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Domestic water supply using rainwater harvesting

Terry Thomas

Development Technology Unit, Department of Engineering, University of Warwick,
Coventry CV4 7AL, UK
E-mail: dtu@eng.warwick.ac.uk

World-wide pressure on water resources is mounting as populations grow, consumption per capita increases, 'fossil' water resources are mined and the climate changes. Domestic water usage is a significant component of water demand. Under favourable circumstances, it can be met in part or in whole by rainwater collected close to an individual dwelling. Interest in such systems is growing especially in rural areas where either rainfall is well distributed through the year, or where surface water is absent, groundwater mineralized and centralized piped supplies unaffordable. Roofwater collection is also being practised on low-rise and high-rise buildings in some cities having wet climates. The principles and components of rainwater harvesting are reviewed. Factors leading to the growing use of domestic rainwater harvesting in three different developing countries (North China, East Africa and Singapore) as case studies are discussed along with current practices, design options for system components and considerations for water quality and treatment. The lessons from developing countries can be applied to a European context as some European towns are beginning to require rainwater collection for toilet/laundry facilities in some new buildings.

La pression mondiale sur les ressources en eau s'élève au fur et à mesure de l'accroissement des populations, de la consommation par habitant, de l'exploitation des ressources d'eau 'fossile' et des variations de climat. L'emploi domestique de l'eau est une importante composante de la demande en eau. Dans des circonstances favorables, elle peut être satisfaite partiellement ou totalement par l'eau de pluie recueillie à proximité d'une habitation individuelle. De tels systèmes connaissent un intérêt grandissant surtout dans les zones rurales où les précipitations sont bien réparties tout au long de l'année, ou les zones dépourvues d'eaux de ruissellement, ou celles dont les eaux souterraines sont minéralisées et où la distribution centralisée par conduites est inabordable. Le captage de l'eau des toits est également pratiqué sur les bâtiments à faible et forte inclinaison de toiture dans certaines villes à climat humide. Les principes et organes de captage des eaux de pluie sont passés en revue. Les facteurs suscitant un recours grandissant au captage des eaux de pluie pour des usages domestiques sont examinés en tant qu'études de cas dans trois pays en voie de développement (Chine septentrionale, Afrique orientale et Singapour), conjointement avec les pratiques usitées, les options de configuration d'organes de système et les considérations relatives à la qualité et au traitement des eaux. Les leçons reçues de pays en voie de développement peuvent être appliquées à un contexte européen, étant donne que certaines villes européennes commencent à ressentir la nécessité du captage des eaux de pluie pour les installations de toilettes et de buanderies dans certains nouveaux bâtiments.

Keywords: domestic water, rainwater harvesting, roofs, alternative technologies, building services, sustainability

Introduction

Drinking water is of course a critical resource for human life, although in most climates only about 2 litres per person per day is required for survival. Domestic water consumption per capita in different countries ranges from 7 to 300 litres a day, so that even at the bottom end of this range drinking water accounts for only a small fraction of total consumption. World-wide the human activity consuming most water is irrigation, an activity being vigorously expanded in almost all hot countries as demand for food rises with population growth. Not surprisingly, therefore, competition for water between agriculture and other human uses is becoming intense in several countries, while competition between adjacent countries is leading to the phenomenon of 'hydro-politics'.

Although most non-agricultural water consumption takes place within buildings, it is rather unhelpful to assign the industrial component of consumption to 'buildings'. For the purposes of this paper we therefore restrict ourselves to discussing water consumption in residential and commercial buildings and adopt the adjective 'domestic' to describe the associated water supply. We are interested in the need for, and the means of attaining, greater 'autonomy' in domestic water supply.

It has long been known (White *et al.*, 1972) that domestic water consumption is highly influenced by the 'ease' with which it can be obtained. Thus a household to which water is hand-carried from a distant spring will typically consume under 10 litres per capita per day (lcd) whereas a household in the same country will consume over 100 lcd if it has a reliable piped supply to taps within the building. This 'ease' does not correlate closely with cost, so it could be argued that water supply is characterized by price distortion. Certainly there are economies of scale such that isolated rural buildings usually cost more to supply than concentrated urban ones. For these and other reasons, in developing countries urban water is often piped while rural water rarely is.

