

Tank costs for domestic rainwater harvesting in East Africa

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Rainwater harvesting from hard roofing can provide safe water to meet the basic domestic needs of several hundred million people in low-income countries. However, rainwater harvesting has a higher household cost than other low-technology water supplies such as protected springs. The storage tank is the most expensive part of the infrastructure required for rainwater harvesting: reducing this cost will enable rainwater harvesting to become a viable water source for many more households in low-income countries. This paper assesses the overall costs and different cost components of rainwater storage tanks. Costs are compared across a selection of tanks prefabricated in factories in Uganda, Kenya and the UK and constructed in situ in Uganda. Constructed tanks were always found to be cheaper than prefabricated ones. Tank size was an important factor, and it was found that tank cost per litre decreases as size increases. For all tank types, materials were the greatest cost.

1. Introduction

Rainwater harvesting has been established as an important contributor to domestic water needs if rainfall patterns allow. This is especially true where surface and groundwater supplies are limited (Gould and Nissen-Petersen, 1999; Pacey and Cullis, 1986). Rainwater harvesting systems are managed at a household level, which is easier than managing community supplies (Thomas and Martinson, 2007), and if they are well managed they can produce water that is as clean as other water sources (Parker *et al.*, 2010; Thomas and Martinson, 2007).

Sturm *et al.* (2009) found that rainwater harvesting techniques were competitive with public water supply in monetary terms in Namibia. However, Cranfield University *et al.* (2006) found that in rural areas, rainwater harvesting still has a higher cost per household than other low-technology water supply solutions such as protected springs and boreholes with handpumps. They concluded that reducing this initial investment is important if rainwater harvesting schemes are to become widely accessible. Storage tanks are the most expensive part of the rainwater

harvesting system, forming 60% of the cost for most domestic systems (DTU, 2002a), so it is this component of the system that is the focus of this paper.

There is extensive literature on the selection of optimal tank size (e.g. Butler and Memon, 2006; DTU, 2001; Fewkes and Butler, 2000; Fewkes and Warm, 2000; Mwenge Kahinda *et al.*, 2007), with Mwenge Kahinda *et al.* (2010) extending their work to recommend how to incorporate climate change into tank sizing. An easy-to-use review is provided by Thomas and Martinson (2007). They point out that in many cases, tank sizing is done by custom (i.e. what is being used by everyone else; this is the case in the Ugandan example described in this paper) or simply buying the biggest tank that can be afforded by the investor. The simplest method is a demand-side approach, where the volume of water required by a household per day is multiplied by the number of days in the longest dry season to give the total storage volume needed. This method gives an approximate size and assumes that there is sufficient roof catchment area and rainfall. A more accurate size can be calculated using a supply-side

approach, which uses average annual rainfall data, the size of the catchment area and the runoff coefficient (i.e. the percentage of rainwater actually captured and stored from a roof catchment) to calculate the potential harvested rainwater. The cumulative harvested rainwater can thus be calculated throughout a typical year using daily or monthly time steps. The cumulative demand can also be estimated. The tank size required can hence be determined on the day or month when the difference between the cumulative harvested rainwater and the cumulative demand is greatest – it is the magnitude of this difference (DTU, 1999).

If the stored rainwater is not sufficient for all purposes all year round, rainwater may be used just for drinking and cooking, with water for washing and agriculture sourced elsewhere; alternatively, the supply may be just for the rainy season (Thomas and Martinson, 2007). Through rainwater harvesting, it is estimated that approximately 1 billion people could potentially receive a minimum of 4 l/day drinking water for more than 6 months of the year and 371 million people could receive 10 l/day all year (Cranfield University *et al.*, 2006). Rainy-season water supply can be beneficial, as during this time, more of the day is spent farming so time for water collection is reduced and there is more illness (e.g. malaria). A clean and convenient water supply at this time is thus essential.

While there are many very low-cost designs under development (DTU, 2002c), many lack durability and are not yet widely used. In developing countries, tanks are principally constructed from cement, high-density polyethylene (HDPE) or galvanised steel (with or without liners). In 1986, ferrocement tanks had the lowest cost per litre of the available designs in all the countries assessed by Pacey and Cullis (1986) but, by 2001, the Development Technology Unit (DTU) ranked ferrocement tanks as one of the most expensive designs. However, an updated study by Thomas and Martinson (2007), which included plastic tanks, found that these could be up to three to five times more expensive again, although cheaper options were available in South Africa and Sri Lanka. Martinson (2007) assessed tank costs and found that the two lowest cost designs were a tarpaulin-lined underground tank and the ‘Thai jar’ (an unreinforced cement mortar jar). The latter are manufactured in workshops, resulting in significant material and labour economies, and they are small enough to be easily transported to households.

