THE ROOFWATER HARVESTING LADDER

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Abstract

The two most important barriers to further roofwater harvesting at the household level are high cost and inadequate service. Systems are too expensive for householders to afford them or, if the capacity is reduced to an affordable level, it is seen as too small to provide adequate service. As the cost of a rainwater harvesting system is a function of its capacity, these two problems are heavily interrelated.

For some years there has been in existence a “sanitation ladder”, a catalogue of designs of varying quality from which a project manager, a community or individual can select an appropriate well designed sanitation system to suit local conditions and the available funds. Such “ranges” are the norm in consumer products and usually form the basis for consumer choice.

Rainwater harvesting systems are very amenable to this product-range approach, as no account of local geology and topography need be taken: the water simply falls from the sky. They are however, slightly more complex than sanitation systems as there are, in effect two ladders, one for service provision – mainly a function of system size and one for quality of construction. It is in fact this quality aspect that is predominant in the sanitation ladder whereas roofwater harvesting systems are dominated by the question of size with a certain quality taken as read. Systems of different sizes and qualities can be clearly presented alongside forecasts of the service they will provide and a community can decide on the solution that is best for them.

This paper describes the making of such a ladder for presentation to a community.

1. Introduction

Roofwater harvesting suffers from the stigma of being "expensive". The two most important barriers to investment in roofwater harvesting at the household level are *high cost* and *poor performance*. Cost is simply the price of installing a system. The performance of the system may be expressed in terms of water yield and water security. As the cost of a rainwater harvesting system is a function of its capacity, these two problems are heavily interrelated. Systems can be too expensive for householders to afford or, if the capacity is reduced to an affordable level, it is seen as too small to provide adequate performance.

This paper reports research, mainly undertaken under a current DFID contract but also under an earlier EU contract, concerning low-cost domestic roofwater harvesting in the tropics. The authors acknowledge the support of these patrons with thanks. Further information can be obtained from the DTU website at www.eng.warwick.ac.uk/dtu. More information about some of the technologies referred to are described in the poster presentation "Low cost storage for domestic roofwater harvesting" at this conference and in "Reducing Roofwater harvesting system cost" presented at WEDC 28 (Martinson et al., 2002).

2. The ladder approach

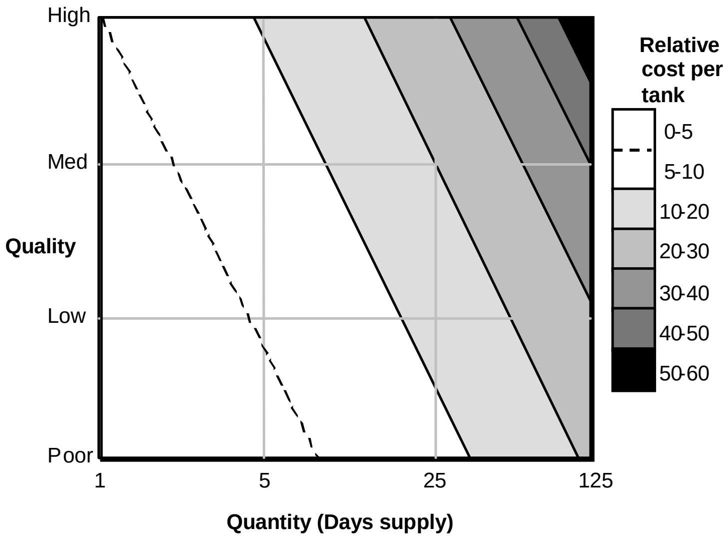
The "sanitation ladder" is a familiar tool for working with communities in participative planning of on-site sanitation projects (Pickford, 1995). It basically consists of a catalogue of designs of varying quality from which a project manager, a community or individual can select an appropriate well designed sanitation system to suit local conditions and the available funds. Such "ranges" are, in fact, the norm in consumer products and usually form the basis of consumer choice.