Unlike irrigation water, domestic water is not consumed in the sense of being lost; it is merely dirtied into 'grey water' from sinks and 'black water' from sanitary appliances. Domestic water autonomy may therefore by pursued by two technically very different routes, namely rainwater harvesting and wastewater recycling. The former is an old technology now being given a new look. On the scale of a single building, the latter is a new technology not generally yet ready for economic use. This paper addresses only the former.

Money can generally buy a good water supply, even if it means transporting water from a very distant source. So it is not surprising that the strongest current interest in domestic rainwater harvesting can be found in poorer (developing) countries. Of the various reasons for pursuing domestic water autonomy, dissatisfaction with the reliability or cost of centralized supply alternatives is the strongest. However, in the longer term we can expect clean-water scarcity to intensify globally, so that water autonomy within buildings – coupled with a reduction in the water intensity of human activities – will become an attractive option even for some living in richer countries.

The writing of this paper coincides with a substantial upsurge of interest in rainwater harvesting. This has been reflected in the recent formation of rainwater associations in several tropical countries, the holding of large national and international conferences on the topic (e.g. in China 1996, and Iran 1997) and the opening of a African 'Rainwater Harvesting Information Centre' in Nairobi.

Domestic rainwater harvesting (DRWH): principles and system components

Historically, domestic rainwater harvesting has been practised wherever conditions for it have been particularly favourable or conditions for other means of water supply have been particularly difficult. Pacey and Cullis (1986) and their 200 references document the history of rainwater harvesting and the methodologies popular a decade ago. The three key system elements are (i) a collection surface, (ii) guttering and (iii) a water store. The first must be large enough to intercept in a year not less than the building occupants' annual water need. Various rules of thumb have been developed to judge this. Existing surfaces such as roofs are usually used. The second element, guttering, is usually the cheapest of the three but often rather neglected. The third poses the greatest cost burden. The storage capacity must be large enough to buffer both the short-term fluctuations in water usage and the longer-term fluctuations in rainfall. The sizing of storage tanks is well covered in the rainwater harvesting literature (McMahon and Mein, 1978; Heggen, 1993; Gould, 1993). Optional additional elements include those to improve water quality – particularly important when the collection surface includes ground surfaces as well as roofing – and those to assist the user to operate the system prudently.

Because the roofing component of any collection area is usually constructed primarily for other reasons than water harvesting, its cost is often not included in the evaluation of DRWH. Indeed the need to build a roof solely for harvesting would usually price DRWH out of the market. The type of roofing clearly affects the quality of the run-off from it, and in several countries interest in harvesting has coincided with a change from soft roofing materials like grass to hard ones like corrugated iron or tiles. As one of the case studies below shows, collection from ground surfaces is not totally ruled out, however, roof collection remains the norm.

Guttering serves several purposes. In Europe it is used to protect the walls of buildings from damp penetration, the soil around them from erosion and passers-by from drenching. In Africa and parts of Asia, by contrast, most single-storey buildings lack guttering and a large roof overhang is used instead to protect the walls. The overhangs also provide solar shading. The installation of guttering may therefore be wholly chargeable to DRWH, although it often has ancillary benefits. (In urban areas subject to tropical rainfall, soil erosion around unguttered buildings is often severe to the point that foundations are undermined.) Guttering both intercepts and transports roof run-off. These separate functions may create design conflicts in very low-cost guttering. This is because increasing a gutter's gradient allows its size and cost to be reduced but may reduce the fraction of run-off that is intercepted. Water losses caused by exceptionally intense rain overshooting gutters may be acceptable from a harvesting point of view yet cause serious erosion damage. Within guttering we may also include gullies and downpipes where they are required (sometimes spouts or chains or guidance rods will serve more cheaply). A satisfactory alternative to guttering with some roof types is a diagonal bead built across the lower part of the roof surface.

