Domestic Roofwater Harvesting
Research Programme

RECOMMENDATIONS FOR DESIGNING RAINWATER HARVESTING SYSTEM TANKS

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Development Technology Unit
School of Engineering, University of Warwick

CONTENTS

1. INTRODUCTION

The water store (the 'tank') accounts for a large fraction of the cost of any roofwater harvesting system. Most poor households cannot afford to buy as large a tank as their roof catchment area might justify. There is therefore a strong incentive to seek cheaper yet adequate forms of tank.

The cost of a tank depends upon its size, the type and quantity of materials used in its construction, the labour needed to build it and in some areas the 'hire' of special equipment. The tank itself might be regarded as having two main parts; a water store and a set of ancillaries to lead water into and out of it (taps, an overflow, a filter, a level indicator etc.). In this paper, we restrict ourselves to considering just the water store.

Rainwater collection is in no way a new technology and is described in many publications (Gould & Nissen-Petersen, 1999; Lee & Visscher, 1992; Pacey & Cullis, 1996)In the last decade, there have been many attempts to identify better tank designs. Therefore this report starts with an analysis of needs and constraints and follows with an analysis of good existing designs. Lastly comes a description of our own work towards making tanks cheaper.

2 TANK REQUIREMENTS & CONSTRAINTS

2.1 Needs and specification

Tanks need to be watertight although some leakage (such as <5% of daily abstraction) might be tolerable if it does not weaken the structure or cause puddles. They also need to hold the required volume and to be adequately durable (say 25 years before they become unserviceable). Beyond these basic requirements we can list many further specific requirements. Tanks should:

- have a means of being charged with water without unduly disturbing tank-bottom sediments and if possible maintaining stratified flow (the bacterial quality of outlet water is maximised if the flow through the tank resembles 'pipe flow', namely 'last in is last out'
- be able to handle excess input by overflowing in a convenient and safe manner - preferably without leading water unnecessarily via the tank (such water may drop unwanted sediment in the tank)
- have a means by which the water can be extracted which is convenient for the user and which does not pollute the water left behind (as dipped buckets may)
- exclude vermin and as far as possible mosquitoes
- exclude light (so that algae do not grow and larval growth is inhibited)
- have some form of ventilation, especially if there is not an efficient filter to prevent organic material from entering the tank and decaying there
- be easy to access for cleaning (where cleaning is needed) and be unlikely to be damaged during cleaning
- have a sufficient structural safety factor to withstand wear and tear, some impacts and occasional large natural forces caused by winds and (in places) earthquakes

- not present hazards to passers-by or small children and (in some societies) offer some protection against deliberate poisoning
- not give the water a bad taste

2.2 Local constraints

There are often also local constraints upon the construction process, such as:

- absence or excessive expense of particular materials (e.g. cement, sharp clean sand)
- constraints upon the plan-area space, height or depth of a tank
- tank location; some designs are easier to locate than others

3 ROUTES TO CHEAPER TANKS

3.1 Changing To cheaper materials

Surface tanks for roofwater storage are commonly made of brick, ferrocement, concrete blocks, plastics and galvanised iron. Some of these materials are themselves variable in make-up (the cement or steel fraction within ferrocement can be varied) and all can be varied in thickness, as is discussed in the next section. Requiring a material to be both strong and waterproof considerably constrains its choice, Once however one accepts that waterproofing and structural strength can be separated and accommodated by different materials – a number of new materials options appear.

Bricks

Burned bricks are often made locally and are available much more cheaply than materials which have to be imported into an area such as plastics or cement. Tanks made from bricks can therefore be cheaper than those of "imported" materials and will also keep more of the money spent on the tank within the community. The challenge when building such tanks is to absorb the tensile stresses typical of water tank with a structure best suited to compressive forces. The Rainwater Harvesting Research Group has experimented with a number of alternatives such as external reinforcing and shaped bricks. This work is detailed in Section 7.

Stabilised soil

Another "earth technology" is to use a small amount of cement to hold together (stabilise) an otherwise soil based block. This technique can dramatically reduce the quantity of cement needed to make a tank of equivalent strength. The wet strength of stabilised soil is considerably lower than cement so the designer must either balance the cement content to ensure the wet strength is sufficient or employ some waterproof barrier to prevent water soaking into the blocks.

Rammed earth

Ramming earth between to walls ("shutters") compacting it, gives the wall a stiffness that simple soil building does not have. The technique uses only local materials and can be achieved without particularly specialised labour, it does however require some specialised tooling such as the shutters and a tamper to ram the earth into place but these can be made locally and used to make several tanks spreading their cost. The tank wall, however, is not waterproof with this technique so a means of waterproofing the inside surface must be employed.

Wattle and daub

A traditional technique for house building in many marts of the world, wattle and daub used mud to fill in a structure made from collected roundwood. The technique is well known and practised at a village level and requires no specialised tooling or knowledge to implement. All materials are available locally and usually need only be collected, thus the only capital requirement is labour making it extremely suitable for “self help” projects.

Like all “raw” earth technologies, the technique, results in a structure that is not waterproof and so a method of holding the water must be employed. One excellent example of this is the Rwandan “tarpaulin tank” which utilises an UNHCR tarpaulin in an excavation to hold the water with a wattle and daub enclosure. This tank is further described in Section 6.

Plastics sheeting

Plastic sheeting is becoming available in many parts of the world and can be used for lining otherwise permeable tanks to render them waterproof. At a basic level this could be simple polythene sheet but this tends to have a short lifespan. There are also several fibre reinforced plastic sheets such as those used for tarpaulins becoming available in centres and also in areas of specialised demand. At present it is unlikely that these materials will shortly become widely available due to a lack of demand but appropriate promotion/dissemination could change this situation.

Waterproof coatings

Waterproof paints are quite common in the developed world where they are used to seal ponds, swimming pools etc. these paints are available in some LDC centres and local variants may be developed. Quality control will become a major issue for these to be used as any uncoated sections could result in dangerous catastrophic failure of the tank.

3.2 Minimising the volume of materials used

A second method of cost reduction is by reducing material quantities. In general we can save materials by four approaches, namely:

- removing material where it is not needed
- reducing overall material use by reducing safety factors if they are unnecessarily high
- making use of some existing structure (e.g. the wall of a house or the ground itself)
- adopting a more efficient shape whereby overall tank wall thickness can be reduced

Removing material

The first of these approaches is sometimes prevented by practicalities. Wall thickness is often dictated not by strength but by buildability. For example the upper part of the walls of a cylindrical tank are subject to lower pressure than the bottom and so theoretically could be thinner. Unfortunately it is impractical to taper bricks or even ferrocement as one builds up the wall. the. It is, however possible to go some way toward this ideal.

- If coiled wire reinforcing is used, the spacing can be varied from close-spaced at the bottom of a wall to wide-spaced near the top.
- Materials can be concentrated so that extra strength is provided only where actually needed; for example cement content of ferrocement or stabilised soil blocks can be varied with height above the base (using least at the top).
- Material thickness can sometimes be reduced step-wise by, for example using a double run of bricks at the bottom and reducing to a single run further up the tank.

Material savings should be balanced against the extra complexity of manufacture. All of these techniques have quality control implications and should be used only when workers are familiar with the techniques or are well supervised.

Reducing safety factors

The stresses in water tanks can be calculated and then the expected stress compared to measurable properties such as maximum tensile strength, compressive strength, change of shape under load, etc. So long as the expected stress is lower than the chosen maximum material stress (usually the tensile yield stress in the case of tanks), then the structure will not fail. In practical problems, the expected stress is multiplied by a safety factor (F_S) for a number of reasons.

- The local load may be larger than we realised (indeed our method of calculation may itself contain serious inaccuracies)
- The material may be weaker than it should have been or some of the original strength may have been lost through wear and tear
- The material will almost certainly not be homogeneous, that is it will be stronger in some places than others (this is especially true of building materials)

A safety factor of 5 is typical for a water tank made of building materials. If the safety factor is very large (say $F_S = 15$) then material is being wasted and savings can be made.

Few practitioners of DRWH in developing countries include a well-considered safety factor in tank design calculations. The safety factor is usually applied to tanks in one of two ways:

- by arbitrary application during design, usually leading to excessive wall thickness as the engineer errs on the side of caution
- by trial and error leading to many trials and many errors

Arbitrary application can be expensive in terms of materials, while trial and error is expensive in terms of broken tanks (and even downright dangerous if field trials use consumer tanks).

Defining a sensible safety factor can be difficult given the extreme variations in quality of materials and workmanship in developing countries. The normal engineering approach to safety factor application is to use standard engineering materials (of more or less known strength) and to look up the appropriate safety factor in an engineering data book or approved ‘code of practice’. The nature of tank construction in LDC’s is however such that ‘standard’ (well-quantified) civil engineering materials are rarely available. Sand and aggregates as found in the local village and cement itself is often of dubious quality. Reinforcement may be of poor quality and the strength of bricks fired in a clamp kiln will vary from one to another. Safety factors will therefore vary depending on the type and variability of the material used and the level of skill available to build the tank.. Some suggested Factors of Safety are in Table 1

Table 1: Factors of Safety

Material	Skill level	Factor of safety
Ferrocement	High	2-3
	Medium	4-5
	Low	7-8
Burned Brick	High	3-5
	Medium	6-8
	Low	9-12
Galvanised Iron	High	1.2-1.4
	Medium	1.5-1.8
	Low	1.9-2.3

Architectural integration

The third approach, of saving costs by integrating a rainwater tank with a house structure, has been discussed from time to time but rarely found to yield decisive economies. For space or aesthetic reasons, tanks have often been located within a house's structure (especially where the house is multi-storey) but it is hard to show that any significant material saving has been so obtained. A shallow tank with a large area may substitute for part of a roof, however the requirement that the tank's top be *lower* than the bulk of the roof from which it is supplied restricts this substitution to say veranda roofing or between stories of a multi-story dwelling. The volume of the tank is also limited by the structural integrity of the roof supports as 1m^2 of water weighs in at one tonne!