Rainwater harvesting systems are very amenable to this product range approach, as uncertainties about geology and topography don' t exist; the water simply falls from the sky. RWH systems are however, slightly more complex than sanitation systems as there are, in effect two ladders, one for service provision (a function of system size) and another for quality of construction. While construction quality is predominant in the sanitation ladder selection of roofwater harvesting systems is usually dominated by the question of size (with construction quality taken as read. Systems of different sizes and qualities can, however be clearly presented alongside forecasts of the service they will deliver and a community can decide on the solution that is best for their needs.

Figure 1 schematically shows the relationship between cistern size, construction quality and cost.

[In graph, rename horizontal axis ‘ size’ , vertical axis ‘ Construction quality’ and make 0-5 not read as 0.5]

Figure 1: Schematic graph of cistern cost versus size and construction quality.

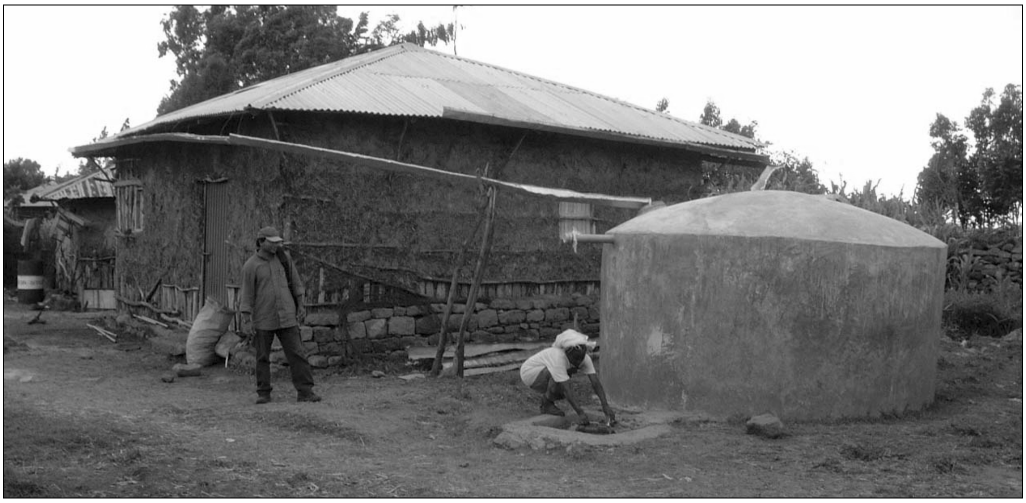


3. The two dimensions

3.1. Construction Quality

Generally, rainwater-harvesting projects in developing countries operate at a medium quality level, using materials and techniques taken from the formal housing sector. Many houses especially those of the poor are built of much cheaper (often free) materials than the cement and brick favoured by such RWH projects. As a result rainwater cisterns are often of an inappropriately higher quality and higher cost than the houses they serve, as can clearly be seen in Figure 2

Figure 2: Typical wattle-and-daub building in Ethiopia with large ferrocement tank



Construction and material quality includes such features as longevity, ease of use, appearance and potential to generate pride of ownership and to satisfy its builder’ s desire to do a “proper job” Construction quality does *not* necessarily equate to water quality. A good example of successfully lowering construction quality is the Tarpaulin tank, designed by ACORD for refugees in southern Uganda shown in Figure 3. The tank uses a plastic tarpaulin in a pit to hold the water while the above-ground structure is wattle and daub.

Figure 3:Tarpaulin Tank in Southern Uganda

Lowering construction quality from a high standard initially mainly affects appearance. The next parameter to suffer is durability – cheap materials like wattle and daub walls do not have the durability of mortar and will need more frequent renewal. Finally the point is reached where water quality itself is degraded, for example by omitting the cistern’ s cover.