Because storage requires the major expenditure in most DRWH systems, minimizing tank costs must be the major objective of any organization working to promote harvesting. Indeed it is useful to distinguish three styles of DRWH by the ratio of storage capacity to daily water consumption (which is a normalized measure of that capacity). The lower the ratio, the cheaper the system but the greater the seasonal dependence on other sources.

Figure 1 illustrates the influence of storage provision. It relates availability of rainwater (as a fraction of each year) to the storage to consumption ratio for two locations in Uganda. Both locations are favourable to DRWH, having two rainy seasons a year. Mbarara receives 900 mm precipitation a year and Kyenjojo 1400 mm. Normally one would design for an average daily demand (consumption) D smaller than the mean run-off R from the roof, so a D/R ratio of 0.8 has been assumed. The plots show that even with only 4 days' storage DRWH can supply water for over half the year, whereas it takes over 2 months' storage to bring that supply availability up to say 97%. Even where the roof area is inadequate – for example the D/R ratio rises to 1.5 so that even infinite storage cannot guarantee a high availability – a week's storage gives a useful 47% availability. From these curves we can recognize three DRWH styles namely:

- *wet-day DRWH* operated with a storage not greater than 1 day's consumption;
- *wet-season DRWH* storage equal to say 3–10 days' consumption;
- *all-year DRWH* storage equals 60–300 days' consumption.

Obviously the storage for *all-year DRWH* depends

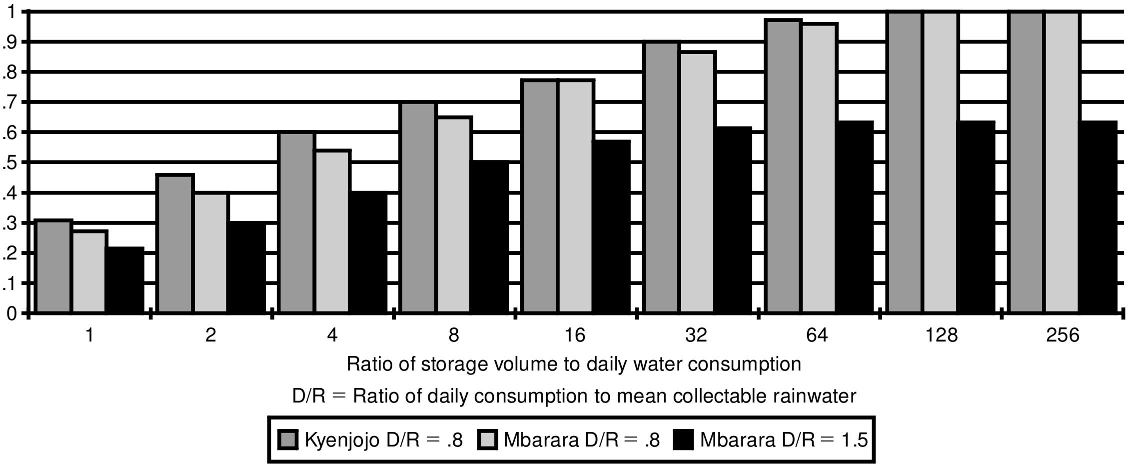

Fig. 1. Availability of rainwater supply (as fraction of year).

critically upon climate. There are humid tropical locations and islands where daily rainfall is so reliable that *all-year* supply can be obtained with negligible storage. Such conditions are quite rare and often correlate with low densities of human settlement. Excluding such locations, it might be expected that areas (like Kyenjojo in the figure) combining high annual rainfall with short dry seasons would demonstrate most use of *all-year* harvesting, but this is not generally so. Many DRWH techniques have been pioneered in semi-arid areas having a very long dry season, not because these areas favour harvesting but because they so strongly disfavour all alternatives. Such areas have no rivers for most of the year and their underground aquifers may be very deep or unacceptably mineralized. An increasing fraction of the world's population is found in such zones.