One way to reduce the reliance on manufactured materials such as cement is to use locally sourced materials. In developing countries, bricks are usually locally manufactured and readily available. However, they do not have the same versatility as cement, are weak against tensile stresses and are rarely waterproof, necessitating a lining (DTU, 1999). Despite a saving in material cost, brick tank walls have to be constructed much thicker than ferrocement tanks and, in general, end up being about twice as expensive (Hazeltine, 2003).

Material costs are a significant contributor to the total tank cost;

for example, the cement typically forms 42% of the total cost (DTU, 2001). Material costs can, however, be reduced as follows.

- Use of a more efficient shape – for example, a cylinder rather than a cuboid, or better, a sphere, although a perfect sphere requires some support unless it is underground (DTU, 2001, 2002b; Thomas and Martinson, 2007). The Thai jar (which has the shape of a classical urn) is a good compromise (Gould and Nissen-Petersen, 1999). However, vertical walls are easier to construct than curved ones (DTU, 2002b).
- Reducing wall thickness if safety factors can be reduced. Underground tanks can also have thinner walls as the ground provides support (DTU, 2001).
- Use of good formwork, which can significantly reduce the amount of cement used as the wall thickness can be tightly controlled and work is done against an inflexible surface (DTU, 2002c; Martinson, 2007).

Another significant cost is labour. This can be 20% of the total cost of a ferrocement tank, but less than 5% of a moulded plastic tank (Thomas and Martinson, 2007). While costs can be reduced by maximising the use of unskilled labour (or asking the tank owner to supply labour), skilled labour or training is still required for the installation of the reinforcement and the mixing of the mortar or concrete (Gould and Nissen-Petersen, 1999). It should be noted that some organisations are also aiming to create employment, so may not be aiming to minimise labour costs (DTU, 2001). Costs can further be reduced by using free or locally available materials (DTU, 2002b; Gould and Nissen-Petersen, 1999; Watt, 1978).

In general, tank costs per litre decrease with size (Ludwig, 2005; Pacey and Cullis, 1986). Thomas and Martinson (2007) showed that tank costs vary proportionately to the square root of volume. However, smaller tanks may be able to reduce their material costs by using less reinforcement (wire mesh) or even none at all (Pacey and Cullis, 1986; Watt, 1978). Conversely, the largest sizes of plastic tanks are typically slightly more expensive per litre than the cheapest ones (Ludwig, 2005).

Reviews of tank design and cost breakdowns have been conducted previously. However, some are outdated (e.g. Pacey and Cullis, 1986), while others compare designs between countries (e.g. DTU, 2001) where basic costs may differ, making it hard to make recommendations for cost minimisation. Finally, some provide only simplistic cost breakdowns (e.g. Sturm *et al.*, 2009; Thomas and Martinson, 2007). In addition, few studies present a detailed comparison of tanks prefabricated in developing countries.

This paper aims to provide a review of two of the existing technologies for rainwater tank design, analyse the cost components of these tanks and identify opportunities for cost reduction. The review includes tanks constructed close to their point of use

in Uganda and prefabricated tanks (made of HDPE and galvanised steel) available in Uganda, Kenya and the UK. The review was undertaken in 2007 (Cruddas, 2007; Rowe, 2007).

2. Method

In order to gain insights into tank costs and potential areas for cost reduction, visits were made to a selection of tank producers. These included projects where tanks were constructed at or near the user and manufacturers of prefabricated tanks that could be transported to site. A summary of the projects and manufacturers visited is given in Table 1. The projects and manufacturers have been anonymised in order to protect the non-governmental organisations (NGOs) who cooperated in this study and are referred to by codes throughout the paper. Identification is available on request to *bona fide* researchers or practitioners.

2.1 Tank construction on site

Projects were selected such that they represented

- a large geographical spread across southern Uganda, with varying access to local markets
- a range of different designs, varying in size and methods of framework
- both well-established leading advocates of domestic rainwater harvesting and newer projects.

The projects were visited over June and July 2007. The visits included semi-structured interviews with masons, technical staff and managerial staff and financial analysis of cost contributions.