In reducing the quality, however, there are a number of critical functional constraints that should not be disregarded. Meeting them defines as a minimum specification:

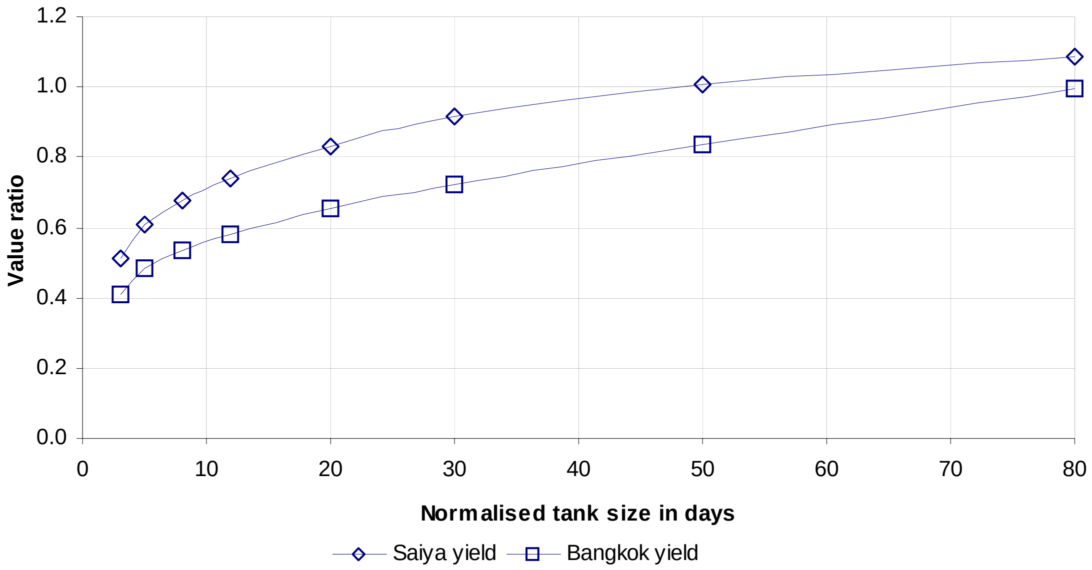
- Gutters should intercept and deliver a good fraction of the water falling on the roof – say $>75\%$
- The tank should not have excessive loss through seepage or evaporation – say $<10\%$ of the water demand
- The tank should not present an excessive danger to its users, either by their falling into it or by the tank failing explosively
- The water must be of a quality consummate with its intended use – water that is used for drinking requires a certain care in interception and storage:
  - The catchment area should be smooth and free from accumulated debris
  - The water should be filtered to remove gross impurities or the first flush removed
  - The tank should be covered to prevent entry of light, and sealed against intrusion by small creatures
  - The tank should be ventilated

3.2. Size

Rainwater harvesting systems show strong *dis*economies of scale, as smaller tanks are cycled more often than larger ones, This means that the storage volume of smaller tanks is used several times in a season whereas for larger tanks the volume may only be used once or twice. It has previously been shown (Thomas & Rees, 1999) that to optimise economic return from a DRWH investment requires use of very small cisterns – so small that they meet only around half a household' s water demands. By contrast to employ DRWH as a 100% reliable sole domestic source requires cisterns 10 to 50 times larger: pursuit of this inappropriate service standard in the past has seriously overpriced DRWH and discouraged its general take-up. Between these extremes, of using typically 400 litre and 10,000 litre cisterns respectively, comes ' medium performance' DRWH. Such systems combined with prudent water management give high convenience and a reliability similar to that currently attainable from many rural point sources. ' Prudent water management' generally consists of adjusting daily demand to reflect both the diminishing unit value of water with increasing daily consumption (i.e. a strongly falling demand curve) and the higher cost of obtaining back-up water during the dry season.

Figure 4 shows how the performance of a RWH system increases with cistern size in two locations, Saiya (Kenya) & Bangkok, representing Equatorial and Monsoon climates respectively.. (The variable plotted is the ratio of the annual ' value' of the water drawn from the cistern to that of the roof runoff. The combined importance of water volume and supply reliability have been crudely reflected here by giving each litre of dry season water twice the value of a wet season litre. The actual cases plotted correspond to a high fixed daily demand: the loci would be higher if that demand were less) The graph shows the diminishing returns from increasing tank size beyond about 20 days consumption – increases in tank costs exceed increases in the value of water delivered..

Figure 4: Diminishing returns with increase in tank size



4. The RWH ladder

In order for the community to make an informed choice among technologies, they will need information about how different sizes systems behave, as well as the costs and trade offs involved in different designs. A finished ladder presents this information in two sections. The top rows are generic descriptions of tanks of various sizes. These figures should not change regardless of tank type. The following rows are dedicated to tank type. They should include:

1. A picture of the tank (ideally, the community should also have access to examples of the actual tanks)

2. Cost if cost recovery is being sought or number that can be built if they are to be subsidised (or given free) from a fixed budget.