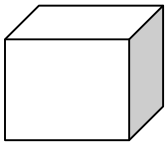
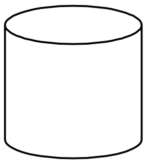
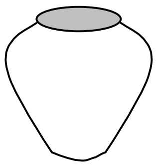
Conversely a very tall tank might substitute for walling. This has been proposed by ??? for Australian houses (ref?) but the architectural detail of moving from normal to tank walling and back again is complex and the long, flat wall will be subject to large bending stresses. Moreover a deep, thin tank has a poor ratio of volume to wall area and may also be difficult to clean. A tank could be made as a core round which a house could be built, in the same way as some traditional village houses in India were built around grain stores. All in-house tanks, however have the problem of ensuring that tank overflow will never inundate the house – as often happens with roofs having 'internal' gullies. Any leakage from these tanks will also enter the house.

Finally tanks can be built into the basements of houses saving space and integrating the tank and house foundations. Laurie Baker has used this technique extensively in his design of The Centre for Development Studies in Karalla India albeit for non-drinking water purposes. If this strategy is to be used, account must be taken of the fact that even ground floor floors will have to be suspended and water will need to be pumped from the storage.

Optimal tank shape

Since the shape of a tank affects both the volume-to-surface ratio and the distribution of forces, it is worth examining the effect of tank shape upon material requirement. As always these material savings must be balanced against the additional complexity in manufacture, straight sides are much easier to form than curves and can be produced with a larger selection of materials. Table 2 shows a summary of tank shape from the viewpoint of induced stress, material use and construction. Three common tank shapes are considered: the cuboid, the cylinder and the doubly curved 'Thai' water jar shape.

Table 2: Relative merits of some common tank shapes

Tank shape or type		Stresses	Material usage	Construction
Cuboid		Stresses are unevenly distributed around the structure. Bending stresses are especially high near the edges.	The ratio between material usage and storage capacity is higher than for a cylindrical or doubly curved tank.	Construction is quite simple using most materials
Cylindrical		Stresses are more evenly distributed with bending stresses only near the bottom	There is an improvement in the material use to storage capacity ratio (a saving of 7.5% over a similarly proportioned cuboid)	Construction becomes more difficult with some materials e.g. bricks, but the shape is well suited to construction with materials that can be bent e.g. ferrocement and GI sheeting or built in sections
Doubly curved tanks (e.g. Thai Jar)		Stresses are well distributed. The base of the tank is of smaller diameter, reducing both hoop stresses and bending stresses there.	Material usage to capacity ratio is very good (savings of up to 20% over a cuboid)	Construction can be difficult, often relying on specialised moulds. Materials must be pliable and able to curve in two directions e.g. ferrocement and clay

The table shows that the cuboid shape fares relatively badly in terms of material use versus storage capacity and it is also associated with high peak stresses. The cylindrical shape deals quite well with stresses in comparison, and it has a lower (better) ratio of walling material to storage volume. It is still easy to manufacture, a technique well suited to circular or irregular forms. The 'Thai' style tank has the ideal shape to cope with the main induced stresses but requires greater skill and tooling to make.

Underground tanks

Significant material savings can be made if the tank is built underground. If the soil is suitable it can take the weight of the water and the walls can be made considerably thinner as they will simply be used as a waterproof layer stopping the water seeping into the soil. The geometry can also be very efficient (hemispherical) as the ground will act as a former for construction and the tank needn't stand up on its base like an above ground tank. This material advantage should be balanced against the additional cost of digging a hole (which can be significant if the ground is particularly hard) and the possibility of the tank becoming contaminated by leaks or a rising water table floating the tank out of the ground.

3.3 Minimising labour and equipment costs

Generally labour costs rise as equipment costs are reduced and *vice versa*, so one should seek to get the best balance. What that balance is clearly depends upon location. In rural Africa digging deep pits by hand is cheapest, in urban Asia it would often be possible and cheaper to hire a back-hoe for the job. Similarly the transport of 'centrally' produced tanks or jars by motor vehicle might incur only modest costs in an urban area but quite excessive ones in a hilly rural area with few roads.

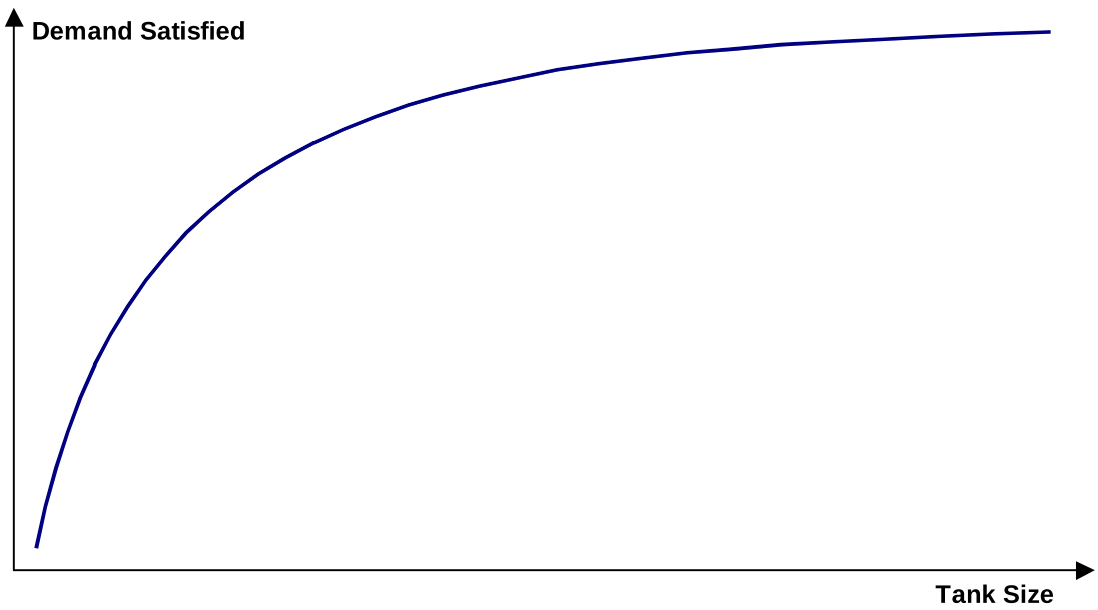
Employing moulds to build tanks improves their accuracy (and thereby may save materials) and also saves labour by reducing 'setting out' times. Moulds themselves become cheaper (per tank) if they are durable and can be used many times. Recycling moulds however requires suitable organisation – such as their attachment to a multi-system programme or availability for hire – and easy transportability.

In many cases, organisations assisting the construction of RWH systems have as their major objective the creation of income-earning opportunities in a specific locality. In consequence they seek to minimise the capital requirement associated with use of complex or motorised equipment, and to maximise the labour fraction of total costs. This approach may or may not minimise overall RWH tank costs.

3.4 Appropriate sizing

One of the simplest ways to make a tank cheaper is simply to make it smaller. Figure 1 shows the water demand satisfied by a tank compared to its size. As can be seen economics of tanks are such that the benefit of a tank is not strictly proportional to its size. The reason for this is that a smaller tank will be filled and emptied (cycled) often whereas a larger tank will only be cycled rarely. A fuller discussion of this is found in section 5

Figure 1: Benefits of tank sizing



Thus, while a large tank may be beyond the affordability of a household, a smaller tank will usually provide significant time-savings, particularly during the rainy season when footing can be wet and slippery. Another tank may also be added later and the total system capacity grown this way. This modular approach has can be seen in many parts of Southeast Asia.

3.5 Mass production

Tanks (particularly smaller tanks) benefit from the economies of scale that come with mass-production. In Thailand, a country that has undergone a massive rainwater harvesting promotion programme, 400 litre jars are produced for less than $US5. Another possibility is the mass production of some parts portion of a tank such a the lining and this way reducing the overall complexity of tank construction and allowing local materials and skills to fill in the balance.

4 STRUCTURAL STRENGTH & STRUCTURAL FAILURE OF TANKS

In a famous case over 150 years ago, the engineer Stephenson (who had no means of analysing structures) designed an early railway bridge by a careful series of experiments on a scale model. He built the model rather weak then loaded it until it collapsed. He then strengthened the part that broke first and repeated the procedure several times. By the end of the process the bridge had increased in weight by 50% but was 6 times stronger. We might use this technique to develop more materials-efficient tanks. Unfortunately the process would be long, expensive and perhaps unreliable (since testing long-term durability is harder for tanks than for steel bridges). Moreover today we have a much better (although incomplete) understanding of theory behind the structure of a tank.

4.1 Failure modes

There are number of possible modes of structural failure for a water jar or cistern, of which the most common are:

- Cracking and leaking (which may be temporarily repairable but often later progresses to failure)
- Leaning over, due to inadequate foundations
- Bursting (which can be dangerous, with fragments flying some distance)

It is a normal pattern that when a product like a RWH tank is first introduced to a new location a very 'conservative' design is used. It is in consequence expensive and may need subsidy. It should be the aim of any such programme to use the period of subsidy to simplify or cheapen the product by some degree of trial and error. Unfortunately failures resulting from a practical search for the design limits are embarrassing and can lead to mistrust of the product. For this reason it is prudent to perform such experiments in private ('behind a hedge') at least until the probability of failure appears low. Moreover the design should be chosen to exhibit functional failure such as leaking before any dangerous failure such as bursting.

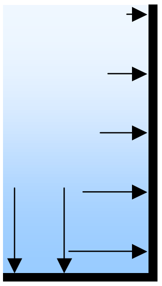
4.2 Stresses due to the stored water

Pressure forces

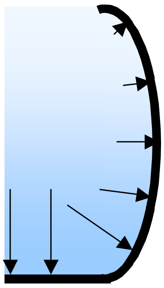
Water exerts a pressure proportional to its depth equivalent to 10 kPa. Per meter. The pressure always applies a force perpendicular to the inside surface of the tank, so at the bottom it acts downwards, over most of the walls it acts outwards and near the top of a doubly curved tank it can even act upwards (see Figure 2)

Figure 2: Action of pressure in a water tank

a. Straight sided



b. Doubly curved



Generally this pressure puts the tank walls into tension (stretch). This is unfortunate because many materials traditionally used for building and transferred to tank construction are only 10% or 20% as strong in tension as they are in compression.