2.2 Tank manufacturers

Six manufacturers were visited in total – two in Kenya, two in Uganda and two in the UK. This sample was not intended to be comprehensive, but rather to provide insight into the major factors that contribute to the cost of manufactured tanks. Uganda and Kenya were selected as they had (and continue to have) similar levels of development – the United Nations classed both Kenya and Uganda as countries with medium human development and low income (United Nations, 2007). This makes cost comparisons valid. However, in Uganda, the rainwater harvesting infrastructure market is more established because there are two rainy seasons and the government is actively promoting rainwater harvesting. The tank manufacturers were selected on recommendations from the Uganda Rainwater Association and the World Agroforestry Centre in Kenya – organisations that promote domestic rainwater harvesting. The UK, a developed country, was also chosen for comparison to see what different factors contribute to tank costs. In the UK, the selected producers were a manufacturer that supplies Oxfam with water tanks for emergency and development programmes and the UK's largest supplier of HDPE water tanks.

3. Results and analysis

3.1 Tank designs

3.1.1 Prefabricated tanks

The construction technology for all the HDPE tanks featured in this study is rotational moulding. This is a low-cost process since no external pressure is required. Powdered HDPE is placed in a mould, which is sealed and heated in an oven. The mould is then rotated on two axes so that the powder tumbles throughout the

Project/ manufacturer	Location	Tank size: l	Material	Tank shape	Tank location
P1	Uganda	1500	Mortar	Jar	Surface
P2	Uganda	5000	Ferrocement	Dome	Partly below ground
P3	Uganda	1500	Mortar	Jar	Surface
P4(420)	Uganda	420	Mortar	Jar	Surface
P4(4000)	Uganda	4000	Ferrocement	Cylindrical	Surface
P5	Uganda	4000	Ferrocement	Cylindrical	Surface
P6	Uganda	25 000	Mortar		Below ground
K1a	Kenya	150–24 000	HDPE	Cylindrical	Surface
K1b	Kenya	500–10 000	HDPE	Nestable	Surface
K2	Kenya	100–24 000	HDPE	Cylindrical	Surface
U1a	Uganda	100–24 000	HDPE	Cylindrical	Surface
U1b	Uganda	250, 500	HDPE	Nestable	Surface
U2	Uganda	100–24 000	HDPE	Cylindrical	Surface
E1	UK	9100–50 000	Galvanised steel	Cylindrical flat pack	Surface
E2	UK	1365–1000	HDPE	Cylindrical	Surface

Table 1. Projects and manufacturers visited as part of this study, with details of tanks

mould. Layers of powder melt, adhere to the hot walls and form an even coating. The mould is cooled with air or water, and the item can then be removed from the mould, which can be reused immediately. Polyethylene can become extremely brittle upon exposure to ultraviolet light, so ‘carbon black’ is added to the pulverised HDPE pellets at the initial stage, typically at a concentration of 2.5%.

Galvanised steel is manufactured by dipping steel sheets into molten zinc or applying the zinc by electroplating. The zinc prevents the underlying metal from corroding. Metal tanks are constructed from corrugated sheets as this provides additional strength while allowing wall thickness to be reduced. The tanks are cylindrical and have liners constructed from polyvinylchloride (PVC), ethylene propylene diene monomer (EPDM), polypropylene or butyl rubber. Tank covers are manufactured from galvanised steel or PVC and woven polypropylene. The tanks considered in this study were as follows.

- K1a, K2, U1a, U2, E2. One-piece cylindrical moulded tanks for above-ground use; corrugated and made from food-grade HDPE using rotational moulding.
- K1b, U1b. These tanks have the same material properties as the K1a, but are made specifically for rainwater harvesting. The tanks can be stacked within each other, due to their tapered design, which allows more tanks to be transported together than the K1a. The tanks come in sizes of 500, 1000, 2300, 3500, 4600, 6000, 8000 and 10 000 l.
- E1. This is a corrugated galvanised steel tank, distributed flat pack. It requires lining with PVC, EPDM (the cheapest), polypropylene or butyl rubber. It also requires a lid, manufactured from galvanised steel or PVC and woven polypropylene.

3.1.2 Cement tanks

There are two basic types – reinforced and unreinforced. Unreinforced tanks typically consist of layers of cement mortar applied onto a formwork of wood or metal. Once the mortar is dry, the formwork is removed. Reinforced tanks have a wire mesh support. First, layers of mortar are applied from the inside, pushed against a flexible non-permeable material on the outside. Further layers of mortar are then applied to the outside. A plinth or base may also be constructed out of mortar. The projects/tanks studied were as follows.