3. Any cash contribution

4. Any HH unskilled labour contribution

The table can either be presented "as is" or can be altered during discussions of trade-offs with the community, e.g. if the household cash contribution were raised, would the community be able to afford better or larger tanks, and what impact would this have on the overall water picture.

Figure 5: An example of a roofwater-harvesting ladder

		1,000 litre	**2,000 litre**	**5,000 litre**	**10,000 litre**
Based on 50 litres per day fixed demand	Demand satisfaction	61%	68%	79%	94%
	Max dry period	163 days	151 days	113 days	51 days
Based on variable demand*	Demand satisfaction	60%	66%	74%	86%
	Max dry period	135 days	112 days	37 days	0 days
	Max low-use period	83 days	98 days	159 days	147 days
Design 1: Pumpkin tank					
	Number of tanks	1,000	680	410	280
	Labour contribution (per tank)	6 days	8 days	13 days	19 days
	HH cash contribution	0	0	0	0
Design 2: Dome tank					
	Number of tanks	2,000	1,360	820	560
	Labour contribution (per tank)	6 days	8 days	13 days	19 days
	HH cash contribution	0	0	0	0
Design 3: Mud tank					
	Number of tanks	3,000	2,040	1,230	840
	Labour contribution (per tank)	9 days	14 days	24 days	35 days
	HH cash contribution	0	0	0	0

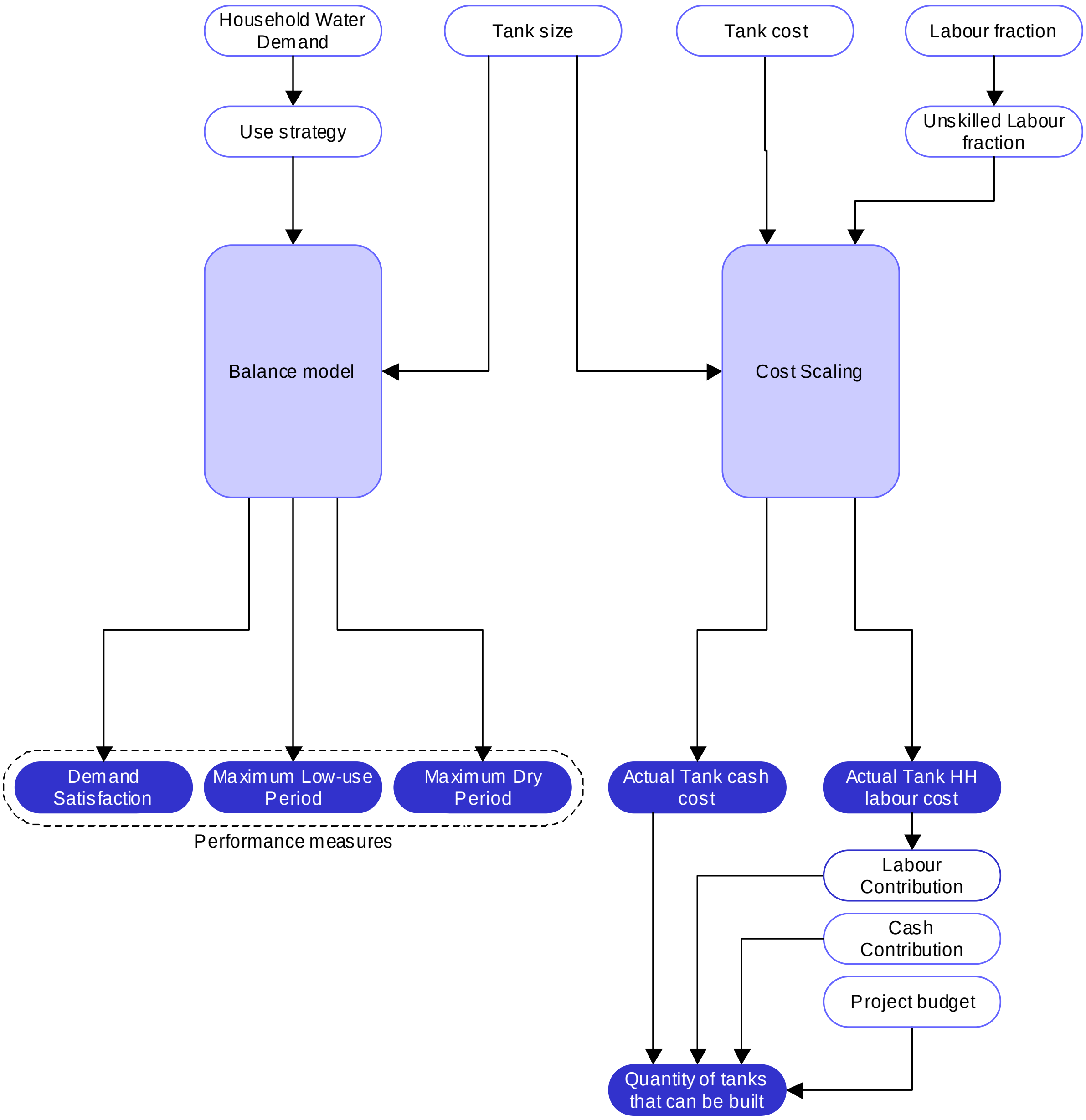
* Variable demand: if tank is more than 2.3 full, 100 litres/day; if it is less than 1/3 full, 20 litres per day; otherwise, 50 litres per day.

