Affordable Roofwater Harvesting in the Humid Tropics

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Abstract

The relatively high cost per household of installing full domestic roofwater harvesting (DRWH) has resulted in its take-up being largely limited to areas of especially high water stress or where DRWH is subsidised. The paper discusses various ways of attaining satisfactory benefit:cost ratios in areas where DRWH is not the only water supply option, for example by adopting partial or seasonal supply and by minimising ‘first cost’ (generally construction cost) at the expense of raising subsequent costs. As water storage accounts for the bulk of expenditure on most systems, the paper then focuses on means of minimising the construction cost of storage tanks in the size range 1000 to 10000 litres. Best cost-cutting practices with respect to both surface and underground tanks are reviewed. An approach of separating the ‘structural’ and the ‘water-proofing’ roles of construction materials is proposed and applications of this approach to both sorts of tank are examined. The paper will particularly reflect experiences in South Asia and East Africa which are the geographical focus of an ongoing 4-country DRWH research programme funded by the European Union.

1 Introduction

All participants at this conference will be familiar with the general properties of harvested roofwater - its generally high but not excellent quality, its seasonality and uncertainty, its convenience in being available very close to dwellings and its often high cost. This paper is mainly concerned with a particular scenario, the ‘humid tropics’, rather arbitrarily defined as a climatic zone for which annual rainfall exceeds 1000mm and where any dry season does not normally exceed 5 months in duration. In comparison with the scenarios commonly addressed by rainwater harvesting specialists, the humid tropics are comparatively easy. Even so the cost of any system capable of meeting all of a household’s water needs throughout the year is likely to exceed $400 - unacceptably high for most low-income households in tropical countries. This cost is dominated by the cost of providing adequate storage. To achieve 95% reliability of roofwater supply where household water consumption is (only) 100 litres per day requires 10 to 15 cubic meters of storage: higher consumption rates require proportionally more storage.

It is therefore arguable that ‘total’ (complete, all-year) roofwater harvesting (RWH) is an inappropriate objective for most households or communities and that ‘partial, seasonal’ RWH should be the norm. Moreover even where total RWH is an ultimate objective, it makes much sense to reach it in stages by the stepwise extension of an initially partial and seasonal system. In the humid tropics there are generally alternative sources of water to roofwater. These sources commonly have defects such as high cost, low quality, unreliability or inconvenience; (indeed if they did not, we would hardly be considering RWH at all). However they are usable and indeed are being used now. In designing a RWH system we therefore need to take these rival sources into account, acknowledging of course that their characteristics vary with the seasons and that they are under greatest stress precisely in those dry months when we need to fall back on them.

2 Combinations of RWH with other water sources

Roofwater is usually premium water, almost certainly more convenient than water from any alternative source and often cleaner. It may be softer and have a better taste (although not if stored in new cement-lined tanks). Whether it is cheaper will depend heavily upon the design of the harvesting system and in particular upon the ‘availability’ standard chosen.

One common pattern of combination - we will call it Scenario A - is rural RWH backed by haulage of water from a distant spring or well. The quality of the roofwater is likely to be similar to that of the other sources. The primary benefit of installing RWH is the reduction in haulage effort it offers. This benefit is more or less proportional to the water consumed whereas the cost of delivering roofwater is a rapidly rising function of quantity so supplied. The economically optimum size of the water store in a RWH system is likely to be between 7 and 30 day’s consumption, with the larger figure applying where the water haul is particularly onerous. A number of water plans (e.g. Indian norms [Teeka Ram, 1996]) appear to use 1500 meters horizontal distance or 100 meters height difference as the threshold of “unacceptably onerous” although these distances are commonly exceeded in developing countries. An economic RWH system may reduce the labour of water fetching by 80%. An interesting side effect is that the possession of say 7 days storage often assists water haulage itself, allowing a household to replace daily water-collection trips on foot by weekly trips by animal cart or even by motor vehicle.

Example of Scenario A : A rural RWH system in a bimodal rainfall region of Uganda
Daily household demand = 120 litres, daily roofwater runoff = 150 litres (averaged over several years)
IOSC denotes ‘Internally Optimised Storage Capacity’ to give minimum unit water cost.

Water storage as a multiple of daily demand (and as m^3)	S/D m^3	1 0.12	2 0.24	**4 = ‘IOSC’** **0.48**	8 0.96	16 1.92	32 3.84	64 7.68	128 15.36
Benefit (% reliability of RWH supply) *	B	31	46	**60**	70	78	89	97	99
Notional system **Cost** in $ **	C	28	31	**37**	49	65	105	185	345
Cost/benefit ratio normalised to its minimum value	$\frac{C/B}{C/B_{MIN}}$	1.46	1.09	**1.00**	1.14	1.35	1.91	3.09	5.65

*Fraction of days on which full demand can be met with roofwater. ** Storage capacity costs $25/m^3 and we assume no economies of scale in tank construction; other system components cost $20.