- P1, P3. 1500 l mortar jars made from unreinforced plaster, cast on a wooden mould. The jars can be constructed in situ or at a depot and then transported on a specially designed cart to the beneficiary household. The P3 tank also has a plinth.
- P2. 5000 l partly below-ground tanks constructed from layers of cement applied to chicken mesh and barbed wire; dome-shaped lids.
- P4(420). 420 l unreinforced jars, the base of which is cast using a metal ring as formwork. The walls of the jar are constructed by applying coats of plaster to a wooden mould.

A plinth is made in the final location using large locally sourced stones and cement.

- P4(4000). 4000 l ferrocement tanks. The base is formed from stone and rough concrete. The walls are supported by wire mesh, to which coats of cement are applied. The roof is made using mesh formed into a dome.
- P5. 4000 l ferrocement above-ground tanks constructed from layers of cement applied to chicken mesh and welded mesh.
- P6. 25 000 l below-ground tanks with only a circular access hatch visible on the surface. The tank sides are vertical, with a domed floor and ceiling. The lining consists of layers of plaster and chicken mesh.

3.2 Overall costs

Figures 1 and 2 show how the cost per litre varies with size for the eight different manufactured lines (K1a, K2, U1a, U2, E2, K1b, U1b and E1) and the seven different constructed tanks (P1, P3, P2, P4(420), P4(4000), P5 and P6) (see Table 1). A surcharge for delivery to remote areas may be imposed for K1a, K1b and U2 tanks. Figures 1 and 2 show that, in general, costs per litre decrease as tank size increases. Exceptions are the K2, K1a and K1b tanks, whose cost per litre increases with the largest tanks because transport costs increase disproportionately and demand for the largest tanks is low. Otherwise, all of the plastic tanks have similar unit prices. There are three exceptions. E2 tanks are slightly more expensive, but are manufactured in the UK (these tanks also do not include delivery). E1 tanks are exceptionally cheap, though they do not include transport or tank covers. K1b tanks are four times more expensive than the other tanks. This exceptionally high cost is because the K1b tank, like the U1b

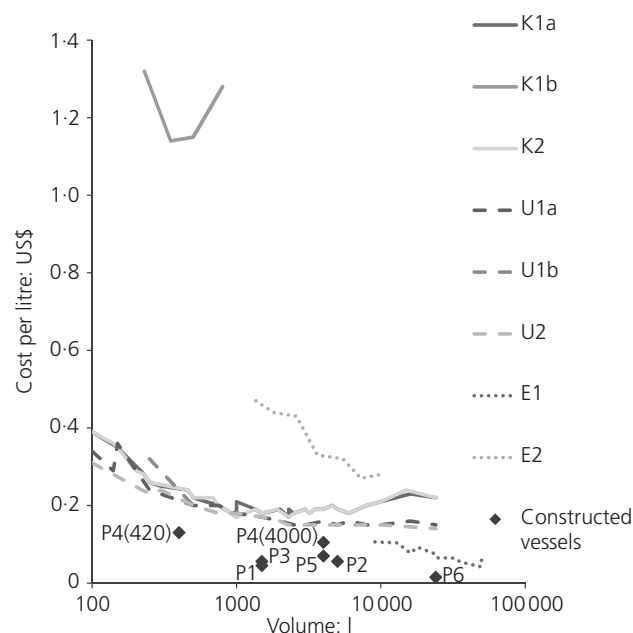


Figure 1. Variation of tank cost per litre with tank size (with outlying K1b data)

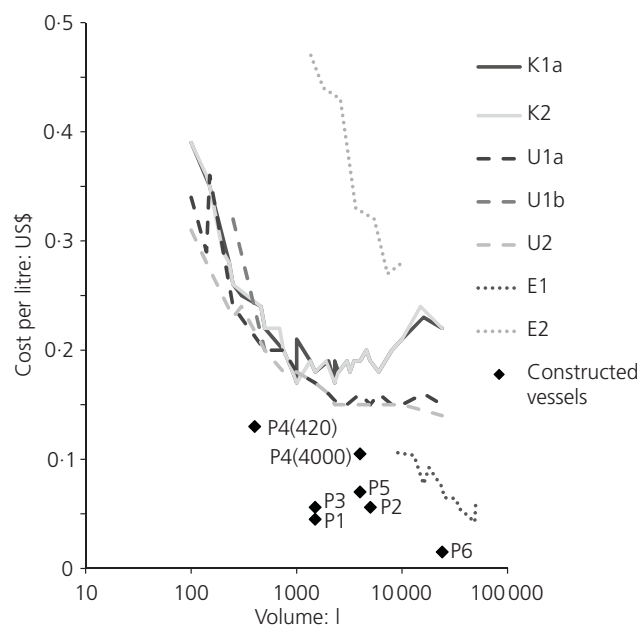


Figure 2. Variation of tank cost per litre with tank size (without outlying K1b data)

tank, is a specialist rainwater harvesting tank, so has some unique features. These include a removable and lockable lid. The lid is threaded, which is a more complex manufacturing process. These features also mean it is a niche product, not for the mass market and with little competition. In Kenya, because there is little competition, K1b tanks have a high cost.