4.1. Inputs and outputs

Figure 6 shows the steps to produce the information contained in the ladder. The size/performance measures presented are, *demand satisfaction*, *maximum dry period* and *maximum low use period*. These measures are described in Section 5.5. To produce these performance outputs, information on rainfall, average roof size and a breakdown of average household water demand are needed

The tanks themselves must also be presented, either as a picture, or better with example tanks built and in use. Cost information should also be presented either as a direct cost or a regular payment (if full cost recovery is a goal) or as a number of systems that can be built (if a fixed donor-led grant is being used), or some combination of the above. Section 6 discusses the calculations necessary to produce this information.

Figure 6: Steps to produce a roofwater harvesting ladder



5. Size and service delivery

5.1. Average daily runoff

It is impossible to draw more water than is available to the system, so the maximum possible constant daily demand can be found by simply dividing the annual runoff from the roof and by days in the year:

$$ADR = \frac{A.R.F}{365} \tag{1}$$

Where *ADR is the Average Daily Runoff, R* is the *annual rainfall* in millimetres, *A* is the *guttered roof area* in square meters and *F* is the *runoff fraction* - usually about 0.8 - which takes into account losses between the roof and the storage tank.

However most roofwater harvesting systems experience some tank overflow so a more realistic figure for maximum possible demand that could be met by the system is about 80% of *ADR*. This figure is a good “reality check” to see if the system is capable of delivering the required water before any more detailed calculations are made.

5.2. Water use strategies

Few households with roofwater harvesting systems use a fixed amount of water every day. Instead they tend to change their water use to suit their needs and the availability of tank water. Several strategies that might be followed are:

Total demand – where the total household water demand is to be met by the RWH system

This can be useful in situations where there is little seasonality in rainfall or where all other alternatives are impractical or unusually costly but usually results in either very large and expensive systems or poor penetration into the dry season. In this case *system demand* (D_s) will be equal to the *total household water demand* (D)

$$D_s = D \tag{2}$$

Fractional demand – where the systems is used to provide part of household water demand

RWH is used say just for drinking water, or just for drinking + cooking + washing dishes, the balance must come from alternate sources. The reduced system demand may be expressed in terms of a *demand fraction* (f_D)

$$D_s = f_D D \tag{3}$$

or simply as a reduced volume.

Variable demand – where the demand fraction fluctuates

This variation can be based on tank level or season.