Stresses in cylindrical tanks

In the case of a simple cylinder, the tensile stress acts around the cylinder and is called “hoop stress”. This stress can be found using the equation:

$$\sigma_h = \frac{p\,r}{t} \tag{1}$$

Where:

σ_h is the hoop stress

p is the water pressure

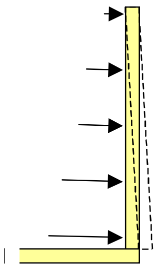
r is the tank radius

t is the wall thickness

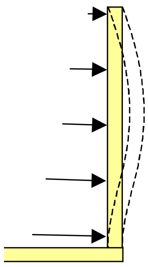
This simple result however is only true when the walls of the tank are free to move as shown in Figure 3a. The movement is only very small and can be achieved by using a flexible material between floor and wall such as bitumen or by allowing the wall to slide along the floor. Where the walls are fixed, such as at the base of a tank, they will tend to bow out as shown in Figure 3b

Figure 3: Movement of tank walls due to pressure

a. Unconstrained



a. Constrained



This will change the hoop stress and also cause two other stresses acting in different directions as are shown in Figure 4.

Figure 4: Stresses caused by constrained walls

a. Shear Stress b. Bending stress

The wall will be stressed in shear at its edge where the water pressure forces it outwards but the base opposes this: the shear stress acts through the wall in a horizontal plane (Figure 4a). Another stress is due to bending of the tank walls as they bow outwards. This is especially high near the joint and will cause vertical compression of its outside face and tension on the inside face of a tank (Figure 4b) both acting vertically up the wall which can cause cracking of the inside face leading to failure.

Quantifying this situation is rather more complex and uses the technique of shell theory where the tank walls are idealised as being very thin (like egg shells). The theory also breaks the problem down into two parts. The first part considers the wall to be very flexible and therefore incapable of being stressed in bending or shear. The second part looks at the bending only and is confined to the boundaries between the wall and the floor where these forces are most prevalent. Furthermore the tank is considered to be made of a material whose properties are constant throughout and which will deform in direct proportion to the forces acting on it (Hooke’s law). The relevant equations (Flugge, 1967) are:

$$N_\theta = \gamma r\left(h - x - he^{\frac{-\lambda x}{r}}\cos\frac{\lambda x}{r} + \left(\frac{r}{\lambda} - h\right)e^{\frac{-\lambda x}{r}}\sin\frac{\lambda x}{r}\right) \qquad (2)$$

$$M_x = -\frac{\gamma r t}{\sqrt{12\left(1-v^2\right)}}\left(\left(\frac{r}{\lambda} - h\right)e^{\frac{-\lambda x}{r}}\cos\frac{\lambda x}{r} + he^{\frac{-\lambda x}{r}}\sin\frac{\lambda x}{r}\right) \qquad (3)$$

$$Q_x = \frac{\gamma t\lambda}{\sqrt{12\left(1-v^2\right)}}\left(\left(\frac{r}{\lambda} - 2h\right)e^{\frac{-\lambda x}{r}}\cos\frac{\lambda x}{r} + \frac{r}{\lambda}e^{\frac{-\lambda x}{r}}\sin\frac{\lambda x}{r}\right) \qquad (4)$$

where:

N_θ is the radial hoop force

M_x is the bending moment

Q_x is the shear force

γ is the specific weight of water (density times gravity)

r is the radius

h is the height water height

x is the height of the stress to be calculated

v is poisons ratio (the ratio of a materials change in shape in the direction of a stress to the change in shape perpendicular to the stress – as a rubber band is stretched it gets thinner)

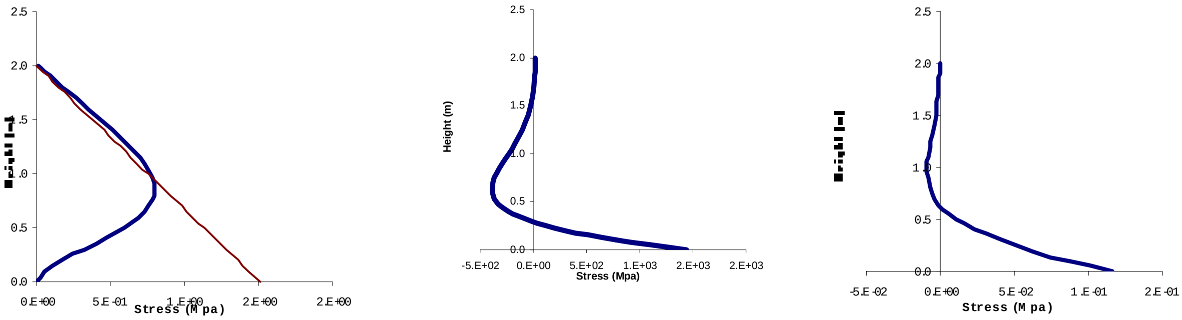
λ is given by

$$\sqrt[4]{3\left(1-v^2\right)\left(\frac{r}{t}\right)^2} \tag{5}$$

These fairly daunting equations can be easily coded into a spreadsheet and used to provide useful curves for designing tanks. Typical output is shown in Figure 5

Figure 5: Stress curves for cylindrical tank with fixed base

a. Hoop stress b. Bending stress c. Shear stress



Design considerations

Design to resist tensile stresses, whether vertical due to bending, radial hoop stresses and shear stresses acting through the wall, obviously includes the use of adequate wall thickness and adequate material tensile strength. It is sometimes assumed that brick and concrete cannot carry *any* tensile stresses without failing, but this is not so. Although it may be prudent to include steel reinforcing in a tank wall to prevent dangerous bursting, it is uneconomic to include so much that the mortar or brick carries negligible tension. If one relied solely on the stiffness of the reinforcing, its movement under water-pressure would almost certainly result in cracking of the mortar or brick matrix, causing perhaps leakage and almost certainly rusting of the reinforcing. Reinforcement that passes from a base into the bottom of a tank’s walls will help resist both shear and bending stresses. Extra wall thickness, or filleting at the joint between wall and base is also a useful strategy.

4.3 Stresses due to materials shrinkage

As well as the cyclic stresses due to the water rising and falling inside the tank, there are other stresses due to the material *shrinking* during construction. Cement mortar, concrete and stabilised soil all shrink slightly (about 1 part in 1000) as they cure or dry out. If mortar or other such material is restrained during curing - for example by a metal mould or by attachment to a base - there will be a struggle between the mortar trying to shrink and the constraint trying to stop it. In consequence large stresses can develop in the mortar causing it to crack. To reduce such shrinkage cracking, we could:

- Remove stiff constraints (e.g. putting lime mortar or a rubber strip between the wall bottom and the base plate or using flexible moulds);
- Reduce mortar shrinkage by using a very dry mortar mix or a low cement content: unfortunately the former makes the mix difficult to work and the latter reduces strength;
- In the case of soil, use a low clay content;
- Spread such cracks that form (so that there are many tiny cracks rather than one big one) by putting a metal or fibre mesh inside the mortar: this is particularly helpful in controlling leakage since splitting one wide crack into two narrow ones will reduce leakage flow about 4-fold;

- Choose a shape (e.g. a sphere) where there are no hard attachment constraints;
- Modify the material by the addition of a slightly expansive component that counteracts the normal shrinkage;
- In the case of a render applied only to achieve water-tightness, it is often possible to apply it in two layers and place a sealant such as cement-plus-water between the layers.

5 ECONOMICS OF TANK SIZING

5.1 Economic overview

All households already have some access to water from point sources. For some days per year, many also employ 'informal' rainwater harvesting, placing bowls and jugs under eaves or even trees during rainfall.

The introduction of more formal (and productive) RWH will normally be accompanied by three benefits. The most obvious is a reduction in the time spent carrying water from point sources – a reduction more or less proportional to the volume of water no longer carried. The second is an increase in household water consumption wherever it was previously constrained by the effort of collection. The third is a common, although not invariable, increase in water quality. All these benefits rise with DRWH storage capacity, albeit in a way showing diminishing returns.

The increase in water consumption with RWH has not been widely measured. Generally any increase is restricted to the wet seasons. DRWH is not generally capable in the dry seasons of supplying quantities larger than already obtained from point sources: this means that it will be used to supplement, but not to substitute point-source water.

The costs of DRWH are overwhelmingly capital costs, as neither operation nor maintenance usually involves significant expenditure. These capital costs are subject to economies of scale. The sensitivity (elasticity) of tank cost to storage capacity is about 0.6

5.2 Value of water

As with many other goods, water has a declining value with quantity. The first litre per day is worth more than the tenth. By examining the limited data available that relates household consumption per day to the effective unit cost of water (i.e. cost per litre), we might construct a curve such as shown in Figure 6. Each socio-economic group would have its own curve.

The cost line on 6 is horizontal, which reasonably represents the situation where water is fetched, each successive litre requiring the same input of labour. Such a line does not fairly represent harvested roofwater, where the effective cost general rises with daily consumption despite the economies of scale in tank construction. A typical cost v volume characteristic for RWH supply is shown in Figure 7.