The constructed tanks are cheaper than all the prefabricated tanks of equivalent size. While the smallest tank (P4(420) with a capacity of 420 l) has the highest cost per litre and the largest tank (P6 with a capacity of 25 000 l) has the lowest cost per litre, there is no correlation between size and cost per litre for the medium-sized tanks. Reasons for this are discussed later in this section.

3.3 Cost breakdown for prefabricated tanks

The costs of prefabricated tanks are now broken down (exact costs are not given as these data are commercially sensitive).

3.3.1 Materials

The costs of the tanks are dominated by the materials – either HDPE pellets, externally sourced from Saudi Arabia, or galvanised steel. Recently, plastic tanks have been redesigned so they are corrugated. This gives them extra strength and hence allows them to have thinner walls, thus reducing raw material costs. The companies involved in the study were reluctant to reveal the extent to which wall thickness could be reduced by corrugation – it was considered to be a trade secret.

Tank liners represent a significant additional cost for galvanised steel tanks. Epoxy resins are being trialled instead of plastic

liners, but they are still undergoing trials for suitability for potable water.

3.3.2 Transport

The next biggest cost is the transport of the materials to the factory and of the finished tanks to the customer. Some tanks have tapered rather than parallel sides so they are nestable and the transport costs of these products are reduced. For example, only six non-stackable 3000 l K1a tanks can fit on a 4 t lorry, but between 20 and 28 K1b tanks of the same volume can be accommodated on the same lorry. However, the reduced transport costs for the K1b tanks is not reflected in the final price, as the K1b tanks are specialised rainwater harvesting tanks and are hence marketed at a higher price. The galvanised steel tanks are distributed in stackable pieces, which saves space during transportation.

3.3.3 Labour

Labour costs are low as unskilled labour is used and the process is mostly automated.

3.3.4 Energy

For HDPE tanks, electricity use is low, as the principal processes that require power are extruding the plastic and pulverising the pellets. Buying ready-pulverised HDPE can reduce energy use, but ultimately this is not as cost effective as pulverising the HDPE in the factory. Gas is used to heat the moulds and to finish (i.e. smooth) the tanks once they have been removed from the mould. Replacing gas with diesel was trialled, but was rejected as it tarnished the plastic. Energy costs are much higher for galvanised steel tanks as steel processing and galvanising are energy intensive.

3.3.5 Equipment and tools

For HDPE tanks, these costs are low – the main expense is the moulds, which can be made locally but by skilled technicians. Other machinery (such as ovens, timers, extruders and pulverisers) may need to be imported.

3.3.6 Waste disposal

Waste plastic can be used to make lower grade items such as latrine slabs where cosmetic irregularities in the plastic are more acceptable. For manufacturers in the UK, more stringent waste disposal regulations result in additional expenses.

3.3.7 Tax

In Kenya and Uganda, 16% value added tax (VAT) is levied on finished tanks.

3.4 Cost breakdown for manufactured tanks

The costs for constructed tanks were divided into the following six components to allow comparison between projects.

- Cement.
- Other materials that have been purchased and transported to

the project site (referred to as externally sourced materials). These typically include reinforcing mesh, bars and binding wire, pipe and tap fittings, waterproof cement agent, bags, sacking and string used for formwork and plastic sheeting.

- Local materials sourced close to the construction site, including aggregate, bricks made in the community, water and sand. They may be bought at local markets or, if they can be gathered locally, they may be costed according to the amount of unskilled labour time taken to gather them.
- Equipment and tools that can be used for the construction of many units, for example, formwork (wooden blocks, papyrus mat), formwork support (access frame, wooden and galvanised iron poles) and tools. The cost is spread over the lifetime of the equipment and tools. For equipment owned by the masons, this is not included as the masons would pay for it out of their own salaries.
- Transporting materials to the site of construction.
- Labour costs include excavating the ground for any below- or partly below-ground tanks, skilled labour, food and board for skilled labourers if they stay in the community and unskilled labour. Skilled labour was costed at the daily wage rate, between 1.70 US/day and 2.80 US/day. Unskilled labour was costed at the local rate for unskilled labour for the district (0.80–1.20 US/day). Some projects (P1, P5 and P6) had fixed labour costs per tank. P3 costed labour as 30% of its materials. Where masons train community members to build further tanks, their costs were not included as they would need to be split between all the tanks subsequently built by the community masons.