Variable demand based on tank level –where the demand fraction fluctuates depending on the *volume water remaining in the tank* (V_p),

The *volume water remaining in the tank* (V_p), is most easily expressed as a fraction of the *tank volume* (V). When the tank level falls below a certain fraction of the volume, the *low-level fraction* (f_l), daily withdrawals are reduced to a *reduced system demand* (D_{sl}). When the tank volume rises above a certain fraction of the volume, the *high-level fraction* (f_h), withdrawals can be raised to a *heightened system demand* (D_{sh}). At other times the nominal system demand (D_s) is withdrawn thus:

If $V_p > f_h V$ then $D_s = D_{sh}$ (4)

If $V_p < f_l V$ then $D_s = D_{sl}$ (5)

Else $D_s = D_s$

Example

A household normally employs rainwater for a large fraction of their water demand, using it for all household activities except clothes washing and bathing (which is done in a nearby river). Using this strategy, they normally draw about 50 litres/day from their RW system, however they ration their water based on tank volume thus:

- When the tank more than 2/3 full, they use the tank water lavishly, with roofwater used for the *total demand* about 100 litres/day)
- When the tank is less than 1/3 full, they drastically reduce their water use to drinking and cooking only (20 litres/day)

Thus in this case:

$f_h = 2/3$
$f_l = 1/3$
$D_s = 50$
$D_{sh} = 100$
$D_{sl} = 20$

5.3. Variable demand based on season – where the demand fraction fluctuates depending on previous experience or anticipated rainfall patterns

If a household gets this right, they can have a large store of water to ration over the dry season, however there is a strong risk of misjudging the date to start rationing and thus waste tank water. High and reduced demands (D_{sl} & D_{sh}) are used as before. Modelling this behaviour can be problematic, as the *average dry season* must be estimated from the rainfall data. A user should have more success as they can also rely on local knowledge and weather predictions from the meteorological office.

5.4. Modelling rainwater harvesting systems

The simplest and most popular model for roofwater harvesting systems is the ' volume balance method' where each day incoming rainwater is added to an existing tank volume and the nominal demand is removed. There also need to be checks to make sure the withdrawals do not reduce the tank volume below zero and that the rainwater does not raise the water volume above the tank volume. This method is covered well in most water textbooks. The model can be set up to present the daily withdrawals, overflows, and times when the tank fails to deliver any water.

5.5. Measures of tank performance

Some method of measuring tank performance must be presented to the community so that they can see the service that can be expected from a system of a particular size. The two used here are:

Demand Satisfaction (S); the fraction of a typical household' s total water demand (D) that will be met by the system. It can be found by summing the total *withdrawals* (W) over a period and dividing by the total demand over that period.

$$S = \frac{\sum W}{\sum D} \qquad (6)$$

Maximum dry period (P_D); the longest period that the tank can be expected to deliver no water. It is found by counting the highest number of consecutive days the system delivers no water over a period and taking the largest number. A slightly better system is to use 5 consecutive non-dry days as the criterion to stop counting, as this will avoid a single, short rainfall event resetting the counter during a long dry spell.