Enlargement of the domain of DRWH is likely to occur on two fronts. As storage costs fall we may see expansion of 'easy' DRWH from areas of well-distributed or bimodal rains into unimodal rainfall areas. We may also expect growing problems of groundwater mineralization (e.g. arsenic in Bengali aquifers, fluorides in East Africa) to encourage more DRWH in areas where it was formerly unnecessary.

Both *wet-day* and *wet-season* DRWH imply that an alternative source of water (invariably less convenient or more costly) is available for dry season use. This mixing of DRWH with another form of supply can also take another form, namely the use of rainwater for some functions and another source for other functions. The allocation of sources to applications depends mainly on quality as is discussed below.

There has been much interest in low-cost forms of domestic water storage (Bambrah, 1995; Skinner, 1995). For *all-year* DRWH the storage volumes required may be high. Three hundred days' dry season storage for a family of six each consuming 20 litres a day (a WHO minimum quantity standard) represents 36 cubic metres. Even with a more favourable climate and a lower consumption, 5 to 10 cubic metres storage is commonly required. Taking into account wage levels in most tropical countries, it is unlikely that DRWH will be affordable unless storage costs can be kept below $15 per cubic metre.

Several DRWH programmes have promoted mortar jars as water stores, usually based upon a Thai model (Gould, 1992). These typically offer around 1500 litres capacity and therefore correspond to *wet-season* DRWH. In many climates this would appear to be the least attractive of the three DRWH styles, being quite expensive yet not offering relief from reliance on other sources. However, field observations suggest that the possession of several days' storage is seen by householders as having benefits beyond DRWH. A weekly trip in the dry season – perhaps with borrowed transport – to refill the big jar with water carried in smaller vessels from a distant well, gives greater peace of mind than having to transport water daily. Moreover, it is attractive to be able to engage with a new technology in easy stages, buying units of DRWH storage piecemeal over several years rather than having a massive outlay in year 1. Finally we may note that expensively splitting storage between several small tanks offers greater security against tank failure and may reduce guttering costs.

Underground tanks (Fig. 2) compete with those above ground and those actually within the building. As relatively few buildings have been designed deliberately for DRWH, the storage has rarely been fully integrated into the building structure. Underground tanks are generally cheaper than surface ones, but possess significant disadvantages. They require pumps with which to extract the water (however they are not vulnerable to emptying because a child has left a tap running). Their integrity is difficult to monitor because leakage flows are not visible: moreover leaks known to exist from observation of water loss are very difficult to locate. Under extreme circumstances they may be polluted by entry of

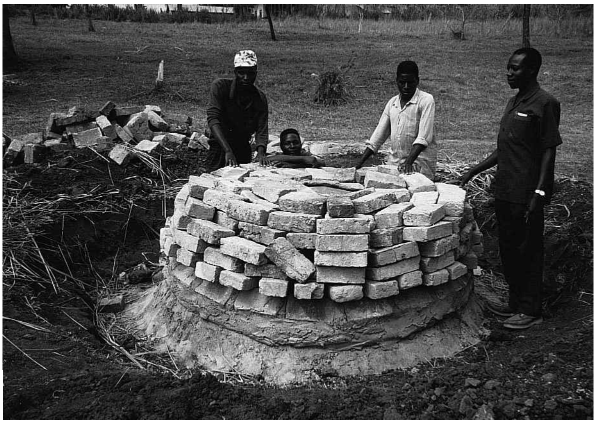

Fig. 2. Dome of a prototype underground rainwater tank in rural Uganda undergoing proof loading to 1500 kg.

groundwater through flaws or of floodwater through their covers. They might float out of the ground; the danger of infants drowning is greater than with above-ground tanks; their covers need to be strong enough to carry people and perhaps even vehicles. An area of important debate is the extent to which underground cisterns can rely on the soil for support and hence be made cheaply thin-walled and unreinforced (McGeever and Thomas, 1997; Anchor *et al.*, 1979).