Figure 6: value vs. quantity

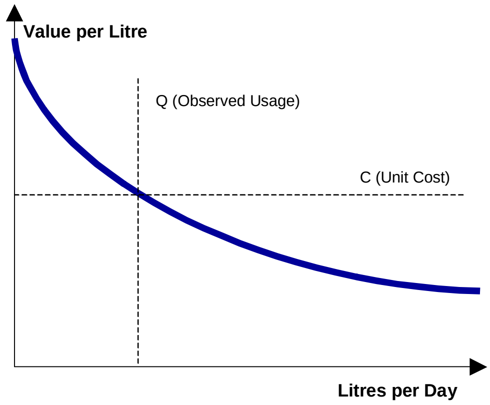
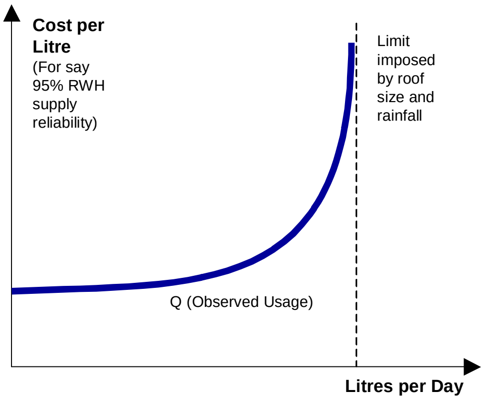


Figure 7: cost vs. volume



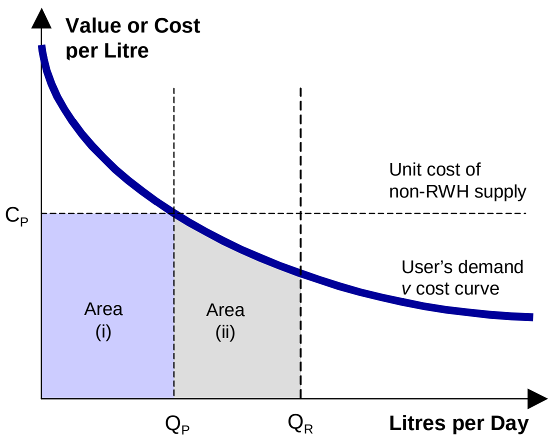
Sometimes we can find examples of water purchase and use them to infer the value of water. Richer households, or those experiencing illness, may pay for water to be brought to the house. More usually we have to infer costs indirectly through conversion of fetching distance/height into time and then time into money. Such costs, like the value of water discussed above, will be lower for poorer households than for richer ones.

5.3 Combining RWH with other water sources

For a given size and location of RWH system and for a given operating strategy, there will be a limit on the water it can supply per day, per week or per year. The maximum per year, corresponding to zero tank overflow, in litres will be the product of roof area (m^2), the annual rainfall (mm) and a run-off / capture factor (typically 0.85).

Consider first the situation where we can disregard seasonal factors, and assume that before RWH arrived, daily consumption from a point source was Q_P (litres/day). Q_P is determined by the interaction of the user's demand (cost v volume) curve and the unit cost C_P of supply from the point source. The daily cost to the user was therefore Q_P x C_P.

Figure 8: Value of rainwater



If the water Q_R available per day from RWH is *less* than Q_P, then the users will draw Q_R from the RW system and the remainder Q_P-Q_R from the point source. The total consumption will not increase and the effective value of the harvested rainwater will be the saving Q_R x C_P .

If the water Q_R available per day from RWH is *more* than $Q_{P,}$ then the users will increase their consumption from Q_P to Q_R and the rainwater will be worth more than the former total cost Q_P x C_P. Exactly how much more will depend on the user's demand curve. The situation is represented in the diagram below, where Area (i) is the saving (Q_P x C_P) while Area (ii) is the value of the extra water.

Note that Q_R is the daily amount *available* from RWH, whereas Q_P is determined by the price of supply (from non-RWH sources). The total value Area(i) + Area(ii)) is less than (Q_R x C_P) because the extra water is per litre less valuable to the user than the water 'replaced'.

5.4 Seasonal effects and water management strategies

In the last section we ignored seasonal effects, although one can identify the condition $Q_R<Q_P$ as representing a dry season and $Q_R>Q_P$ as representing a wet one. However seasonality is central to the operation and performance of a RWH system. A user can choose to emphasise dry season security or alternatively to emphasise roofwater capture. To some extent the dry and wet season water needs are in competition with each other. Consider the following four water management strategies for an already built RWH system.

To make the strategies easier to visualise, assume a scenario typical of a homestead in the Great Lakes region where mean daily roofwater runoff is R = 100 litres). Assume that 'dry' weeks (runoff less than 350 litres per week) comprise 1/3 of each year and that the RW storage capacity is 700 litres (7 x R or '1 week'). This storage is only modest, but corresponds to perhaps 50 days drinking water or 14 days total water under very careful management.

Strategy 1 – *High Water Capture* – Water is withdrawn at a high rate, Q = 1.5 R, (e.g. 150 litres/day under our scenario) whenever it is available. This will result in fairly low occurrence of tank overflow, but leave little reserve for dry weeks.

Strategy 2 – *High Security* – Water is withdrawn at a low rate, Q = 0.5 R, (e.g. 50 litre/day) whenever it is available. Much water will overflow the tank, so annual capture will be low.

Strategy 3 – *Adaptive* – Water is withdrawn at a rate Q determined by how much is in the tank, thus:

Q = 1.5 R (e.g. at 150 lpd) if tank > 2/3 full;

Q = R if tank < 2/3 but >1/3 full;

Q = 0.5 R, if tank < 1/3 full.

Strategy 4 – *Maximum Security* – Water is saved for the dry seasons and drawn frugally (e.g. 50 litres/day) *only* after nearby point sources have run dry or after 2 weeks without rain.

The trade-offs involved between these alternatives are summarised in the following table, in which the word 'security' is taken to mean the fraction of days the demand is met by RW (the tank does not run dry). The factor K is the dry-season value of water (valued at its cost from the nearest point source) divided by its wet season value. Thus K=1 represents places where point-source water is unvarying through the year, whereas the extreme value K=10 represents places where in the dry months all local sources dry up, so water must be queued for, then carried from, very far away. A typical value of K in the humid tropics might be 2.

Table 3 suggests how we might account for seasonal differences in our economic evaluation, namely by assigning different wet and dry season values for water and operating the system to maximise their sum.

Table 3:System Performance under Different Operating Strategies

Strategy No	Annual consumption	Relative value of annual water harvested		Wet season security	Dry season security
		if K=1	if K=10		
1	high	high	med	high	v. low
2	low	med	med	high	low
3	medium	low	v. low	high	low
4	very low	med	med	nil	med

Table 4 represent the simulation of the four strategies applied to respectively a small DRWH system (storage volume V = 7 x mean daily run-off, R), a medium size system (V/R = 21) and a large system (V/R = 63). Daily rainfall data for 10 years has been used and a roof area of 45 m^2 has been selected to give the assumed mean run-off R = 100 litres/day. For Mbarara, the town used, the dry season (defined by rain in the last fortnight being under 50% of mean fortnightly rainfall) is 36% of the year.

Table 4: Relating RWH system performance to operating strategy and storage volume

Strategy number / type	V/R	Capture Efficiency	Tank Utilisation	Mean daily consumption Q in litres		'Security' (*S*) = fraction of days demand is satisfied by roofwater		
	tank size days	*E*	*U*	Q_1 *K*=1	Q_5 *K*=5	S_w Wet	S_d Dry	All year
Small tank,								
1 High demand High capture	7	**0.70**[1]	36.5	70	**95**	0.75	**0.22**	0.56
2 Low demand High security	7	**0.41**[3]	21.4	41	**80**	na	**na**	na
3 Adaptive	7	**0.66**[2]	34.4	66	**93**	0.94	**0.38**	0.74
4 Max security in dry seas	7	**0.17**[4]	8.9	17	**84**	na	**0.52**	na
Medium size tank								
1	21	**0.91**	15.8	91	**125**	0.90	**0.25**	0.67
2	21	**0.47**	8.2	47	**107**	na	**na**	na
3	21	**0.86**	14.9	86	**138**	1.00	**0.66**	0.88
4	21	**0.26**	4.5	26	**128**	na	**0.73**	na
Large tank								
1	63	**1.00**[1=]	5.8	100	**165**	0.92	**0.38**	0.72
2	63	**0.51**[3]	3.0	51	**123**	na	**na**	na
3	63	**0.99**[1=]	5.7	99	**203**	1.00	**0.98**	0.99
4	63	**0.37**[4]	2.1	37	**182**	na	**1.00**	na

Notes:
1. Data is for Mbarara, Uganda
2. Annual run-off = annual demand
3. na indicates strategy does not allow demand to be met.
4. Highlighted cells indicate best strategy or within 3% of best
5. Strategy 1 gives best $\mathbf{Q_1}$ (highest water capture)
6. Strategy 3 gives best $\mathbf{Q_5}$ (highest benefit if K = 5)
7. Strategy 4 gives best $\mathbf{S_d}$ (highest dry season security)
8. Strategy 3 is always best or second best by all measures.

‘Value’ is calculated assuming first litre per day is worth 1.5 falling via 0.5 at the 100^{th} litre to zero at the 150^{th} litre

Strategy 1 is to withdraw 1.5 times base demand when available (and otherwise what is available)

Strategy 2 is to withdraw 0.5 times base demand when available (and otherwise what is available)

Strategy 3 is to withdraw 1.5, 1 or 0.5 times base demand, according to amount in tank

Strategy 4 is to withdraw nothing in wet season and in dry season base demand when available (and otherwise what is available).As well as water supplied (column 5), a ‘weighted’ water supplied column is shown alongside in which effectively K = 5. This yields the weighting (a ‘wet season litre’ is a cost-equivalent volume): 1.0 dry season litre is deemed to be worth 5.0 ‘wet season litres’

The **bold** columns in the table contain the performance measures of most interest.

Column 3 shows ‘Capture efficiency’, (*E*) – a high value indicates that most of the roof run-off is being consumed.

Column 8 shows ‘Dry season water security’, (S_d) – the fraction of dry season that tank does not run dry and so demand has been satisfied; note however that under Strategy 1 the dry season demand is maintained very high at 1.5 *R*, whereas the other strategies are using demand of only 0.5 *R* for the dry season.

Column 6 shows weighted annual water consumption, Q_5, which is a measure that attempts to combine quantity, and security measures, by valuing wet season water much more highly than dry season water.

Examination of the top part of the table – which is for a small system with V/R only equal to 7 days – indicates that Strategy 1 (in which water is drawn generously whenever available) gives the highest annual water yield E, the lowest level of dry season security S_d, yet a high value for the seasonally-weighted yield W_e .

By contrast Strategy 4 (water is drawn sparingly and only in the dry season) gives the highest dry season security at the cost of the lowest annual yield. The seasonally-weighted yield is however also low. In fact we can dismiss Strategy 4 because even here, where per litre we have valued dry season water at *five times* wet season water, it still gives the lowest output valuation.

Strategies 2 and 3 are intermediate in performance, with Strategy 3 (adaptable) generally outperforming Strategy 2 (fixed low-demand).