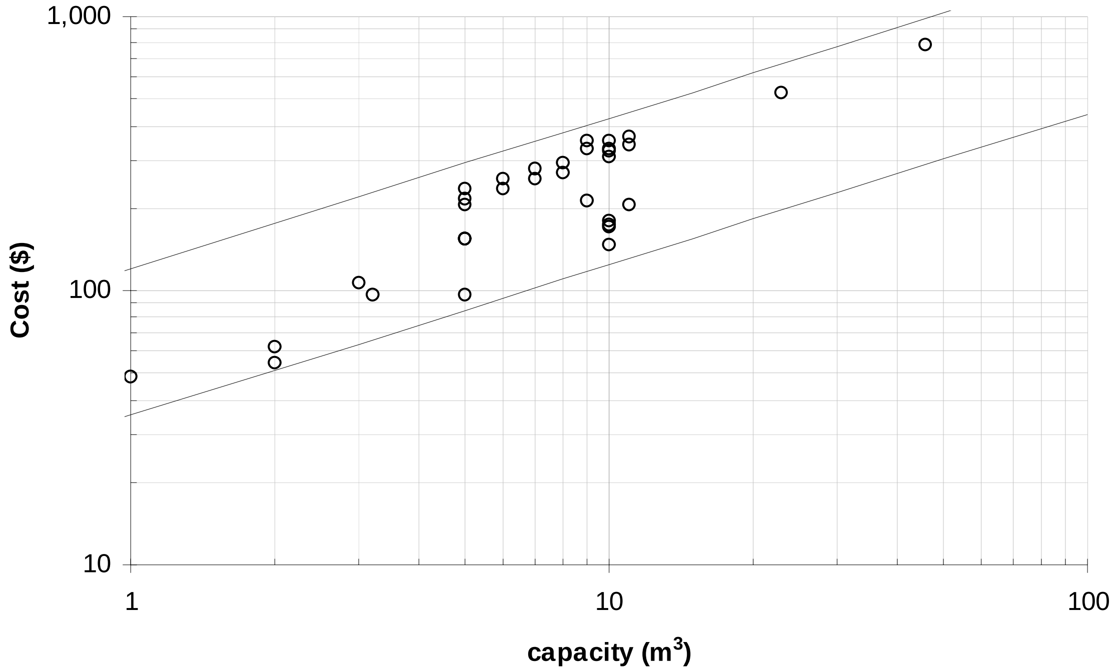
If it is envisaged that the households will use a variable strategy (which is likely), a further measure can be introduced: *Maximum low-use period (P_L)*; the longest period that water demand will need to be reduced. It is found in the same way as the maximum dry period but using delivery = *reduced system demand (D_{sl})* as a criterion rather than delivery = zero. The DTU has a web-based service that delivers these outputs based on monthly rainfall data. The URL is http://www.eng.warwick.ac.uk/dtu/rwh/model/index.html. An Excel version is also downloadable and available from the authors that can use 10 years daily, 10 years monthly or average monthly data (with corresponding levels of uncertainty).

6. Costing a range of designs and sizes

6.1. Comparing tank costs

Water tanks, like many products exhibit economies of scale. Larger structures generally cost less per litre of storage than smaller structures so comparing tank technologies is a more complex task than simply dividing the cost by the capacity and revealing a cost-per-litre-storage. Additionally costs should only be compared within a country or different designs costed from bills of materials, as material and labour costs vary markedly throughout the world. Figure 7 shows a number of tank costs based on Ugandan data.

Figure 7:Tank costs (based on bills of materials and Ugandan cost data in 2002)



The costs follow a mathematically predictable rise, particularly when they are of a similar design. A cost estimate of a tank of any required size can therefore be made from cost data of another sized tank by using the relation:

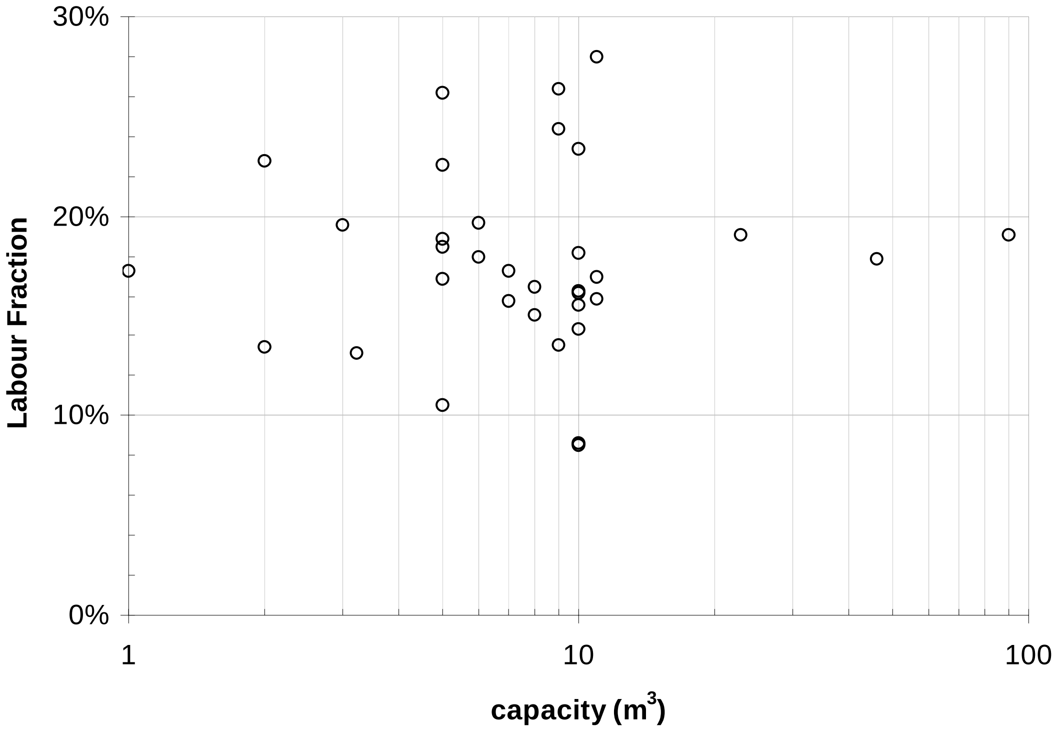
$$\frac{C_1}{V_1^{0.55}} = \frac{C_2}{V_2^{0.55}} = C_u \qquad (7)$$