The distribution of costs of constructed tanks is shown in Figure 3 in US dollars and in Table 2 as percentages. Table 2 also shows ranks of the cost components for each tank and gives a median ranking for each component.

3.4.1 Cement

This is one of the largest cost components of the tanks, ranking either highest or second highest. Table 3 shows the number of

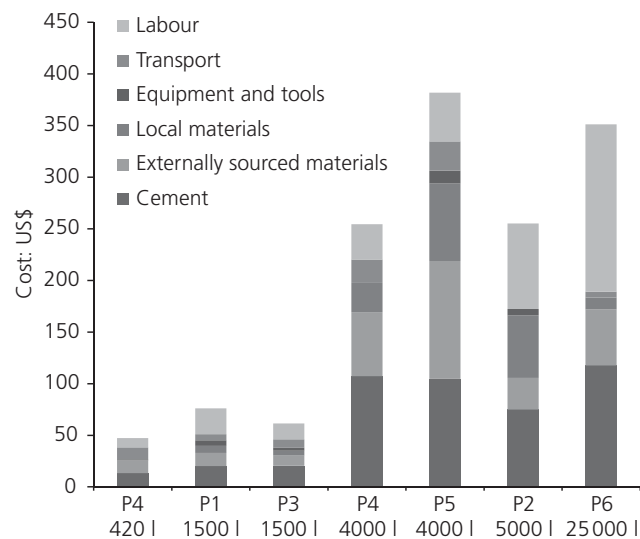


Figure 3. Cost breakdown of constructed tanks

bags of cement used for each tank and the cost paid for that cement. The smallest tank (P4(420)) uses the most cement per litre capacity, and the largest tank (P6) uses the least cement per litre, although this is a fully below-ground design so uses earth walls for support and hence does not use as much cement.

However, the cost of cement is sensitive to fluctuations in the market price and can vary between regions. P3 uses the cheapest cement, but even in this project, cement still ranks as the highest cost component. Kaujju (2007) explains that cement prices can increase if there are increased demands from major construction projects (such as those for the Commonwealth Heads of Government Meeting in Uganda in 2007) or a reduction in supply because of power cuts at the manufacturing plant.

3.4.2 Externally sourced materials

This is usually a medium ranking cost, except at P5 where it is the highest cost. This is because in this location, no sand is

Project	Size: l	Cost: US	Cost proportion: %					
			Cement	Other externally sourced materials	Local materials	Equipment and tools	Transport	Labour
P1	1500	76.17	27	17	9	7	8	33
P2	5000	256.40	29	12	24	2	0	33
P3	1500	61.43	33	16	8	5	13	35
P4(420)	420	47.33	28	25	1	2	24	19
P4(4000)	4000	254.43	42	24	11	0	9	13
P5	4000	381.88	27	30	20	3	7	12
P6	25000	351.13	33	16	3	0	2	46

Table 2. Tank cost components

Project	Type	Size: l	Number of 50 kg bags of cement	Cement bags per m ³ capacity	Cost of cement: US/kg
P1	Above ground	1500	1.6	1.1	13
P2	Partly below ground	5000	6.0	1.2	12
P3	Above ground	1500	2.0	1.3	10
P4(420)	Above ground	420	1.0	2.5	13
P4(4000)	Above ground	4000	8.0	2.0	13
P5	Above ground	4000	8.0	2.0	13
P6	Below ground	25 000	9.0	0.36	13

Table 3. Cement use for each tank

available locally and it has to be bought at market price. The two projects that spent the most (in absolute terms) on externally sourced materials were P4(4000) and P5 (both with 4000 l tanks), but these were not the largest tanks. Over half of the externally sourced materials budget for these tanks was spent on reinforcement (chicken mesh, reinforcing mesh, binding wire and reinforcing bars). Constructors of the two largest tanks spent much less on these materials as these tanks were either below ground or partially below ground, and support is provided by the earth walls of the excavation. Costs can be reduced if larger programmes can negotiate a discount on externally sourced materials.