From this table we can conclude that unless dry season water has exceptional value – e.g. it is per litre worth more than the 5 times wet season water assumed in the table – Strategies 1 (high usage) and 3 (adaptive) are superior to the other strategies.

The bottom band of the table is for a much more expensive system with 9 times larger storage. With such a large tank, the relative superiority of Strategy 3 is increased. We also see the benefit of the larger store. Comparing say Strategy 3 for the very large tank with that for the small one, we find a 50% increase in water harvested (E), a nearly 4-fold increase in dry season security (S_d) and under the assumed value ratio (K=5) a 120% increase in water value. Table 5 shows the variation in value of water harvested for varying values of K and for various sizes of tank. It confirms that small systems (V/R < 10 days) give a generally acceptable performance unless dry season water is deemed very much more valuable (e.g. K=5) than dry season water. Note the clear ‘diminishing returns’ with increase in tank size. If water value had been plotted against tank *cost* rather than tank *size*, the same pattern of diminishing returns would appear but with a slightly reduced strength.

A small system in the humid tropics, attached to a $50m^2$ roof, might be expected to harvest around 25,000 litres of water per year (say 75% of run-off), averaging about 90 litres per day in the wettest 8 months and 30 litres per day in the driest 4 months.

Table 5**:** Performance under Strategy 3 – Table showing variation of value ratio, capture efficiency and security with tank size

	dry:wet value per litre	Normalised tank size – V/R in days								
		1	3	5	7	14	21	30	60	90
Benefit ratio = value of water harvested ÷ value water demanded	if K=1	0.29	0.49	0.60	**0.66**	0.79	0.86	0.91	0.98	1.00
	if K=2	0.24	0.40	0.49	**0.53**	0.65	0.72	0.79	0.90	0.94
	if K=5	0.18	0.30	0.35	**0.38**	0.48	0.56	0.65	0.82	0.88
Capture efficiency		0.39	0.66	0.76	**0.82**	0.90	0.93	0.95	0.99	1.00
Security		0.15	0.41	0.57	**0.67**	0.81	0.86	0.90	0.98	1.00

Notes:
1. Under this strategy the demand is varied from 0.5 to 1.5 times the mean daily runoff according to how much water remains in the tank
2. V/R is tank size (normalised to mean daily run-off); K is dry-to-wet season water value ratio; the bold column shows the performance of a typical very-low-cost RWH system

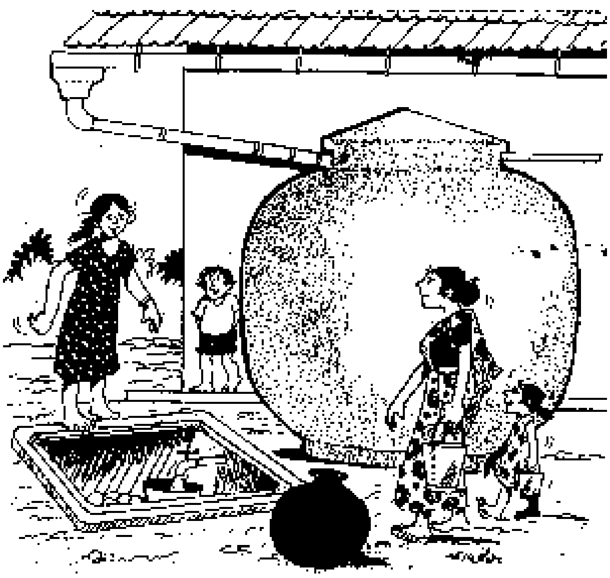
6 ANALYSIS OF EXISTING TANK DESIGNS

In the course of the project a number of tank designs have been investigated by the RHRG. These have been written up as "case studies" and are available on the project web site at:

www.eng.warwick.ac.uk/dtu/rainwaterharvesting/casestudies.htm.

A summary of these designs is set out below

6.1 The Pumpkin Tank, Sri Lanka



The Sri Lankan Pumpkin Tank, and the associated construction technique, was developed as part of a World Bank sponsored Water and Sanitation Programme that was implemented in the country between 1995 and 1998. The Community Water Supply and Sanitation Programme (CWSSP) covered 3 districts within the country – Badulla, Ratnapura and Matara Districts. Hundreds of these tanks have been built in areas where conventional supply schemes, such as piped supplies or groundwater supplies, were difficult to provide.

Catchment (typical) – 32m^2

Storage – 5 – 7 m^3

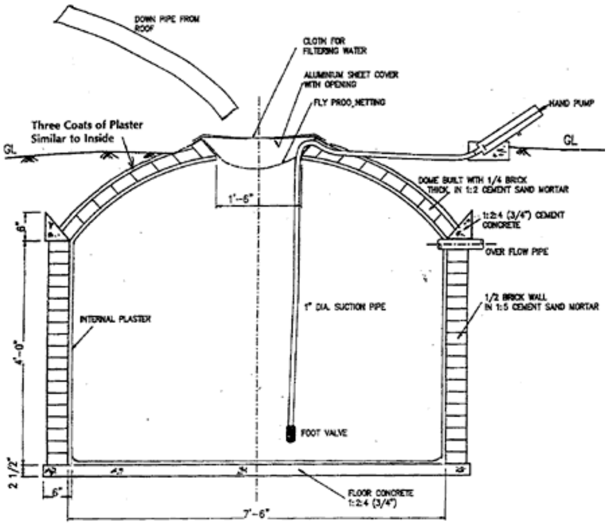
Storage cost - £112 (skilled labour - £19, Unskilled, £21 unskilled)

Material - ferrocement

Lessons

- Doubly curved structures
  - Material economies
  - Specialised techniques needed
  - Ferrocement construction
  - Use of mould for many tanks

6.2 Underground brick dome tank, Sri Lanka



This is another RWH system which was developed by the CWSSP programme in Sri Lanka. The tank, a 5m^3 underground brick built tank.

Catchment – 28m^2

Storage – 5m^3

Storage cost - £125 (skilled labour - £15, Unskilled, £28 unskilled)

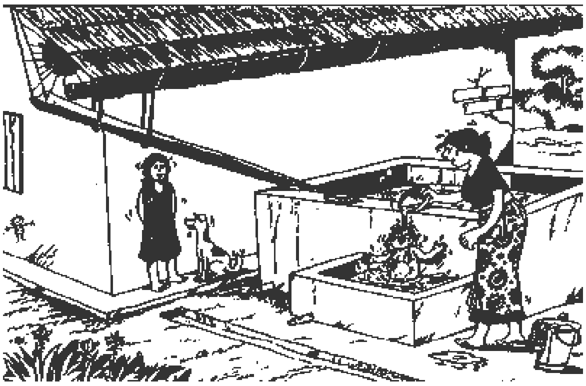
Material - Brick

Lessons

- Brick tank construction
  - Less skilled
  - *but* used as much cement as pumpkin tank

- Brick dome roof
- Low cost pumps for water extraction

6.3 Brick built storage tank, Sri Lanka



This is an example of local initiative in design and manufacture in DRWH. The tank in question was constructed in the village of Ahaspokuna, near Kandy, in the highlands area of Sri Lanka. The tank was built 10 years ago by a local mason for the Rajasomasari family and has since been copied so that there are now several of these tanks in the area.

Catchment – 90m^2

Storage – 3m^3

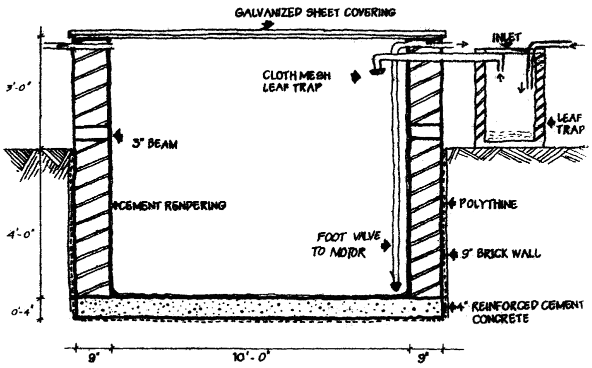
Storage cost - £80 (est.)

Material – Brick with cement render

Lessons

- Square construction
  - Good for bricks
  - Simple for local labour

6.4 Partially below ground brick built tank, Sri Lanka



This tank was built by Mr G. Victor A. Goonetilleke in the hill town of Kandy,. Mr Goonetilleke decided to build his RWH tank after experiencing difficulty in sinking a well to sufficient depth to have a reliable perennial source of groundwater at the site of his newly built home.

Storage – 10m^3

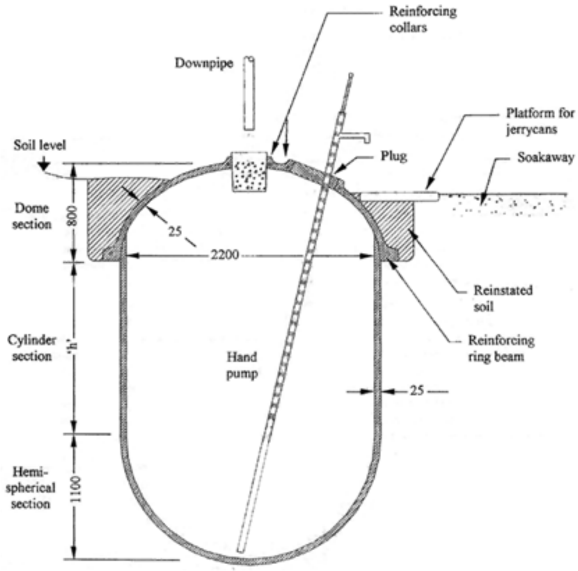
Storage cost - £550

Material – Brick with cement render

Lessons

3 Partially below ground construction – many of the advantages of below ground construction but with several of the advantages of above ground construction

6.5 Underground storage cistern – 4 to 10 cubic metres, Uganda



This tank (or cistern) was developed in Uganda by members of the Development Technology Unit, Warwick University and members of the Uganda Rural Development and Training Programme (URDT), between 1995 and 1997. Work is still continuing on the refinement of the tank. URDT is a service NGO located at Kagadi in Mid-Western Uganda. Several of these cisterns were built and tested with the aim of developing a low cost (under US$150), alley, domestic, water storage technology for the surrounding region.