Tanks, whether above or below ground, need to be covered to control evaporation and mosquitoes (now the major disease vector in the tropics) and for safety reasons. There is much to be said for excluding light and thereby preventing algal growth, even though strong sunlight has a bactericidal property. Achieving cheap and effective coverage while still maintaining aeration and the easy entry of water is not a trivial design problem.

Water quality

The essence of rainwater harvesting is the interception of precipitation before it gets dirtied. However, contamination could take place in the air itself, on the collection surface or in the store, such contamination being either by biological pathogens or by dissolved chemicals. It may therefore be desirable either to treat harvested water, to restrict its use or under the most unfavourable circumstances to forego using it.

In all but the most industrially polluted areas, we can neglect the contamination of rain as it falls. There is no evidence that pathogens can be picked up, and the absorption of say acid gases is very slight. 'Acid rain' may affect lakes and certain trees, but its degree of acidity is well within that tolerable to humans. Moreover any subsequent storage is likely to expose the water to acid-natralizing substances such as mortar. The very lack of dissolved calcium or magnesium accounts for the historical construction of rainwater catchment systems – for example in some areas of Britain – specifically for washing clothes. The replacement of laundry soap by detergents in industrialized countries after 1950 has reduced the demand for such 'soft' water although demand for hyper-filtered drinking water has recently risen in those same countries.

Contamination by the surface onto which rain falls is a more serious matter, even if we restrict ourselves to collection from roofing. The roofing material itself, if impermeable and hard, usually poses few problems. Even rusty corrugated iron does not give an unacceptable iron content to run-off and asbestos roofing is generally now thought *not* to cause carcinogenically significant levels of asbestos in water (its installation may however endanger health via airborne fibres). It is what accumulates on roofs that matters. By the end of a dry season in the tropics, most roofs are coated with dust and organic material. Where trees overhang roofs, bird droppings are common. These contaminants may silt up or deoxygenate water stores, discolour water and occasionally cause disease. It is therefore quite common to make provision for throwing away the first wet-season flush from a dusty roof (which can have the consistency of brown soup!), but it is less common to actually treat the collected water other than by natural sedimentation and bacterial die-off during storage. Sometimes boiling drinking water from roofs is 'recommended' and certainly the regular cleaning of tanks is advisable. Faecal coliform counts (the commonest measure of bacterial cleanliness) of stored water sampled by the author have rarely exceeded 4 per 100 ml – a tolerable figure in tropical rural areas although unacceptable in a European urban supply. The suspicion that bird droppings can occasionally propagate typhoid is more worrying.

There are several ways forward. Where roofwater is generally cleaner than water from alternative sources, whether due to the latter's contamination at source or during its transport to a house, any treatment can be left to the household's discretion. Where standards are very high (as in the Singapore case study below) it is simplest to restrict the use of run-off to non-critical applications like toilet flushing, livestock watering or garden horticulture. Water-use allocation by water quality has implications for storage, for plumbing, for water standards and for quality control; it can even result in the physical relocation of water-using activities, for example doing laundry at the stream-side not in the homestead. There is the beginnings of a move in industrialized countries to define a hierarchy of water standards associated with different usages: this move has been prompted by interest in both DRWH and in greywater recycling. A recent review of possibilities is that of Mustow and Grey (1997) for the British Drinking Water Inspectorate. In Germany the recently formed rainwater association is rapidly expanding its membership, publications (e.g. FBR, 1997) and public education programme. The main focus there is supply of water of less than drinking water quality. A significant number of specialist architects and DRWH component suppliers are in business.

In the long term, however, we will probably need to develop simple, reliable and cheap forms of household water treatment. Boiling is resource intensive and presents some danger of accidental scalding. Chemical disinfection is well understood, compatible with water storage but requires some management. Disinfection by natural or artificial radiation is awkward to organize where flows are very intermittent. Filtration, especially slow sand filtration, is being researched for incorporation in domestic tanks; kitchen filters have long been widely available. A key decision affecting the speed with which 'domestic water autonomy' is adopted in rich societies is whether householders are *allowed* to encounter water of less than the highest quality, even where their designated 'drinking' water is guaranteed to be sterile. In poorer societies cost factors will dominate any change in water supply.