Assuming negligible running costs, the normalised cost/benefit measure will also stand for the normalised cost per litre of roofwater supplied. In this example the internal optimum storage capacity (IOSC) is only 4 days' consumption; it is shown in bold in the table. Were the calculations to be repeated for a unimodal (Monsoon) rainfall region, the 'reliability of supply' figures would be lower and the tank size for minimum unit cost, IOSC, would be a little higher.

Another common pattern - Scenario B - is to combine urban or village RWH with an unreliable piped supply. The harvested roofwater directly reduces the consumption of piped water and gives the household a much higher level of water security. The storage facilities are of use with both roofwater and piped water sources. Holding low-quality piped water (any intermittent piped supply is likely to be seriously contaminated) in a darkened store is likely to improve its quality, especially if the internal flow-paths in the store have been designed to prevent 'short-circuiting' from inlet to outlet.

A further Scenario C is where roofwater is much superior in quality to any alternative source. In this case it is prudent for a household to reserve roofwater for premium uses (drinking and cooking) and use other sources for laundry, bathing etc. During any dry season the stored water is used only for the premium uses (for which as little as 8 lcd may be sufficient) and the storage is sized to give a high reliability against this low demand. However even here it is uneconomic to aim at over say 97% reliability, since employing expensive water treatment (like boiling) for a few days a year would be cheaper than constructing a larger tank. During any wet months, once the 'premium water' store is largely refilled, roofwater can also be applied to non-premium uses.

A final Scenario D [Appan, 1997], rather uncommon in the tropics, is where there is a piped supply of excellent quality but high cost. Sometimes the piped supply is facing problems of rising demand that can only be met by a major and high-cost investment which the water company is eager to delay. Here roofwater may be deemed of inadequate quality for general use, but may be acceptable as a substitute for piped water for specific 'non-premium' uses such as toilet flushing. Optimum storage capacity will generally be small.

With all these scenarios, RWH is ruled out if its *minimum* cost per litre (corresponding to the *internally* optimum storage capacity - IOSC) is higher than that of any acceptable alternative. However normally it is economic for a RWH system to be built and indeed for a storage higher than IOSC to be used. Once storage exceeds about four times IOSC, the cost per litre rises rapidly and soon becomes economically unacceptable. There will exist some *externally* optimum storage capacity, EOSC, at which the cost of the combination of RWH and other water sources is minimised. This EOSC will always be higher than the IOSC.

As dry season water is more costly to supply than wet season water, it is prudent with RWH to vary consumption with the season. Most owners of RWH systems do this to a modest extent and thereby effectively reduce the mean cost per litre.

3 Strategies for reducing the cost of RWH systems

In the preceding section the emphasis was put upon economically optimum *sizing* of the storage capacity built into a RWH system. Clearly costs are reduced if tank sizes can be reduced, guttering can be made smaller or even roof area can be reduced.

We now look at ways of reducing the cost of a given volume of water storage. The general strategies we could follow, whether in researching cheaper tanks or in specifying them for a specific RWH project, are mostly covered by the following list:-

a) *reduce the quantity of materials used*
b) *reduce the quality (and hence unit cost) of the materials used*
c) share tank materials with other functions (such as house structure)
d) reduce labour costs of tank construction
e) reduce transport costs
f) *remove the need for special shuttering etc*.

Within this list we will concentrate here upon the italicised items (a), (b) and (f).

Materials incorporated in a rainwater storage device have two primary roles, namely to provide structural support and water retention. The same material may perform both roles or alternatively one material may be used for ‘strength’ and another for ‘waterproofing’. As we shall see, there is considerable interaction between the two.

Strength is the ability to contain the forces applied to a structure so that it operates satisfactorily (e.g. does not yield and leak) and does not collapse. This strength needs to be maintained for a number of years in the face of deterioration processes like rusting. Even if performance is eventually degraded, there should be little chance of a dangerous collapse. The forces of interest are gravity forces, water-pressure forces and external loading.

Gravity forces are quite large (each cubic meter of water weighs one tonne) but easily resisted provided the tank is not elevated. Because even slight movements may induce cracking in brittle materials, tanks - like house walls - require foundations that spread their weight over a sufficiently large area of ground that sinking or tilting do not occur over time. It is not uncommon to see jar type tanks leaning like the Tower of Pisa some years after their construction. The gravity forces of most difficulty to resist are those acting on horizontal members - in the case of tanks this means covers. Constructing covers of more than two meters diameter requires greater skill and more equipment than does constructing walls. Possibilities for simplifying cover construction are discussed in Section 6 below.

