RAINWATER HARVESTING

FOR

URBAN LIVING

By

Sisuru Sendanayake

B.Sc. (Eng), M.Sc., Ph.D.

South Asian Institute of Technology and Medicine

Sri Lanka

S. Sendanayake B.Sc. Eng. (Hons), M.Sc, Ph.D
South Asian Institute of Technology and Medicine (SAITM)
P.O. Box 11, Millennium Drive,
Off Chandrika Kumaratunga Mawatha,
Malabe 10115, Sri Lanka.

Tel.: (+94) 11 241 3351
Fax: (+94) 11 241 3332
E-mail: sisuru.s@saitm.edu.lk, sisuru.saitm@gmail.com
Web: http://saitm.edu.lk/

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This book is presented to the benevolent visionary

Dr. Neville Fernando

The Founder Chairman of

South Asian Institute of Technology and Medicine

Sri Lanka

PREFACE

Urbanization is a global trend that is irreversible in the face of difficulties faced with providing the expected living standards to the masses in rural landscapes. During the last few decades millions of people all over the world have migrated to urban environments, mostly cities located near sea, resulting in over one quarter of the global population living in coastal urban habitats that have less than 10% of the global renewable water supply and are at the same time undergoing rapid population growth [290].

Moreover, it is estimated that over 50% of world population to be living in cities, with that figure to be as high as 70% in the developed countries [279].

Sri Lanka is no exception where poor infrastructure, inadequate flow of resources and income to the rural areas, lack of employment opportunities and depletion of natural resources, including ground and surface water resources, driving an ever increasing number of families to urban centers. In this scenario, the most stressed out resource is water, which however is the most fundamental need for living. With the ever increasing population on one hand and the fast depletion of ground and surface water resources on the other hand, local authorities are facing an uphill task providing safe to drink reticulated water to every household at a reasonable cost. The situation is aggravated by the high cost of construction and maintenance of necessary infrastructure to store and distribute service water, high utilization of energy in such projects and the associated impacts brought upon the environment, which in turn having a negative impact on the natural resources, particularly the water cycle.

In this background, a renewed interest on Rain Water Harvesting (RWH), an age old practice all over the world, has been growing with the possibility of capturing rainwater locally with comparatively a minimum requirement of infrastructure. Rain is available in adequate quantities in most countries, is relatively devoid of pollutants and contaminants compared to ground or surface water and can be collected with zero input energy, limited only by the collection surface area and rainfall depth.

Many countries, including Sri Lanka, have enacted laws, making provision for RWH mandatory in new buildings, but it is the positive attitude of the potential householder towards using harvested rainwater that would proliferate RWH systems. Of the many factors that influence the inclination towards RWH, the cost of installation, maintenance, energy requirement, the quality of harvested water and the convenience in using the system stand out. This book attempts to address these very concerns by presenting relevant information gathered from sources around the world, together with the published research findings of the author, with the intention of proliferating of RWH in urban environments.

Chapter 1 looks at the fundamental concepts of RWH, needs, benefits and limitations of RWH and Chapter 2 and 3 exploring the global and Sri Lankan RWH scenarios respectively, particularly looking at current systems, models, methods and issues, and also presenting published information on small and large scale systems. Chapter 4 is dedicated to system components and their optimization with details on methods and design tools available. Chapter 5 gives possible configurations of RWH systems in single and multi level urban dwellings while Chapter 6 introduces a novel energy efficient RWH system of distributed storage capacity, with minimum disturbance to building structure. Details of the system, identified as the Cascading Multi Tank RWH (CMTRWH) system, are presented on total energy security, optimum energy efficiency and minimum total storage for a given demand, rainfall depth and collector area values. Chapter 7 addresses quality issues of collected rainwater, use of photo voltaic (PV) systems to minimize energy costs in RWH and also selection of appropriate pumping options.

Information and contents relevant to RWH from as many research articles, documents and technical papers as possible are included in the book to encourage those who are interested in RWH into further research and for future contributions to advance knowledge in the subject. Throughout the book sources of information are identified and listed for reference and further reading. It is the author’s sincere wish that the contents presented in the book would encourage implementation of this modified and refined ancient technique for the sustenance of millions of urban lives in the face of increasingly acute water stress.

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The author is ever grateful to Dr. Neville Fernando, founder and Chairman of South Asian Institute of Technology and Medicine (SAITM) for the inspiration, benevolence and guidance , encouraging not only publishing this book but to strive for many career achievements.

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Chapter 1

RAINWATER HARVESTING CONCEPTS

Defined as the collection, control and utilization of rainwater close to the point it reaches the earth, Rain Water Harvesting (RWH) is an age old practice throughout the world for obtaining natural soft water, potable as well as non-potable indoor usages and for sustaining livelihoods such as in agriculture. RWH can also be used in aquifer replenishment, erosion control as well as flood control. As the populations grow, consumption per capita increases, water resources are over exploited and the climate changes, RWH has gained a renewed significance in the recent times. Rainwater is usually free from physical and chemical contaminants such as pesticides, Lead and Arsenic, color and suspended materials and it is low in salt and hardness. With the world urban water demand expected to rise to 6.4 billion m^3 in 2050 [282], the likelihood of climate change with the increase of variability of precipitations and the number of floods and drought episodes [123], coupled with the absence of surface water, mineralized ground water and unaffordable centralized piped supplies, there is a dire need to focus attention on RWH more objectively.

Historical evidence in RWH is found in countries all over the world with good examples from Jordan (Roman pools in Ajlun and Madaba, 850 BC) [82], India (Rajasthan) and Sri Lanka (Sigiriya, 5th century AD) where extensive surface water harvesting was practiced to irrigate vast tracts of agricultural lands. In the simplest form of RWH, rainwater can be diverted to a vessel using a broad leaf such as of Banana attached on a tree trunk when a rain event occurs and at a much larger scale, collection is made as surface runoff directed to small and large scale ponds or tanks to be used for agriculture. Therefore, essentially, RWH can be described as a technology that is flexible and adaptable to a very wide variety of conditions, being used in the richest and poorest societies on our planet and in the wettest and driest regions of the world [6].

While rainwater is the only source of water in arid and semi-arid regions where surface water sources such as streams, rivers and lakes are either absent or highly polluted and at locations where tapping ground water offbore holes and dug wells not viable,it has been mostly a supplementary source of water in other regions, making life easier from fetching water from a distance. Provided that the rainfall pattern in a given location is regular and spread more or less evenly throughout the year, such harvesting of rainwater therefore could provide both potable and non-potable water at the door step releasing the householders, particularly the womenfolk who traditionally do the fetching of water, for other chores.

1.1Benefits accrued from RWH

It is important to note that while at a domestic level, RWH depends on many factors such as the demand for water at a dwelling, based on the number of users and the per capita consumption, quality of the available surface or ground water, the number of days the regular sources would be dry or with a low volumes of water and the number of rainy days per year, globally at a wider scope the need for RWH can be summarized as;

- Inadequacy of existing water supply systems in the face of rapid population growth, creating frequent water shortages and scarcities.
- Degradation of water quality in primary sources such as rivers, ground water aquifers and natural lakes as a result of wide spread use of chemicals in agriculture (pesticides, herbicides and fertilizer) and their contamination due to industrial and human waste.
- Escalating cost of providing water (cost per m^3) due to high cost of constructing reservoirs for storing reticulated water, high costs in pumping from centralized locations to end user points, filtering and purification costs, distribution system maintenance costs and financial costs on investments such as opportunity costs.
- Risk of disruption to mains water supply due to break downs or prolonged draughts. The storage facility of the RWH system can act as the buffer for such an emergency.
- Non-availability of potable water in isolated areas through conventional methods due to lack of water bodies in the vicinity, difficulty in reaching ground water aquifers due to excessive depths and high capital outlay in drilling through rock, non-availability of

power supply inherent to isolated hamlets in arid, semi arid and mountainous areas.
- Depletion of water levels in underground aquifers thus limiting the draw-offs as a result of minimal ground water recharging and increased use of ground water.

Apart from the obvious benefits of availability of potable water at virtually no cost excluding pumping cost from the storage tank to end user points, there are a host of direct and indirect benefits from a well designed RWH system that can be described as follows:

- Reduced demand on conventional water supply systems by supplementing rain water for needs which do not require high quality water such as WC flushing, washing, gardening, vehicle washing etc., thus saving on purified, treated drinking quality water. This would facilitate managing demand for water and rationalize new investments.
- Minimized depletion of ground water by recharging in surface run-off harvesting and preserving it at higher levels and quality, minimizing water stress during draughts and enhancing the vitality of all life forms.
- Increased decentralized water security and local self reliance whilst encouraging family level operation and maintenance.
- Facilitating urban home gardening and small-holder food production, supplementing rural irrigation and stimulating income generation.
- Lowered risk of flash flood situations by taking off a sizable quantity of roof run-off from the drainage system.
- Reduced national energy consumption and water loss in the treatment and conveyance of reticulated water.
- Reduced conflictive invasion of rural water sources to cater for urban demand by meeting requirements close to the point of harvesting.
- Increased domestic water security by reducing the unproductive labor, time and hazards faced mainly by women and children in fetching water from a distance, and improved accessibility to safe water for many marginalized communities.

- Minimized consequences of increased salinity intrusion due to sea level rise, and the threat caused from pollution to traditional sources of water by infiltration.

1.2 Demand for Service Water

RWH system design is mostly based on the demand and whether that demand is for drinking or for secondary use. In most climates only about 2 liters per capita per day (lpcd) is required for survival and depending on the lifestyle, climate and environmental conditions, domestic per capita consumption can range from 7 to 300 liters/day, with the standard minimum quantity of 20 lpcd set by WHO. It is an important finding that in many studies confirming that a given user in a given geographical location using an approximately constant amount of water per day which can be attributed to his or her lifestyle and the ease with which water can be obtained [298],[240],[115].

1.3 Storage of Service Water

Based on the percentage of service water that rainwater would be supplementing, there arises a need for storing devices resulting in vessels of various sizes, shapes and makes utilized for the purpose. The tanks can be clay pots, used oil tanks etcas the most commonly used types to reinforce cement concrete (RCC), ferror cement, fiberglass or HDPE tanks.

1.4 Collection of Rainwater

While the storage capacity gives the maximum number of days a particular demand can be met without any input from a rain event, for any RWH system, it is the collection area which determines the amount of rainwater that can be harvested in any given rain event. Simply taken as the product of the projected surface which is exposed to rain (A) and the rainfall depth (R), the maximum amount of rainwater that can be harvested therefore is given by, Collection Area (A) x Rainfall depth (R) = AR

Depending on the surface texture and type of the roof, equation (1) can be modified to indicate the actual roof collection as,

Collection Area (A) x Rainfall depth (R) x Collection Efficiency (C_f) = $(AR)_{Actual}$

Where generally C_f is a function of texture and absorption quality of the surface and also a function of the roof pitch, wind speed at the time and other minor system losses in the case of roof as the collector surface.

Connecting the collector surface and the tank is the rainwater transport or conveyance system, which could be the drainage system or streams in the case of surface water harvesting or guttering in the case of rooftop harvesting.

The three main components, namely the collector surface, rainwater transport system and the storage tank constitute a system that can be used to harvest rainwater as per the demand as well as supply, i.e. rainfall depth and collector area. In addition, to improve the quality of collected rainwater, various devices can be introduced, particularly to flush out the initial amount of roof or surface collection that could mostly be contaminated after a prolonged dry period, to filter out debris and other contaminants before use and for extraction of water out of the tank or cistern.

Chapter 2

RAINWATER HARVESTING IN GLOBAL CONTEXT

"Having access to quality potable water is a fundamental human need". (United Nations)

It is reported that in 2015, at least 1.8 billion people use a drinking water source that is contaminated; 663 million people rely on unimproved sources, including 159 million dependent on surface water. It is estimated that by 2025, half of the world's population will be living in water-stressed areas [315].

It is found that a fifth of the world's people, 1.2 billion, live in areas of physical water scarcity, where there is not enough water to meet all demands. A further 1.6 billion people live in areas experiencing economic water scarcity, where the lack of investment in water or insufficient human capacity makes it impossible for the authorities to satisfy the demand for water [316]. According to the Falkenmark water stress indicator, a country or region is said to experience water stress when annual water supplies drop below 1700 m^3 per person per year. At levels between 1700 and 1000 m^3 per person per year, periodic or limited water shortages can be expected while below 1000 m^3 the country facing water scarcity [322].

In the light of these facts there is a grave concern on the availability and supply of water with growing interest towards RWH. International interest in RWH spans a wide spectrum of topics ranging from supplementing drinking water to environmental concerns of constructing large reservoirs for water supply schemes, which would alter the ecological balance. In depth research has been carried out from Europe to Africa on various aspects of RWH systems covering Water Saving Efficiencies (WSE), optimum system capacities, cost against benefit analysis and impact on environment and the subject is considered a major component of sustainable development. Some of them are summarized indicating the general scenario.

Currently, RWH is practiced in many forms throughout the world. While surface run-off is collected for agricultural purposes as well as for mitigating flash floods, roof run-off is used to supplement potable water, mainly to households. Even though treated rainwater is used for drinking and cooking, in most urban houses it is a case of rainwater supplementing the reticulated supply for activities such as toilet flushing, gardening and laundry. It is estimated that in developed countries these 3 activities account for 30% of the total service water utilization with laundry alone using 20% of the total.

However, per capita consumption of water is a relatively elusive figure in practical terms as water usage patterns vary significantly with life style, draw-off source, and geographical location of the end user as well as the climatic conditions prevailing in the area. While per capita water consumption is low in dry and low humid areas, it tends to increase in areas with abundant rain. It is observed that the relative ease of availability of water tends to increase the usage while the biggest variation occurs along with life style differences.

Research in many countries has shown that modern household equipment and amenities such as WC in toilets, washing machines, dish washers as well as car washing has significantly increased water consumption. Studies carried out on water usage patterns reveal that a sizable quantity is being used for WC flushing, car washing and other external uses which do not require drinking quality water. For example, in Sweden, 20% of household water use is for flushing toilets, 15% for laundry and 10% for car washing and cleaning [289]. In the UK, 30% of the potable water supplied to the domestic sector is used for WC flushing and the transportation of foul waste [85]. In Australia, studies of water usage in homes located in different climatic regions indicate that on average 15% of supplied water being used in toilets while 30% being used for external purposes [1].

Many practical Roof Top Rain Water Harvesting (RTRWH) systems are in use globally and differ to each other mostly on cost factors and the level of sophistication. While many developing countries use simple systems similar to what used in Sri Lanka, most of the developed countries use RTRWH systems as supplementary water sources for existing mains supply. In these systems the discharge is automated so that when collected rainwater in the storage facility drops to a predetermined level, provision is made for automatic change over to mains supply.

2.1 International experiences in RWH

It is useful to examine RWH experiences in different continents and in a few selected countries at domestic and community level to understand the current trends and new developments. At the global level, some of the largest RWH projects are underway in China, Brazil and India while in many countries, including Sri Lanka, Bermuda, Guinea-Bissau, US Virgin Islands and a few states in India, laws have been enacted to include RWH in all new building constructions.

2.1.1 South America and the Caribbean Islands

For more than three centuries, rooftop catchments and storage have been the basis of domestic water supply on many small islands in the Caribbean. It is estimated that more than 500000 people in the Caribbean islands depend at least in part on RWH systems supplied water [74]. Further, large areas of some countries in Central and South America such as Honduras, Brazil and Paraguay, use RWH as an important source of water supply for domestic purposes, especially in rural areas.

While RWH for domestic purposes is carried out extensively in semi-arid regions of Brazil and Argentina, in Central American countries like Honduras, Costa Rica, Guetamala and El Salvator, RWH using roof top catchments is widely practiced [77].

In a recent water supply study, the continued use of rooftop and artificially constructed catchments was contemplated for those parts of rural Jamaica lacking access to river, spring or well water sources. It is thought that more than 100000 Jamaicans depend to a major extent on rainwater catchments. While accessibility to water sources is the main concern in interior of Central and South America, for the coastal areas and the island nations, salinity intrusion into ground water aquifers is compelling towards RWH.

2.1.2 Australia

Australia is the driest inhabited continent in the world, with the mean household water use of over 300,000 L per year, placing Australians amongst the highest water users in the world. In 2004, 17% of Australians sourced water from their rainwater tanks with 48% of all households in South Australia relying on tank water as their primary drinking source [1].

Australia faces rapid urbanization and its huge migrated population mainly concentrated in a few coastal cities it has become compelling to look into centralized RWH and storage systems which can provide water for domestic use in large housing schemes. At present Australia faces acute water shortages during summer months, imposing restrictions on car washing, garden watering and in some states pet washing and drive-way cleaning.

2.1.3 Europe

In Europe, attention is now focusing on alternative water resources such as Rainwater Catchments Systems as supplementary water sources with multi-purpose functions.

Despite water in Europe is still an abundant natural resource, for example in Sweden only 0.5% of the naturally available water resources being used [289] rapid changes in ecological factors such as the low renewal rate of ground water (in Upper Franconia, Germany where annual precipitation is around or less than 650 mm, the renewal rate is 100 – 120 mm/annum [11], contamination of ground water by nitrates, and pesticides from agriculture and effluent from land fill sites, have diverted the attention of authorities on RWH.

Contributory natural environmental factors affect the limitation provided by the protective shield of soil and rock above the water table of prelatic aquifers. These include low slopes, shallow water table, high recharge and hydraulic conductivity, permeable soils, low natural ground cover, high coefficient of recharge etc. Such natural aspects of the ambient environment can become un-sustainability factors with regard to maintenance of ground water quality.

In the steady state situation of coastal aquifers, ground water drains towards the sea-shore. Excessive pumping clearly has a severe detrimental effect upon ground water reservoirs. Water table drops, significantly altering ground water flow directions. Where excessive pumping situations apply, saline sea-water tends to intrude into the fresh water inland reservoirs, a phenomenon which can make salinization almost irreversible. Taking into consideration the origin of public drinking water supply in Europe in general where for example 72% is from ground water and spring water, 22% from surface water and 6% from bank filtrate in Germany, 75% from lakes and streams with 25% from ground water in Sweden, the above researched ground water quality problem has caused concern [115], [289].

Further, Europeans are focusing on the educational and prestige benefit of using harvested rainwater water. Thinking behind the above theory is that it would be easy for people to make the connection between natural resources and their behavior, thus encouraging a feeling of responsibility towards water use. In terms of prestige, residents will be a part of a forward thinking, innovative project that benefits society and the environment.

2.1.4 Africa and Middle East

For African and Mid-Eastern countries the public water supply overwhelmingly depends on ground water and the draw backs with regard to quality of ground water plus high energy cost of drawing water from deep underground aquifers makes it mandatory to look into RWH systems. Apart from desert areas where the annual rainfall is 0.5 mm or less, other semi-arid and arid areas use run-off collection either in individual storage devices or detention ponds such as the community detention ponds in Tanzania [77].

2.1.5 Asia

The need for RWH systems vary significantly country wise as well as region wise in Asia due to its environmental factors which differ from one extreme to the other. While developed countries such as Japan, Taiwan and South Korea are looking at advantages such as capturing and storing significant quantities of storm water for landscape maintenance and improvement in residential areas, reducing of peak demand on public water supply, conservation of water and importantly mitigating storm water management problems and flash floods. The developing countries such as India, China and Pakistan are looking at reducing high cost of providing potable water to its massive populations, both rural and urban, thereby providing water-security diverting funds for more productive new investments. Rapid depletion of groundwater levels causing desertification is another major concern in Asia.

Most of the Far Eastern countries such as Malaysia, Indonesia and Philippines are blessed with high annual rainfall but rapid urbanization is already causing flash floods and increased cost of providing drinking water to its city populations. Singapore, the city state is a unique case where more than 80% of its water requirement being imported from neighboring Malaysia. Therefore, Singapore has made it mandatory to have RWH systems to be in-built for new developments [11].

In Northern China, where the annual average rainfall is below 600 mm and concentrated during summer months, ground water conditions difficult and formerly perennial rivers drying up, there is a severe shortage of service water to millions of people, compelling the extension of RWH as a public policy [156]. To maximize the rainwater collection, households in northern China are using gutter-less tiled roofs and paved courtyards giving collection areas in excess of 100 m^2 with the runoff stored in underground cisterns build without reinforcements.

In Brazil, the government is supporting a program to install one million rainwater harvesting systems in the semi-arid areas of the country. In Belgium, new buildings with a roof area greater than 100m^2 are required to install rainwater harvesting and storm water attenuation systems.

In the Caribbean Islands and Central American countries, for example, storage tank is made of steel drums of 200 L capacity, large polyethylene plastic tanks of 1300-2300 L capacity or underground concrete cisterns of 100000 – 150000 L capacity and the respective government regulations have made it mandatory that all developers construct a water tank large enough to store a minimum 400 L of rain water per m^2 of roof area [74].

In eastern Africa where climates vary from arid to humid equatorial, commonest water sources are springs and shallow wells. Local population with a very low average annual income are compelled to travel on average 1.5 km to fetch water resulting in water consumption of under 10 lpcd which is not compatible with good hygiene. In semi-arid regions such as northern Kenya and Somalia, large water stores have been constructed as brick lined holes in the ground, sometimes covered [270]. In such areas RWH can be popularized at domestic level if technical advances can minimize the cost of tanks.

Jordan, a Middle-Eastern nation is one of the world's 10 most water stressed countries. With a considerable variation in spatial distribution of rainfall of which over 85% evaporating back into the atmosphere and only 4% recharging the ground water, RWH is fast becoming a necessity. It is estimated that even with the low potential, 5.6% of the total domestic water supply of Jordan can be met by RWH [82].

In the tropical city state of Singapore on the other hand, RWH is proposed on rooftops of their multi-story building blocks as a means of collecting a portion of the year round rainfall of 2000 mm to supplement the costly service water, particularly in non-potable use such as toilet flushing [12]. In this case, an economical mixed system of a rooftop tank supplying toilet cisterns can be considered, fed both by rainwater from a catchment surface as well as by mains.

2.2 Fundamental types of RWH systems

Design wise RTRWH systems are classified into two basic types. They are as follows:

- Dry systems

  A dry system for rainwater collection involves down pipes leading directly into the storage tanks, so after a rain event, no water remains within the collection pipes as shown in Figure 1

- Wet systems

  A wet system usually involves underground pipes with the entry to the storage tank being above ground level thereby trapping water within the pipes after rain as shown in Figure 2

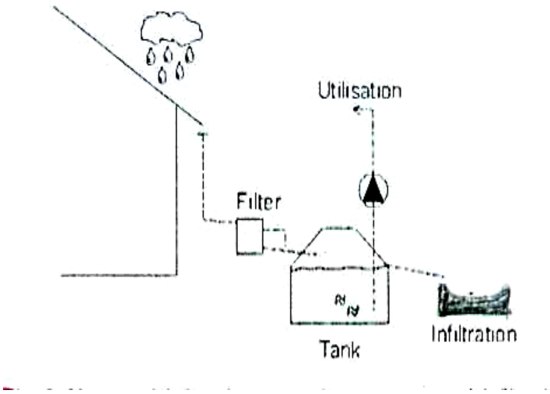

Figure1: The Dry RTWHS

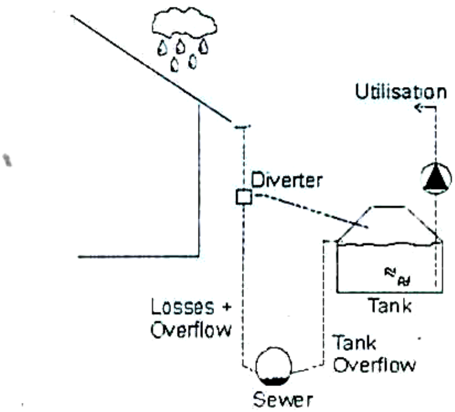

Figure 2: The Wet RTWHS

The dry system is preferred as the wet system can lead to water trapped in the conveying pipes going stale and in some cases breeding mosquitoes if the pipe entrances are not securely sealed. Since this additional volume need to be jettisoned through the first flush device thereby increasing the capacity required by the first flush (FF) device.

2.2.1 Main types of global RTRWH systems

There are 4 main types of typical RTRWH systems in use internationally, distinguished according to their hydraulic properties. They are as follows:

The Total Flow type

The Diverter type

The Retention and Throttle type

The Infiltration type [115]

2.2.1.1 The Total Flow type

The total run-off flow is confined to the storage tank, passing a filter or screen before the tank as shown in Figure 3. Overflow to the drainage system only occurs when the storage tank is full. It is important that in the case of a clogged screen or filter, that there is no overflow allowed before the tank.

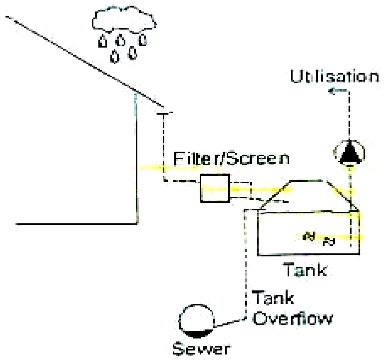

Figure 3: The Total Flow type RTRWHS

2.2.1.2 The Diverter type

The diverter type, which contains a branch installed in the vertical rainwater type after the gutter or in the underground drainage pipe as shown in Figure 4 The collected fraction is separated from the total flow at this branch and a surplus is diverted to the sewerage system; most of these branches contain a fine-meshed. Sieve diverting most of particles to the sewer. These devices are a typical invention of the period, when rainwater usage was only looked onto save drinking water and the diversion of storm water to a sewer was the usual and accepted habit. The ratio of efficiency of the diverting devices decreases with increasing flow. Therefore, during heavy rain, most of the run-off is diverted to the sewerage system. At low precipitation rates, a minimum flow is diverted to the sewer and the efficiency decreases.

