavy rain) of run-off was intercepted by vessels *D* to *G* and hence would have overshot a 75 mm gutter centred 300 mm under the roof edge. Moving such a gutter outwards (so that its inner edge was directly under the roof edge) would have resulted in its catching some of this overshoot but missing all the flow into vessel *A* which was 10% or more of expected run-off.

Clearly much more careful experimentation - with a more typical roof and wall combination, and including measurement of rainfall *intensities* - is needed before strong conclusions can be drawn about what gutter width is adequate at various drops. The indications are however that guttering systems allowing water to fall more than about 100 mm from the roof edge are likely to be expensive (wide gutters) or ineffective in intercepting intense rainfall. Some crude field experiments at the same site, which compared the water quantities collected by several 75 mm wide gutters set at different distances below the roof edge, supported these indications.

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5 CONCLUSIONS

For economy, gutters should not be laid horizontal, but at an angle that ideally increases towards the discharge end. Unfortunately the combination of a sloping gutter and a horizontal roof edge results in the drop from the latter to the former that increases towards the discharge end. Experiment and theory suggest that this drop should be kept less than 100 mm if intense rainfall from a *corrugated* domestic roof is all to be intercepted by a 75 mm (3") gutter. A hemispherical gutter of such a size, laid at 4% slope at its discharge end, should be able to carry all the precipitation on a domestic size roof (up to 40 m^2) even during intense storms of up to 4 mm rainfall per minute . The requirements of 4% *final* slope and not more than 100 mm drop restrict the gutter length to 7.5 m. However if the primary purpose of the gutter is to collect water (rather than protect the lower wall from rain) a lower design standard should suffice. Rainfall intensities up to only 1 mm per minute need be wholly intercepted, since only a tiny fraction of annual precipitation occurs at intensities higher than this. Strong winds will however result in some loss of interception even where the roofedge-to-gutter drop is kept small.

Gutters for domestic buildings therefore do not need to be large, but the problem of attaching and aligning them to achieve adequate slope yet only a small drop has to be solved. Moreover proper alignment of the gutter so that its inner edge lies just inside the drip line from the roof edge is necessary if small gutters are to be used. Some ways of doing this were discussed in Section 2.4.

Where flat, ribbed or tiled roofing material is used, there should be little occurrence of run-off overshooting a gutter unless the drop is large or the wind very strong.
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Appendix A Measured Runoff Trajectories from corrugated roofing

(Data from laboratory experiments described in Section 3)
(available upon request from DTU)

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Appendix B Theory of flow down corrugations

The furrow of a corrugated iron roof has an approximately parabolic shape described by the equation

$y = a\, x^2$ [1]

where *y* is the rise above the furrow bottom at a distance *x* fom its centre. The constant 'a' is normally approximately equal to 1/W where W is the pitch of the corrugations (typically 0.08 m). The cross-sectional area of a flow that is of depth *y* is

$A = {}^4/_3\, a\, x^3$ and the hydraulic radius is approximately $R = {}^2/_3\, y = {}^2/_3\, a\, x^2$

giving (at equilibrium):

flowrate $Q = A\, R^{2/3}\, S^{1/2} / n \propto x^{13/3}$ and velocity $v = Q/A \propto x\, 4/3 \propto Q^{\,4/13}$ [2]

Thus a doubling of the flowrate (due to a doubling in rainfall intensity or of roof length) will increase the run-off velocity by only 24%. Most of any increase in flowrate is accommodated by an increase in the depth (*y*) and hence area (*A*) of the flow; rather than the increase in velocity.

Taking a representative flow of $5 \times 10^{-6}\ m^3/s$ (1 mm/minute falling on a furrow 4.2 m long x 8 cm pitch), a slope of $S = 0.5$ and a value of .01 for Mannings 'n', we get an equilibrium velocity of $v = 0.50$ m/s and a flow depth of $y = 0.9$ mm.

(This velocity of 0.5 m/s corresponds to a free fall of only 12 mm, i.e. 0.025 m of furrow length, so we may assume that flow velocity is always close to its equilibrium value.)

In order to make comparisons with measurements, we need to be able to convert velocity *v* to ‘throw’ at some specified drop. The following table does so for a drop of 100 mm. (The relationship between run-off velocity and throw is a complex one; however for velocities less than say 0.5 m/s we can use the approximation ‘throw is proportional to velocity’.)

	v = 0 m/s	v = 0.5 m/s	v = 1.0 m/s	$v \to \infty$
Throw for S = 0.2	0 mm	65 mm	120 mm	490 mm
Throw for S = 0.5	0 mm	51 mm	86 mm	173 mm

Thus for v = 0.50 m and S = 0.5 we should expect a throw of 51 mm. The corresponding measured value for a roof only 4.2 m long (mean of readings for S = 0.4 and S = 0.6) is 65 mm, which is 27% higher than expected. The disagreement could be due to the furrow curvature being greater than assumed.

The same rainfall on a plane roof of similar slope and roughness gives

v = 0.32 m/s and a flow depth of y = 0.31 mm.

Any change from a plane roof to a corrugated one therefore substantially increases the run-off velocity (by 56% in this example). Indeed only corrugated roofs usually give rise to significant gutter overshoot problems.

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