Where C_1 is the cost of a tank of volume V_1, C_2 is the cost of a tank of volume V_2 and C_u is the cost of a $1m^3$ tank which serves as a convenient "equivalent unit cost" for the design that can be used to compare it to other designs

6.2. Labour content

Generally, labour will be local, so money spent on this will generate employment in an area Thus designs with a high labour content will be good for the local community as a whole. Figure 8 shows the labour content, expressed as a fraction of the total cost, for a number of designs. This "labour fraction" varies from design to design, but does vary much with tank capacity.

Figure 8: Labour content of construction costs (based on bills of materials and Ugandan cost data)



The labour fraction varies strongly from country to country as the relative costs of labour and materials change.

As the fraction of labour does not change with tank capacity, a good estimate of the total labour can be gained using a similar relation to equation 7:

$$\frac{L_1}{V_1^{0.55}} = \frac{L_2}{V_2^{0.55}} = L_u \qquad (8)$$

Where: L_1 is the labour (in days) to build a tank of volume V_1 and L_2 is the labour to build a tank of volume V_2

L_u - namely the labour content of a 1 m^3 tank of that design -can also be used to compare different tank designs; we can call L_u the design's 'equivalent labour content'.

6.3. Unskilled labour

Often, a household's contribution to the cost of a new RWH system is in the form of unskilled labour. If householders are willing, choosing a design with a higher labour content allows them to afford a larger system than otherwise without an increase in cash outlay. This, of course will only continue until the householders consider the need for labour and the organisation thereof to be a burden – an issue that should be discussed with the community at the technology selection stage. As the fraction of total labour that is unskilled labour is fairly constant within a design, the unskilled labour content can readily be calculated and presented to the community as a commitment of time. The cost of this labour can also be calculated and used by a provider in budgeting

6.4. Other costs

There are a number of other costs that should be included in calculations that will be site specific:

- 'Local' materials; any materials that can be provided at no cost by the community – the time necessary for collecting and processing these should be added to the unskilled labour time and can be scaled.
- Implementation effort; One of the main reason agencies use expensive plastic tanks is their ease of implementation – just deliver and connect. Other designs, particularly those with a high householder labour content, will require close scrutiny throughout the building process. The managerial cost will depend on the organisation but it may

be significant and should be explicitly included in the tank costs. Some of these costs will scale with tank size others will not.

7. Conclusions

Any community, agency or individual household contemplating installing roofwater harvesting needs to select between different tank types and sizes. To assist this process it is very helpful to present the relevant performance and cost information as a ' ladder' reaching from the smallest and cheapest system to the largest and most elaborate (elaborate = highest construction quality / best materials). The performance of the different tank-size options can usefully be presented as measures of (i) demand satisfaction, (ii) longest period (in a year) when the tank is dry and (iii) longest period in a year during which demand has to be reduced to a low level in order to best conserve the stored water. The last measure is only relevant where a household operates a variable daily demand strategy. The costs of different designs can be presented in various ways, most commonly as (i) total costs and (ii) the unskilled labour requirement for each size option.

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