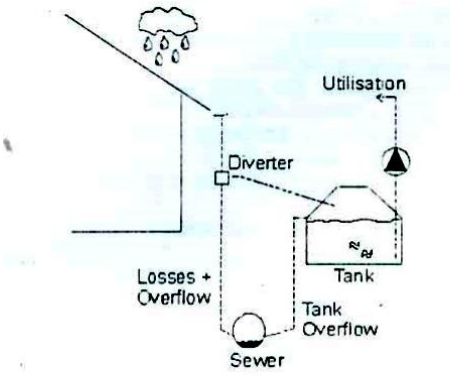

Figure 4: The Diverter type RTRWHS

2.2.1.3 The Retention and Throttle type

The storage tank here provides an additional retention volume, which is emptied via a throttle to the sewer as shown in Figure 5.

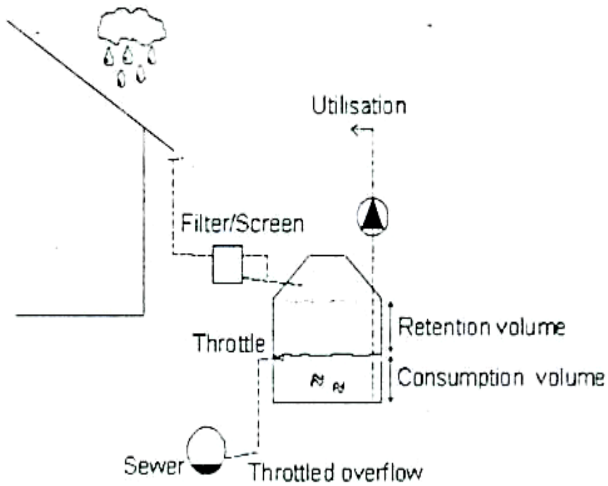

Figure 5: The Retention and Throttle type RTRWHS

2.2.1.4 The Infiltration type

Local infiltration of the surplus tank overflow is a possible alternative to the diversion to the sewer as shown in Figure6. Hydraulic impacts for an infiltration site were calculated by Herrman & Schmida [115] and showed that by the combination of rainwater usage and local infiltration, the natural local water balance can be restored and maintained independent of the infiltration capacity of the soil, and independent of available surface for infiltration facilities.

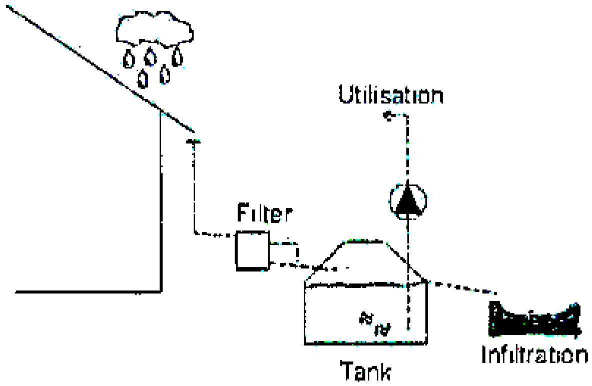

Figure 6: The Infiltration type RTRWHS

2.3 International examples of large-scale in-building rainwater re-use

Many countries in the world have successfully adopted rain water harvesting (RWH) to provide service water in large scale building projects such as apartment blocks, sports stadiums and in public buildings. Following is a brief description of successfully operated large scale RWH systems in a few countries.

2.3.1 Japan

In Japan, there are several examples of large-scale rainwater collection systems. They are presented here since it can indicate the level of sophistication reached in other countries.

In three multipurpose stadiums located in Tokyo, Nagoya and Fukuoka with capacity for a large number of spectators, rainwater is used for WC flushing and irrigation of plants. The catchment areas are 16000, 25900, and 35000m^2, respectively. Tank volumes are 1000, 1800, and 1500 m^3, respectively. A 19 month follow-up study carried-out at the Fukuoka Dome showed that rainwater provided 65% of the volume of low quality water. Approximately 75% of the total rainfall on the roof was used, representing a significant economic saving [305].

At the Kokugikan Sumo Wrestling Stadium, Tokyo, rainwater from an 8400 m^2 roof is stored in a 1000 m^3 reservoir in the basement, and used for toilet flushing and cooling the building.

At the Izumo Dome in Izumo City, rainwater run-off from the dome and the surroundings with a total catchment area of 13200 m^2 is stored in two storage tanks with a total volume of 270 m^3 [101].

At Sumida City office, rainwater is collected from 5000 m^2 of roof and stored in a 1000 m^2 tank located in the basement of the building. The total amount of rainwater used for toilet flushing was 4658 m^3 in 1998, which represented 36% of the WC water consumption [191].

2.3.2 United Kingdom

The Millennium Dome in London is another example of a large-scale rainwater scheme. The roof of the dome has a surface area of approximately 100000 m^2 from where rainwater is collected, using large hoppers, which discharge into a collection ring-main, that runs around the circumference of the Dome. The captured rainwater is then discharged into a storm water culvert containing an 800 m^3under ground sump with three storm discharge pumps, from which rainwater can either be discharged into the River Thames, or pumped to the treatment plant [45].

A study of the performance of the system showed that rainwater provided around 10% of the water demand though collection was limited by storage constraints on site; thus, a maximum of 100 m^3 a day of rain could be collected [117].

Also in London, rainwater is collected from a 2200 m^2 roof to a 14.56 m^3 tank and used for toilet flushing in commercial building; an overall annual efficiency of the system was estimated on 51% [45].

2.3.3 Singapore

At Nanyang Technological University, Singapore, a study showed that roof run-off from an area of 38700 m^2 could be collected and used for toilet flushing in the north spine of the University. Computer simulations have shown that a 2542 m^3 rainwater tank would save 12.4% of the monthly cost for water used [12].

2.3.4 Germany

In Berlin, at Daimler Chrysler Potzdamer Platz, roof run-off from 19 buildings (total area 32000 m^2) is collected and stored in a 3500 m^3 rainwater basement tank [283]. The water is then used for flushing toilets, watering gardens and roofs with vegetative cover, and for the replenishment of a vegetated pond.

Another example in Berlin is the Belss-Luedecke-Strasse building estate. Rainwater from roofs (7000 m^2) is stored in a 160 m^3 tank along with rain run-off from streets, parking places and pathways (4200 m^2). After treatment, the water is used for toilet flushing as well as for garden watering. About 58% of the rainwater is retained locally by using this system. A 10 year period simulation showed that a 2430 m^3 potable water savings per year can be achieved [283].

It is estimated that in Germany, there are more than 100 commercial manufacturers competing in the rainwater usage market and rainwater usage is being applied increasingly to commercial applications in schools, car washing centres and service water demanding industries. While many city councils in Germany has given incentives or subsidies to promote the installation of rainwater usage systems, for example in Hansestadt, Hamburg, [115], today there is a tendency to split-up charges for urban drainage in a consumption-dependent amount for waste water and an impervious surface area dependent amount for storm water. So there is a permanent financial incentive to disconnect the roofs from the sewers.

Chapter 3

RAINWATER HARVESTING IN LOCAL CONTEXT

Sri Lanka has a rich culture of RWH dating back to 400BC and beyond. History records that the early Sinhalese had transformed the dry zone, which is devoid of natural lakes, into a vast network of tanks and canals originally fed by rainwater. In fact, King Parakramabahu the Great (12th century A.D.) is credited with being the greatest water harvesting earthworks engineering of all time with 165 dam walls, 3910 canals, 163 major and 2376 minor reservoirs (tanks), 328 sluices and 1969 embankments constructed or renovated within a span of 33 years. Also, at the historical sites of Sigiriya, the rock fortress (5th Century A.D) an extensive network of reservoirs and ponds had been fed by harvested rainwater. RWH therefore is a technique that has been practiced since antiquity in Sri Lanka. Evidence of RWH in ancient times for potable use is still visible in forest monasteries such as Rajagala in Ampara District.

With an annual average rainfall of 1800mm from a bimodal climatic pattern, Sri Lanka, a tropical island nation, has wide temporal and spatial variations in its rain pattern. Divided into two main climatic zones, the wet and dry zones, the wet zone occupying 30% of the land area in the South West quarter of the country experiences an average of 2350 mm of rain per year, while the dry zone receiving 1450mm of rain. The wet zone is receiving rain mainly through the South-West monsoon, active from May to October while the dry region gets most rain from October to April (Fig. 7). Thus, rainfall depth in both zones of Sri Lanka can be considered as adequate to initiate RWH, which could be practiced at domestic or institutional level in all parts of the country.

Within the respective regions however, rainfall varies with an average 900 mm in the North West and the South East to 5000 mm in the western slopes of the mountainous terrain located in the centre of the country. It is estimated that of the total annual rainfall accumulative 33.4 km^3 escape to sea, which is 65% of the runoff. The wet zone releases most of its runoff with 20.4 km^3 and with highly urbanized areas, facing frequent flash flood during monsoons, overburdening the local drainage systems. In the Colombo municipality alone, 74 million m^3 of annual runoff is estimated to escape into sea [145].

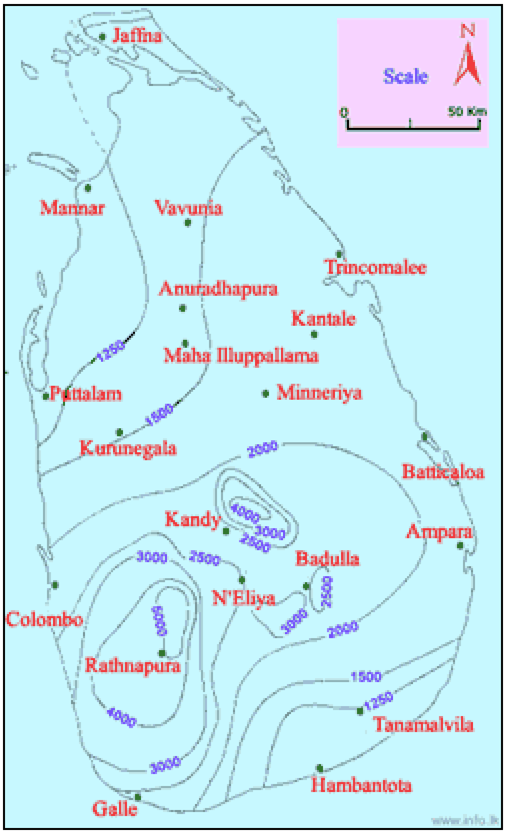

Figure 7: Rainfall map of Sri Lanka

With a background of an adequate rainfall in most areas of the country, it did not warrant extensive use of rainwater for domestic purposes in households nor did it encourage research on the subject since its water resources of rivers, natural and manmade water bodies and its rich ground water aquifers get replenished frequently. However, during the past few decades, along with global trends, Sri Lanka also has been experiencing problems of providing adequate water supplies to its population due to pressure exerted from urbanization. For example, in developing countries, the level of urbanization is still rising and expected to reach 83% in 2030 [280]. Population growth, industrialization, depletion of forest cover, disruption to water supply resulting in prolonged droughts, short duration-high intense rainfall, depletion and contamination of natural water bodies and ground water aquifers and importantly, increased per capita consumption of water due to introduction of modern amenities and needs such as WC flushing in toilets, washing machines, car washing and garden watering are some of the problems that needs to be tackled with carefully devised strategies. Though urbanization in the country occurs parallel to global trends, for a relatively small country with a population of 22 million over a land area of 64850 square kilometers, its human habitation is wide spread due to the culture of land ownership and the agriculture based population distribution. According to the Central Bank of Sri Lanka over 50% of the population was in agriculture in 2015.

At present, over 70% of potable water used in Sri Lanka is tapped from ground water aquifers through bore holes and wells, while the rest is from natural water bodies and springs. However, fast depletion of ground water levels due to prolonged droughts and excessive draw-offs plus contamination of ground water from increased use of pesticides, herbicides and fertilizer warrants finding ways of providing potable water in the coming decades. Further, the initial cost of tapping ground water and the energy cost of drawing it on to the ground level is another aspect which has to be closely examined in the context of an impending energy crisis.

Thus far, Sri Lankan experience on RWH has been mainly focused on providing safe drinking water to low income households which have poor or no access to reliable sources of water. This includes communities living in hilly terrains, near polluted waterways and where aquifers are contaminated or drying up regularly. Inhabitants in such areas use highly polluted water or suffer from lack of any water for most basic needs resulting in high incidents of water related diseases. In the face of colossal expenditure required in providing such communities with reticulated water, RWH has provided a viable alternative. Many organizations, both government and non-government such as the World Bank (CWSSP) and Lanka Rainwater Harvesting Forum (LRWHF) are already engaged in RWH projects at the rural level.

In rural areas user demand can vary between 25 to 30 lcpd depending on the season and availability of water [15] while in urban areas it could be as high as 200 lcpd used mainly for toilet flushing, gardening and car washing [240].In Sri Lanka, an extensive survey was carried out [240] and average usage for WC flushing was found to be about 25% of the total water demand. Importantly, this demand was found to be approximately a constant as the water usage in a household is generally of habitual nature. However, it is important to note that harvested rainwater is to be used as a supplementary source of water taking a sizeable load off the reticulated centralized supply.

A few large scale RWH systems have been reported in Sri Lanka, implemented mainly as projects to cut down the cost on service water. However, given the prevailing subsidized tariff structure for reticulated supply a low payback periods may not be realized. To cite a few examples, a centralized RWH system has been introduced at the six storey Sabaragamuwa Provincial Council building complex in Ratnapura as supplementary source of service water to cater to 400 office workers and 200 visitors on any given week day [145]. The system located in a region where the annual average rainfall is almost 3000 mm and well spread throughout the year, harvests 4.2 million liters per year using a metal roof of 2842 m^2 coupled to a 18.5 m^3 storage tank. Pumps are integrated to the system to lift the collected rainwater to upper floors thus reducing the net cost saving.

A RWH system has been operation at Millennium Information Technologies (MIT), Malabe to cater to a projected total service water demand of 195 m^3 per day for toilet flushing, swimming pool and landscaping, utilizing a roof area of 5525 m^2 with rainwater storage in ponds of combined volume 2315 m^3. The system, designed for 90 day dry period meets 70% of the water demand [16].

Another large scale RWH system is at David Peiris Motor Company, A leading motor company in Sri Lanka, located at Madapatha, 30 km south of Colombo in the wet zone of Sri Lanka. A total roof area of 5800 m^2 is utilized for a monthly demand of 1000 m^3 of service water for sanitary and gardening needs. Storage is mainly in open air collection ponds and 51% of the water demand is met [145].

It is interesting to note that all 3 projects are located in the wet zone of Sri Lanka where rainfall is bimodal with a high annual average of 2500 – 3000 mm, requiring relatively smaller storage capacities. It appears that the projects have been implemented more as to strengthen the principles of sustainability rather than for cost saving or due to water shortages.

A few community-based medium scale RWH projects are reported from Iriyagama and Kundasale in the Kandy District and a project at Galle in the Galle District, both districts within the wet zone experiencing more than 2500 mm of annual average rainfall. Therefore, optimum sizing of storage capacities do not seem to be an essential requirement as in the case of low rainfall regions.

Sri Lanka has introduced regulations in 2007 (Gazette notification L.D. –O. 18/2007) amending the Urban Development Authority law of No. 41 of 1978, including RWH in the development plan prepared in terms of section 8A in keeping with the National Rainwater Policy and Strategies.

3.1 RWH systems in Sri Lanka

Rain Water Harvesting (RWH) systems in Sri Lanka are mainly classified according to the positioning of their storage tanks.

3.1.1 RTRWH system with above ground Ferro-Cement tank

This model is introduced to rural areas by the Ministry of Urban Development and Water Supply of Sri Lanka as shown in Figure 3.7. However, space requirement for the tank hinders use in small dwellings where land area is limited.

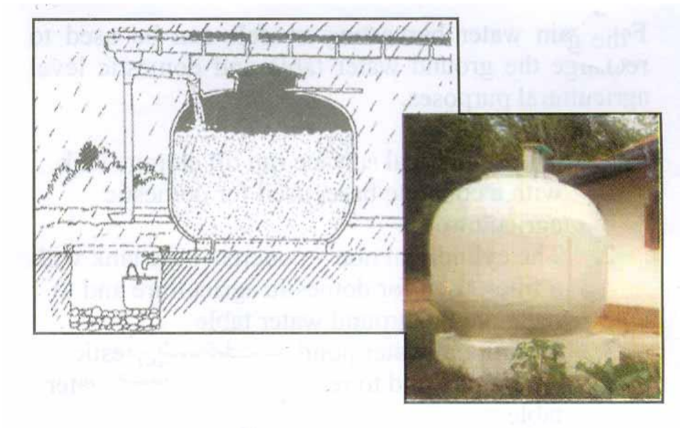

Figure 8: RTRWHS with above ground Ferro-Cement tank [145]

3.1.2 RTRWH system with partial underground tank

This model, as shown in Figure 9, is introduced to the rural areas by, the Ministry of Urban Development and Water Supply of Sri Lanka. The ease of draw-off due to lower depth is an advantage. However clearing sediments is the biggest drawback.

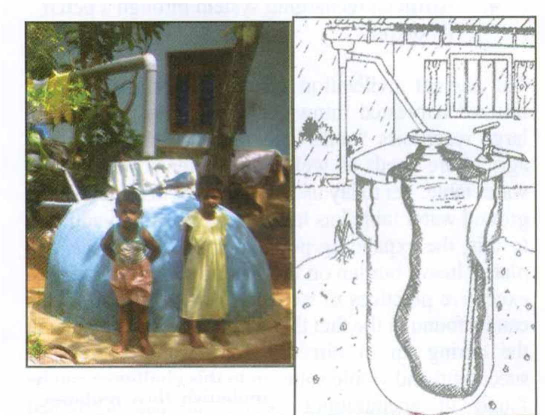

Figure 9: RTRWHS with partial underground Ferro Cement tank [145]

3.1.3 RTRWH system with below ground brick tank

In this system the space and aesthetics are saved as shown in Figure 10, but cleaning of sediments and ease of draw-off is hampered. Another practical difficulty encountered is the roots of nearby vegetation damaging the brick/cement structure of the underground tank. Therefore, for this particular model plastic tanks are recommended.

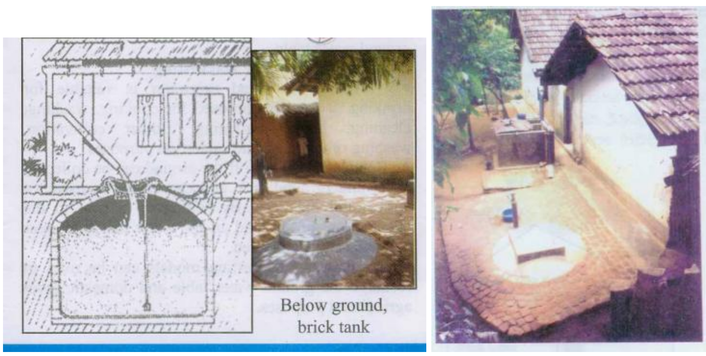

Figure 10: RTRWHS with below ground tank [145]

Studies on harvested rainwater in Anuradhapura district have revealed that physical and chemical parameters of stored rainwater meet Sri Lanka Standards (SLS) of potable water quality, but the biological parameters such as the total coli form count are always above the expected SLS [311]. This compares well with studies in rural areas of other countries in the world. However, in a RWH system, if the water is kept stored for a longer period its quality may deteriorate resulting in various health problems to the consumer. This perception is influencing more than 90% of the households to refrain from consuming harvested rainwater in Sri Lanka. This situation may be partially attributed to bad practices such as improper sealing of tank openings and absence of filters helping mosquito breeding and contamination of water with bird and animal droppings and growth of algae due to increased nutrient content in the water.

Chapter 4

OPTIMIZING SYSTEM COMPONENTS

A practical RWH system can be as simple as a vessel as the storage placed under a piece of cloth or plastic sheet with a hole in its center as the collector surface tied at its corners to four poles.

An operational RTRWH system consists of five basic components. They are, the collector surface also known as the effective roof area or the catchment area, the conveyance system or the piping to convey rain water to the tank, the storage facility or the tank, various filtering devices and a suitable draw-off device.

4.1 Collector surface

The collection area in most cases is the roof of a house or a building. Typical material for roofing include corrugated iron sheet, Asbestos-Cement sheet, tiles or thatch made from a variety of organic materials if thatched tightly[101]. The effective roof area and the material used in constructing the roof influence the efficiency of collection and water quality. All catchment surfaces must be made of non-toxic material. Painted surfaces should be avoided if possible, or, if the use of paint is unavoidable, only non-toxic paint should be used. Lead, chromium or zinc based paints are not suitable for catchment surfaces due to presence of heavy metals. Overhanging vegetation should also be avoided. Steep galvanized iron roofs have been found to be relatively efficient rainwater collectors, while flat concrete roofs are very inefficient [77]. However, roofs covered with corrugated galvanized mild steel are found to be easiest to use and giving the cleanest water [312]. GI sheets also have the potential to kill bacteria as a result of maintaining high temperature when exposed to sun.

Rooftop catchment efficiencies range from 70% - 90%. These losses are due to roofing material texture, evaporation, losses occurring in gutters and storage tanks and inefficiencies in the collection process. It has been estimated that 1 cm of rain on 100 m^2 of roof yield 10000 L. More commonly, rooftop catchment yield is estimated to be 75% of actual rainfall on the catchment area, after accounting for losses due to evaporation during periods when short, light showers are interspersed with periods of prolonged sunshine [77], though occasionally, runoff coefficient for hard roofs in humid tropics is taken as 0.85[271]. In Sri Lanka, typical runoff coefficients are taken as above 0.9 for GI sheets, 0.6-0.9 for glazed tiles, 0.8-0.9 for Aluminum sheets, 0.6-0.7 for flat cement roofs, 0.8 for Asbestos-Cement and 0.2 for thatched/organic roofs [145].

Asbestos roofs, apart from relatively lower collection efficiency of 0.8 due to its rougher surface texture, could promote the growth of coli forms from bird and animal droppings. More seriously asbestos fibers can come loose if the sheet is damaged having the potential for human ingestion causing cancer in gastro-intestinal track and pulmonary fibrosis. However Asbestos on the other hand is not uncommon in most domestic supplies with concentrations in rivers and lakes around 1 million fibers per liter. The US Environmental Protection Agency (EPA) in 1992 has set drinking water standards for Asbestos at 7 million fibers per liter for fibers longer than 10 micro metres. However research has indicated that slow sand and gravel filters can remove up to 90% of Asbestos fibers and other particulate matter (RHIC network priority).

Microscopically, the coarser surfaces of tiled or asbestos cement roofs allow for higher depositions and entrapment of pollutants from the atmosphere compared to the relatively smoother galvanized iron roofs [304]. High intensity rain, which Sri Lanka often experiences during the Monsoon periods, is more efficient in removing the pollutants due to the greater amount of energy present in the rain drops upon impact with the roof surface.

Roofs painted with lead based paints should not be used to collect rainwater for drinking due to potential leaking in the cases of rainwater having low pH values. Therefore, unpainted and uncoated roof surfaces are the best options to provide drinking water [58].

4.2 Conveyance system

A conveyance system usually consists of gutters or pipes that deliver rainwater falling on rooftop to tanks or other storage vessels. These should be properly supported and sufficiently strong to carry and keep loaded water during the heaviest rain.

Gutters both intercept and transport roof runoff. Increasing a gutter's gradient allows its size and cost to be reduced but also may reduce the fraction the fraction of runoff intercepted [270]. Water losses caused by occasional high intensity rain overshooting gutters are generally acceptable in RWH since for most roofs the actual rainwater collection is taken as about 80% of the product of average rainfall depth and projected roof collection area. The sizes of the gutters depend upon the area of the roof and the rainfall amounts and are typically in the range of 20-50 cm diameter. To prevent the loss of collection during high intensity rain events, splash guards can be used.

As a rule of thumb, in humid climates, gutter cross section is taken as 1 cm^2 for every 1 m^2 of catchment surface with a roof coefficient of 0.9. Typically, gutters are installed with steeper gradient than 1:100 which would increase the water flow by 10-20% [145].

It is important that the conveyance system to be constructed of chemically inert materials such as plastic, Aluminum, or fiberglass in order to avoid adverse effect on water quality.

4.3 Storage facility

The rainwater storage capacity must be large enough to buffer both the short term fluctuations in water usage and the long term fluctuations of rainfalls. Storage tank or recharge tank can be stationed above ground, partly underground or fully underground depending on the design and spatial arrangements and can be made of reinforced cement concrete (RCC), Ferro cement, masonry, plastic (polyethylene) or metal (galvanized iron) sheets. Storage can be classified broadly as above ground, called tanks and below ground called cisterns. Tanks can also be purchased off-the-shelf and they also allow easy inspection for leaks. Further, water extraction can be through gravity and the outlet pressure can be increased by raising the tank above ground. Cisterns on the other hand are unobtrusive, needing a pump to extract water and also are susceptible to root penetration from the micro climate. They also pose the problem of detecting leaks. Tanks and cisterns need to be kept covered to control evaporation and more importantly to prevent mosquito breeding and also as a safety measure. Algal growth could be inhibited if sunlight is prevented into the storage but still maintaining proper aeration is vital to preserve the water quality. There are a number of key requirements common to all effective tank designs;

i. A functional and water-tight design.
ii. A solid, secure cover keeping out insects, dirt and sunshine.
iii. A screened inlet filter.
iv. A screened overflow pipe.
v. A manhole allowing access for cleaning.
vi. An extraction system that does not contaminate the water.
vii. A maximum height of 2 m, preventing high water pressures.