Catchment – Varying

Storage – 4-10m^3

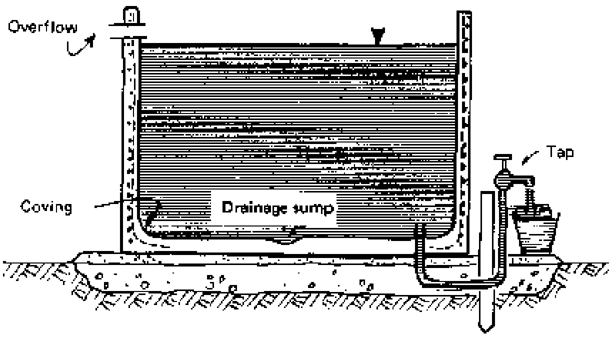
Storage cost – £90 (8m^3)

Material – Cement Mortar

Lessons

- Underground tanks – very thin walls are possible in appropriate soil
- Unreinforced mortar dome roof – lower cost due to no steel
- Ground as formwork – reduced cost amortisation of formwork

6.6 Ferrocement water tank using former



Used for many years in parts of Africa these tanks have been designed to be as simple as possible to build in self-help programmes. The users, who are at first unskilled in this sort of construction, can contribute their time and efforts in collecting sand and water, digging the foundations and preparing the mortar under the general guidance of a trained builder. With experience they quickly learn how to make the tanks without further guidance. A trained builder with 5 helpers takes approximately 3 days to complete the tank. The users often contribute some money towards the cost of the tank, which helps to cover the builders' wages, the cement, reinforcement and the hire of the corrugated iron formwork

Catchment – Varying

Storage – $10m^3$

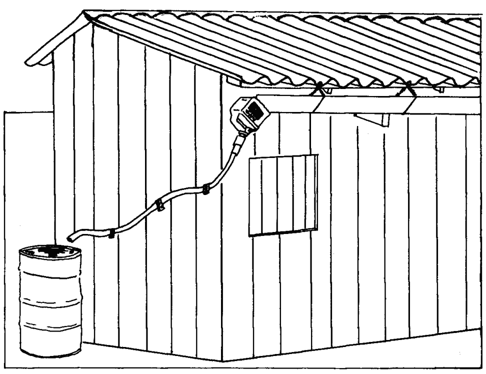
Storage cost – £90 ($8m^3$)

Material – Ferrocement

Lessons

- Reusable formwork with built-in depth gauge (corrugations)
- Adapted from successful commercial design from New Zealand
- Wire reinforcement graded through structure (more on bottom)
- Reinforcing from base to walls and filleted base join to avoid cracking at base

6.7 RWH in the barrios of Tegucigalpa, Honduras



Health statistics show that the residents of the barrios are suffering from a number of water related diseases that could easily be avoided with provision of a reliable, clean water supply. Unfortunately, more than 150,000 residents have to find their own water. Although technically unsophisticated and lacking some good health practice, the systems show what urban settlement have done to improve their own lot. Many of the systems make use of recycled or scavenged materials and some examples show high levels of initiative.

Storage – $0.2m^3$ used barrels (up to 3) or $1\text{-}2m^3$ open concrete tanks

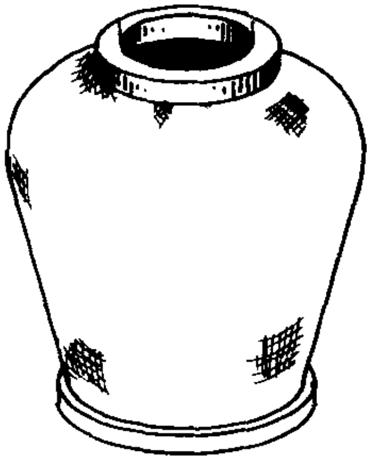
Storage cost – £10 (drum) - £18 “small tank

Material – Steel drum or plastered bricks

Lessons

- Impact of very small storage
- Use of available containers

6.8 Tai Jar



This type of water vessel was originally developed for a large country wide programme in Thailand that has installed over 10 million jars. Small jar making became a successful business with many companies producing up to 30 jars a day. The design has also been adopted in East Africa and South Asia

Storage – $0.5\text{-}2m^3$

Storage cost – £ 30 for a $2m^3$ jar

Material – Pottery or cement

Lessons

- Small tanks used modularly – several houses have more than one and up to 10 are used commercially
- Mass production – lead to much cheaper tanks
- Critical mass – the programme grew exponentially and became self sustaining within a few years

6.9 Plastic Lined tanks

Several experiments have been done using plastic sheets as a waterproof membrane in an otherwise wholly traditional structure. The bamboo tank developed by ARTI in Pune India uses a polythene sheet in a basket structure that is traditionally used for grain storage. In East Africa Rwandan refugees have used a tarpaulin distributed by UNHCR as a liner for an underground tank over which a wattle and daub enclosure is built to protect the water.

Lessons

- Small, portable imported input bolstering principally local technique – greatly reduced cost
- Some questions of durability

6.10 Summary

Table 6: Summary analysis of case study material

	Material costs	Percent Labour costs	Unit costs (per m^3)	Skills required	Equipment/ tools required	Space requirement	Suitability for incremental adoption	Reliability	Water quality, safety and health	Impact on insect breeding	Stage of maturity or experience
Pumpkin Tank	✓	✓	✓	✗	✗	O	✗	✓	✓	✓	✓
Underground brick dome tank	✓	✓	✓	O	✗	✓	✗	✓	✓	✓	✓
Brick built storage tank	O	O	O	✓	✓	O	O	✓	✗	✗	✓
Partially below ground brick built tank	✗	✗	✗	✓	✓	O	✗	✓	✓	O	O
Underground storage cistern	✓	✓	✓	✗	✓	✓	O	✓	✓	✓	O
Ferrocement water tank using former	✓	✓	✓	✓	✗	O	O	✓	O	O	✓
RWH in the barrios of Tegucigalpa	O	O	O	✓	✓	O	✓	O	✗	✗	O
Tai Jar	✓	✓	✓	O	✗	O	✓+	✓	✓	O	✓
Plastic Lined tanks	✓+	✓+	✓+	✓+	✓	O	✗	?	O	O	✗

Key ✓ Good O Medium ✗ Bad

7 RHRG RESEARCH INTO MEANS OF REDUCING TANK COSTS

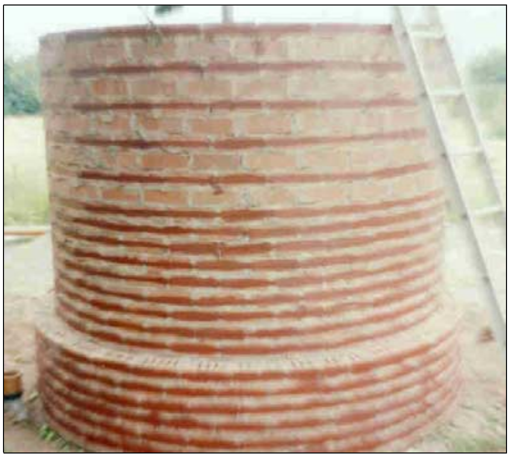
7.1 Research strategy

Having collected information on existing rainwater systems and identified probable areas for design improvement, the RHRG has developed several cheaper tanks, concentrating on materials substitution and material reduction while working mainly with smaller tanks suitable for incremental adoption. The main materials investigated have been:

- Rammed Earth
- Stabilised soil blocks
- Bricks
- Plastic linings

Various underground tanks have also been developed mainly on the partly below ground model. A lift-on tank cover has also been developed to remove the need for formwork from the cover making process.

7.2 Use of externally reinforced bricks



Brick is a material that is used widely in developing countries and is thus readily available. It is ideally suited to wall construction, but not quite so well suited to conventional larger volume tank construction. As it;

- has a poor strength in tension
- has a poor adhesion one brick to another through the mortar and so tensile forces must be spread through the brick runs which will be in sheer with one another
- can need more cement than an equivalent Ferrocement tank due to poorly fitting bricks

One way of improving the suitability of brick to low cost tank manufacture is by using external steel reinforcing to give additional hoop strength to cylindrical brick tanks. If an empty circular tank is wound with steel reinforcing wire on the outside, and the wire is then tightened, we will achieve ‘post tensioning’ whereby the masonry (brick/concrete) is initially in compression and the steel in tension. Putting the steel on the outside not only facilitates the post-tensioning but also makes it easier to protect the steel from being rusted by seepage from inside the tank. Filling the tank with water will result in a lowering of the compressive stress and strain in the mortar and an increase in the tensile stress and strain in the steel. One such tank has been built and was detailed in Milestone Report A2

The technique holds some promise as it is easy to implement, however there is some doubt over the availability of tensioning tape as described in the report. It should, however be possible to use galvanised wire for this purpose although more will be necessary due to its lower tensile strength.

Table 7: Pros and cons of brick tanks

Pros	Cons
• low material cost • suitable material readily accessible locally in many parts of the world • a well-known and widely-used technology in many parts of the world • a simple technology that is easily taught to semi-skilled people	• not ideal for round tanks as extra mortar or special angled bricks are needed • Poor in tension – Needs reinforcing or very thick walls

7.3 Use of rammed earth

The use of rammed earth has been the subject of a previous report to the EU (Milestone A5: *Stabilised Soil Tanks for Rainwater Storage*, submitted September 2000) so only a brief summary will be presented here.

Rammed earth is a technique which is experiencing a resurgence of interest, particularly in developing countries where cement is expensive and in "green" architecture where its low energy use and excellent thermal properties are particularly appreciated. The technique has been used for centuries for the construction of houses many of which are still standing, attesting to its stability and longevity.

Just as it's name suggests this technique involves earth being rammed between two shutters, using a rammer or tamp. The shuttering is removed to reveal the wall. Walls are usually constructed in sections of a few feet long by a foot or two deep with shuttering moved along to form a continuous wall. The shuttering is then raised and placed on top of the first 'lift' to construct the subsequent 'lifts'.