Pressure forces give rise to lateral tensions in walls - so-called ‘hoop’ tensions in cylindrical walls. This is problematic because most cheap durable building materials have a low tensile strength. Equally troublesome, their tensile stiffness is low and they may respond to tension by developing small vertical cracks that compromise water tightness. In the absence of any flexible waterproof lining, we should seek to minimise the tensile *strain* due to pressure forces to as little as .01% (100 microstrain) for cementitious materials or masonry. Better still we should strive to keep such materials in permanent compression and hence negative strain.

The need to resist external loads arises because of safety (covers should not collapse when climbed on) and because it is often socially impossible to prohibit such loading as a lorry driving over an underground tank. In this sense surface tanks are often less vulnerable to large external loads than underground tanks. In some countries earthquakes are another source of loading: a severe quake can generate temporary horizontal forces up to 10% of the weight of a tank plus the water in it.

Against this general background, the Development Technology Unit at Warwick University UK is researching ways of :-

- making the walls of cementitious or masonry surface tanks thinner (than current practice)
- substituting weak materials like stabilised soil for concrete/ferrocement
- simplifying tank-cover construction
- going underground and using the ground to resist pressure forces
- improving water quality by better tank design

of which only the first three are reported here. This research is part of a three-year four-country collaborative research programme funded by the European Union. The other components are studies of health aspects of RWH led by the Indian Institute of Technology, Delhi, India, studies of water security issues led by Lanka Rainwater Forum in Colombo, Sri Lanka and examination of institutional/professional constraints on the expansion of RWH led by FAKT, an NGO in Stuttgart, Germany. The programme also has a small E African component. As part of this programme, case studies of well-designed RWH system components are being documented. [RHRG, 1999]

4 Making tank walls thinner

The walls of above-ground tanks are usually built with zero initial strain (although the shrinkage of concrete during curing may generate tensile strains near the bottom of walls whose contraction is resisted by connection to a rigid base). Introduction of water therefore generates tensile stresses and strains. For a cylindrical tank of diameter D and wall thickness t, the hoop stress in the walls at depth h below the water surface will be up to $\sigma = \rho g hD/2t$ ($= 5hD/t$ kPa in MKS units) and in masonry or concrete this corresponds to about $\varepsilon = 0.15\ hD/t$ microstrain.

Inserting exemplary values of $h = 2$ m, $D = 2.5$ m and $t = 0.04$ m gives tensile stress equal to $\sigma = 625$ kPa and tensile strain $\varepsilon = 20$ microstrain. For cementitious materials these figures are acceptably low, even in the absence of reinforcing, *provided* that the construction process has left no cracks. Unfortunately the shrinkage of mortar while setting, curing and drying may exceed 1000 microstrain and in the presence of constraints to movement may set up substantial cracks. Poor curing will make these even worse. Including steel reinforcement has little effect upon the loading strain in the mortar, but may help prevent the formation of a few large cracks by converting them into numerous micro-cracks. Ferrocement construction requires the steel mesh more as a 'former' against which the mortar is applied than as strength reinforcement.

In theory one should be able to go down to a wall mortar thickness of as little as .01 m (1 cm) in a ten cubic meter tank without exceeding the tensile strain limit of the walling material. Such a low value is however not used [Skinner, 1995] because there is a belief that the steel needs a mortar 'cover' of 1 cm or more on each side to protect it from rusting. Moreover the quality control and skill problems of applying such a thin layer are considerable. There are however moves to make ferro-cement thinner and one important aid would be a low-cost (electronic?) means of monitoring the mortar thickness as it is applied to a steel mesh.

If thinning the mortar requires better micro-crack control [Neville,1995 p298-300, Chap 9 & p525-9], then reinforcement of the mortar by a small amount of modern and cheap water-resistant fibre is an interesting option, as is the use of controlled permeability 'formwork' (backing the wire mesh) to dry the surface layer [Price,1990], use of additives like micro-silica [Parker,1985] to reduce permeability or plasticisers to allow lower water/cement ratios and of course higher quality curing.

Experiments are underway concerning the development of surface cracks and the use of reinforcing fibres and micro-silica.