[58]

As a general rule, water tanks should ideally be cylindrical. While both spherical and cylindrical shapes optimize the use of materials and increase wall strength, spherical shapes were proven too be less feasible [52].

Tanks should be light-proof to minimize algal growth. Moth algae will not make water unsafe for human consumption but can adversely affect taste, odor and the appearance of the water [290]. It is reported that the unit cost of construction of rainwater tanks shows a negative relationship with increasing size of the system.

4.4 Filtering devices in RWH systems

Filters are used to filter out the debris that comes with the rooftop water and prevent them being added to the storage tank. These are of two broad types:

4.4.1 Mesh Filters

A wire mesh fixed at the mouth of or on the down pipe to prevent leaves and debris from entering the system. While preventing larger objects these filters alone are not sufficient to obtain a reasonable quality rain water collection. Also mesh filters tend to corrode over time unless the wires are plastic coated. A typical mesh filter is shown in Figure 11.

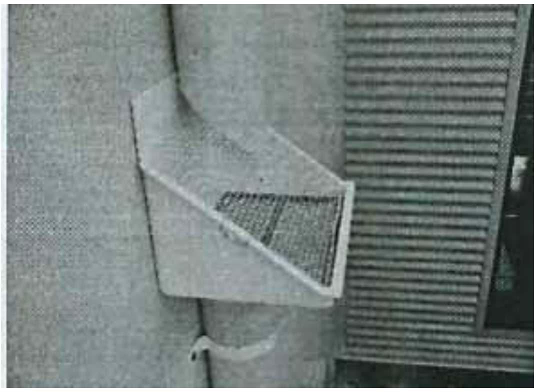

Figure 11: A typical mesh filter

4.4.2 First Flush (FF) devices

First Flush **(**FF) device is a valve that ensures the run-off from the earliest rains is flushed out and does not enter the system. The first flush of run-off water that occurs at the beginning of a storm event has been reported to contain a high proportion of the pollutant load [85]. The main cause of this phenomenon is the deposition and the accumulation of pollutant material to the roof during dry periods. The longer the dry period, the greater the probability of a higher pollutant load in the first flush. It is relatively straightforward to install a device for diverting the first flush away from the collection system [89].

The sizing of the FF devices can follow a simple equation relating to the collection area and estimated pollution load on the roof.

Flush Volume (L) = Roof Area (m^2) x Pollution Factor x 100 [1]

Pollution factors are 0.0005, for nil to light pollution, and 0.001 to 0.002, for heavily polluted sites. This corresponds to 1 mm to 2 mm of initial rainfall [310]. As a rule of thumb, the first 1 mm rainfall on a catchment area is to be released through the FF device.

FF devices have a slow release valve which allows the captured water to slowly drain to the garden or storm water outlet and thereby empty and reset for the next rain event. The concept is to flush the contaminants from the roof and gutter into the device which then closes mechanically when full, allowing the remaining roof water to flow into the tank. The release of the

FF water commences immediately and the study by Miller (2003)[182] showed that this release rate can be significant to the efficiency of the storage system. A typical First Flush device is shown in Figure 12.

Figure 12: A typical first flush device

The simplest of First Flush devices consist of a stand pipe and a gutter down-spout located ahead of the down-spout from gutter to the tanks or cistern. In this, the length of the extended down pipe to accommodate the first flush volume is calculated according to the catchment area. The initial runoff can also be manually diverted or have a tipping bucket arrangement though the method the cumbersome.

Safe rain system is another method where hollow ball is allowed to float inside an auxiliary tank blocking the inlet when the tank is full diverting the flow to the storage.

4.5 Draw-off devices used in RWH systems

Draw-off devices are used to deliver stored rainwater from the tanks to end user points and can vary according to the design of the particular RTRWH system. A draw-off device can be:

- A simple outlet to the tank

- A hand pump which is widely used with underground and partial underground storage devices.
- A centrifugal or positive displacement pump which can be used to pump collected rainwater from storage facility on the ground to an overhead tank.

However, for RWH to be integrated in to the mass culture, its basic components should be of low cost and easily attainable nature. Most importantly the harvested rainwater storage device, which is the highest costing item, should be of optimum capacity so that for a given particular set of parameters the total cost of the storage device is viable and the system pays back within a short period of time while providing an acceptable water saving efficiency that lead to a reliable system. Therefore, special attention should be made to identify and refine a suitable design tool independent of location specifications, so that for a given demand, the optimum tank size can be calculated.

The following key factors influence determining the volume of a rainwater storage tank.

a) Average annual rainfall
   Higher average annual rainfall influences selecting a larger or smaller volume tank.

b) Period of water scarcity
   Smaller volume tanks for areas with evenly distributed rainfall patterns and larger volume tanks when rain is confined to a few months or weeks of the year.

c) Type and size of rain water catchment area: Larger catchments facilitate installing of larger volume storage.
d) Water requirements: end uses of harvested water
e) Number of users: If the number of people using water is high, a large volume tank is to be stationed.

4.6 Optimization of storage size

The storage device is the highest cost component of a typical RWH system and therefore its accurate sizing determines the cost of the overall system. The sizing of storage tanks is well covered in the RWH literature [85], [98], [101], [178]. There are a number of different methods used for sizing the tank, from the simple demand based sizing to computer models but sizing the storage for a given collection area (A), rainfall depth (R) and demand (D) using graphically presented correlations less sophisticated but accurate and practical solutions.

4.6.1 General methods of determining the tank capacities of RTRWHS

Two simple methods of determining tank capacities in a typical RTRWH system have been employed for general use. They are:

Demand side Approach

Supply side Approach.

4.6.1.1 Demand side Approach

This simple approach assumes sufficient rainfall and catchment area. Calculation of the required tank capacity is as follows:

If consumption of water per capita per day = C

Number of people per household = n

And the longest average dry period = t

Then, the daily consumption = Cn

Storage requirement = Cnt (2)

4.6.1.2 Supply side Approach

In this approach a suitable catchment area with appropriate capture efficiency is determined to optimize the available tank capacity.

Supply S (m^3) =Catchment Area (m^2) x Rainfall (m) x Run-off coefficient (C_f) ….. (3)

If roof top rainwater harvesting is to be practiced on a large scale, such as in a centralized water supply, or as a system catering to a particular need for example, using collected rainwater for WC flushing only or used as a supplementary system to mains supply, then a more scientific approach is needed to satisfy various parameters to obtain optimum sizes and maximum collection efficiencies. Such systems can be used to compare costs against conventional reticulated water supply systems and to determine cost and energy savings as well as beneficial ecological effects.

4.6.2 Sizing based on supply (Mass balance method or rainfall mass curve analysis)

This simple method helps determine the storage capacity by balancing the rainwater supply and demand for a specific catchment in a specific geographical location. For the calculation, first a bar graph for cumulative mean monthly roof runoff has to be plotted for the 12 months of the year, then on the same chart, the cumulative rainwater demand is plotted. The plot starts with the first month of the rainy season after a dry period. In the case of the dry zone of Sri Lanka, therefore, starting month is October. The capacity of storage is calculated as the greatest excess volume of water over the cumulative water use at any time.

4.6.3 Sizing based on computer models

Computer based programs, developed incorporating behavioral algorithm of RWH system, can be used to determine tank sizes accurately for a given set of system parameters. Such models can predict the performance of a RWH system with fluctuating rainfall when long term monthly rainfall figures are available for a given geographical location. The accuracy can be further increased if long term daily rainfall data can be obtained which would be particularly important in areas where rainfall is more evenly distributed and more sensitive calculations are necessary. 'RainCycle' software [226] which allows modeling the tank volume through continuous daily water balance of supply and demand through the year and SimTanka (http://www.geocities.com/RainForest/Canopy/4805) are some examples.

"Rain Cycle" software can be used, which model the tank volume through a continuous daily water supply and demand throughout the year. An optimum volume is chosen when the increase in capacity does not represent significant gains in water collection. WSE of a RWH system can be calculated using the hydraulic computer model Rain Cycle. Rain Cycle is a deterministic mass-balance hydraulic system based on the Yield After Spillage (YAS) algorithm (227).

4.6.4 Sizing based on design charts

For Sri Lanka, a country specific set of graphs, numbering 23, called Design Charts for RWH, has been developed for corresponding locations to size rainwater tanks by Eng. Mansur in 1998, using over 120 years of monthly rainfall data. For a particular location, daily demands are plotted against plan roof area for a series of storage capacities with the readings having 95% reliability. Roof coefficient is taken as 0.8 and the graphs can be used to estimate storage capacity for a given demand and catchment area. Graphs are available for locations where weather stations are situated, and therefore are not spatially independent. Sizing of a tank at a particular location therefore need to refer to the graph for the nearest specific location.

4.7 Advanced methods of determining optimum tank capacities of RTRWH systems

McMahon and Mein (1978) [178] identified three general types of reservoir sizing models, namely:

Critical period model

Moran model

Behavioral model

4.7.1 Critical period model

This method identifies and uses sequences of flows where demand exceeds supply to determine the storage capacity. The sequence of flows or time series used in this method is usually derived from historical data. This method is an improved version of previously mentioned “demand side approach” to determine tank capacities.

Temporal and spatial fluctuations of rainfall data, compounded by climate changes due to global warming, severely limit generalized use of the method over many locations. Further, it is apparent that high rainfall variations affect the overall system efficiency to a great extent.

4.7.2 Moran model

Moran related methods are a development of Moran's (1959) [186] theory of storage. A system of simultaneous equations is used with this method to relate to reservoir capacity, demand and supply. The analysis is based upon queuing theory. Moran model also display similar limitations as discussed in Critical period model, affecting the overall system efficiency.

Therefore, a more advanced model, which can readily accommodate temporal and spatial fluctuations in rainfall, is required and the resultant graphs developed depicting system efficiency can be used as a powerful design tool to determine optimum tank capacities.

4.7.3 Behavioral models

Behavioral models simulate the operation of the reservoir with respect to time by routing simulated mass flows through an algorithm which describes the operation of the reservoir.

The operation of the rainwater collection will usually be simulated over a period of years. The input data, which is in time series form, are used to simulate the mass flow through the model and will be based upon a time interval of either a minute, hour, day or month. Fewkes (1999a) [85] used behavioral model to simulate the performance of rainwater collectors and incorporated the spatial variations of rainfall into the model by using rainfall time series from five different locations and temporal fluctuations in rainfall by using two behavioral models each with different time intervals.

4.8 Investigating the Performance of RTRWH System using Behavioral model

Behavioral models have been used by other researchers [129], [148] to investigate the performance of rain water stores.

The generic configuration of a rainwater collection system is illustrated in Figure 13.

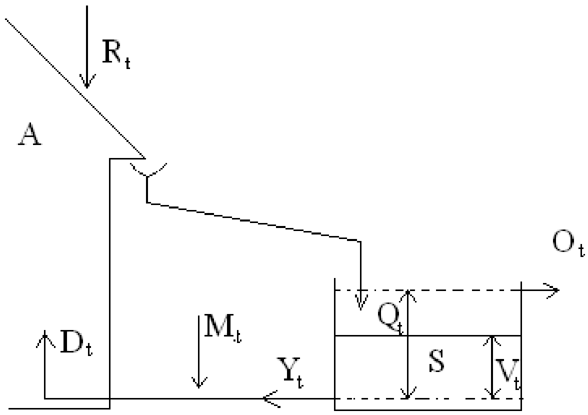

Figure 13: Generic configuration of a rainwater collection system

Where,

R_t is Rainfall in time t

D_t is the Demand (time t)

Y_t is the Yield (time t)

A is the roof area

S is the storage volume

Q_t is the roof runoff (t)

O_t is the overflow

Two fundamental algorithms have been identified to describe the behavioral model [129]. They are:

a) The Yield After Spillage (YAS) operating rule
b) The Yield Before Spillage (YBS) operating rule

4.8.1 Yield after spillage (YAS) operating model

YAS operating rule is;

$$Y_t = \min \{D_t t; \quad V_{t-1}\} \qquad (4)$$

$$V_t = \min \{V_{t-1} + Q_t - Y_t; \quad S - Y_t\} \qquad (5)$$

Where,

R_t is the rainfall (m) during time interval, t,

Q_t is the rainwater run-off (m^3) during time interval, t,

V_t is the volume in store (m^3) during time interval, t,

Y_t is the yield from store (m^3) during time interval, t,

D_t is the Demand (m^3) during time interval, t,

S is the Store capacity (m^3)

A is the roof area (m^2)

The YAS operating rule assigns the yield as either the volume of rainwater in storage from the preceding time interval or the demand in the current time interval whichever is the smaller. The rainwater run-off in the current time interval is then added to the volume of rainwater in storage from the preceding time interval with any excess spilling via the overflow and then subtracts the yield.

4.8.2 The Yield Before Spillage (YBS) Operating model

YBS operating rule is,

$$Y_t = \min (D_t; \quad V_{t-1} + Q_t) \qquad (6)$$

$$V_t = \min (V_{t-1} + Q_t - Y_t; \quad S) \qquad (7)$$

The YBS operating rule assigns the yield as either the volume of rainwater in storage from the preceding time interval plus the run-off in the current interval or the present demand whichever is the smaller. The rainwater run-off in the current time interval is then added to the volume of the rainwater in storage from the preceding time interval before subtracting the yield and allowing any excess to spill via the overflow. A behavioral model can be used to define the reservoir operating algorithm in a more general form [Latham]:

$$Y_t = \min (D_t; \quad V_{t-1} + \theta Q_t) \tag{8}$$

$$V_t = \min ((V_{t-1} + Q_t - \theta Y_t) - (1-\theta)Y_t; \; S - (1-\theta)Y_t) \tag{9}$$

Where, θ is a parameter between 0 and 1. If $\theta = 0$, then the algorithm is YAS and if $\theta = 1$, the algorithm is YBS.

4.8.3 Predicting the performance of RTRWH System using Behavioral model

Using the YAS algorithm and a monthly time interval, the reliability or performance of the rainwater store can be expressed using either a time or volume basis [129]. In either case, a reliability or performance of 100% indicates complete security in provision of service water.

The accuracy of behavioral models for the sizing of rainwater collection systems using both different time intervals and reservoir operating algorithms applied to a comprehensive range of operational conditions. The preliminary analysis of their study indicated that the hourly YAS model could be used as a standard of comparison against which other models could be compared and calibrated [36].

The YAS reservoir operating algorithm was found to give a conservative estimate of system performance irrespective of the model time interval and therefore is preferred for design purposes compared to the YBS operating algorithm.

Components of a rainwater collector sizing model is depicted in Figure 14.

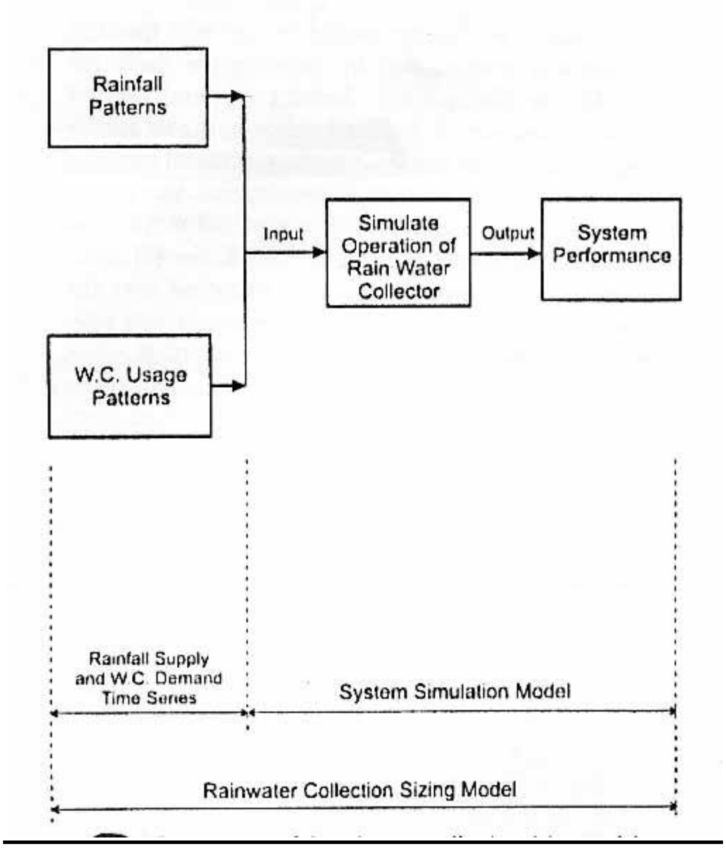

Figure 14: Components of a rainwater collector sizing model

In developing the system performance curves, two models were used to incorporate the temporal fluctuations of rainfall.

The first model uses a daily time interval, which ignores fluctuations with a time scale less than a day, to predict system performance for different combinations of roof area, demand, storage volume and rainfall level. A set of curves is produced which enable the performance of rainwater collection systems to be predicted in different locations. The main limitation of this approach is the requirement of daily rainfall time series, which can be both costly and difficult to manipulate.

The second method of modeling uses a larger time interval of one month resulting in a more compact model and economic data set. However, the coarser monthly time interval does not take into account rainfall fluctuations with a time scale less than one month, which may result in an inaccurate prediction of system performance [86].

The poor resolution of the monthly interval model compared to the daily model is countered by the introduction of a parameter, referred to as the storage operating parameter. The short time scale fluctuations of the daily model are in effect replicated in the monthly model by the storage operating parameter. Values of the parameter are selected so that the monthly model mimics the system performance predicted by the corresponding model using a daily time interval. This approach provides a simple and versatile method of modeling the performance of rainwater collectors which takes into account temporal fluctuations in rainfall.

The performance of the rainwater collection system is described by its Water Saving Efficiency (WSE) [36], [68], [86].

Water Saving efficiency is a measure of how much mains water has been conserved in comparison to the overall demand and is given by,

$$WSE = \frac{\sum_{t=1-}^{t=T} Yt}{\sum_{t=1}^{t=T} Dt} \times 100\% \qquad (10)$$

Where, Y_t is the yield from storage facility (m^3) during time interval, t, D_t is the demand (m^3) during the time interval, t. T is the total time under consideration.

In the study conducted by Fewkes (1999b) [86], the demand component of the models was limited to WC usage which accounts for approximately 30% of potable household water usage in the UK (Department of the Environment and Welsh office 1992) and was assumed to occur at a constant daily or monthly rate. This assumption was reasonable because the demand time series generated by WC usage did not exhibit excessive daily or monthly variance.

In studies conducted elsewhere, including in Sri Lanka, it is reported that the service water usage is relatively constant and depends on the lifestyle of the users at a particular geographic location. However, if the demand from other domestic appliances such as washing machine was considered the demand pattern would not be constant and the demand time series required.

The detailed analysis undertaken enabled constraints to be proposed for the application of hourly, daily and monthly models expressed in terms of storage fraction. It was recommended that hourly models should be used for sizing small stores with a storage fraction below or equal to 0.01. Daily models can be applied to systems with storage fraction within the range 0.01 to 0.125. Monthly models were only recommended for use with storage fractions in excess of 0.125. Generally, daily models can be used to predict the performance of all stores except small stores with a storage fraction less than or equal to 0.01 [86].

4.8.4 Generic curves for system performance of a RTRWH System

Fewkes (1999b) [86] developed a generic set of curves using a YAS daily time interval model, for a range of storage and demand fractions. Different combinations of roof area, store capacity and demand were expressed in terms of two dimensionless ratios, namely the demand fraction and storage fraction.

The Demand fraction is given by D/AR, where D is the annual demand (in m^3), A is the roof area (in m^2), and R is the annual rainfall (in m). The Storage fraction is given by S/AR, where S is the store capacity (in m^3). The above fractions can be used to predict the performance of rainwater collectors within a particular geographical area. The performance of the rainwater collection system is described by its Water Saving Efficiency (WSE) [68].

It was observed that the Water Saving Efficiency (WSE) curves at each demand fraction ratio for different sites are of close proximity to each other suggesting system performance could be adequately represented by a set of average or generic curves. The average water saving efficiency of a rainwater collector at demand fractions of 0.25, 0.50, 0.75, 1.00, 1.25, 1.50, 1.75 and 2.00 each with a storage fraction range of 0.005 – 0.40 is illustrated in Fig. 15

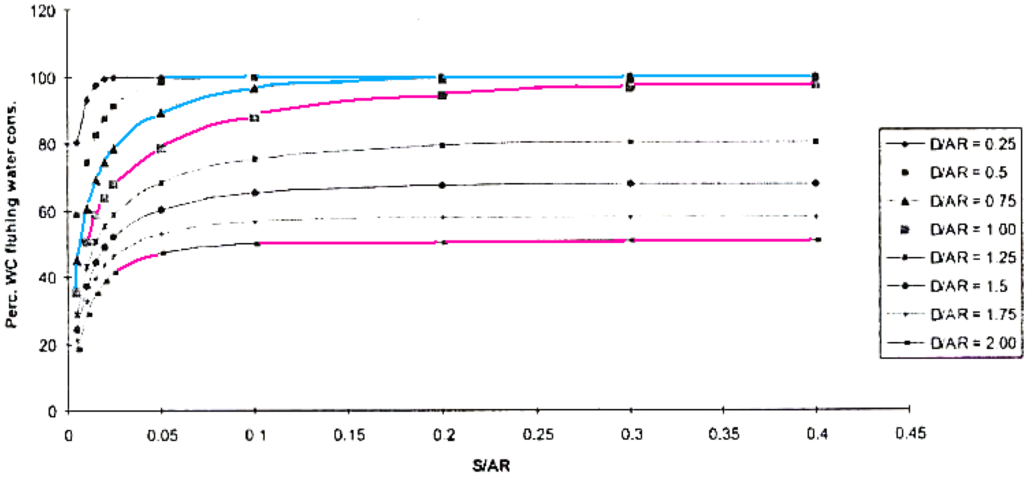

Figure 15: Generic curves for Water Saving Efficiency (WSE) [86]

4.8.5 Important observations and parameters with regard to generic curves on WSE

Three important factors are considered in developing the generic curves for their effects on performance of the curves. They are; the effect of demand pattern, the roof run-off coefficient (C_f) and rainfall data.

Effect of demand pattern

Effect of roof run-off coefficient (C_f)

Variation in rainfall data

4.8.5.1 Effect of demand pattern

The generic curves of WSE were plotted against different storage fractions (S/AR) for a given demand fraction (D/AR). In doing so, demand is assumed to be a constant for a particular situation and in the case of WC flushing appears to hold true. It was observed that for a period of 12 months, that WC flushing water demand remained at a fairly consistent level from day to day [86].

Demand patterns which exhibit significant daily variance will require more precise modeling. Therefore, the generic curves for WSE can be fairly accurately used where demand can assumed to be a constant.

4.8.5.2 The effect of roof run-off coefficient (C_f)

Rainfall loss during collection occurs due to absorption by the roofing material and wind effects around the roof. The rainfall loss was modeled using an initial depression storage loss (L) with a run-off coefficient (C_f) [85].

The model is of the general form;

$$Qt = \sum_{t=1}^{T} Qt = \left(\sum_{t=1}^{T} RtACf\right) - L \qquad (11)$$

Where, Qt is the rainwater run-off during rainfall event, t,

T is duration of rainfall event, t (min)

L is the depression storage loss (L)

C_f is the run-off coefficient

R_t is rainfall during rainfall event, t (mm).

It is noted that L can also be expressed in mm by dividing the depression loss by collection area. L can also be used to accommodate the first flush volume in a rain event which contributes to storage loss. The sensitivity of WSE to rainfall loss is illustrated in Fig. 16

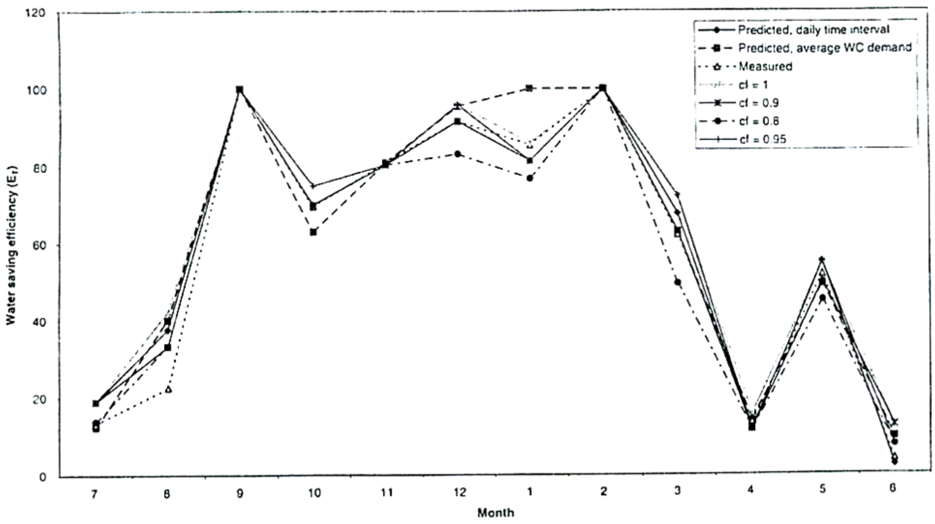

Figure 16: The sensitivity of WSE to rainfall loss [85]

In the analysis the depression storage loss was set to zero and the sensitivity of the rainwater collection sizing (RCS) model investigated using constant proportional losses or run-off coefficients ranging from 0.8 to 1.00 [86]. The amount of rainwater collected was not found to be significantly affected by wind speed and direction.