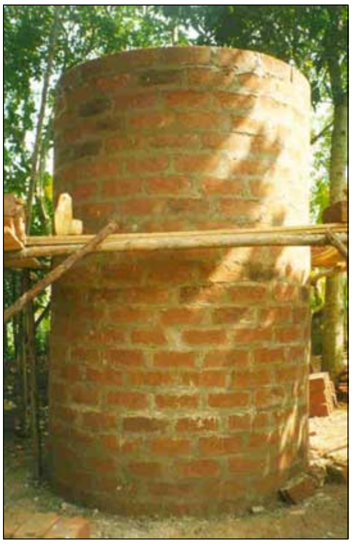
Several experiments with rammed Earth have been undertaken by the RHRG both in the lab and in the field. The material has proved capable of withstanding the forces typical of a tank however there are some practical problems. The pros and cons of Rammed earth tank construction are listed in table

Table 8: Pros and cons of rammed earth tanks

Pros	Cons
• very low material cost • suitable material readily accessible locally in many parts of the world • a well-known and widely-used technology in many parts of the world • a simple technology that is easily taught to semi-skilled people	• not suitable for below-ground tanks or cisterns • in the case of leaks serious problems can develop, especially if unstabilised earth is used • high labour input

The main problem with rammed earth is its wet strength. The tank must be fitted with a waterproof lining to hold the water. If this liner becomes damaged and *any* water leaks, then the tank will almost certainly fail as any water ingress will ultimately seep out along with some soil, this process is continued until a hole forms ultimately growing large enough to destroy the tank's structural integrity.

7.4 Use of stabilised-soil



Stabilised soil has also been covered in a previous report (Milestone A5: *Stabilised Soil Tanks for Rainwater Storage*, submitted September 2000)

Stabilised, compacted, soil block technology involves compacting a suitable soil, which is often mixed with a small percentage (typically 5 – 10%) of cement, using a manual or hydraulically assisted ram or press. This compaction reduces the voids in the material and hence it susceptibility to attack from water. Special moulds can be manufactured to produce blocks of different shapes for special purposes.

Work has been carried out on stabilised soil blocks for tank construction in two locations (Uganda and Sri Lanka) In the case of the cylindrical tanks manufactured in Uganda, curved blocks were produced. For a cylindrical above-ground tank. In Sri Lanka a square underground tank was produced.

The Uganda work involved the building of two experimental cylindrical water tanks in collaboration with Dr Moses Musaazi, a lecturer at Makerere University. Both were built above ground of curved stabilised-soil blocks with end interlocking, 280mm x 140mm x 110mm high, made with an Approtec

(Kenyan) manual block press. The soil used was a red somewhat pozzolanic local soil previously known to make strong blocks. The tanks were built on concrete plinths, lined with 'waterproofed' mortar (3 parts sand, 1 part cement and .02 parts 'Leak Seal' waterproofing compound). There was no metal reinforcing.

Tank 1 was 2m high, with an internal diameter 1.3m, wall thickness 140mm (+ 15mm render) and used blocks incorporating 6% cement. It has been filled with water and briefly withstood a maximum head of 2.m at the wall bottom before failing catastrophically (and spectacularly). 2, for test purposes, has been built to 5m high, has internal diameter 1.0m and the same wall thickness, but with only 3% cement. It has been filled with water and therefore withstood a head of 5.0m at the wall bottom. The inconsistency of the result could be attributed to an undersupply of cement to the blocks which made up tank one resulting in a low wet strength, coupled with a cracking of the mortar used to line the tank.

The pros and cons of stabilised soil construction tank construction are listed in table 7

Table 9: Pros and cons of rammed earth tanks

Pros	Cons
• Reduced cement content resulting in inexpensive blocks •	• Low wet strength • Reduced cement content must be balanced against lower strength requiring thicker walls • Needs specialised tooling for compacted blocks • Low tensile strength of block joints

7.5 Lining tanks with plastic bags

Plastic linings can considerably reduce the cost of the tank by removing the need for any building work to be watertight. Indeed they can be simply placed in a hole to form a very cheap and portable tank (although a cover should be constructed). Plastic liners also allow removal for inspection, cleaning, maintenance and occasional repair.

Work on plastic linings by the RHRG includes the development of a technique for welding 250 micron construction or damp proof membrane (DPM) plastic sheet to make 'bags' (similar to large bin liners) that fit inside the tank structure to form a waterproof lining. The welds themselves have proved successful with the weld both watertight and stronger than the plastic itself. The technique uses simple tools and can be taught in a couple of hours to a reasonably skilled craftsperson. One skilled person should be able to make a bag in a single day and productivity can be greatly enhanced by batch production. However, while the welding technique has been successfully developed, there are still problems to be overcome in relation to the quality of 'off-the-shelf' plastic sheet and failure of the lining due to abrasion. Observations in the field suggest that plastics with a woven structure may be more resilient, however these will not weld with the technique developed at Warwick.

The availability of plastic tubes from local markets is quite wide spread and a 600litre "plastic tube tank" was also developed in the course of the project. Details of this tank can be found in DTU Technical Release *TR-RWH08 Plastic Tube Tank (600 litres) – Instructions for manufacture*. (Rees & Whitehead, 2000b)The 87cms diameter tube is the largest that was found at the time but the design could be easily modified for different sizes of tube. The tank is based on the partly below ground concept and consists of a brick parapet wall, which incorporates the inlet basin and handpump and the lower section ground excavation, lined with two plastic liners one inside the other. The tanks have developed slow leaks reducing their effectiveness but are still holding water and making a significant contribution to household water where they have been installed.

Table 10: Pros and cons of plastic linings

Pros	Cons
• Greatly reduced cost • Portable • No clambering on or in the tank is required during construction. • No curing time is required. • Can be removed for cleaning./inspection • Can be batch produced	• Fragile – likely to tear, subject to pin holes • UV degradation • Joining requires specialised techniques

7.6 Simple underground tanks in stable ground

The RHRG has also experimented with creating underground tanks using stabilised soil with bamboo reinforcing and a plastic liner for waterproofing. The work (undertaken by the Open University in Sri Lanka) .The tank was designed to contain 3600 litres of water. It is trapezoidal with 100cm x 100cm square cross-section at the top and 80cm x 80cm square cross-section at the bottom of the tank. Strips of bamboo are used both as a support to the tank walls and to protect the lining material, which is 500 gauge polythene sheet. During the development soil samples were tested for strength and durability and a 1:12 cement:soil ratio was found to be optimum with the local soil. This will, however differ with location.

The problems of covering such pits can still cause cost problems absorbing more than 2/3 of the cost of such a tank. Tanks have also been broken due to raising water table, punctured by tree roots and are vulnerable to infiltration by runoff.

Table 11: Pros and cons of simple underground structures

Pros	Cons
• Greatly reduced cost as surrounding ground gives support allowing lower wall thickness. • More difficult to empty by leaving tap on • Can be made unobtrusive	• Water extraction is more problematic – often requiring a pump • Leaks or failures are more difficult to detect • Contamination of the tank from groundwater and surface runoff • Tree roots can damage the structure • There is danger to children and small animals if tank cover is left off • Flotation or breaking of the cistern can occur if groundwater level rises

7.7 Partly-below-ground tanks

Several of the problems of underground tanks can be overcome by siting the tank partly above ground and partly below ground. These tanks have been described in Milestone Report A3. Details can also be found in the DTU Technical release *TR-RWH 01 Partially Below Ground (PBG) Tank for Rainwater Storage – Instructions for Manufacture,* (Rees, 2000b) available at: the DTU website. Over 20 of these tanks have been built in East Africa and feedback suggests that the tanks are easy to construct by masons with some training, at a reasonable cost.

Table 12: Pros and cons of Partially below-ground tanks

Pros	Cons
• Lower material requirements • Difficult to empty by leaving tap on • Reasonably unobtrusive • Surrounding ground gives support allowing thinner walls and thus reduce costs	• Requires a pump • Leaks or failures are difficult to detect • Contamination of the tank from is possible • Tree roots can damage the structure • Flotation of the cistern may occur

7.8 Lift-on tank covers

The lift on tank cover developed by the RHRG has been detailed in Milestone Report A2 and in DTU Technical Release *TR-RWH 04 – Low-cost, thin-shell, 2m diameter ferrocement tank cover - Instructions for manufacture (Rees, 2000a).* The thin-shell ferrocement tank cover is designed in such a way that it can be manufactured without the use of a mould or shuttering. It can also be manufactured remote from the tank to which it is to be fitted and moved into place once complete. The aim is to reduce the cost of the tank (cover) by eliminating costly shuttering or moulds and by reducing the quantity of material used to manufacture the cover. It also means that the cover can be removed at a later date for maintenance, refurbishment or cleaning. The cover can be manufactured by two persons (one skilled and one unskilled) in a single day (with some time required after that for curing) using tools required for the construction of a simple cylindrical ferrocement tank.

The design is based on a frame known as a reciprocal frame, that has spokes that, when loaded, put little radial loading onto the structure on which it sits. The frame is covered with a wire mesh that is then rendered with a sand cement mix.

Table 13: Pros and cons of lift on lank covers tanks

Pros	Cons
• low cost – reduced use of materials • no shuttering or mould required • strong and lightweight – the tank cover is designed to be strong (through good quality control) and light at the same time • good quality control can be achieved through easy working environment • can be manufactured by two people in a single day (one skilled and one unskilled) • no clambering on top of tanks required during construction • can be cured easily – in the shade and at ground level • can be batch produced at one site	• Needs skilled craftspeople • Needs good quality control to be effective • Available in one-size-only as frame angles must be recalculated for other sizes

8 COSTS ANALYSIS OF RWH TANKS

The aim of this exercise is to compare tanks from different parts of the world and to carry out a costing exercise so as to assist those considering DRWH to make an informed choice. Such choices are usually complicated by the fact that material costs, labour costs, per capita income, currencies and exchange rates all vary from one country to another. Cost of storage per litre also varies as tank size increases. To take into account this variability an effort has been made to normalise some of the figures.

- 8 tanks have been costed for each of three countries i.e. Uganda, Sri Lanka and Brazil using bills of materials from the designs and material cost information obtained from each of the countries in 2000/2001.
- All tank costs have been converted to 5m^3 equivalent using sensitivity to size of 0.6.