Three case studies

Where rainwater harvesting is currently practised on a significant scale, it is done more out of necessity than out of any commitment to autonomy. Its practice in special circumstances such as in Bermuda and Gibraltar (out of, respectively, geological and political necessity) is quite well known. The three cases below have been chosen because they offer models for wider-scale adoption.

China

Parts of northern China present extreme problems for water supply. Rainfall is low (generally under 600 mm) and concentrated in the summer months. Groundwater conditions are difficult, especially in the loess sand areas where water tables are extremely deep or rapidly falling. Several formerly perennial rivers have become seasonal or even permanently dry. There is a population of tens of millions dependent on diminishing and fragile supplies: climate change and water scarcity are seen as the main physical constraints on future development. Not surprisingly the revival and extension of rainwater harvesting is public policy in the most affected provinces (Lijuan and Gouyou, 1997).

Of several large-scale programmes started in the last five years, that in Hebei Province is one of the most vigorous (Mou, 1995), having been extended since 1994 to benefit over 100 000 households. Like variants elsewhere in China, the system design had a low cost target (under $100 per household) and employs a combination of collection surfaces – gutterless tiled roofs and paved courtyards totalling 100 m^2. Storage is in underground tanks built without reinforcing (6 m^3 per household corresponding to only about 15% of mean annual run-off) and extraction is by simple handpump. There has been debate in China about the merits of segregating the cleaner roof run-off from the dirtier courtyard water by using separate stores and about means of filtering the latter. However, separate storage increases costs and may entail provision of two pumps. As in other farming societies, water for livestock and kitchen gardens may be included in the homestead demand although the storage provided in this scheme is adequate for only sparse human use during the dry winter months.

China's distinctive political/institutional structure allows it to combine research into new rural technologies with large-scale rural dissemination of innovations. In this case the combination looks effective and may generate a model for use in other semi-arid areas of the developing world.

Rural East Africa

East Africa is an area of historically low population density now subject to rapid population growth and urbanization. Climates vary from arid to humid equatorial. Average rural income levels are very low. Piped supplies, whether pumped or gravity fed, are rare in rural areas and at present old ones are falling into disuse faster than new ones are being constructed. Springs and shallow wells are the commonest water sources and the carriage of water from such sources is part of the daily routine of most households. That chore falls mainly upon women and is often intensified during dry seasons when more local wells dry up. It is common to meet water plans where the aim is to *reduce* the haulage distance from source to homestead down to say 1.5 kilometres. Existing consumption is often under 10 lcd which is not compatible with good hygiene. Water programmes based on spring and well protection or on the sinking of boreholes (much less successful in Africa than in Asia) rarely reduce average haulage distances below the 400 metres needed to increase consumption to adequate levels. There would seem to be much scope for DRWH systems in at least those homesteads possessing a hard roof whose area exceeds 5 m^2 per inhabitant in a humid area or 10 m^2/inh in a semi-arid one.

Rainy Day harvesting has long been practised using saucepans, bowls and small jars, today from corrugated iron roofs (now quite widespread) and in the past from tree trunks. *Wet Season* harvesting has been promoted by several agencies using 1500-litre cement jars or corrugated iron tanks. *All Year* harvesting can be observed in individual households which have built concrete or iron tanks and such tanks are often also associated with schools. In semi-arid areas such as Northern Kenya and Somalia large water stores have been constructed as brick-lined holes in the ground, sometimes covered. However, all these initiatives, many going back to colonial times, have not resulted in more than a few per cent of rural households having a sufficient supply of rainwater.