The accuracy of the (RCS) model maintained within the range is indicating that a simplified approach to the modeling of rainfall losses appears valid. Therefore, the overall run-off coefficient for the trial period can be estimated using the relationship:

$$C_f = Q_T/R_T.A \qquad (12)$$

Where, Q_T is the quantity of rain water collected in time T

R_T is the rainfall in time T

A is the capture area

4.8.5.3 Variation in rainfall data

The generic curves for Water Saving Efficiency (WSE) were developed for a particular set of rainfall data. The model was simulated with rainfall data collected in 5 sites where average annual rainfall varies from 620 – 1600 mm/year [89]. The performance curves predicted for each site were found to be close together, almost coalescing into a single curve. The modeled performance of rainwater collectors at various demand fractions, except when D/AR is closer to 1.00 when slight sensitivity is shown appears therefore to be relatively insensitive to fluctuations in daily rainfall patterns experienced at each location. Therefore, for the given rainfall range, the generic curves developed can be adequately used to suggest system performance for given demand and storage fractions.

4.8.6 Sample calculation for sizing storage of a RWH system

It is observed that the harvested rainwater can be utilized for WC flushing and cleaning purposes the where the amount of water used is approximately 40% of the total water usage. However, such requirements need the delivery of collected rainwater to utility points at a sufficient pressure to be used at any given time. One possible energy efficient arrangement is to position the storage tank at an elevation near the capture area (at roof level) so that the collected water can be fed to utility points through gravity. However, when the tank size increases, the space and strength requirements to support the tank will be beyond the meaningful utilization of harvested rainwater. Further, due to limited availability of ground space in urban multi-story buildings, positioning of a larger storage tank above ground will not be feasible and the entire quantity of harvested rain water will have to be pumped up to utility points. Therefore, typical sizes of storage tanks will have to be studied to make the model more practical.

Considering a typical household in the wet zone of Sri Lanka, where the annual rainfall is the highest (1500 mm to 6000 mm), with a capture area of 50 m^2, the daily water usage for four occupants can be taken as 800 L (at per capita demand of 200 L)

If harvested rainwater is utilized only for WC flushing and cleaning,

Then the demand for harvested rain water is 800x40% = 320L/day (116.8 m^3/year)

As the minimum annual rainfall in the wet zone, $R_{min-wet}$ = 1500 mm

The value for D/AR can be calculated as D/AR = 1.56

(It should be noted that the minimum rainfall values are selected as a safety factor for performance reliability)

From the WSE curves (Fig.15), the maximum possible WSE that can be achieved is found to be 65% and the corresponding value for S/AR = 0.15 giving an optimum storage size (S) of 11.25 m^3. Even when the capture area is doubled (100 m^2), it would still give a value of 1.5 m^3 as the storage capacity for the same WSE of 65%. If however, a WSE of 95% is desired, then the optimum storage capacity (S) will be 15 m^3. Therefore, if a reasonably high and economically acceptable WSE is to be employed (typically over 80%), then a higher value for the optimum tank size (S) to be expected. Moreover, as the minimum annual rainfall figure (R_{min}) tends to be smaller for the intermediate and dry zones, higher tank capacities are required if the WSE to be achieved above 80%.

It can be observed that in order to provide running water facility, the storage tank has to be placed at a higher elevation-which is not feasible due to volumes concerned. While such bigger tanks can be accommodated in rural single story houses with abundant ground space, for urban multistory houses with the necessity of running water will need a different model to use rain water harvesting effectively and meaningfully.

It has been shown that Fewkes generic curves for water saving efficiencies (WSE) can be used to determine the optimum storage capacities for a given demand and for a desired WSE. The curves are validated for Sri Lanka by Sendanayake et al.[250]. These minimum annual rainfall figures defining the boundary of the domain in which the generalized curves hold true are below the minimum annual rainfall figures in the dry zone of Sri Lanka. As such, the curves given in Fig.15 can be used for RWH model system sizing in any region of the country and can be accepted as universal within Sri Lanka. However, as the sizing applications move towards drier regions, unless the capture area is significantly increased D/AR tends to increase thus falling into regions of lower WSE of the curves. To maximize the WSE for the given D/AR value, S/AR values will have to be chosen beyond the 0.15 range, indicating bigger storage tanks. A similar scenario can be seen when the demand (D) for harvested rain water increases, even in the wet zone.

Chapter 5

RAINWATER HARVESTING SYSTEMS IN URBAN HOUSES

Water scarcity is recognized as an increasingly severe problem with global implications [236]. Urban areas are among the most vulnerable systems as they bear great environmental pressures, are associated with large ecological footprints and are dependent to a great extent on water from distant sources which are transported by means of large infrastructures [6]. It is reported that approximately 50% of the world's population is concentrated in urban areas [279] where the water scarcity and the reduction of conventional resources promoting greater dependence on sometimes lower quality imported water from distance sources to cater to the need.

At present, in urban landscapes, addressing of water scarcity is more focused on costly desalination techniques and water recycling processes. But in an urban landscape RWH can provide free water that can be easily sent to non-potable water uses, mitigate the pressure on aquifers and surface courses, reduce water stress and pollution to surface waters, help to prevent floods caused by soil scaling resulting from urbanization while reduce loads on sewers allowing larger storage volumes of high intensity rainfall events [6], [87], [146], [208], [309]. Additionally, the use of rainwater on a large scale is perceived as an adaptive strategy to climate change against the reduction of water availability [275].

RWH systems have been historically applied to a variety of uses in population settlements and isolated homes [107] particularly as a viable water source for the flushing of toilets, laundry, irrigation of gardens and other activities related to potential non-potable uses [197] and recently there has been an increasing interest in the use of water resources generated within the urban boundary for drinking water supply substitution [81]. RWH systems therefore can be considered as shrinking the urban water cycle and making more visible the components of the hydro-social cycle to the citizens.

With RWH systems, in addition to the water security, the owner would be consciously involved with the maintenance of the system, integrating effectively with environmental aspects of urban living, allowing the residents to play a central role in the implementation of RWH systems as they become the owners and managers of the systems.

In integrating a RWH system to an urban building many factors are to be considered in depth. While at the installation stage, the availability of space, structural and aesthetic aspects associated with the positioning of the system components, the piping and plumbing network and local building regulations are important, at the operational stage, the utilization of energy, the cost incurred and the possible contributions to Green House Gas (GHG) emissions should be considered. It is seen that many of these issues are related to the selected method of positioning the rainwater storage tank in relation to the building structure.

5.1 Alternative methods of storage tank positioning for urban houses

Various methods of positioning rainwater storage tanks and the corresponding plumbing configurations possible for typical households are presented below. Practical water supply situations for both single and two story houses where RWH systems supplementing the service water needs are looked at in five scenarios.

5.1.1 The storage tank at ground level, and draw-off through pressure operated pump

Collected rainwater is fed to a separate pipeline, feeding WC end user points, at a higher pressure than the mains. A level sensor operates the pressure pump, to prevent the pump running dry. The system can be used in multi-storey situations, but no energy saving is possible. Reticulated supply is to be directly feeding the service points with appropriate valve arrangements to prevent backflow with the cistern solely for storing harvested rainwater. A schematic diagram is shown in Figure 17.

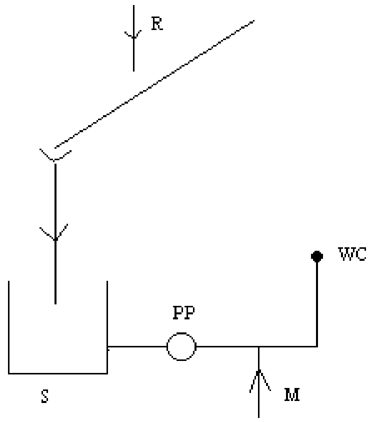

Figure 17: Plumbing configuration for RTRWHS

5.1.2 The storage tank mounted on the eve of a multi-storey house

Rainwater is supplied through gravity, hence no energy consumption occurs. However, supply of water to upper stories is not possible due to lack of head. Since the tank is mounted on the eve, space restrictions could occur. Also, a strength analysis of the eve for its load bearing capacity is required [240].

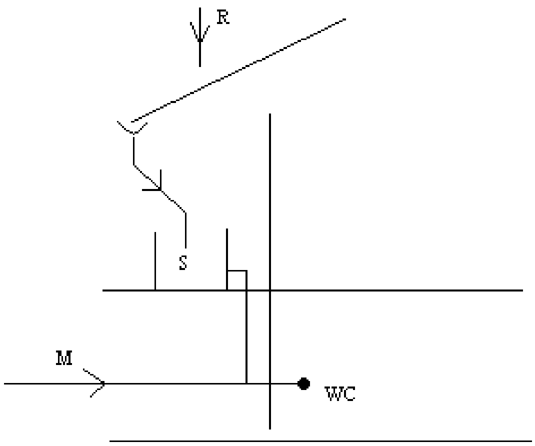

Figure 18: Plumbing configuration for RTRWHS [240]

It should be noted that if the capture area is > 200 m^2, a smaller tank of 2000 L can be utilized, so that the eve can support the additional weight since the tank size is smaller compared to that for a smaller capture area. A schematic diagram is shown in Figure 18.

5.1.3 Rainwater pumped from storage facility to a header tank

In this situation an extra energy input is required to pump the collected rainwater to the header tank. A level sensor to operate the pump P1 fixed in the header tank could improve the efficiency in water saving. This system is suitable for locations, where ground water levels drop seasonally. A schematic diagram is shown in Figure 19.

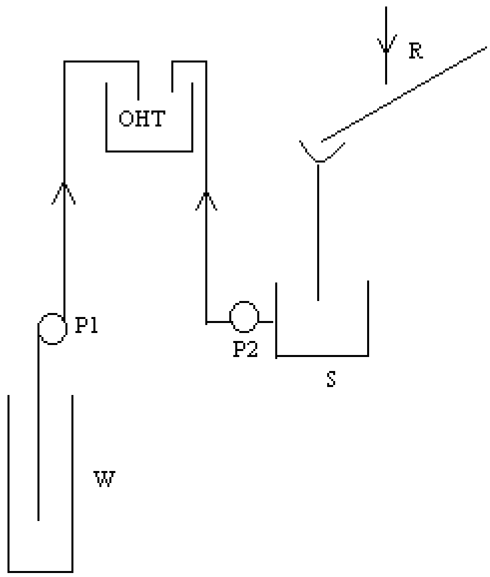

Figure 19: Plumbing configuration for RTRWHS [240]

5.1.4 Rainwater collected in a split cistern

To mitigate the unreliability of mains water supply, many households utilize underground cisterns. By partitioning the cistern so that one part receives roof collection while the other part receives the mains supply, savings can be made on service water. A 5000 L capacity tank connected to a minimum roof area of 45 m^2 is recommended for WC flushing water requirement. A schematic diagram is shown in Figure 20.

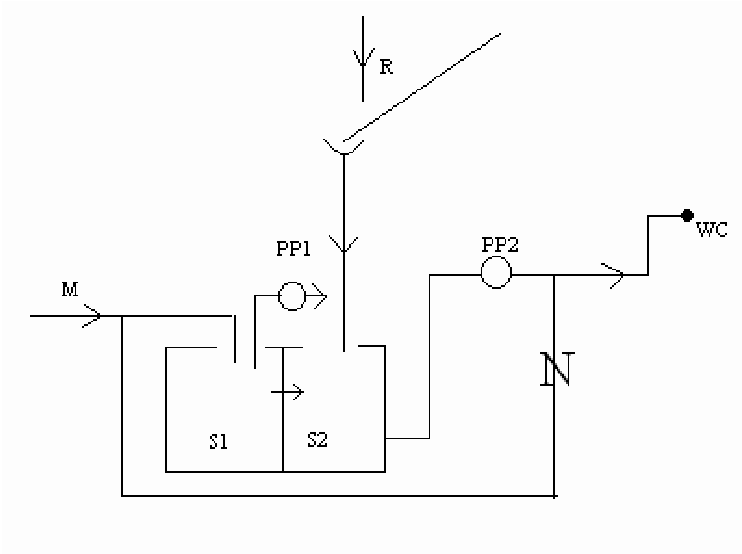

Figure 20: Plumbing configuration for RTRWHS [240]

5.1.5 Rainwater collected in a cistern with draw-off through filtration

Employing a series of filters such as Carbon and Sediment filters and a UV sterilizer, drinking quality water can be obtained from the collected rainwater. It can be envisaged that, by selecting suitable storage capacities and collection surfaces, substantial water saving efficiencies can be achieved. A schematic diagram is shown in Figure 21. In this scenario, untreated rainwater can be allowed to mix with reticulated mains water as the supply to service points is through a series of filters.

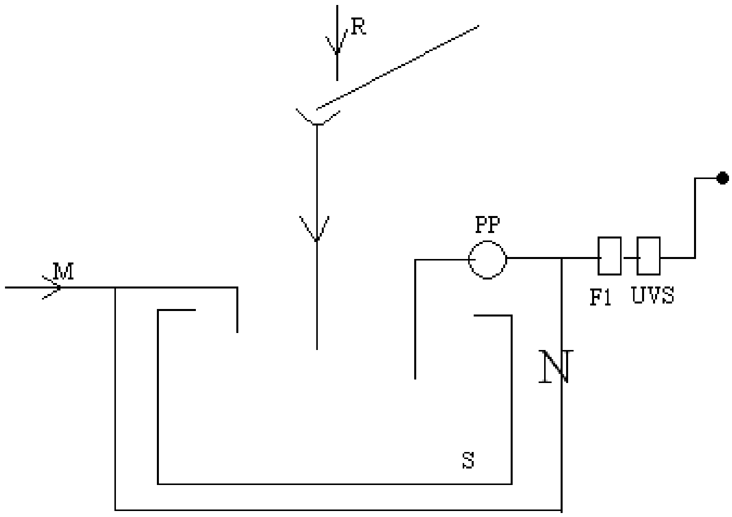

Figure 21: Plumbing configuration for RTRWHS [240]

Except in scenario 5.1.2, in all other scenarios the requirement of a pump to provide the harvested rainwater either to an overhead tank or directly to the utility points can be observed. Such arrangements while preserving water, utilize energy to transfer the entire quantity of collected rainwater and as such cannot be considered as energy efficient or as promoting the principles of sustainable development for built environments.

5.2 Integration of RTRWH systems to multi-storey situations

Integrating of RWH systems multi-storey households are looked at in the light of the following;

- Inadequacy of service water supply pressure for upper floors at peak hours, requiring header tanks for water security.
- Increased trend to build multi-storey houses in urban areas due to high cost of land.
- Multi-storey buildings confirming to sustainable development through energy conservation and cost effectiveness.

To overcome water security problems, most multi-storey and other households use an underground sump from where service water is pumped to a header tank. Therefore, in calculating payback periods for RTRWH systems, the investment on the cistern, header tank and the centrifugal pump are excluded. As such, Investment on solar pumping is taken as follows;

Capital outlay = Cost of solar pumping unit – Cost of Centrifugal pump [13].

5.2.1 Different scenarios of integrating RTRWH systems to service water supply in multi-story houses

5.2.1.1 Scenario 1

In this scenario, the mains service water supply is connected to a header tank (H1) for water security. Rainwater is harvested in to a storage facility at ground level, the capacity of which is calculated for WSE of 80%. Rainwater is pumped to a header tank of 1000 L capacity (H2), by using a solar powered positive displacement pump. Both H1 and H2 are fitted with floater switches to control overflow. The H2 is used to feed WCs as shown in Figure 22.

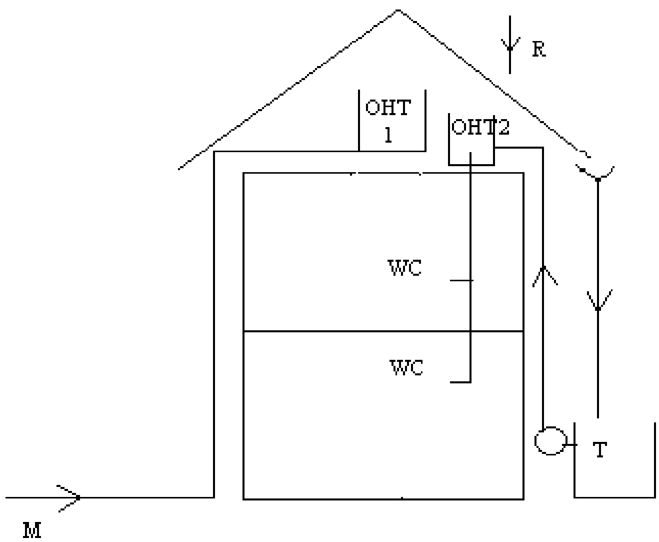

Figure 22: Integration of RTRWHS for multi-story situations, scenario 1 [241]

5.2.1.2 Scenario 2

Service water from mains is supplied direct to an over head tank (OHT). The RTRWH system is supplementing the service water. Rainwater harvested is collected into a storage facility placed on RCC/Steel structure positioned just below the eve. The limitations of the system include space restrictions and lower water pressure at upper floors. A schematic diagram of the scenario 2 is shown in Figure 23

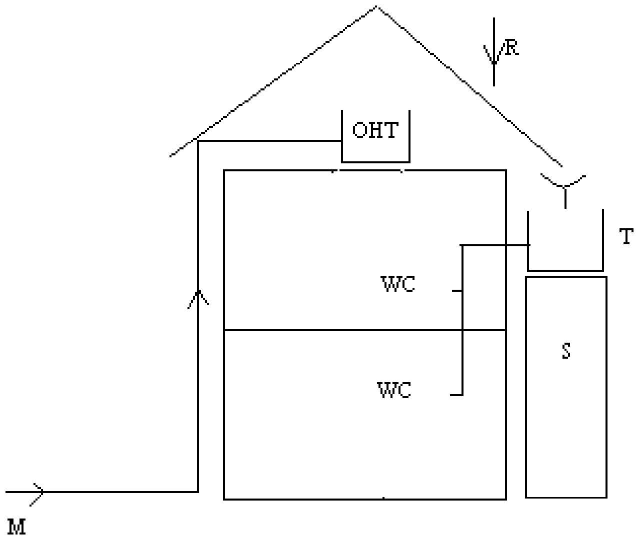

Figure 23: Integration of RTRWHS for multi-story situations, scenario 2 [241]

5.9.1.3 Scenario 3

Rainwater is collected to an underground sump, with mains supply as a backup. Water from the sump is pumped using solar power to an OHT, which feeds the user points via a series of filters (sediment & carbon) and the kitchen line through an UV Sterilizer to remove bacteria. Rain water conveying lines are fitted with sieves at gutter level and at entry to the sump to prevent vegetation entering the tank. A First Flush (FF) device is fitted as an integral part of the RTRWH system. A schematic diagram of the scenario

3 is shown in Figure 24. Collected and filtered water can be used for all household chores. In this situation, night filling is not allowed to save service water.

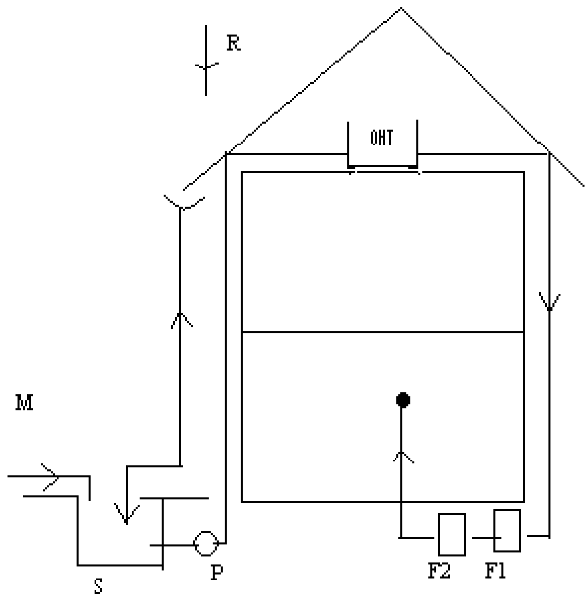

Figure 24: Integration of RTRWHS for multi-story situations, [241]

5.2.1.4 Scenario 4

In the light of the general aversion to use of rainwater in cooking and drinking in Sri Lankan households, an improved version to scenario 3 is proposed. The existing sump is partitioned, so that 75% of the service water is from rainwater as shown in Figure 25.

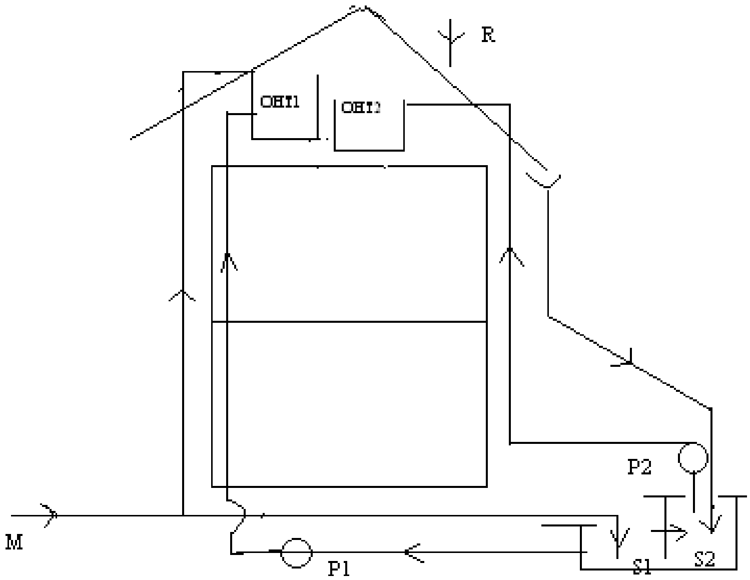

Figure 25: Integration of RTRWHS for multi-story situations, scenario 4 [241]

Solar pumping can be used to fill an additional header tank (H2), which will feed all user points except at kitchen.

While it is possible to reduce the sump capacities required by increasing the collector area, it is prudent to employ a larger capacity sump for water security since prolonged draughts can be anticipated due to climate change.

Of the various pumping options available, except for hand pumping, all other options require energy input, where in the case of electrically operated systems, the possibility of Green House Gas (GHG) emissions occur. In Sri Lanka, where 65% of electricity generated is from fossil fuel burning, every electrical appliance including the water pump, contributes to GHG emissions in operation. Hence, alternative renewable energy sources are looked at to make RWH confirming to sustainable development.

It is reported that a RWH system designed as an integrated component of a new construction project is generally more effective than retrofitting a system to an existing building [313].

5.3 Impact of RWH systems on design loads of local drainage systems

Rain Water Harvesting (RWH) is a useful proposition for medium and large scale suburban housing schemes where the service water demand can be partially met reducing the investment on reticulated supply (Jayasinghe et al 2007). Particularly ideal for tropical countries where sufficient rainfall is available throughout the year, the individual housing units with optimum capacities for their rainwater storage tanks, can gain further advantage through economies of scale in reducing the overall system cost. At the same time, increased impervious surfaces have made the urban areas susceptible to flash floods during storm events with severe strain on the local drainage system. Since the rain water storage tanks retain a percentage of roof collection during a storm event and only the excess flowing into the drains, collectively the tanks can be used to reduce the peak load on the drainage system by judiciously increasing the retention volumes. If an inter-relationship between the storage volume of a RWH system and the overflow quantities for a given climatic region, with service water demand and storage capacity as system variables, can be developed, such a relationship, once graphically presented, could be a significantly useful design tool to estimate rainwater storage capacities for a given scenario.

As RWH systems trap a certain amount of roof collection in rain events, increasing of retention volumes can be effectively used to mitigate the overflow thus reducing the design peak load on the local drainage system while enhancing the overall WSE. In this scenario it is useful to investigate the impact of increasing the storage capacity on both the overflow quantities and WSE and select the optimum capacity for the overall viability of the system.

The overflow quantity of rainwater (Q_{OF}) from a RWH system on a given ith day can be given by,

$$(Q_{OF})_i = (Q_{AVL})_i + (Q_{IN})_i - (Q_{USE})_i \qquad (14)$$

Where, $(Q_{AVL})_i$, $(Q_{IN})_{i,}$ and $(Q_{USE})_i$ are the balance quantity of rainwater available in the storage tank after the yield of the previous day, the roof collection during the day and the amount of rainwater drawn from the tank (yield) respectively on the i^{th} day. Q_{IN} in fact is the product of the effective roof collection area (A) and the average rainfall depth of the day $(R)_i$ and therefore can be taken as $(AR)_i$. $(Q_{USE})_I$ which is the daily yield and can be indicated as Y_i.

Therefore, for annual quantities (14) can be modified as,

$$(\sum Q_{OF}) = (\sum Q_{AVL}) + AR - \sum Y \qquad (15)$$

where 'R' is the annual average rainfall depth.

Further, the overall WSE of the system can be defined as,

$$WSE\% = \sum Y_i / \sum D_i \qquad (16)$$

By simulating (14) with daily rainfall values, daily overflow quantities can be obtained for a given demand, storage capacity and roof collection area.

Plotting overflow as a percentage of roof collection ($\sum Q_{OF}\%/AR$) against storage fraction (S/AR) for constant daily demands of 100 L and 200 L (Fig. 26), a set of characteristic curves can be observed. It can be seen that for a given roof collection area (A) and rainfall depth (R) overflow quantities drop with the increase of storage capacity. However, the percentage overflows show only a marginal drop for an increase of storage fraction beyond 0.02 indicating that increasing of the storage capacity beyond that of S/AR = 0.02 for a given A and R is not having a substantial mitigating effect on the overflow quantities for a given RWH system [244].

From the equation for calculating overflow quantities (14), it is seen that for a given A and R, Q_{IN} is a constant and $Q_{USE,}$ which is the yield from the system, is depending on the demand and the WSE of the system. Further, it can be seen that Q_{AVL} for a given day is a function of the yield and the roof collection related to the previous day and therefore essentially is a function of the WSE of the system for a given A, R and D. Therefore, it can be deduced that $\sum Q_{OF}\%/AR$ varies with the WSE of a RWH system for a given

D and storage capacity (S) with the overflow quantities reducing with the increase of system efficiency.