3.4.3 Local materials

This is usually a medium ranking cost, except for the P4(420) tanks, where it is the lowest cost. This design needs only clay and sand, which can be gathered locally rather than bought at a local market. The absolute costs are also low at P6, because this below-ground tank simply requires sand, no aggregate, clay, rubble or bricks.

3.4.4 Equipment and tools

This is the lowest cost contribution, ranking either lowest or second lowest. It was noted that masons tend to care more care of equipment they own themselves, so the tools last longer. Some tank designs had no costs relating to equipment and tools, for example, the P4(4000) and the P6 tank. In both cases, the masons bought their tools out of their salary, so tools cannot be costed in this category. Mesh for construction of the P4(4000) tank was used as formwork for five tanks and as reinforcement for the base and lid of a sixth tank. It is therefore included under the externally sourced materials category. The P6 tank was fully below ground, so required no formwork.

3.4.5 Transport

It might be thought that the most remote areas would have the largest transport costs. P5 was included in this study because it is particularly remote. However, its transport costs rank similarly to the other projects, so remoteness may not have as much influence on tank costs as anticipated. For the P2 tanks, the cost to the project of the sand includes its transport, so it cannot be separated and recorded here as a transport cost. For the smallest tanks –

the P4(420) tanks – transport costs were disproportionately higher than for the larger tanks. This is because the P4 project cannot store large amounts of material at its base so cannot take advantages of economies of scale with the transport costs.

3.4.6 Labour

This is usually one of the largest components, with three projects ranking it as the highest. If the project has trained masons within the community, the skilled labour costs may be lower than if the project uses its own masons or trains masons to operate small businesses.

Differences in labour costs are the main differences between the P3 and P1 tanks, which have identical designs. The costs are otherwise similar, with the major difference being in the skilled labour costs. P3 values its labour as 30% of its material costs. However, this gives a total labour cost of just 61% of P1's labour costs, suggesting that either labour costs are lower where P3 is based or that P3 undervalues its labour.

3.4.7 Organisational overheads

Although not analysed in detail here, organisational overheads, which include office staff wages, building rental, vehicle maintenance and marketing to communities, present additional costs. In an unpublished report titled *Policy Study: Constraints to the Adoption of Roofwater Harvesting*, Thomas, Kiggundu and Karungi claim that these costs could equal the construction costs of rainwater tanks.

4. Discussion

This review suggests that below-ground tanks represent exceptionally good value because it is possible to have thinner tank walls (as suggested by the DTU (2001)) and no formwork. However, there is an additional cost that is not factored into the foregoing analysis. Below-ground tanks need a pump or other water lifting device. Of the 44 P6 tanks completed between 1997 and 1999, by January 2000, 64% were not functional due to a faulty or absent pump. Alternatives are available using a jerry can attached to a wooden pole as a dipping device, but this can introduce contamination into the water. It should also be noted

that not all areas have soils stable enough for building below ground.

Prefabricated tanks are still the most expensive option, although estimates that prefabricated tanks are three to five times as expensive as ferrocement tanks (Thomas and Martinson, 2007) are an exaggeration, at least in Uganda. Prefabricated tanks can be as little as 1.5 times as expensive (e.g. the P4 4000 l tank compared to the U2 4000 l tank; see Figure 2). However, prefabricated tanks do present other advantages.

- They can be moved to other locations if required (for example, if the owner moved).
- They require less maintenance than constructed tanks – simply requiring washing with mild detergent to remove any chemicals and bird faeces.
- They may come with a manufacturer's guarantee.
- They are quicker and easier to install.

The uniformity of design of prefabricated tanks can be important as it reduces training costs for installation, operation and maintenance. It also means that other components of domestic rainwater harvesting systems can be standardised, with similar advantages. However, factories that construct tanks use partially automated processes and typically import their machinery, so creating limited local employment.

The total tank costs found in this review are more than those found by Thomas and Martinson (2007). Thomas and Martinson costed unskilled labour at 50% of the local rates, whereas this review used the full local rate. As labour costs were the largest cost component of many of the tanks, this would explain the difference.

In Uganda, gross domestic product per capita is US 453, ranking it 167 out of 179 countries (IMF, 2009). For rural populations, per capita income is likely to be significantly lower. Despite efforts to reduce tank costs, they were still found to be US 47 for a 420 l tank and US 381 for a 4000 l tank. Tanks are thus unaffordable by rural populations without outside funding. Many NGOs have schemes in place to make the tanks more affordable; examples include the following.