There are several barriers to the spread of DRWH. Most of the agencies operating water programmes are committed to community rather than household technologies, for reasons of both equity and 'economies of scale'. Up to 50% of households lack suitable roofs even in high rainfall areas. The present cost of *All Year* DRWH is high, so that compared with the alternatives it represents a superior performance but at a higher price. Other factors favour DRWH in the near future include the declining ability of government and NGO water programmes to keep pace with rural population growth (so that long queues are common at existing public sources), local problems of groundwater mineralization and surface water pollution, the continuing growth in the use of hard roofing (iron or, in Rwanda, tile) and some technical advances in DRWH itself. It seems likely that rural piped water will not be widely available for another generation and that regardless of its long-term role DRWH has a substantial short-term potential.

However, considerable further development and demonstration of technical alternatives will be needed before there is widespread take-up of rural DRWH. The areas in most need of attention are storage costs (their reduction below $25 per cubic metre), roof design to allow very small gutters to be used, and devices for household-scale lifting, filtering and indicating water that are compatible with village maintenance skills and household budgets. It is not clear who will undertake this development work, as it offers little profit to commerce yet lies outside the remit of the present water supply agencies.

Singapore

Singapore is a city state most of whose inhabitants live in tower blocks (typically 12–16 storeys high). Its climate is superb for rainwater harvesting, as rainfall approaches 2000 mm and is quite uniformly spread through the year. The nation is prosperous and its water consumption and quality are correspondingly high. Due to the high-rise construction and high floor occupancies, roof area per person is inadequate for roofwater harvesting to meet all domestic needs, however it can provide a partial supply. In some places harvesting at ground level – for example from the airport runways – has potential, but in this article we restrict ourselves to discussing catchment close to dwellings.

Professor Appan and colleagues have made detailed studies of roofwater catchment of toilet flushing water in apartment blocks (most recently reported in Appan *et al*., 1997). They have found a mixed system to be most economical, a rooftop tank supplying toilet cisterns being fed both by roofwater from an auxiliary light catchment surface and by mains. (The architectural alternative of placing the tank on the topmost floor *below* the roof slab is considerably more costly.) The full tank weight of 150 tonnes is bearable without structural changes, but the overall cost would be reduced if the harvesting system had been part of the original building specification.

Such a system only supplies 4% of total consumption (18% of toilet flush water) but appears to offer cost savings. At realistic rates of interest and capital repayment, the rainwater component would be about 25% cheaper than the mains water it would replace. As Singapore's water supply is coming under greater pressure, so that even desalination is being considered, the marginal cost of extra water (and therefore the value assignable to replacement rainwater) will rise. As yet such rooftop harvesting has not been implemented in Singapore since building codes need to be altered; however, that partial DRWH is cost-effective even in such extreme urban conditions suggests that harvesting is not just a technique for the rural poor.

Conclusions

Of all the services to a residential building, water supply is probably the most universal and critical. Such water reaches buildings in three main ways. A small fraction of the world's homes have functioning piped supplies. The majority depend on water being carried from wells, springs, lakes and rivers. Rainwater harvesting constitutes a third way. Such harvesting has more of a past and a future than a significant 'present'. Its use has diminished, except in special situations like city states and low islands, due to the world-wide expansion of the first two alternatives above.

However, interest in DRWH is reviving due to growing inadequacies in supplies based on aquifers or reservoirs, to a rising desire for water autonomy (whether for water security, economy or out of ideology) and to improvements in the technology of water harvesting itself. For the less poor in tropical rural areas, DRWH offers almost the only means of improving their household's water supply without waiting decades for an upgrading of the community system. For inhabitants of the many areas where aquifer quality is deteriorating or aquifer levels are dropping (as in the China example above), DRWH is frequently cheaper than transporting water from distant sources. DRWH is most appropriate where the product of precipitation and roof area per capita exceeds per capita water consumption, but it can be used as a partial supply where that condition is not satisfied (as in the Singapore example). Technology is under development to reduce storage costs and assure adequate DRWH quality. Harvesting is likely to expand rapidly in the coming century and, like all building services, will work best where it has been designed into the structure rather than retro-fitted.

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