Comparing the two curves for the daily constant demands of 100 L and 200 L, it is clear those higher demands having profound impacts on the overflow quantities. This can be explained by (15) and (16), in which the yield (Y) is given by WSE*D, thus showing that any decrease in WSE as a result of increasing daily demand (d) is offset by the increase in total demand (D). In fact the drop in WSE, and thereby the percentage annual overflow quantities with the decrease of S/AR, can be explained by the behavior of the generalized curves developed for WSE for RWH systems [86], in which WSE values dropping with decreasing storage fraction (S/AR) for a given demand fraction (D/AR) value [244].

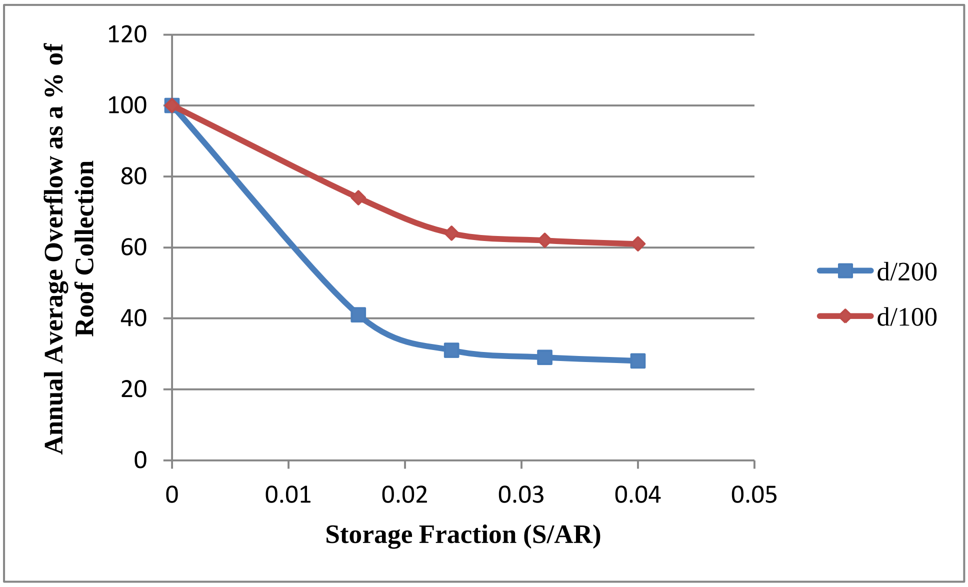

Figure 26: Annual average overflow percentages for storage fractions at given daily demands

The graph depicting the variation of overflow percentages with storage fractions (Fig. 26) shows optimum values for S/AR of around 0.02 for both daily service water demands of 100 L and 200L. For S/AR values greater than 0.02, the drop in the overflow percentage for a given D, A and R are marginal and hence it can be concluded that increasing the storage capacity beyond 2% of the annual roof collection (AR) will not have any significant impact on the overflow quantities and therefore on the local drainage system.

From the graph (Fig. 26) it can also be seen that the daily demands having a high impact on the overflow quantities. In fact doubling of the daily demand has reduced the overflow percentages by as much as 30% for S/AR values greater than 0.02, showing that the load on the local drainage system can be more effectively reduced by increasing the use of rainwater for most of domestic service water needs [244].

It is also important to note that since the overflow quantities and storage capacities are divided by the roof collection (AR), the impact of spatial and temporal variation of rainfall on system performance is avoided and therefore allowing the determining of required storage capacities for any given combination of A and R values.

Therefore, it can be concluded that the curves can effectively be used as a design tool to determine the optimum storage capacity of a RWH system for a desired overflow quantity at a given service water demand. In the simulation, system losses are considered as negligible [244].

In developing the percentage overflow against specific storage volume chart, if data from a longer time series is taken, more accurate overflow quantities could be possible.

Since the maximum overflow occurs during periods of maximum rainfall, it can be safely assumed that the results obtained from measuring and calculating overflow quantities in a single year closely resembles a similar data set collected over a longer period of time. It is clear from historical data, that the average rainfall during peak rainy months is approximately same with a maximum variation of 15% [244].

It can be seen from the graph, that for a significant percentage drop in overflow, the specific storage volume has to be largely enhanced. In any case, practically, overflow percentage cannot reach zero due to unpredictability of the strength and intensity of rain events in any particular period of time. However, if a minimum of 50 years of rainfall data are collected for a particular region and simulated to calculate overflow percentages, the maximum additional retention volume required for maximum rainfall occurred as well as average additional retention volume required for annual average rainfall during peak rainy period can be calculated. Whilst the former can be useful in flash flood control situations the latter is useful in RWH situations. Further, it can be seen from the graph that a more pronounced impact can be affected on the overflow percentages by increasing the specific rain water consumption. Therefore, if harvested rain water can be used further to WC flushing, a steeper reduction in overflow quantities can be achieved.

RWH controllers such as OptiRTC, based on software and online weather forecasts, are available now which receive Internet-based weather forecast data to automatically empty rainwater systems in advance of storm events to maximize storage as well as reduce impacts to the storm water system.

Chapter 6

CASCADING MULTI TANK RAINWATER HARVESTING SYSTEMS

In any RWH situation, the storage tank has to be placed at a lower elevation than the collection area, thereby facilitating the flow of collected rain water into the tank under gravity. The storage can be at a positioned above the ground level, in which case the collected rainwater can be fed to service points under gravity or it can be placed below the ground level as a sub-surface cistern. In both the above and below ground level scenarios either a pressure activated pump or a pump and a header tank are required, where the collected rainwater is first pumped to the header tank and through which water is fed to the service points under gravity. In the first scenario of elevated storage, the retention volumes required for improved WSE levels pose problems on the building envelop in structural and aesthetic aspects. In the case of placing the tank at ground level on the other hand require space, which in most situations is limited in built up areas. In the case of underground cisterns, issues of cleaning and difficulties in detecting leaks are common. In any case, the bigger problem is the pumping of the harvested rain water in to service points so that the system performance is on par with the centralized systems. However, there is a risk of RWH negating the sustainable principles, which it espouses, if a high amount of energy is consumed in the pumping operation.

Taking the above factors into consideration and focusing on minimizing the energy requirement in transferring collected rainwater to service points, a novel RWH model called the Cascading Multi Tank Rain Water Harvesting (CMTRWH) model is introduced with detailed features.

The rain water harvesting model introduced is a novel concept of decentralizing the storage capacity where the roof collection cascading down through storage tanks located at different elevations making it particularly attractive for multi-level compact and diffuse urban dwellings [245].

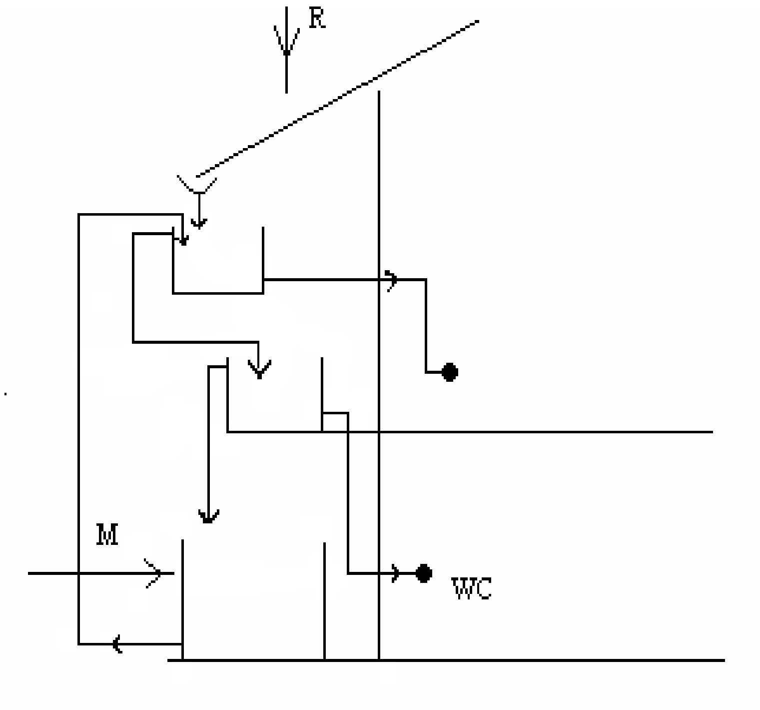

Figure 27: CMTRWH system for a two storey house [241]

In the model, a number of smaller capacity tanks are positioned at each floor level, with the top most tank just below the collection area, and a bigger volume tank, identified as the parent tank, at the ground level. Rain water is fed first into the upper tank, the overflow of which cascading down to the lower tanks, finally ending up in the parent tank at ground level. Supply to each floor is from individual smaller capacity tanks, called feeder tanks, by gravity floor and the final collection at the parent tank pumped back to the top most feeder tank as and when required. The pump is activated through a floater switch arrangement at the lowermost feeder tank when its water level drops. Essentially the concept of CMTRWH model attempts to distribute the storage capacity of the RWH system at various floor levels so that the requirement for pumping is minimized for an improved overall WSE.

6.1 Assumptions adopted in system operation

In developing an algorithm for the operation of a CMTRWH system, the water usage at any given floor level is taken as a constant for a given set of operating parameters. As research across the globe indicates, service water usage pattern is habitual, therefore constant for a particular set of uses in a given location.

6.2 System dynamics

For the CMTRWH model, development of an algorithm to describe the dynamics of the system is an important step to understand the operational aspects fully.

By developing a system algorithm, the effective run-off to each storage tank and the pumping requirements can be determined, which could be used to analyze the performance of the model for energy efficient rainwater harvesting.

An algorithm for the performance of a CMTRWH system is developed based on the Yield After Spillage (YAS) behavioral model for generic RWH systems [129] with annual demand (D), storage capacity (S), collector area (A) and annual average rainfall (R) as variables. Equations are formulated to determine the amount of collected rainwater that can be pumped up and the amount of roof run-off received by tanks at each level.

The capacity of each tank is determined according to the generalized curves developed for the water saving efficiency (WSE) η, defined as the percentage of yield against demand for a given constant service water demand D (in m^3/year), roof collection area A (in m^2), annual rainfall R (in m) and storage capacity S (in m^3).

In order to analyze the performance of the system, the effective roof collection fed into each tank and the amount of water that can be pumped up from the lower tank to the uppermost tank for given WSE values has to be determined. If the water saving efficiency (WSE) of the upper tanks are η_i and the parent tank is η_p for a given capture area A (m^2), annual rainfall R (m) and demand D (m^3/year), and the tank capacities are S_i and S_p respectively, from YAS algorithm and generalized curves for WSE;

$$\eta_i = f\{S_i, D, A, R\}$$

$$\eta_p = f\{S_p, D, A, R\}$$

This can be used to determine the optimum storage tank capacities for the system.

Considering the tank at the lowermost level, called the parent tank, from where pumping is to occur, for a given A, R and D, D/AR can be calculated. Then for a desired efficiency (η_p) the optimum tank size, S_p can be found using the generalized curves for WSE.

As space and weight restrictions dictate the installation of a smaller capacity tanks for the upper floor levels, a suitable tank size, S_i is selected. Then for each $(AR)_i$ and D_i, η_i can be found from the curves.

For cascading multi tank situations, the following algorithms are valid.

For each floor, If the yield is Y_i, for i = 1 to n

Pumping requirement Q_i ;

$$Q_i = D_i - Y_i = D_i(1- \eta_i) \quad [17]$$

Then for the i^{th} floor (i^{th} tank),

When the demand is D_i, supply is $(AR)_i$

But, $(AR)_i = (AR)_{i+1} - Y_{i+1}$

Since $Y_{i+1} = D_{i+1} * \eta_{i+1}$

$$(AR)_i = (AR)_{i+1} - D_{i+1} * \eta_{i+1} \quad [18]$$

Further, if the total demand is D,

$$D = \sum_{i=1}^{n} Di \quad [19]$$

The overall WSE for the system is denoted as η_o

Therefore, if the number of floors are n and the ground floor is taken as i = 0,

it can be shown that;

The amount of water that can be pumped up in CMTRWH system, Q,

$$Q = \sum_{i=1}^{n} Qi - \sum_{i=1}^{n} Qi\,(1- \eta_P) = \sum_{i=1}^{n} Qi * \eta_P$$

From Equation 3.2,

$$Q = \eta_P \left\{ \sum_{i=1}^{n} Di - \sum_{i=1}^{n} Di\eta i \right\} \qquad [20]$$

When,

$$(AR)i = AR - \sum_{i=i+1}^{n} Di * \eta i \qquad [21]$$

When the demand at each floor level is taken as D_i, and the total system demand is taken as D, for i = 1 to n;

Since $\sum D_i = D$,

$D_1 = D_2 = \ldots\ldots\ldots\ldots = D_n = D/n$

Therefore, from equations 20 and 21,

$$Q = \eta_P \left\{ \sum_{i=1}^{n} Di - \sum_{i=1}^{n} Di\eta i \right\}$$

$$Q = \eta_P D\left\{1 - 1/n \sum_{i=i+1}^{n} \eta i \right\} \qquad [22]$$

$$(AR)_i = AR - D/n \sum_{i=i+1}^{n} \eta i \qquad [23]$$

The algorithm developed can be used to simulate the performance of the system, particularly to estimate the fraction of roof collection feeding to each tank and the amount of collected rainwater at the parent tank that can be pumped up. The model allows the flexibility of varying the WSE desired for a given demand fraction, limited only by the spatial and structural allowances in a given building envelop. It also provides a means of determining the amount of makeup water from the reticulated mains service water supply required to maintain the water security of the building. The

CMTRWH system with storage tanks at each floor level, optimized for a desired WSE against a constant daily demand, therefore is a viable solution to minimize the energy requirement to provide collected rainwater to service points by pumping.

Consisting primarily of a collector surface, usually a section of the roof, conveyance system and a storage tank, these new types of models with distributed storage capacities have a pumping unit to lift the collected rainwater from the ground level parent tank to upper level feed tanks as an integral part of the model and its operation therefore should be optimized for the overall viability of the system. Identifying the optimum pumping quantities in cascading multi-tank RWH models for a given set of annual demand, rainfall depth and collector surface area values is significant therefore to select suitable pumping options.

6.3 Optimum pumping requirement of a CMTRWH system

Compared to a conventional RWH system of an equivalent capacity operating with a header tank, a CMTRWH model is required to pump up a much less a quantity of collected rainwater thereby reducing the running cost. As the collected quantity of rainwater that can be pumped up from the parent tank, Q, has a direct bearing on the overall water saving and energy efficiencies of the system as well as on the selection of pumping options, it is useful to study the variation of Q with respect to annual demand 'D' for a given set of system parameters A, R, S_i and S_P.

The quantity of rainwater that can be lifted up from the parent tank of a CMTRWH system (Q), can be compared to that of 'Q_E', which is the corresponding amount for a conventional RWH system equipped with a header tank to estimate the amount of energy saving in the pumping operation. Additionally, 'Q' can also be used to calculate the shortfall in fulfilling the cumulative demand at the feeder tanks, indicating a measure of the overall Water Saving efficiency (WSE) or η of the system.

Of the system parameters, 'R' for a given location is assumed as a constant and the S_i values are selected as 1 m^3 each for the minimum structural and aesthetic disturbance on the building envelops. Selection of 'S_P' can be based on the generalized curves developed for WSE of a generic RWH system [86] and validated for tropical climates [250] which show that for a given R, D and A and for all $0.25 \leq D/AR \geq 2.0$, storage capacity should be such that $S/AR \geq 0.1$ for maximum WSE. It should be noted that D is taken as a constant since typical daily demands are found to be governed by usage patterns [115].

For CMTRWH systems, the shortfalls in demand, calculated as the difference between the demand on the parent tank and Q (i.e. $D_P - Q$) can be taken as percentage values of the total demand D. The calculated percentage is named as Effective Shortfall in Yield (ESY %) where,

$$ESY\% = (D_P - Q)/D \tag{24}$$

For,

$$D_P = D - \sum_{i=i+1}^{n} Di * \eta i \tag{25}$$

Plotting Q against D/AR values for the Three Tank and Two Tank systems (Fig. 28), it can be seen that in both cases the respective curves peaking at D = AR, indicating a maximum pump utilization compared to D < AR and D > AR scenarios. The behavior can be explained with the WSE (η) values obtained for feeder tanks where for D < AR, high efficiencies and therefore high yields demanding lesser pumped up quantities Q and when D > AR, lower efficiencies rendering a lower effective runoff AR_P to the parent tank. This makes the required quantities not available for pumping, resulting in under-utilization of the pump in both cases.

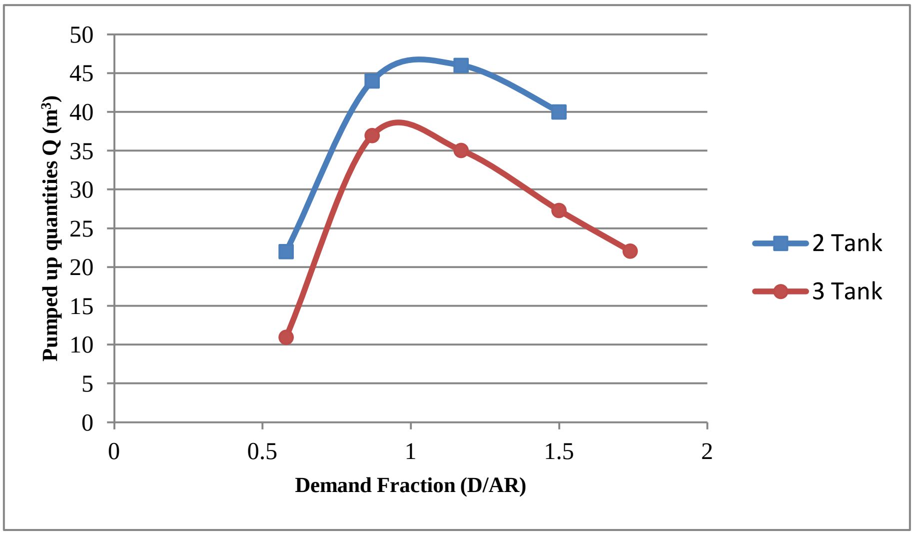

Figure 28: Pumped up quantities vs. Demand fraction for Two and Three Tank models [248]

The energy utilization for pumping can be seen when Q/Q_E% values are plotted against the corresponding D/AR values (Fig. 29). Curves peak at D = AR indicating that the energy savings possible compared to a conventional RWH system are at a minimum. Comparing the Three Tank and Two Tank models, the energy savings (Q/Q_E %) in the Three Tank model is approximately 10% more for the same A, R, D and S_i. This is a direct result of doubling the total feeder tank capacity in the Three Tank model thereby enhancing the overall WSE for the system, reducing Q. It should be noted that even though the increased capacity of the parent tank of the Two Tank model (9 m^3 against 8 m^3 in the Three Tank model) marginally enhances η_P, it does not have a significant bearing in increasing Q [248].

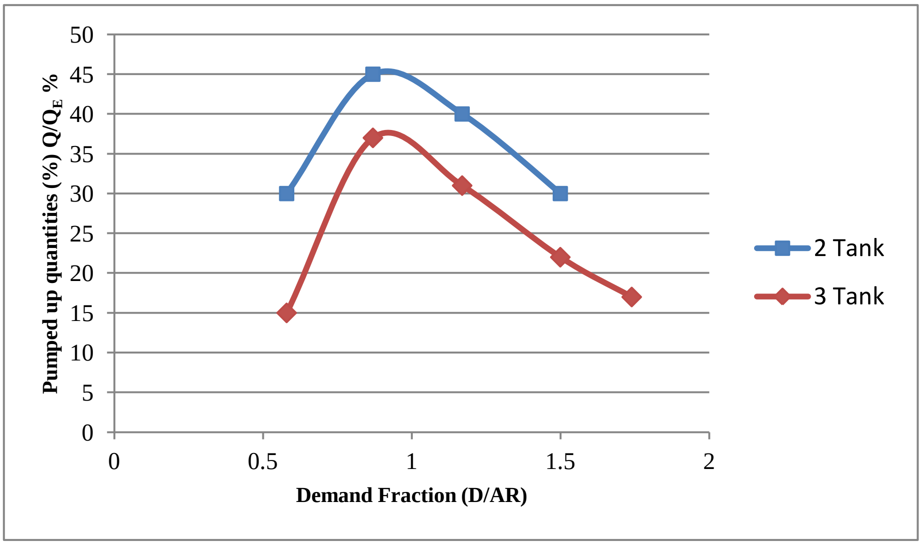

Figure 29: Energy utilization % vs. Demand fraction for Two and Three Tank models [248]

Plotting ESY% against demand fractions D/AR (Fig. 4) it can be seen that for both Two Tank and Three Tank models when D < AR, ESY% remains very low indicating the pumped up quantity Q can satisfy the shortfall in yield and when D > AR, ESY% rapidly increasing highlighting the underperforming of the system. Since low ESY% values when D < AR is clearly due to over designing of the storage capacity, the threshold D/AR value for zero ESY%, identified as the D = AR scenario, can be considered as the optimum condition at which the overall WSE of the system maximizing [248].

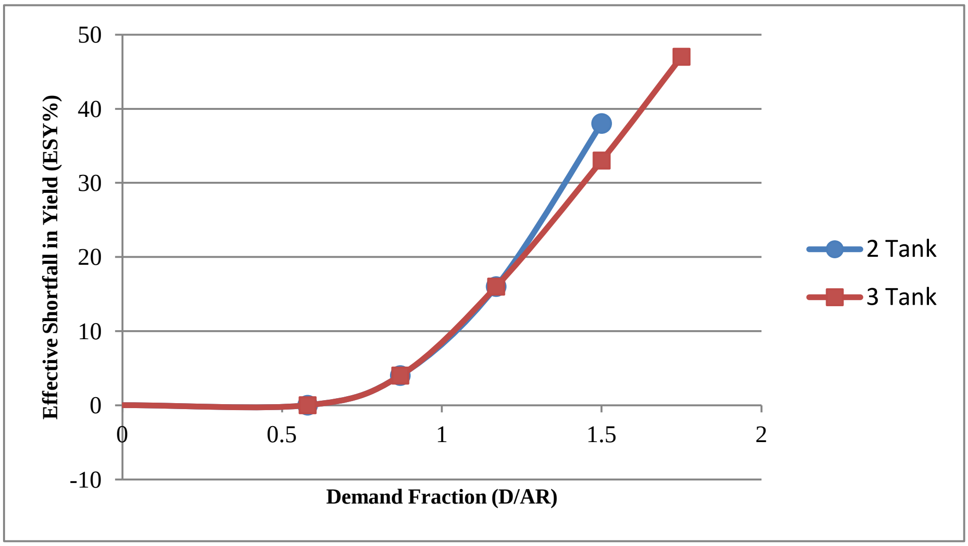

Figure 30: ESY % vs. Demand fraction for Two and Three Tank models [248]

The results show that for CMTRWH systems, D = AR scenario is unique where the maximum pump utilization occurring along with achieving the maximum overall WSE while the energy saving compared to an equivalent conventional RWH system minimizes. Therefore it can be concluded that the optimum pumping conditions for CMTRWH systems are occurring when the annual demand 'D' is fully supported by the annual roof collection quantity 'AR' at which integration of a suitable pumping option is fully justified.

Further, it can be seen that for CMTRWH systems D < AR scenario is a case of an over design while D > AR is an under design for a given set of D, A, R, S_i and S_P values. In both scenarios pumping requirement is not fully met and the systems under performing. From the result it is also evident that for the same system parameter values of D, A, R, S_i and S_P, the pumping quantities Q for the Three Tank model is less for all D/AR values hence indicating higher energy efficiency. The higher performance of the Three Tank model is further highlighted by the ESY % curve (Fig. 30) attributed to the enhanced distributed storage. Therefore, it can also be deduced that the water saving efficiencies in CMTRWH systems to increase with the number of floor levels [248].

6.4 Optimum demand for energy security

It is seen that the CMTRWH model is in requirement of a pumping unit to re-circulate the collected rainwater intermittently, as and when needed, to keep the cascading cycle sustained to maintain a desired WSE, incurring a running cost on power. However, there are many remote locations where grid power is not available or installing of a pumping unit, even with an alternative power source, is not viable for RWH applications thus requiring a model which would be meeting the service water demand at each floor level only through gravity, eliminating the need of a pumping unit. If the need for pumping can be eliminated, a significant improvement can be made to the model in reducing both the capital investment and the running cost, which would proliferate the use of RWH for multi-storey buildings while enhancing the system reliability. Besides, such a model will not require a larger parent tank at the ground level reducing the total cost of the system further. Therefore finding the threshold values for service water demands in order to achieve total supply reliability of harvested rain water fed, only through gravity, where no pumping is required is important [242].

But for $n \geq 2$, $\sum_{i=i+1}^{n} \eta i$ = n-1 for all $\eta_i = 1.00$

Therefore,

$$(AR)i = AR-D(n-1)/n \quad (29)$$

From the generalized curves for WSE, it can be seen that,

For $0.25 \leq (D/AR)_I \leq 0.5$ and $(S/AR)_i \geq 0.05$, WSE is 100%.

It implies therefore, that if a CMTRWH system can be designed with $S_i/AR \geq 0.05$ for individual tanks at upper stories, total supply reliability can be ensured for all $D/AR \leq 0.5$.