- Communities make a cash contribution to the tanks. They are also expected to contribute local materials such as stone, sand and water and unskilled labour. This is how construction of tanks P2 and P5 operates.
- Projects focus on training masons in rainwater tank construction and business management. Masons then operate as independent businesses, being contracted by the community to construct tanks. Subsidies are usually available. These are the principles behind the construction of P1 and P6.
- Skilled masons work with groups in the community for 3–4 weeks to construct tanks, after which the community is

expected to undertake independent construction, with only occasional visits from project staff. Once the masons have been trained, the communities are then expected to fund any further tanks constructed, with some subsidies available. This model is used for the P4(4000) tanks.

However, as prefabricated tanks are manufactured by profit-making companies, there are currently no schemes to reduce costs below the market price for communities. This can be observed in the high price of the K1b tanks, which have features designed for rainwater harvesting. While these tanks have a design that requires a more complex manufacturing process, they are also cheaper to transport because more can be stacked onto each lorry. The tanks are marketed with a high profit margin because they are specialised rainwater harvesting tanks.

Tax relief would also reduce the costs of prefabricated tanks, and companies are lobbying for this. In Uganda, tax relief already applies to sanitation products, but has not yet been extended to rainwater harvesting equipment. The only credit schemes available are typically inaccessible to low-income customers.

The conclusion of this research is similar to the work of the DTU (2001) and Thomas and Martinson (2007) in that material costs in all tank designs were found to be the largest cost component. Below-ground tanks were found to be the most cost effective in terms of cement used (as explained earlier), but the P1 and P3 surface tanks were also efficient because of good formwork, as recommended by the DTU (2002c).

Contrary to the work of Ludwig (2005), Pacey and Cullis (1986) and Thomas and Martinson (2007), this research found that there was considerable scatter in the inverse relationship between tank size and cost per litre across constructed tanks. This scatter may have been reduced if costs were compared between tanks of the same design but different sizes. This was not done as part of this study, and would be impractical because all of the tanks were based on formwork so the size is inflexible. Smaller, cheaper tanks will either reduce the length of time over which harvested water is available or would necessitate collecting water from other sources for washing and agriculture. These may be acceptable compromises if there are significant benefits from reducing the burden of water collecting in key seasons and decreasing illness throughout the year.

If a small tank is chosen initially, it may be possible to add other tanks at a later stage to increase water availability when more money is available. This means incremental, affordable steps can be made towards an improved water supply.

Taking the cost per litre of storage from this study as US 0.20 and assuming that this represents 60% of the cost of the domestic rainwater harvesting system (DTU, 2002a), then the cost of providing 1 l/day continuously over the life of the system lies between about US 10 and US 20. A rural water supply borehole

equipped with a handpump in sub-Saharan Africa typically costs about US 5000–10 000 (Cranfield University *et al.*, 2006). The limiting factor in terms of supply is often the pump itself (combined with hours of operation and queuing times). The authors' experience is that a typical handpump will deliver 6000–8000 l of water over a day. Consequently, the cost of supplying water at a rate of 1 l/day continuously over the lifetime of the equipment is US 0.6–1.7. In other words, even under favourable conditions, the cost of a reliable water supply delivered by a domestic rainwater harvesting system is about ten times that of a community water supply provided by a borehole and handpump.

5. Conclusions

In general, tank costs per litre decrease as size increases – that is, economies of scale are operational. This relationship is stronger in prefabricated tanks than in constructed ones, although some companies price their larger tanks more expensively because demand is low. Constructed tanks are generally cheaper than prefabricated ones. Below-ground tanks can be cheap if ground conditions are suitable and a scheme is in place for pump maintenance. Galvanised steel tanks are the cheapest of the prefabricated tanks; HDPE tanks are the most expensive option, although there are advantages to these designs.

For all tank types, materials represent the greatest cost. Labour costs were the second greatest cost in constructed tanks, but were only a small fraction of the costs of prefabricated tanks. Labour costs can be reduced and communities can benefit if community members are trained as masons. Transport costs were the second greatest cost in prefabricated tanks, but the third greatest cost in constructed tanks.

6. Recommendations

To reduce constructed tank costs further, design development needs to continue, including new designs, novel materials and options for mass production. There is a clear need for tanks that are cheaper, easily transportable, durable, resistant to puncture and repairable. There needs to be dissemination between projects of current technologies. Working with banks to provide low-cost credit and other financing options would also make tanks affordable to more people.

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