5 Using weaker, cheaper walling materials

One would like to be able to move away from using cement mortar, as cement accounts for a high proportion of the cost of a surface tank made in a country where labour is cheap and cement is not. The main candidates for cheaper walling materials are brick (especially low-quality clamp-fired brick) and stabilised soil (whether in the form of blocks or of rammed earth). In some locations stone masonry may be an option. Plastics already have a significant share of the water tank market, but even using recycled plastics it seems unlikely that they represent a route to much lower costs. More promising is the combination of small quantities of plastics with bulkier but less water-resistant materials. Organic materials such as wood and fibre seem inherently unsuited to long term use in water tanks (where the water level varies so that materials may be cyclically wetted).

Cheap brick and stabilised soil are not widely used for surface tanks because of their low ‘wet’ compressive strength, their high permeability or their unreliability in tension. Clearly a material with *no* compressive strength when wet is difficult to use near water. Mud architecture has a long history showing it is possible to so protect the top and bottom of mud walls (even in moist climates) that they last for centuries. However a water tank’s walls are so vulnerable to extensive wetting that it seems prudent to insist on any construction material in them to have some wet compressive strength - say 1MPa - a figure that can be reached fairly easily by the two materials under discussion.

Excessive permeability can be combated by incorporating special additives within the material itself but is most easily handled by the use of an internal waterproof lining such as a cement-water render, proprietary sealants or thin plastic membranes. (However membranes such as 250 micron polythene sheeting, are hard to attach and may be too easily punctured during construction or maintenance.) If the render is not flexible it may crack during the dimensional cycling that accompanies filling and emptying of the tank, so it becomes attractive to limit that cycling, or to prevent the opening up of any initial cracks, by keeping the render permanently in compression.

Unreliability in tension is probably the greatest barrier to using low-quality walling materials, but it may be overcome either by adequate internal reinforcing or more easily by external post-tensioning. In the latter case, wire or strapping can be wrapped round the outside of newly-built cylindrical tanks and then tensioned to say 30% of its yield strength (15% of UTS). Thus we might tension a 2 mm diameter steel wire to around 400 N. If this initial wire tension also corresponds to the hoop tension in the wall required to contain the internal water pressure of a full tank, one can guarantee that the walling material is permanently in compression. Since the required hoop tension varies from zero at the top of the tank to a maximum value at the bottom, the number of turns of wire can be varied in sympathy. Although the tension in the steel rises above its initial value as the tank is filled, it only does so by a small fraction. A ten cubic meter tank requires about 13 kg of such mild steel wire.

Post-tensioning raises many technical issues, such as protecting the exposed steel from rusting (is galvanising sufficient?), actually tensioning the wires, anchoring the wires to themselves or to the mortar, and accommodating any creep, shrinkage or swelling of the brick or mortar following tensioning (only about 100 microstrain change may be tolerable). The likely success of post-tensioning in closing micro-cracks in a tank's render is also hard to calculate. These are all research issues.

Three experimental tanks are under construction (February 1999) and their performance will be reported when this paper is presented.

6 Simpler covers for tanks

Tanks require covers to control evaporation, guard against contamination, maintain child safety, exclude insect vectors and impede algal growth. The covers can be built directly into position (before or after the walls) or built alongside the walls and later lifted onto them. The latter technique simplifies cover construction but raises its own problems of local over-stressing during lifting and the waterproofing of the cover-wall connection. Covers can be designed to be wholly in compression (arch and inverse catenary shapes) [McGeever, 1997] or partly in tension (flat discs and cones). The latter require use of materials capable of sustaining bending moments.

Following construction of two 'lift-on' ferrocement tank covers in UK using a thin shell 'reciprocal' structure and hence no formwork, similar covers will be tested in Uganda in June 1999 on both surface and underground tanks. Provided initial strength test results are confirmed, this structure looks a promising way of simplifying construction and perhaps also of reducing material content via simpler thickness control. For underground tanks, the interface between such a lift-on cover and the top of the underground bowl may be used to anchor a polythene sock liner hanging within the bowl.

7 Conclusions

The cost of high reliability RWH systems in low-rainfall areas is extremely high. In more humid areas there is considerable scope for reducing costs, firstly by using realistically small storage volumes (and relying to a small degree on alternative sources) and secondly by economising on the quality and quantity of construction materials. Simulations suggest that the economically optimum storage volume in the humid tropics lies in the range 4 to 20 day's consumption. Calculations suggest considerable scope for making tanks with thinner walls or using materials like low-quality brick or stabilised soil blocks, provided the construction technique can deal with the problem of surface cracking in mortars. Cover construction may also be considerably simplified.

This paper is based on new research started in late 1998 which has yet to yield much experimental data. The paper therefore reports mainly strategies to make RWH cheaper. By the time of the Conference however, more experimental data will be available for presentation.

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