Since for each i^{th} level, demand is D/n and (AR)i = AR-D(n-1)/n,

And $\eta = 1.00$ when $S/AR \geq 0.05$ for $0.25 \leq D/AR \leq 0.5$,

$D/n(AR-D(n-1)/n) \leq 0.5$, for $S/AR \geq 0.05$

$D/AR \leq n/(n+1)$ (30)

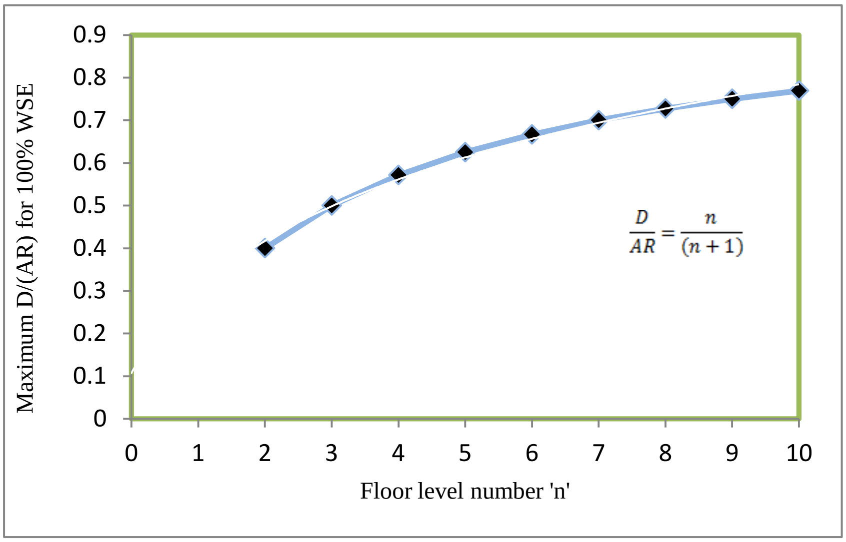

Figure 31:Upper limiting values for D/AR for different floor levels [242]

It can also be shown from WSE curves that;

$\eta = 1.00$ when $S/AR \geq 0.05$ for $D/AR \leq 0.5$

In multi-story situations, $S_{Total} = \sum_{i=1}^{n} Si$

Therefore, for housing units of 2 story, for $\eta_o = 1.00$ and $\eta_i = 1.00$

$D/AR \leq 0.67$ for $S_i/AR \geq 0.05$

And for housing units of 3 story, for $\eta_o = 1.00$ and $\eta_i = 1.00$

$D/AR \leq 0.75$ for $S_i/AR \geq 0.05$

For example, for a two story house in Colombo, Sri Lanka, where R = 2000 mm/year and a roof collection area of 50 m^2, when all S_i are selected as 5.0

m^3, the total demand can be a maximum of 0.67*AR, i.e. 67 m^3 per year at 183.6 L/day. Such a demand will ensure that both floor levels are supplied with collected rain water at 100% WSE. It implies that, by increasing the roof collection area A, an increased demand can be met for a CMTRWH system without the requirement of a pump. However, in designing the system, taking into account that in certain months the rainfall could be so low, the month with the lowest average rainfall for a given location can be selected to calculate the annual rainfall for a foolproof design, though with the disadvantage of having to select a sub-optimum roof collector area.

From (30), the limiting value for D/AR for the system to function totally under gravity is obtained as a function of the number of floor levels, 'n'. It implies that when D/AR is below the limiting value D/AR $\leq$ n/(n+1), the system is capable of operating without the requirement of a parent tank and a pumping unit, thereby significantly reducing the capital outlay on the system in addition to zero running cost in energy and maintenance. Therefore, a cascading multi tank rain water harvesting (CMTRWH) system with D/AR below the threshold value could be ideal for high rise buildings when the demand can be catered with increased roof collection area (A) for a given annual rainfall (R). However, it is important to note the variation of the storage capacity of the composite system (S) as well as the capacities of individual feed tanks (S_i) with the increase of floor levels for the threshold value of D/AR. It can be seen from (28), for the system to function totally under gravity, $\sum\eta_i$ should be maximum requiring η_i = 1.00 for i = i+1 to n. Further, the water saving efficiency (WSE) of the composite system η_o should also be 1.00. Therefore, two limiting values for S and S_i can be considered. From generalized curves for WSE [86] it can be seen that as S_i = S/n, for n $\geq$ 2, and S/AR $\geq$ 0.05 for D/AR $\geq$ 0.67. Similarly, η_o = 1.00 for all S when S/AR $\geq$ 0.05 for all D/AR $\geq$ 0.67. From Chart 1 it can be seen that when the number of floor levels 'n' increases, the threshold value for D/AR increasing [242].

This increment of D/AR is compensated by the increasing capacity of the composite system S, so that when the number of floor levels increase η_o = 1.00. However, since the WSE curves are valid only for D/AR $\geq$ 0.25, a minimum value for S_i can be determined when S_i/AR $\geq$ 0.05, D/AR $\geq$ 0.67 for η_i = 1.00. Therefore, for any CMTRWH system totally relying on gravity feed of collected rain water, should have its upper level feed tanks with capacities greater than 0.05AR. However, it implies that if the collection area A is increased for a given annual rainfall R to compensate for the increased demand D, the increased size and hence the weight of feed tanks would pose a problem of accommodating upper level tanks within the building envelop [242].

CMTRWH systems can be effectively used without a ground level parent storage tank at ground level and a pumping unit subject to a maximum annual demand for a given AR value and for a given number of floor levels ‘n’. Such a model by not utilizing energy for pumping not only will allow rainwater harvesting fully conforming to sustainable principles but will also be cutting down the total cost of the system by eliminating the need of a parent tank and a pumping unit. Further, the elimination of pumping reduces the amount of collected rainwater that would be retained in the piping network affecting the overall WSE of the system. The proposed model, however, needs all the storage tanks filled up at the commencement of the operation to reduce the time required for the system to be fully functional, with the cascading effect taking place. As all the service points are gravity fed, with the tanks for each level located at only one level up, the service pressure could be low and may have to be boosted if necessary [242].

6.5 Differential demand on CMTRWH systems

In Cascading Multi Tank Rain Water (CMTRWH) Systems, the daily demand at each floor level is the parameter which is having a direct impact on the water saving and energy efficiencies for a given collection area, storage capacity and rainfall depth. Houses with two or more floors are common in urban settings and Rain Water Harvesting (RWH) is encouraged as a supplementary source of service water. Typically, in multi storey houses the water usage between the ground and upper floors differ and an investigation on the impact of uneven demand loading at floor levels on system efficiency will have a significant effect on service water using patterns.

Analyzing the behavior of CMTRWH systems, it is identified that the optimum operating conditions are achieved when the average annual roof collection (AR), which is the product between the effective roof collection area (A) and the annual average rainfall depth (R), is equal to the annual demand (D) [248]. At D = AR, a comparatively higher WSE is achieved and the integration of the pumping unit is justified with a higher volume of collected rainwater pumped up. The total annual demand calculated on the basis of constant daily usage scenario [115] however is typically unevenly distributed among floor levels particularly in two storey housing units. As the upper level feeder tanks and the ground level parent tanks of CMTRWH systems calculated to be of optimum storage capacities using the generalized curves for WSE [86] (Fig. 31), and the effective roof runoff cascading down varies [247], there is a possibility of a significant impact on the amount of collected rainwater that can be pumped up (Q) and therefore on the overall WSE as a result of uneven demand loading [243].

It is important to investigate the effect of variation in demand loading conditions among the floor levels, on the water saving and energy efficiencies of CMTRWH systems for a given set of system parameters A, R, S_P and S_i. It is equally important to determine more favorable distribution of demand with respect to energy efficiency in two storey housing units using Cascading Three Tank RWH systems.

In CMTRWH systems, for a given set of parameters D, A, R, S_P and feeder tank capacity at the i^{th} level S_i, the quantity of collected rainwater that is possible to be pumped up from the parent tank (Q) is given by,

$$Q = \eta_P \left\{ \sum_{i=1}^{n} Di - \sum_{i=1}^{n} Di\eta i \right\}$$

For which the effective roof collection at each level is,

$$(AR)i = AR - \sum_{i=i+1}^{n} Di * \eta i$$

Where $D_{i,}$ and η_i are the demand and WSE at the feeder tank at the i^{th} level and η_P is the WSE of the parent tank for $n \geq 2$ where 'n' is the number of floor levels.

For a CMTRWH system with a feeder tank for each floor level and a parent tank, the demand on the parent tank can be given by,

$$D_P = D - \sum_{i=i+1}^{n} Di * \eta i$$

D_P, therefore, is the gross shortfall in the total yield, which requires to be satisfied by the quantity of collected rainwater that can be pumped up from the parent tank (Q).

Therefore, (D_P – Q) is the effective shortfall in the yield (ESY) and when taken as a percentage of the total demand, indicates a measure of the overall WSE of the system. A high overall WSE is indicated by a low ESY% and vice versa.

$$ESY\% = (D_P - Q)/D \qquad (31)$$

Analyzing the variation of Q as a percentage of Q_E with D_2/D_1 ratio, where Q_E is the corresponding pumping quantity in an equivalent conventional RWH system with the same total capacity and D_2 and D_1 are the annual service water demands at upper and lower feeder tanks, the impact on the overall energy efficiency can be determined. Further, to find the impact on the overall WSE of the system, the variation of ESY% can be calculated for a range of D_2/D_1 ratios

To investigate the impact of differential demand, a hypothetical case of a cascading Three Tank RWH system installed at a two storey house located in a tropical setting receiving annual average rainfall of 2500 mm is selected. Feeder tank capacities are taken as 2 m^3 each, the parent tank capacity is selected as 10 m^3 so that the total capacity ($\sum S_i + S_P$) is 14 m^3 satisfying the condition $S \geq 0.1AR$ for maximum WSE values for a given D/AR value [86] Since the optimum performance of a CMTRWH system is when the total annual demand is equal to total annual roof collection (i.e. D = AR) scenario

[248], an effective roof collection area of 110 m^2 is taken for a total daily service water demand of 600 L.

For D_2/D_1 ratios of 5, 2, 1, 0.5 and 0.2, $Q\%/Q_E$ and ESY% values are calculated (Table 1).

Table 1: Variation of system performance with Demand Ratio [243]

D_2/D_1	η_1	η_2	AR_P (m^3)	D_P (m^3)	Q (m^3)	D_P-Q (m^3)	η_P	Q%/ Q_E	ESY%
5	0.92	0.55	87	86.5	74.4	10.8	0.86	44	4.9
2	0.80	0.68	62.5	61.3	57	4.4	0.91	33	2
1	0.67	0.75	64.6	63.5	53.2	3.2	0.95	31	1.5
0.5	0.60	0.86	69.6	68.6	63.1	5.5	0.93	37	2.5
0.2	0.50	0.98	93	92	81.0	11	0.88	47	5

The quantity of collected rainwater that can be pumped up from an equal capacity conventional RWH system (Q_E) is calculated for the same constant daily demand (d), roof collection area of 110 m^2, annual average rainfall of 2000 mm, storage capacity of 14 m^3 feeding the service points through gravity from a header tank. For the equivalent conventional system, WSE is calculated as 78% and therefore Q_E as 171 m^3 [243].

Plotting $Q\%/Q_E$, where Q_E is the amount of collected rainwater that can be pumped up from an equivalent conventional RWH system with a same total storage capacity equipped with a header tank and a pumping unit, against D_2/D_1 ratio, a marginal increase can be seen when D_2/D_1 ratio increase (Fig. 32). This shows that the comparative energy saving in pumping is lesser when the usage in the ground floor is more. This can be attributed to the higher effective roof runoff to the parent tank $(AR)_P$ resulting in a higher amount of collected rainwater that is possible to be pumped up (Q) as and when needed. In fact, as indicated by higher $\boldsymbol{\eta_P}$ (Table 1), $(AR)_P$ is influenced by the individual efficiencies of the feeder tanks $\boldsymbol{\eta_2}$ and $\boldsymbol{\eta}_1$. It is also seen that the increase in WSE of the upper header tank ($\boldsymbol{\eta_2}$) with ground floor usage is getting higher compared to the increase in WSE of the lower feeder tank (η_1) when the ground floor usage is getting lower [243].

In fact, comparing the $D_2/D_1 = 5$ and $D_2/D_1 = 0.2$ scenarios, when the ground floor usage is high (i.e. $D_2/D_1 = 0.2$), η_2 is 98% and η_1 is 50% whereas when $D_2/D_1 = 5$, η_2 is 55% and η_1 is 92% showing the impact of the reduced effective roof runoff cascading down to the lower feeder tank of the same capacity as that of the upper. Since this situation drives up the demand on the parent tank (D_P) as well, for scenarios where D_2/D_1 is lower, the effective shortfall in demand (D_P – Q) which is in fact $D_P(1-\eta_P)$ increases despite a slight increase in η_P. Therefore, when ESY as a percentage of total demand (D) is plotted against D_2/D_1, the value is marginally higher when the ground floor usage is high, indicating a corresponding drop in the overall WSE of the CMTRWH system (Fig. 33) [243].

However, it can be shown that this situation can be somewhat arrested by increasing the capacity of the lower feed tank thereby increasing its WSE (η_1). For example, by increasing the capacity of lower feeder tank (S_1) by 50% to 3 m^3,it can be shown that Q and D_P dropping resulting in both the major efficiency indicators Q%/Q_E and ESY% decreasing, indicating an overall improvement in the system performance (Table 2).

Table 2: Impact of lower level feeder tank capacity on system performance [243]

Storage (S_1) (m^3)	Q (m^3)	D_P (m^3)	D_P-Q (m^3)	η_P	Q%/ Q_E	ESY%
2	81	92	11	0.88	47	5
3	67.5	73.7	6.2	0.87	39	2.8

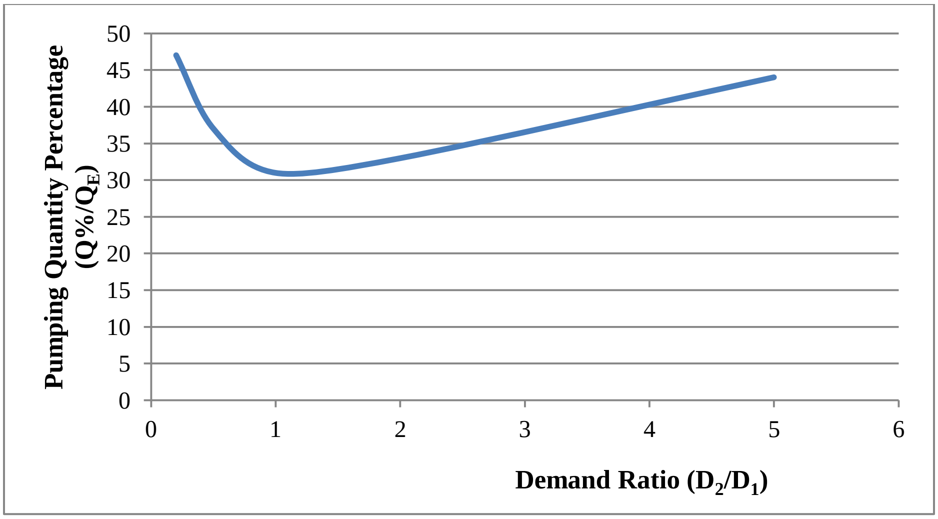

Figure 32: Pumping Quantity Percentage (Q%/Q_E) versus Demand Ratio (D_2/D_1) [243]

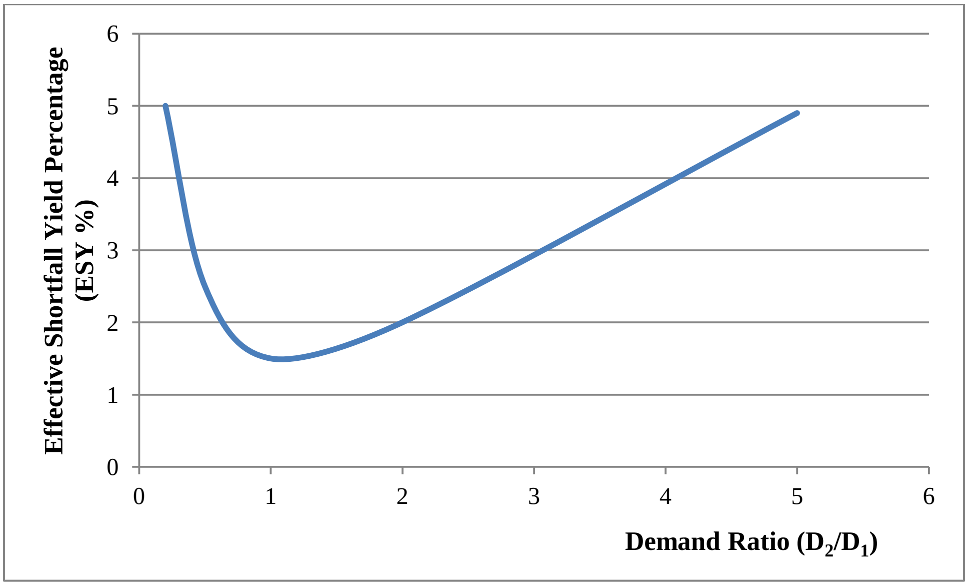

Figure 33: Effective Shortfall Yield Percentage (ESY %) vs Demand Ratio (D_2/D_1)

It can be concluded that for a cascading Three Tank RWH system in a two storey house with feeder tanks of equal storage capacity, uneven demand at the upper and lower floors is not having a significant impact on the overall

WSE or the energy efficiency of the system when the total annual demand for harvested rainwater (D) is equal to the annual roof collection (AR). However, due to the cascading manner in delivering the roof collection to the lower feeder tank, a marginal drop in system performance can be seen when the water usage at the lower floor level is higher.

The situation can be rectified by increasing the capacity of the lower feeder tank allowing a higher water usage at the ground level aligning well with the typical usage pattern in a two storey house. It can also be concluded that since h calculations are based on equations developed for CMTRWH systems, the overall performances to drop with the increasing of the number of floor levels unless a progressive increasing of the capacities of lower level feeder tanks introduced in situations where the usage at lower levels are high.

6.6 Minimizing the parent tank capacity

In Cascading Multi Tank Rain Water Harvesting (CMTRWH) systems the upper level feeder tank capacities can be restricted to as low as 1 m^3 posing a minimum disturbance to the building envelop, but the parent tank which collects only the excess roof runoff cascading down from the feeder tanks still occupies a considerable space at the ground level. If the storage volume of the parent tank can be further reduced while having a marginal effect on the overall water saving efficiency, it could have a significant impact on minimizing the system cost.

The parent tank capacity (S_P) is usually taken to complement the difference between the cumulative volume of feeder tanks and the storage volume of an equivalent conventional RWH system in order to achieve a comparative WSE. If however, the capacity of the parent tank (S_P) can be optimized with minimum impact on the performance of a CMTRWH system, it will significantly reduce the foot print of the parent tank while reducing the overall cost. The result will be more important for single and two storey houses with cascading two or three tank rainwater harvesting systems. Since RWH is prolific at household level, the study is focused more on Three Tank and Two Tank models suitable for two and single storey houses respectively.

It is useful to investigate the impact of the variation of the storage capacity of parent tanks (S_P) on the quantities of collected rainwater that can be pumped up (Q) and therefore on the overall WSE of cascading two and three tank rainwater harvesting systems in single and two storey houses. It is also important to determine the threshold values for S_P for D < AR, D = AR and D > AR scenarios for given D, A, and R values while maintaining the feeder tank capacities at 1 m^3 for the minimum disturbance on the building envelop.

For a CMTRWH system with a feeder tank for each floor level and a parent tank, the demand on the parent tank can be given by,

$$D_P = D - \sum_{i=i+1}^{n} Di * \eta i$$

When modified for equal demand loading at each floor level, the equation can be given as,

$$D_P = D – D/n \sum_{i=i+1}^{n} \eta i$$

D_P, therefore, is the gross shortfall in the total yield, which requires to be satisfied by the quantity of collected rainwater that can be pumped up from the parent tank (Q).

Therefore, (D_P – Q) is the effective shortfall in the yield (ESY) and when taken as a percentage of the total demand, indicates a measure of the overall WSE of the system. A high overall WSE is indicated by a low ESY% and vice versa.

$$ESY\% = (D_P – Q)/D$$

Analyzing the variation of ESY% with respect to the reduction of parent tank capacities, (ΔS_P) as a percentage of the original capacity S_P (i.e. $\Delta S_P/ S_P\%$), for scenarios of D < AR, D = AR and D > AR, threshold values for S_P can be found for the minimum impact on overall WSE.

To investigate the optimum values for the parent tank capacity S_P with respect to system parameters D, A, R, S_P and S_i, hypothetical cases of cascading Three Tank and Two Tank RWH systems installed at two storey and single storey houses located in a tropical setting receiving annual average rainfalls of 2000 mm are selected. With an effective roof runoff area of 50 m^2, feeder tank capacities are taken as 1 m^3 each, the parent tank capacities are selected as 8 m^3 for the Three Tank model and 9 m^3 for the Two Tank model to ensure that the total capacity ($\sum S_i + S_P$) is 10 m^3 satisfying the condition $S \geq 0.1AR$ for maximum WSE values for a given D/AR value [86].

For constant daily demands of 200, 300 and 400 Liters, (D_P – Q) values are calculated for S_P values of 12, 8, 4, 2 and 1(in m^3) for Three Tank model and 9, 6, 4, 2, 1 and 0.5 (in m^3) for Two Tank models. The daily demands are selected to suit the three scenarios of D < AR, D = AR and D > AR. (D_P – Q), identified as the Effective Shortfall in Yield (ESY) is calculated as a percentage of the total demand D against $\Delta S_P / S_P\%$ where ΔS_P is the variation introduced to the parent tank capacity and S_P is the original capacity of the parent tank (in this case 8 m^3) [247].

When the Effective Shortfall in Yield as a percentage of the total demand (ESY%) quantities are plotted against the percentage change in the parent tank capacity ($\Delta S_P / S_P\%$), in the D = AR scenario, in both Three Tank and Two Tank cases only a marginal increase in ESY% can be observed till $\Delta S_P / S_P\%$ reached a value of 50% indicating a parent tank half the capacity of the originally selected tank of 8 m^3 is sufficient to maintain the cascading cycle without significantly affecting the WSE of the system (Fig 15) [247].

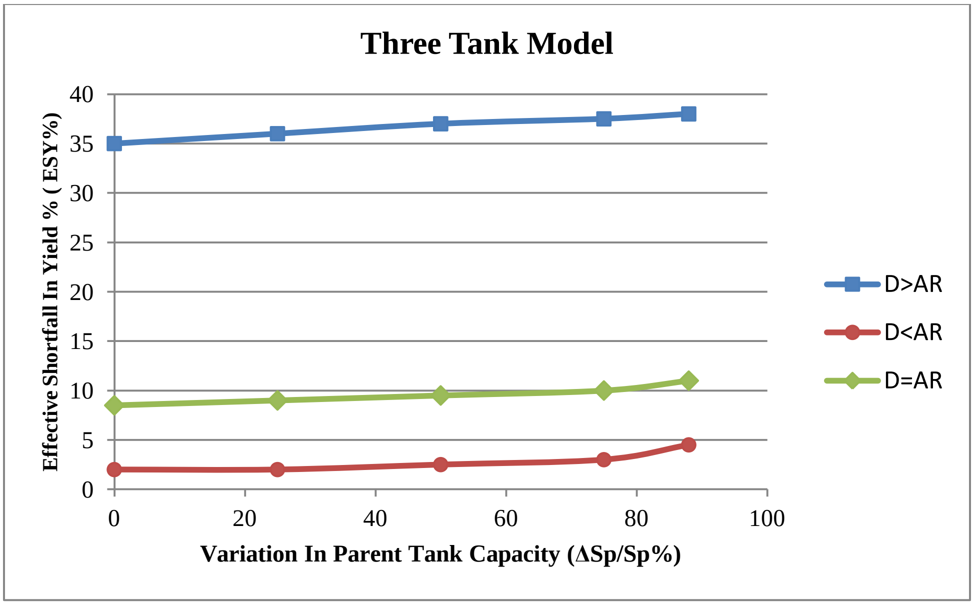

Figure 34: Effective Shortfall in Yield vs.Parent tank capacity, Three Tank Model [247]

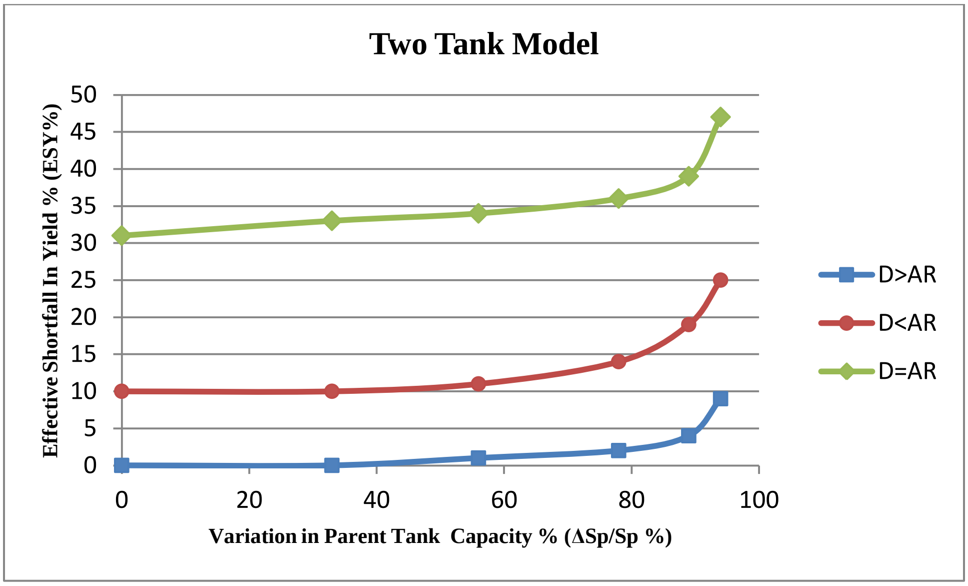

Figure 35: Effective Shortfall in Yield vs.Parent tank capacity – Two Tank Model [247]

Comparing the Three Tank and Two Tank models it is seen that the ESY% values corresponding to $\Delta S_P / S_P\%$ at the optimal D = AR scenario are lower in the Three Tank model whereas the Two Tank model outperforming the Three Tank model at sub optimal D < AR and D > AR scenarios [247].