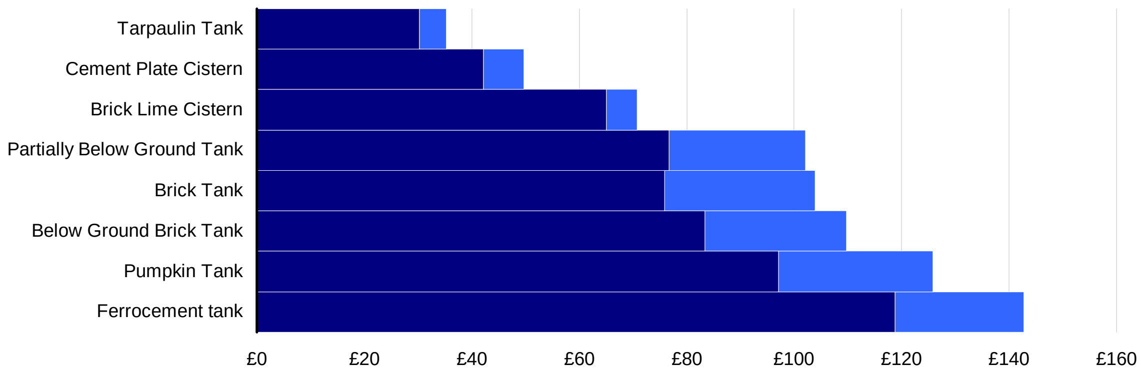
The tanks under consideration are taken from 4 countries in 3 continents. The countries are Kenya, Uganda (Africa), Sri Lanka (Asia) and Brazil (South America). The tanks are listed in Table 14 and the final costings are in Figure 9

Table 14: Tanks used for costing exercise

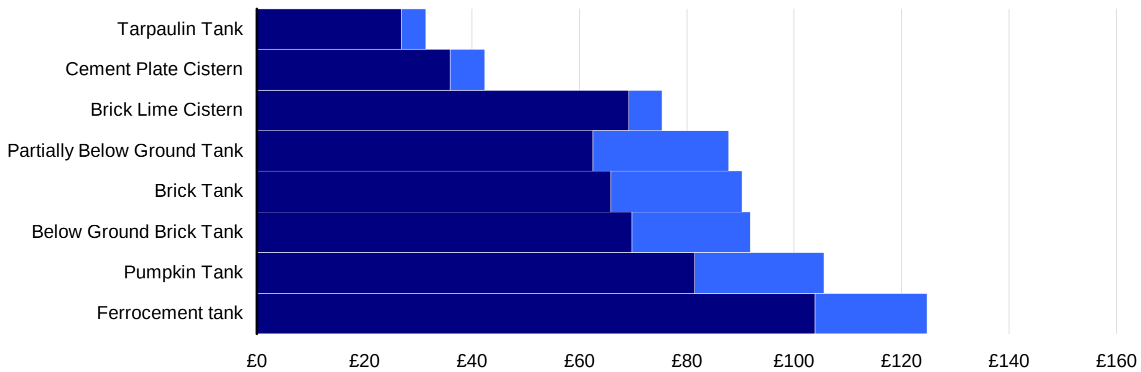
	Tank name	Tank size(s)	Source of information
1	PBG Tank	10,800 litres (size can be varied)	DTU Technical Release 01
2	Ferrocement tank	3,000 and 11,000 litres	Eric Nissen-Peterson, ASAL, Kenya (Nissen-Petersen & Lee, 1990)
3	Small brick jar	750 litres	DTU Technical Release 07 (Rees & Whitehead, 2000a)
4	Tarpaulin tank	4,000 – 5,000 litres	ACORD, Uganda and DTU Web Page
5	Ferrocement Pumpkin Tank	5,000 litres	Lanka RWH Forum and CWSSP Reports, Sri Lanka (Hapugoda, 1995)
6	Below ground brick tank	5,000 litres	Lanka RWH Forum and CWSSP Reports, Sri Lanka (Hapugoda, 1995)
7	Cement Plate Cistern	10,000 and 20,000 litres	Johann Gnadlinger, IRCSA. Data from Juazeiro, Bahia State, 1998 (Gnadlinger, 1999)
8	Brick lime cistern	10,000 and 20,000 litres	Johann Gnadlinger, IRCSA. Data from Juazeiro, Bahia State, 1998 (Gnadlinger, 1999)

Figure 9: tank costs in three countries

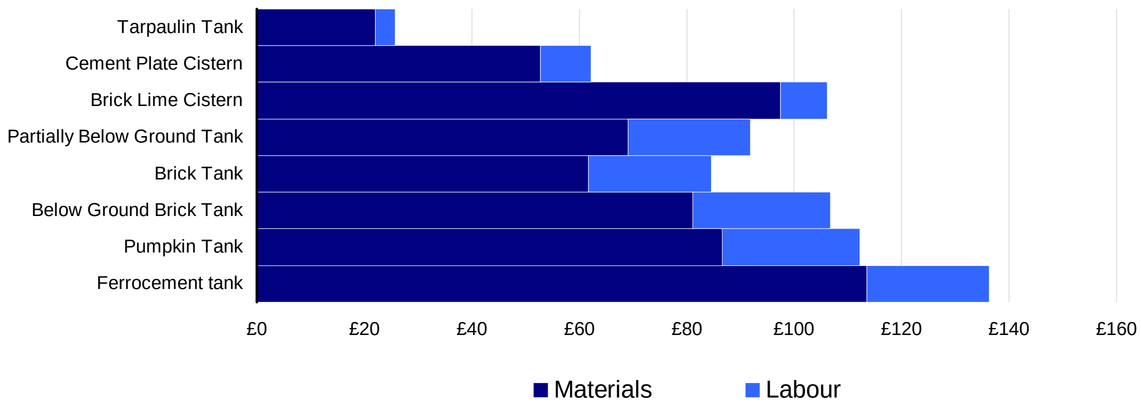
a Brazil



b Sri Lanka



c Uganda



As can be seen the cost of building the tanks differs by quite some margin:

- The traditional ferrocement tank fares most badly, this is probably due to the design being quite old and suffering many years of “improvements” at various hands
- The Pumpkin tank would appear to provide some savings mainly through its more optimised shape and also due to the youth of the design
- The partially below ground tank also provides good economies with reduced material usage and similar labour costs to other cement tanks
- The brick tanks show some materials savings but a slightly higher labour content tends to favour countries where labour is cheap and materials expensive such as Uganda
- By far the cheapest tank is the tarpaulin tank, due in part to its extensive use of “free” local materials and also because of its quick construction
- The cement plate cistern is also an inexpensive option particularly in countries with cheap cement such as Brazil and Sri Lanka. Its unique construction using closely controlled sections of concrete assembled together on site results in substantial savings in material thickness. In more developed countries, this would be an excellent option as it is both durable and desirable as a household asset

Further insight is gained by discounting the labour content of the tanks as the community itself can often provide this. The Brick lime cistern is a case in point here. In Sri Lanka it is a fairly inexpensive option, however its low labour content means that for a self-help project it is less attractive (in Uganda it is the second most expensive in terms of material use!).

9 CONCLUSIONS

Rainwater harvesting tanks represent a mature technology. Their use goes back many centuries and development has been going on throughout history. This does not mean, however, that there is no room for improvement of the technology. Modern techniques and materials have great potential for the manufacture of rainwater tanks. Some of the most promising areas for cost reduction are:

- Plastic bag tanks such as the tarpaulin tank and the DTU tube tank
- Mass produced parts such as the cement plate cistern and lift on covers

- Partially below ground structures to combine the economies of below ground tanks with the safety and desirability of above ground tanks
- Considering the diseconomies of scale inherent in large tanks and using smaller tanks to provide partial supply or seasonal supply.

In considering cost reduction local conditions play a large part.

- Labour and material costs vary widely throughout both the developing and developed world resulting in different designs becoming cheaper
- Conditions may favour one design over another e.g underground tanks are only suitable for areas with stable soils and low water tables, plastic bag tanks are only suitable where insects are not a problem

These caveats notwithstanding the designs tried within the EU programme and many encountered in the field have demonstrated the cost of tanks can be significantly lowered. Domestic rainwater harvesting remains almost unique in that it allows householders to provide their own water supply without the need to wait for outside intervention and the challenge is to produce a system within the means of every household. With appropriate dissemination, the designs presented in this paper should go some way toward this.

REFERENCES

Flugge, Wilhelm (1967) *Stresses in shells*, Springer Verlag New York.

Gnadlinger, J. (1999). "Technical presentation of various types of cistern built in the rural communities of the semi-arid region of Brazil" *9th IRCSA Conf*, IRCSA - Johann Gnadlinger, IRCSA, Brazil.

Gould, John and Nissen-Petersen, Erik (1999) *Rainwater catchment systems for domestic supply*, IT Publications London.

Hapugoda, D. (Nov/1995) *Action Research Study on Rainwater Harvesting*, (Report No. Project Report 2). CWSSP, Ministry of Housing, Construction and Public Utilities, Sri Lanka.

Lee, Michael D. and Visscher, Jan Teun (1992) *Water harvesting - aguide for planners and project managers*, IRC International Water and Sanitation Centre The Hague.

Nissen-Petersen, E., & Lee, M. (1990) *Harvesting Rainwater in Semi-Arid Africa - Manual Number 1: Water Tanks With Guttering and Handpump*, ASAL , Nairobi.

Pacey, Arnold and Cullis, Adrian (1996) *Rainwater harvesting: The collection of rainfall and runoff in rural areas*, IT Publications London.

Rees, D. (Nov/2000a) *Low-Cost, Thin-Shell, Ferrocement Cover - Instructions for Manufacture*, (Report No. TR-RWH04). DTU, UK.

Rees, D. (Nov/2000b) *Partially Below Ground (PBG) Tank for Rainwater Storage - Instructions for Manufacture*, (Report No. TR-RWH01). DTU, UK.

Rees, D., & Whitehead, V. (Sep/2000a) *Brick Jars : Instructions for Manufacture*, (Report No. TR-RWH07). DTU, UK.

Rees, D., & Whitehead, V. (Sep/2000b) *Plastic Tube Tanks : Instructions for Manufacture*, (Report No. TR-RWH08). DTU, UK.