Further, when the demand is varied, for both D > AR and D < AR scenarios, the respective curves for Three Tank and Two Tank models, even though show a slight increase in ESY% values for the increase of $\Delta S_P / S_P\%$ values, maintain the same shape characteristics. Comparing the curves for the Three Tank and Two Tank models, it can be seen that at D = AR, the Three tank model showing lower ESY% values and in all other scenarios, the Two Tank showing marginally lower ESY% values. In the D < AR scenario, the behavior can be attributed to the relatively high roof runoff to the parent tank resulting in high η_P, hence Q, resulting in low ESY%. In the D > AR scenario comparatively, both D_P and Q drop, lowering the ESY%.

When D > AR, for both Three Tank and Two Tank models efficiencies of the individual feeder tanks drop for given S_i values, pushing the D_P values high. Further, in this scenario, the effective runoffs to the parent tanks (AR_P) are small compared to D < AR, D = AR scenarios, hence increasing the D_P/AR_P ratio resulting in low η_P values. As a consequence therefore, (D_P – Q) increase, hence high ESY% values for all corresponding $\Delta S_P / S_P\%$. The rapid increasing of ESY% values with increasing $\Delta S_P / S_P\%$ can also be attributed to the behavior of η_P decreasing rapidly with increasing D_P/AR_P ratio [247].

In all situations a rapid increase in ESY% is seen for ($\Delta S_P / S_P\%$) over 80%, i.e. when $S_P < 1\ m^3$, where the parent tank capacity is less than that of feeder tank capacity. In that scenario, since S_P/AR_P values getting positioned in the sensitive region of the generalized WSE curves, a rapid drop in η_P makes low Q hence resulting in high ESY%. This trend is slightly mitigated in the D > AR scenarios due to drop in AR_P values, keeping the S_P/AR_P values away from the sensitive region of the WSE curves.

In both cascading Three Tank and Two Tank models the effect on ESY% for the variation of ($\Delta S_P / S_P\%$) are less than 3% and therefore are marginal up to 50% for all three scenarios of D < AR, D = AR and D > AR. Since ESY% is a measure of the overall WSE of the system, it can be concluded that reduction of parent tank capacity by as much as 50% is possible without a significant impact on the system performance. Of the three scenarios, the rate of increase of ESY% for the reduction of S_P is highest when D > AR, highlighting the continued underperformance of an under designed system. On the other hand D < AR scenario corresponds to an over designed system while in the optimum D = AR scenario, less than 10% ESY values in both Three Tank and Two Tank models, indicating a small drop in WSE can be justified by the expected cost saving due to reduction of the parent tank capacity S_P by as much as 50% [247].

It can also be recommended that the reduction of S_P should not be below 1 m^3 for the risk of high inefficiencies (η_P) resulting in high ESY% values and hence low system performances. Further, since the equations used for the calculation of ESY% are based on the equations developed for CMTRWH systems, the above findings can be extended to multi tank models as well. Comparing the two models it is clear that at the optimum system performance condition of D = AR for a given AR, Three Tank model is outperforming the Two Tank model. Since this is a result of a higher fraction of the storage capacity distributed to upper floor levels, it can be deduced that at D = AR the overall WSE to increase with the number of feeder tanks.

In actual practice, due to collection inefficiencies, ESY% could marginally increase but will not pose an impact on the result. System losses and water retained in the piping network is not considered for the calculation due to its negligible scale [247].

6.7 Performance of a cascading Two Tank RWH model – A Case Study

To gain advantage of the limited land available, many housing units of diffuse settings are built with two or three levels. This, not only reduces the building footprint but also reduces the overall building material requirement, hence cost, thus aligning well with sustainable principles. Therefore, the case of a typical two storey house installed with a cascading two tank rainwater harvesting system is investigated for its performance.

In the proposed CTTRWH model, two storage tanks are utilized. A smaller capacity tank is positioned at a higher elevation (possibly at the eve level) into which the captured rainwater be directed. This upper tank (S_U) will supply the utility points and feed a bigger tank (S_L) at ground level via the overflow. As such when a rain event occurs, captured rainwater will flow into the upper tank and then cascade down into the lower tank and any excess water to be disposed through the overflow of the lower tank. The total storage capacity of the system consists of the combined capacities of the two tanks and a pump is utilized to transfer collected rainwater from the lower tank to the upper tank when the water level in the latter drops. A schematic diagram of a CTTRWH model is shown in Fig. 36.

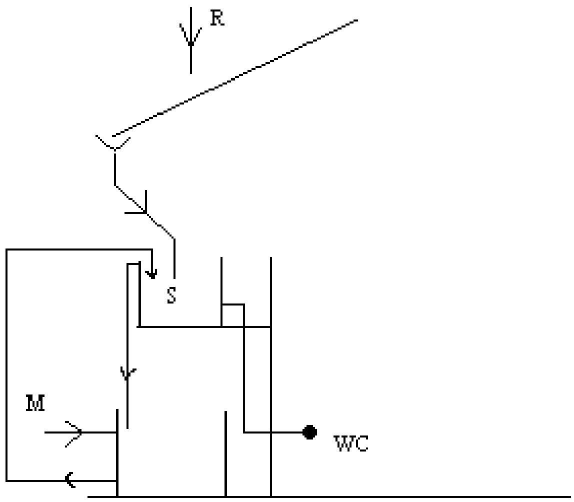

Figure 36: Schematic drawing of a CTTRWH model [246]

A set of equations are developed based on the WSE of the storage tanks to analyze the behavior of a CTTRWH system for a typical two story building with a constant daily service water demand. The equations are then used to determine the possible variations in the system performance with regard to annual demand (D), annual average rainfall (R), roof capture area (A) and the capacity of the upper storage tank (S_U) subject to the operating domain of the generalized curves for WSE.

6.7.1 System dynamics – CTTRWH Model

The WSE of a RWH system can be defined by Y/D and denoted by η, where Y and D are the annual yield and demand respectively for a given storage capacity S at a given location with a collection area A and an annual rainfall of R. When the WSE for the upper tank and for the overall system are η_U and η_O respectively, for a given annual demand D in m^3, collection area A in

m^2 and annual average rainfall R in m for given storage capacities of S_U for the upper tank and S_P for the parent tank, the yield from the upper tank Y_U and the overall system Y_O are given by;

$Y_U = D^* \eta_U$ and $Y_O = D^* \eta_{O,,}$ where η_U and η_O are the WSE of the upper tank and the overall system.

It can be shown that the quantity of collected rain water that is possible to be pumped up (Q) is given by;

$$Q = D(\eta_O - \eta_U) \qquad (32)$$

However, when calculating the storage fraction (S/AR) to obtain the WSE (η) values from generalized curves [2]**,** the values η_O and η_L are almost the same due to the capacity of the lower storage tank (S_L) being significantly larger than S_U and also since AR is much greater than S. For example, if the capacities of upper and lower tanks are 1 m^3 and 5 m^3 respectively, installed in a location where the annual average rainfall is 2000 mm and the roof collector area is 50 m^2, S_O/AR and S_L/AR values would be 0.06 and 0.05. Since the objective of the multi-tank system is to have a smaller upper tank for gravity feeding the harvested rainwater to service points as well as to be accommodated readily into the building structure and a larger lower tank to ensure water security, the above argument holds true. Therefore, without significant errors (32) can be modified as;

$$Q = D(\eta_L - \eta_U)$$

Therefore, when the system is fully functional, Y_U should reach Y_O, though with reduced pumping due to distribution of the storage capacity between the floor levels.

Based on (32), the following equations can be developed to determine the minimum storage capacities and minimum pumping quantities in a functional CTTRWH system for a constant daily service water demand.

As $S_L > S_U$, for the same A, R and D $\eta_L > \eta_U$

Since for a given demand D,

The shortfall in the upper tank (S_U) is given by $D(1 - \eta_U)$ and

The shortfall in the lower tank (S_L) is given by $D(1 - \eta_L)$

The amount of water that can be pumped up is given by Q;

$Q = D(1 - \eta_U) - D(1 - \eta_L)$, which simplifies to,

$$Q = D(\eta_L - \eta_U) \quad (33)$$

Additionally, if the total demand for water is D_T, then the amount of water required from the mains is given by M;

$M = D(1 - \eta_L) + (D_T – D)$, which simplifies to,

$$M = D_T - D\,\eta_L \quad (34)$$

The performance of the CTTRWH model can be studied using the equations (33), (34) and the generalized curves for WSE, varying the parameters A, R, D and S_U.

6.7.2 System performance with change in demand (D)

If the demand is reduced by, for example, using water saving devices, the water saving efficiencies η_L and η_U increases rapidly for $D/AR > 1.0$ and slightly for $D/AR < 1.0$

This is due to the under-performing of the system for $D/AR > 1.0$

6.7.3 System performance with change in rainfall (R)

It can be noted that moving from wet to dry climatic zones, where the minimum annual rainfall (R_{min}) drops, both η_L and η_U dropping and as a result, the dropping of pumping requirement due to lower value for $(\eta_L - \eta_U)$ [246].

6.7.4 System performance with change in capture area (A)

It can be observed that by increasing the capture area A, for a given R, D and S_U that the dimensionless ratio, D/AR, decrease and as a result achieving higher values for η_L. However since S/AR decrease with the increase of A, the difference between the water saving efficiencies of lower and upper tanks, (η_L - η_U), tends to rise, increasing the quantity of water that has to be pumped up [246].

6.7.5 System performance with change in upper tank capacity (S_U)

By increasing the size of S_U for a given set of parameters A, R and D, η_U increases reducing the quantity of water required to be pumped up Q, and as a result negating the purpose of a two tank system. It also implies that greater the difference in capacity of the two tanks, the higher the pumping requirement [246].

The operating domain of the generalized curves dictates that a performing CTTRWH model can be designed only for $0.25 \leq D/AR \geq 2.0$. For values of D/AR beyond this range the behavior of the curves are found to be unreliable, particularly in the critical zone of $S/AR \leq 0.05$. Further, it is noted that for the system to achieve a WSE of over 80% (i.e. $\eta_L \geq 80\%$), $D/AR < 1.0$

Therefore it can be deduced that, for

$\eta_L \geq 80\%$, $D < AR$

It can also be observed that when the system parameters are selected so that $D/AR > 1.0$, when either A or R is increased or the demand D reduced, η_L increases rapidly while the increase in η_U is moderate due to the fixed nature of the upper tank capacity (S_U).

The implications of the above behavior becomes apparent when $R > R_{min}$, which is a usual occurrence since for the reliability of delivery, the minimum annual rainfall, R_{min} is selected in design calculations. It can be shown that when $R > R_{min}$, due to the increase in (η_L - η_U), the quantity of water to be pumped up Q increases which in turn will increase the demand on the power source. The effect will be more profound if a stand- alone power source is employed to operate the pump. However when $D/AR < 1.0$, for

$R > R_{min}$ the value (η_L - η_U) actually reduces, preventing excess loading on the power source.

It can be shown that for tank capacities S_U, S_L and annual demand D, the maximum number of days the system can supply without rain water input is given by,

$$d_{dry} = (S_U + S_L)365/D \qquad (35)$$

In the case of Sri Lanka, from historical data, the average maximum number of non-rainy days (rainfall $\leq$ 0.5 mm) can be taken as, 30 and 50 days for the wet (annual rainfall 1600-4000 mm) and dry zones (annual rainfall less than 600 mm) respectively (National Meteorological Department of Sri Lanka). Hence, when selecting a value for S_L, it should satisfy Equation 35 for system reliability.

Therefore, from (35),

$d_{dry} \geq 30$ and 50, for the wet and dry zones.

Hence, the two tank RWH model can be effectively integrated into single or multi storey households, with suitable variation in storage sizes and collection areas for a desired WSE, in combination with an effective pumping system. It should be noted that, the effect of the volume of retained water in the piping network to the overall performance of the system is not considered. However, for typical two storey housing units it can be of negligible influence taking into account the average pipe lengths and diameters.

However when D/AR < 1, for $R > R_{min}$ the value ($\eta_L - \eta_U$) actually reduces, preventing excess loading on the power source.

It can be shown that for tank capacities S_U, S_L and annual demand D, the maximum number of days the system can supply without rain water input is given by,

$$d_{dry} = (S_U + S_L)365/D \qquad (36)$$

From historical data, the average maximum number of non-rainy days (rainfall $\leq$ 0.5 mm) can be taken as, 30 and 50 days for the wet and dry zones respectively. Hence, when selecting a value for S_L, it should satisfy equation 36 for system reliability.

Therefore, from Equation 36,

$d_{dry} \geq 30$ and 50, for the wet and dry zones.

6.7.6 Pumping requirements for water security

Considering the upper tank S_U, the maximum number of days for which it can supply without an input from pumping is given by $d_{U(max)}$,

$d_{U(max)} = 365S_U/D$

From Equation 32, $Q = D(\eta_L - \eta_U)$

If the pumping frequency is taken as N_P per year, then the number of days between consecutive pumping events is given by $365/ N_P$

It can be deduced therefore, for supply reliability,

$d_{U(max)} > 365/ N_P$

i.e. $365S_U/D > 365/N_P$

Hence, $N_P > D/S_U$

To compensate for sudden demand loadings, a safety factor K_1 can be used,

Where, $K_1 > 1.5$, thus,

$N_P = K_1D/S_U$

For a pumping frequency of N_P, the pumping volume required at a time is

Q/ N_P

Substituting Equation 36 in 32 gives,

$$Q/ N_P = S_U(\eta_L - \eta_U)/ K_1 \qquad (37)$$

Therefore, when the water level in the upper tank S_U drops by a quantity equivalent to

Q/N_P, a floater switch arrangement can be made to cut-in to activate the pump.

6.7.7 Make-up water requirement for water security

From the Equation 35, mains water requirement, when the total demand is D_T is given by, $M = D_T - D\,\eta_L$

However, the mains water requirement for the RWH system,

M_L (i.e. to the lower tank, S_L) is $M_L = D(1 - \eta_L)$

If the number of days the system can supply the demand without mains water is d_{sup}

Then, $d_{sup} = 365(S_L + S_U)/D$

If the frequency of supplying mains water is N_M, then the number of days between consecutive supply events is given by; $365/N_M$

Since, for system supply reliability,

$365/N_M < 365(S_L + S_U)/D$

$N_M > D/(S_L + S_U)$

To compensate for demand surges, a safety factor K_2 can be used,

Where, $K_2 > 1.5$.

Thus, $N_M = K_2 D/(S_L + S_U)$ (38)

Since the quantity of mains water supply required at a time is given by, M_L

$M_L = D(1 - \eta_L)/N_M$

Substituting in Equation 38,

$M_L = (S_L + S_U)(1 - \eta_L)/K_2$ (39)

Chapter 7

WATER AND SERVICE QUALITY IMPROVEMENTS IN RAINWATER HARVESTING SYSTEMS

Many areas suffer from water scarcity but, paradoxically, a local source of water such as rainwater is mostly treated as a risk rather than a valuable resource [144].Fuelled partly by ignorance and the general perception of an urban environment to be highly polluted appears to keep potential users away from using rainwater. Much research has been carried out on the quality of rainwater, which naturally is the cleanest and softest form of fresh water available on the planet before reaching the surface of the Earth. Except for the possibility of marginal reduction in pH values in highly industrialized locations (acid rain) and increased nitrate levels under conditions of local lightning, rainwater displays much lower turbidity, hardness and mineral contents compared to surface or ground water. In fact, it is the odorless and tasteless nature of harvested rainwater that is discouraging the use of it for drinking purposes. Rainwater gains most of its contamination at the point of contact and the quality of harvested rainwater, therefore, is largely determined by the condition of the collector surface. It is reported that rainfall intensity and the number of dry days preceding a rainfall event significantly affects the quality of harvested rainfall. This could be due to higher energy levels in rain drops removing more pollutants off the pores on the catchment surface.

Therefore, even though RWH systems are attractive from an ecological point of view, potential health risks from ingesting of harvested rain water related to microbiological and chemical contaminants should be taken into account [236].Usually, contamination is either by biological pathogens or by dissolved chemicals. Chemical contamination of the rainwater can occur due to traffic emissions and industrial pollution in urban areas or due to agricultural usage of fertilizers and pesticides in rural areas. Earlier studies have reported that the rainwater stored in tanks has been of acceptable quality [67], but in more recent ones, either chemical or microbiological contaminants have been found in the collected rainwater, often in levels exceeding the international or national guidelines set for safe drinking water [43], [252], [309]. It is seen that the quality of the harvested and stored rainwater depends on the characteristics of the location, weather conditions and proximity to sources of pollution, the type of catchment area [43], the type of water tank [67] and the handling and management of the collected water [213].

Therefore, Participants involved in rainwater harvesting schemes must be made fully aware of the health consequences and risks of the microbiological, organic and mineral contamination in the runoff water which they are collecting and to take appropriate measures to avoid such contaminated water in their systems [304]. The high level of atmospheric pollution in and around large cities, particularly those with heavy industrial and coal-fired power stations often make harvested rain water unsuitable for personal uses such as drinking or cooking [95]. Since water quality requirements for non-potable uses are lower than those for drinking water one option is to decrease any potential risks from tanked rainwater is to minimize oral exposure by limiting the use of collected water to hot water services, laundry, bathing, toilets or gardening [50].

In a research carried out in a built-up urban area in the Greek island of Ketalonia [236], harvested rainwater was tested for common anions and major cations as well as metals Fe, Mn, Cd, Pb, Cu, Cr, Ni, and Zn. In addition, the presence of three major groups of organic compounds Polycyclic Aromatic Hydrocarbons (PAHs), Organo-Chloride Pesticides (OCPs) and volatile organic compounds (VOCs) screened by analytical techniques. High lead concentrations are found in harvested rainwater samples collected in urban locations close to highways [304], indicating a direct impact of vehicle emissions on rainwater. It could be attributed to a washout effect of particulate lead in the atmosphere.

In most studies, the lack of fluoride in harvested rainwater is evident while containing concentrations of Ca and Mg. Therefore, in cases of utilization of rainwater as the only source of drinking water, consumers should be advised to take fluoride supplementation in order to prevent dental decay [175]. There is evidence to show that rainwater harvested in coastal areas has relatively high concentrations of chlorine and display a higher electrical conductivity. While the chemical compositions are in the acceptable range of WHO standards, in most areas, the three widely used bacterial indicators, total Coli forms, E-coli and Euler-ococci have been detected.

In many industrialized areas, the rain is acidic with reported pH values starting at 4.17 [43]. In this pH range, the leeching of various metals is promoted and this deteriorates the quality of harvested rainwater. Increased concentration of metals has also been attributed to particulate matter in the atmospheric air [304] while petrochemical and plastic-chemical industries can contaminate the collected rainwater [309]. However, the presence of microbial indicators and pathogens are found to be varying greatly depending on the geographic location [252]. It is important to note that in industrialized areas, rain water with low pH values could contain high concentrations of Zn if harvested off GI-sheet-covered roofs. The WHO limit for zinc concentrations in drinking water is 5000 mg/litre.

Generally, in many studies on harvested rainwater quality, parameters such as pH, total Chlorine concentration, electric conductivity, total dissolved solids, Oxygen saturation present and total hardness are found to be within WHO standards, except the total coli form count which usually is moderate to high based on maintenance of the collector surface.

In a study in Jordan it is found that harvested rainwater from residential roofs indicating that the measured inorganic compounds generally matching the WHO standards for drinking water, while the fecal coli forms, which are an important bacteriological parameter, exceeding the limits for drinking water [82].

Analysis of stored rainwater samples in Anuradhapura district in the dry zone of Sri Lanka, has revealed that most of the water quality parameters such as Colour, Turbidity, Electrical Conductivity, total alkalinity, Nitrates, Nitrites, Chlorides, Suphates, Phosphates, total Iron BOD and Fluorides are well within the acceptable potable water quality standards in Sri Lanka (Sri Lanka Standards; 614, 1983). The presence of fluorides in the study, however, is contradictory to other findings and should be investigated further, taking into consideration the high levels of fluorides in ground water in the Anuradhapura region. Analysis of samples of harvested rainwater in the wet region of Sri Lanka has revealed that the values of turbidity, pH, total hardness are well within the acceptable drinking quality standards.

Chlorination seems to be a viable option in making harvested rainwater safe from bacteria. However, during this process, organic matter that may be dispersed into the water body due to sediment disturbance can react with chlorine and found undesirable by-products [100].

Rainfall intensity and the number of dry days preceding a rainfall event significantly affect the quality of harvested rainfall.

Taste plays a major role in drinking water. As rainwater does not contain any minerals and does not carry any taste, it is not widely accepted in urban areas as drinking water.

7.1 Energy Efficiency of RWH Systems

If RWH is to proliferate in urban areas, collected rainwater has to be fed to taps and other water using appliances in par with the centralized reticulated supply. For this, integration of a pumping unit to the system is essential. It is seen that the pumping energy requirement is reduced in CMTRWH systems () but still requiring appropriate pump selection for the maximum efficiency. Even though in the typical grid-based power supply scenarios, centrifugal submerged pumps are widely used for the purpose, it is useful as well as keeping to the sustainable principles if the pumps can be operated using an appropriate energy source. In this sense, pumps more adaptable to the particular renewable energy source have to be selected.

7.2 Integration of renewable energy with RWH systems

No system is viable and sustainable if it is not energy efficient in the context of the global energy crisis.

Out of the alternative energy sources, such as solar power, wind power and bio gas, solar power seems the most suitable for tropical climates, given the abundance of sun throughout the year as well as the relative low cost of components compared to wind turbines, apart from the durability and the viability in domestic usage compared to other sources. Hence, for RWH systems to be of self-sustaining and eco-friendly nature, solar pumping of harvested water is important and development of viable, low cost solar pumping devices are vital.

In the following sections, attention is focused on energy consumption in pumping water from RTRWH systems, various pumping methods, associated costs and the contribution to Green House Gas (GHG) emissions as a result of burning fossil fuel. Alternative energy sources, primarily solar power, are looked at in detail in running pumps so that it can be an integral part of RWH systems.

7.3 Requirements for pumping in RWH systems

Draw-off from the storage facility requires a pumping mechanism when:

a) The draw-off point of the tank at a lower elevation than the end use point

b) The system supplements water to the mains/municipal supply requiring pressure matching between the two systems.

c) A specific pressure is required at the end user point. Certain appliances such as shower heads and dish washers are calibrated to function at specific water pressures.

d) In centralized rainwater storage situations, such as apartment blocks, supermarkets, schools etc. when multiple end user points are to be serviced.

7.4 Pumping options

There are various pumping options available in the market. The most commonly used pumps are:

a) Hand pumps

b) Centrifugal pumps

c) Positive Displacement pumps

a) Hand pumps:
Hand pumps are the most widely used in rural Sri Lanka, as well as in most developing countries where RWH systems are primarily used as the only potable water resource. Hand pumps can also be classified as positive displacement pumps, working on the same

principle, but are operated manually thereby limited to small scale draw-offs.

b) Centrifugal pumps:
Centrifugal pumps, working on the principle of creating a vacuum for suction by rotating an impeller at high speed, are the most widely used pumping option. However, the high starting torques required, low pumping heads and low pump efficiencies are the main draw backs of centrifugal pumps thereby needing higher energy input.

c) Positive displacement pumps:
There are different types of positive displacement pumps, namely the diaphragm, rotary and vane types. These are generally higher efficiency pumps at 60% to 70% efficiency and are capable of pumping to high heads. The advanced positive displacement pumps display low starting torques hence operating at low energy inputs [241].

7.4.1 Energy consumption of electric pumps in RTRWH situations

It is found that the average Sri Lankan urban household uses 30% of service water for WC flushing, garden watering and car washing. Assuming that 80% of the above requirement is met by a conventional RTRWH system with a header tank, the energy consumed in pumping such water to end user points is calculated as follows:

If the total annual service water demand = X Litres

Quantity of non-drinking quality water required to be

pumped up from RTRWHS = 0.3*0.8X

If collected rainwater is to be pumped from

ground level up to a maximum head of 10m (header tank)

in a typical household, for a P (kW) pump at a

discharge rate of D (L/min) consumes (kWh) = 0.3*0.8XP/60DN
(Where, N is the pump efficiency) (40)

7.5 Energy required pumping rain water& Green House Gas emissions

It is observed that a sizable energy component, though small compared to the total energy consumed, is required to pump collected rain water from the storage tanks of RTRWH systems to either a header tank or end user points. Therefore if RWH is to be adopted on a mass scale, though the individual household energy usage on water pumping may not be significant, the cumulative energy usage on water pumping on a national scale could be significant and would stretch the annual power demand [248].

In the light of electricity generation depending more and more on fossil fuel based power plants, as against renewable energy sources such as hydro, the possible impact of the resultant GHG emissions should be looked at, if RWH is to be considered as a true component of sustainable development.

There are 3 major gaseous emissions released as a result of fossil fuel burning, viz. carbon dioxide (CO_2), sulphur dioxide (SO_2), and oxides of nitrogen (NO_x). It is mainly the CO_2 emissions that have drawn special attention of the scientists' world over in recent times, since it poses a major threat to the global environment in the form of the green house effect (atmospheric warming resulting in climate change) and acid rain.

Carbon dioxide and other emissions per unit of electricity generation are dependent on the characteristics of the fuel and power plant. Characteristics of a fuel include its energy contents, and contents of carbon, sulphur, nitrogen or their compounds. The power plant characteristic includes the fuels heat rate, i.e., the amount of heat required to produce one unit of electricity.

The emission factors of different kinds of fuel used in power plants is given in Table 3. The emission factor indicates the mass of a particular gas emitted in producing one unit (1 kWh) of energy.

Table 3: Emission factors for different types of fuels

Fuels	Emission factor (kg/kWh)			
	CO_2	SO_2	No_x	CO
Coal	1.18	0.0139	0.0052	0.0002
Petroleum	0.85	0.0164	0.0025	0.0002
Gas	0.53	0.0005	0.0009	0.0005
Hydro	0.00	0.000	0.0000	0.0000

"For simplicity, generating 1000 kWh of energy using petroleum fuel is taken as emitting 1 Ton of GHG".

The worldwide residential energy consumption, it is found varies from 16% - 50%, depending to what extent the country is industrialized. For Sri Lanka, the world average of 31% can be assumed to be valid [57].

7.6 Pumping harvested rainwater using solar power

Sustainable, low carbon, energy scenarios for the new century, emphasizes the untapped potential of renewable resources. Solar radiation arriving on earth is the most fundamental renewable energy source in nature. On a clear day, the solar radiation incident on the earth's surface can reach 1000 W/m^2. Photovoltaic (PV) is a technology in which the radiant energy from the sun is converted to direct current.

A PV cell consists of two or more thin layers of semi-conducting material, most commonly Silicon. When the Silicon is exposed to light, electrical charges are generated and this can be conducted away by metal contacts as Direct Current (DC). The electrical output from a single cell is small, so multiple cells are connected together and encapsulated, usually behind glass, to form a module (sometimes referred to as a "panel"). The PV module is the principal building block of a PV system and any number of modules can be connected together to give the desired electrical output. The photovoltaic process produces power silently and is completely self-contained, as there are no moving parts. These systems can also withstand severe weather conditions. PV systems are so reliable that most manufacturers give a 10-year warranty, and a life expectancy beyond 20 years. The PV array consists of a number of individual photovoltaic modules connected together to give the required power with a suitable current and voltage output. Typical modules have a rated power output of around 75-120 Watts peak (W_p) each. A system with a PV array tilted towards south would generate approximately 750 kWh/year per kW_p installed [248].

In the following section, the possibility of employing Photo Voltaic (PV) Panels to power pumps to deliver water from RTRWHS storage facilities to end use points is discussed in detail and the viability of integrating solar power with RTRWH systems explored to focus on an eco-friendly, sustainable water supply system [249].

Normally, the solar water pumping system consists of three components: The PV array, the direct current (DC) motor and the pump. Each component has its own operating characteristics, which are: The I-V characteristics for the PV array and the DC motor, and the torque-speed characteristics for the motor and pump. The DC motor drives the pump whose torque requirements vary with the speed at which it is driven. The DC motor is operated by the power generated from the PV array whose I-V characteristics depend non-linearly on the solar radiation variations and on the current drawn by the DC motor. For the efficient operation of the system, the two sets of PV output and DC motor input characteristics should be matched. Electronic matching devices known as Maximum Power Point Trackers (MPPT) allow solar pumps to start and run under low-light conditions. This permits direct use of sun’s power without bothersome storage batteries.

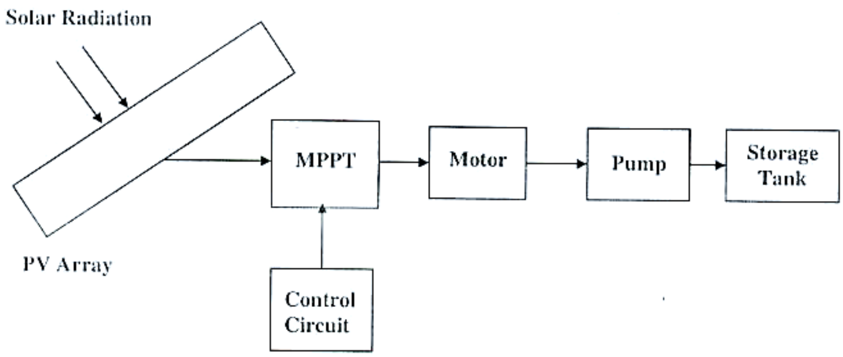

Figure 37: Schematic drawing of solar pumping [248]

Many researchers have studied the performance of photovoltaic powered water pumping systems (PVPS). The results of several experimental studies and theoretical analyses of PVPS have been published. Bany and Appelbaum (1979) [22] analyzed a direct coupled PV pumping system under steady state conditions. The starting characteristics of a DC motor and pump powered by a PV array without maximum power point tracker (MPPT) have been examined. The solar cell modules can only provide maximum power at specific voltage and current levels. So, for the PV array, there is a unique point on its I-V curve at which the power is at its maximum value, and for optimum utilization, the equilibrium operating point of the PV array should coincide with this point.

However, since the maximum power point varies with radiation and temperature, it is difficult to maintain optimum matching at all radiation levels, except for a specially designed DC motor. In order to improve the performance of a PV pumping system, a DC-DC converter known as a maximum power point tracker (MPPT) is used to match continuously the output characteristics of a PV array to the input characteristics of a DC motor. The MPPT normally consists of a power electronic circuit controlled by a signal circuit, which drives the power electronic circuit to force the PV array to operate at its maximum power point. Under such conditions, the MPPT will improve the efficiency of a PVPS.

Any off-the-shelf water pump allows itself to be powered by Photo Voltaic panels in some way or other and turned into a solar water pumping system.

The most common pumps used for this purpose are centrifugal, positive displacement and Helical Rotor pumps. Some are matched with AC, others with DC motors. If a pump has an alternating current (AC) motor, an inverter would be required to convert the DC electricity produced by the solar panels to AC electricity. Due to the increased complexity and cost, and the reduced efficiency of an AC system, most solar-powered pumps have DC motors.

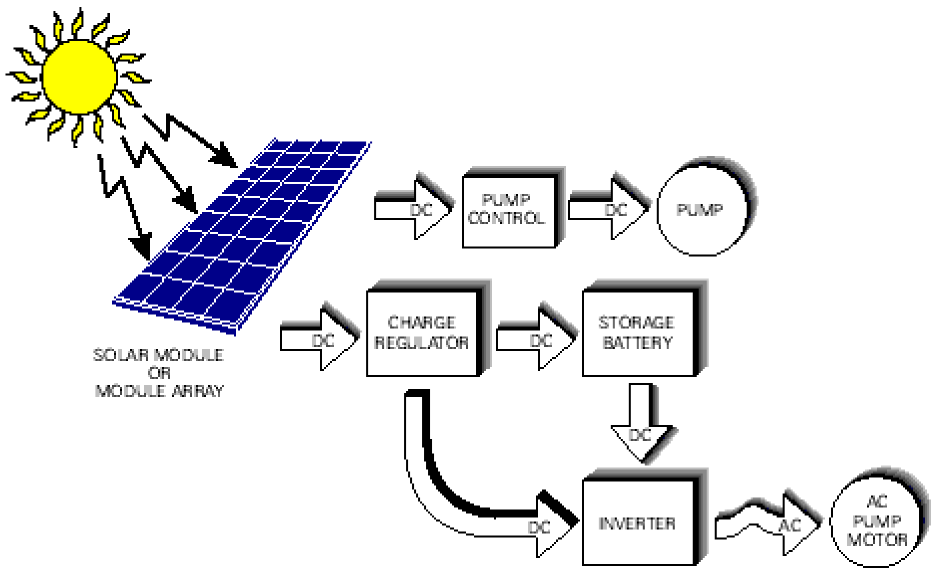

Figure 38: Direct and In-direct solar pumping

Solar modules, usually the greatest expense item in any solar design convert sunlight into electricity quite inefficiently by 14% on average. A highly productive, cost effective solar water pumping system therefore, will require careful matching of all component parts.

7.6.1 Design Requirements in Solar Pumping

Following are the fundamentally important design requirements of a solar water pumping system to render it durable, cost effective and affordable.

7.6.1.1 Versatility when pumping low or high heads

Most solar powered water pumps have little difficulty pumping from shallow depths of less than 30 m. Therefore, height of the head does not pose a problem in almost all RRWH systems. However, linear output characteristics of the pump are highly desired [240].

7.6.1.2 Low long term maintenance cost

When there is necessary maintenance, the costs should be reasonable, when compared to the original capital investment. This important because high incidence of frequent break downs may defeat the whole purpose of using harvested rainwater, especially when installed in remote areas [240].

7.6.1.3 Running without batteries and inverters

Preference should be given to high tech, but elementary, DC to DC solar water pumping technology, eliminating the power loss inherent in battery storage and conversion necessary when using, among others, AC motors with multi stage centrifugal pumps. (An inverter is used to convert the low voltage DC to higher voltage AC). Power losses come close to 25% of total solar array output, where batteries and conversion electronics (inverters) are used [240].

There are several reasons to avoid batteries in a pumping system listed as follows:

Using batteries in a solar pumping system lowers the efficiency as compared to going solar direct since it usually lowers the operating voltage of the pump which lowers the operating speed and flow rate of the pump [240].

Adding batteries to a pumping system, costs more money for the batteries

- Adding batteries to a pumping system, costs more money for the batteries themselves plus a required charge controller, battery enclosure and additional disconnects and wiring.
- Batteries performance level and expected life time are closely connected with the temperatures that they are subjected to. If batteries are overcharged and subjected to high temperatures their life time will be shortened dramatically. Batteries can be useful when weather is

frequently cloudy; water is to be drawn on-demand and when the water source available is low-producing and the need to pump as much water out of it each day. The battery system can be compensated by installing a larger volume storage tank which can be used as the buffer. Power generated by the solar modules should flow from the modules through the motor controller directly to the electric motor attached to the pump unit with absolute minimal loss. Where available, the motor controller should be primarily, digital. This will allow a controller design that is both a linear current - booster, and a maximum power point tracker in a single device. Such a device allows for real time compensation of reduced voltage levels emanating from the solar array at high ambient temperatures. This translates into greater water delivery (efficiency) in very hot climates, marginal light conditions and both simultaneously.

7.6.1.4 High generic efficiency

Overall efficiency, when taking sunlight as 100% before it reaches the solar modules, should be converted to water delivered at a ratio of at least 8% on average. Taking into account that solar modules convert sunlight to electricity at an average efficiency of only 14%, the pump/motor/electronics combination of the solar water pumping system must achieve an average mechanical efficiency of at least 57% to arrive at an overall efficiency of 8%.

Taking into account that about 50% – 80% of the cost of a solar pumping system is taken up by the cost of the solar module; the impact of operational efficiency is enormous on the cost effectiveness of the system [240].

7.6.1.5 A low starting torque requirement

Sufficient radiation must be available for a PV pumping system to start its pumping operation. This radiation level is called the radiation threshold. Most solar pumps have difficulty starting at first light, or at marginal light conditions (heavy cloud). The problem of poor performance in marginal conditions can be overcome in two ways:

i) By mechanical means, through the use of an application specific solar water pump, with a generically low starting torque requirement.

ii) By electronic means. This deals with any residual inertia, through the judicious choice of the motor controller specified. An electric motor always requires much more power to start than, eventually, to run. The motor controller needs to have an integrated auto-start circuit that will start the pump motor early in the morning, when enough sunlight is present to make the motor run at a given head.

7.6.2 Solar powered pumping options

Many solar (Photo Voltaic) powered water pumping projects rely on the use of large scale (> 1 kWp) Photo Voltaic (PV) arrays, coupled to multi stage centrifugal pumping units. However, smaller pumping units are in demand, which can be used in domestic services such as service water pumping.

Of the approximately 100 Photo Voltaic Pumps (PVP) installed in the 'International Demonstration & Field Testing Program, for Photo Voltaic Water Pumps (PVP Program)', funded by the German Government and implemented by GTZ, worldwide, 21% were rated at less than 1 kW. Similarly, of the 626 PVPs installed under the 'Programme Regional Solaire' (PRS) in the Sahel region of Africa in 1998, over 20% were rated below 800 W. At these low values of input power, the choice of pump type, centrifugal or positive displacement, is crucial as they demonstrate very different output characteristics.

Fig.39 is adapted from results of research conducted by Riez and Hanel (1995) [229] and demonstrate the difference in hydraulic energy output (proportional to flow rate multiplied by total discharge head), exhibited by the two types of pumping devices.

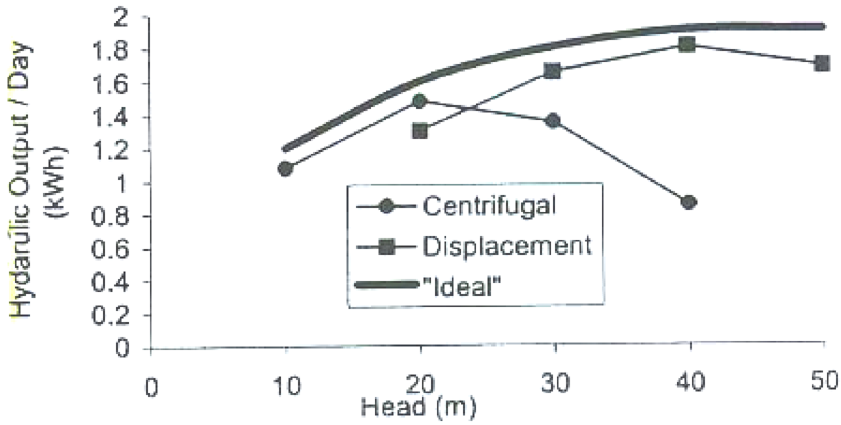

Figure 39: Hydraulic energy output for water pumps

It is evident that, for identical constant input power, neither pump could be considered 'ideal' across the entire range of heads. At lower heads centrifugal pumps produce the greater hydraulic output per day and therefore, the greater volume of water pumped per day, whilst at higher heads, positive displacement pumps dominate.

7.6.3 Solar power with centrifugal pumps

Centrifugal pumps are conventional, faster and deliver higher quantities, but needs to operate at higher speeds and at low Total Dynamic Heads (TDH). Smaller, stand alone, PV pumping units of less than 500 W do not usually employ centrifugal pumps, except for at the lowest heads. For any significant lift, multi staging is required and even then the low specific speed required and the size of impeller, inevitably lead to efficiencies of 25% – 30% (wire to water) compared with 65% – 70% for the best positive displacement units.

Centrifugal pumps are of surface mounted and submersible types. Run at variable speed from a permanent magnet DC motor, the centrifugal pump does have one particular advantage, in that its power demand curve matches well to the I-V characteristic of the PV array. With increasing power from the array, current and voltage will increase until there is just enough voltage (hence rotational speed) for the pump to overcome the static lift and start to deliver water.

It can be seen that the flow output is rapidly reduced, for a given voltage, as head is applied [22].

One of the disadvantages of a centrifugal pump is that it has to operate at a high enough rpm to push the water all the way out of the well/tank. If it is cloudy and the solar array is not producing enough power, the pump/motor may be turning but not fast enough to do this. Using a tracker is highly recommended with a centrifugal pump since it increases the solar arrays power output over a longer period of time which increases the daily volume of water delivered. Centrifugal pumps do not work efficiently below 25 L/min, but their performance drops off disproportionately at reduced speeds (under low light conditions). Also, conventional pumps use AC motors that do not work at reduced voltage. One solution to these problems involves the use of storage batteries and a conventional AC pump. Energy accumulates over time in the batteries and is discharged quickly to run the pump for short periods.

A battery system complicates the installation, operation and maintenance of a system and loses 20% of the stored energy. Operation of the AC pumps with DC power requires an inverter. The inverter adds cost and complexity and increases energy requirements by an additional 10%.

The most efficient low volume, non-battery systems use positive displacement DC Pumps.

7.6.4 Solar power with Positive Displacement pump

Unlike the centrifugal pump, the positive displacement pump will produce discharge flow whenever it is rotating. Positive Displacement pumps are of several different types, namely; Diaphragm, Rotary Vane Piston and Jack pumps. They are available in a wide range of sizes from 1 HP down to an incredible 0.1 HP. The low power pumps offer cost savings due to smaller PV arrays and reduced pipe size (pipe size is minimized by low rate pumping)

Positive displacement pumps however require higher starting torque (current) and are usually coupled to the PV array through a MPPT. MPPT or Linear Current Boosters (Solar pump controllers) deliver high current even in low light conditions by increasing the current at the expense of lower voltage. This allows pump operation throughout the solar day, however slowly, even in moderately cloudy conditions.

As long as sufficient current is available to overcome the torque required to start the pump, water will be discharged even at very low irradiance such as early in the morning or under cloud cover. However, it is worth noting that, for a particular irradiance, increasing the head from Low Head (LH) to a High Head (HH), leads to an increase in current being drawn, resulting in the pump running at high voltage, with consequence danger of over speed, particularly ay lower heads [240].

7.7 Features of solar pumping (PVPS)

Solar pumping also known as photo voltaic pumping display unique features different to that of conventional pumping. Following are the important features salient to solar pumping:

7.7.1 Mounting of solar array

The photovoltaic array (solar panels) can be mounted on a post, frame or on the roof, but whatever the array mounted on, it should be stable enough to withstand strong winds. The array should ideally be oriented toward true south, but deviations of 15 degrees east or west should not significantly affect performance [240].

It is found that tracking units that track the sun as it moves across the sky significantly enhances the performance of the PV array (by as much as 50%), though costly, is suitable for higher pumping outputs in direct drive systems. The solar panels should be tilted at an angle to horizontal to maximize power output. For year-round use, the tilt angle should equal the latitude of the site plus or minus 10 degrees.

7.7.2 Battery use

For the battery powered systems, it is important to use good-quality deep-cycle batteries and to incorporate electrical controls such as blocking diodes and charge regulators to protect the batteries [240].

7.7.3 Efficiency improvement of PVPS

Solar pumping technology continues to improve. In the early 1980s the typical solar energy to hydraulic (pumped water) energy efficiency was around 2% with the photovoltaic array being 6%-8% efficient and the motor pump set typically 25% efficient. Today, an efficient solar pump has an average daily solar energy to hydraulic efficiency of more than 4%. Photovoltaic modules of the mono-crystalline type now have efficiencies in excess of 12% and more efficient motor and pump sets are available. A good sub-system (that is the motor, pump and any power conditioning) should have an average daily energy throughput efficiency of 30-40%.

7.7.4 Maintenance of a PVPS

One of the main advantages of a solar powered pumping system is its simplicity and durability. The pump is the only part of the system having any moving parts, and it comprises a relatively small portion of the total system cost. Unless the system is installed in an extremely dusty area, occasional inspection of the wiring and the general appearance of the panels will be all that is necessary. Panels can be cleaned with plain water and a soft cloth. The frequency of inspection should match the amount of storage available. For example, if the system incorporates a three day supply of water and/or energy in storage, then it should be inspected at least every three days [240].

7.7.5 Sizing solar pumps

The hydraulic energy required (kWh/day)

= volume required (m^3/day) x head (m) x water density x gravity/ (3.6×10^6)

= 0.002725 x volume (m^3/day) x head (m) (41)

The solar array power required (kW_p)

$$= \frac{\text{Hydraulic energy required (kWh/day)}}{\text{Av. daily solar irradiation (kWh/m}^2\text{/day x F x E)}} \quad (42)$$

Where F = array mismatch factor = 0.85 on average and

E = daily subsystem efficiency = 0.25 – 0.40 typically

7.7.6 Solar powered pumping for typical RTRWH systems in Sri Lanka

For a typical domestic RTRWH system, the storage facility is placed at or just below ground level, thus presenting a low pumping head, usually less than 25 m for a single or two storey houses. In domestic situations, the service water requirements are small (approximately 210 L per person, per day), hence the average daily pumping demand is maintained below 1000 L for a typical household of 4 occupants.

Sri Lanka, is a tropical country with a latitude (6^0-9^0) above the equator in the northern hemisphere, experiencing an abundant solar irradiation at 4.5 – 6 KWh/m^2, ideally suitable for harnessing solar power for pumping water throughout the year. However, as in most tropical countries, frequent cloud cover block direct solar radiation varying the PV power output thus affecting the smooth operation of the pump requiring a battery backup. Solar tracking could improve performance but the high cost associated and the absence of extreme weather conditions does not warrant such. Since most roofs are of inclined type at 14^0 – 25^0, solar panels could be easily mounted on the roof without additional support structures.

Of the pumping types, centrifugal pumps are found to be not so suitable for solar pumping in Sri Lanka due to the following reasons:

- Inherent low efficiency of centrifugal pumps (30% -35%) requiring larger solar arrays increasing the total system cost.
- Requirement of inverters and battery systems further dropping the system efficiency
- Availability of relatively high heads, in two story houses for example, requiring multi-staging
- Low average daily service water demand not requiring a high speed, high volume operation.
- Frequent non-operational time-outs as a result of power output variations due to cloudy conditions inherent to climatic conditions of Sri Lanka.

Hence, a slow operating, low discharge DC positive displacement pump is ideally suitable for RTRWH systems in Sri Lanka. Such a pump could ideally be diaphragm type, surface mount and low discharge at a minimum 2 L/min, with the system being assisted by MPPT for smooth operation. Further, positive displacement pumps usually operate at 60% - 70% efficiency, lowering the power requirement thus dropping the cost of the PVPS [241].

Using a battery backup is not desirable due to drop in overall efficiency, but could be useful in monsoon periods when prolonged cloudy conditions occur. However, a bigger water storage facility in the header tank can eliminate the battery hence eliminating the maintenance cost though the overall system cost could be the same. That is because the cost of a higher capacity header tank with a support structure could be closer to the cost of a battery.

It can be calculated that the availability of 8-9 hours of sun in the intermediate climatic zone (ICZ) can be utilized to the maximum in installing 2 L/min diaphragm type positive displacement pump for RTRWH situations in Sri Lanka, pumping approximately 1000 L/day, fulfilling the daily water requirement. A set of sensors installed at the OHT can be used to cut-in and cut-off the pump according to the water level.

7.8 Economic and environmental impact of RWH systems

To assess the economic and environmental impact of RWH systems, life cycle based computer models such as EEAST has been developed. (EEAST stands for Economic and Environmental Analysis of Sanitary Technologies). The criteria that EEAST calculates for decision making are; water savings, Net Present Values (NPV) and payback periods (PP) for energy, GHG and discounted cost. EEAST provides a foundation framework for LCA studies on RWH systems. It is reported that the PP for cost is generally more than the PP for energy, which in turn is greater than the PP for GHG primarily due to energy and emission intensive nature of the centralized water and waste water infrastructure.

Life cycle cost (LCC) of using rainwater systems can be estimated and compared to the costs of alternative water sources for households over the same period of time and if LCC of RWH systems are greater than the cost of alternative water sources, they are not financially considered viable from the perspective of the households. In the models, building characteristics, occupancy and precipitations are used for sizing and then life cycle costing (LCC) and life cycle assessment (LCA) methods are used to estimate cost, energy and GHG emission payback periods.

The application of environmental criteria to the study of RWH utilization is so far underdeveloped and LCA is a useful tool to obtain quantitative data for decision making. In the LCA of RWH systems in urban environments, a more accurate and broader understanding can be achieved if analyses on alternative water supply methods, alternative water infiltration systems, distribution infrastructures, different methods of rainwater disinfection are included in addition to environmental evaluation of different components of the system and treatment processes. Research indicates that in terms of energy and materials, RWH system manufacturing and operation have more impacts on the environment than a reticulated water supply, especially when a pump is needed [6].

The possibility of integrating a tank distributed over the roof in the design of a building rather than constructing an underground tank generally reduces the environmental impacts up to 4.7 times in the compact urban design, and 1.5 times in the diffuse [6].

REFERENCES

[1] ABS 2000, Australian Bureau of Statistics, Aust-Stats, Environmental Issues: Peoples' Views and Practices, Water use and Conservation. www.abs.gov.au/auststats.

[2] Adger, W.N., (2006), "Vulnerability," Global Environmental Change, Volume 16, Issue 3, Pages 268-281.

[3] Ahrens, C.D. (1998), "Essential of meteorology, an introduction to the atmosphere", 2nd ed. New York: Wadsworth Publishing Company.

[4] Akinoglu, A., Ecevit, L. (1993), "Modeling of Solar Radiation," Turk. J. Phys. 17: 269.

[5] Allen, R.G. (1995), "Evaluation of procedures for estimating mean monthly solar radiation from air temperature," Report submitted to the United Nations Food and Agricultural Organization (FAO), Rome, Italy.

[6] Ansrll, Estral (2012), " Environmental Analysis of rainwater harvesting infrastructures in different and compact urban models of Mediterranean Climates" International Journal of life Cycle Assess., vol17, No 25-42.

[7] Angstrom, A., (1924), "Solar and terrestrial radiation," Quart., J.R. Met. Soc., 50, 121-126.

[8] Anis, W.R., Metwally, H.M.B. (1994), "Dynamic performance of directly coupled PV pumping systems," Solar Energy, 53(4): 369-77.

[9] Anon (1884) Guidelines For Drinking Water Quality. Volume 1. Recommendations. World Health Organization, Geneva.

[10] Anon, 1998. EU Council Directive of 3 November 1998 on the quality of water intended for human consumption. Official J.L 330, 32-54

[11] Appan A. , Economic and water quality aspects of rainwater catchment system. Proc. Internat. Symp. Efficient Water Use in Urban Ares, UNEP Int. Environ. Tech. Center, Osaka, Japan, 1999.

[12] Appan, A. (1999), "A dual mode system for harnessing roof water for non-potable uses", Urban Water, 1(4): 345-54.

[13] Appan, A., Chan, H.H. and Jih, W.H. (1997) Alternative dual- mode working systems for the high-rise buildings for non-potable purposes. *Proceedings of the 8th International Conference on Rainwater catchment Systems*, IRC-SA/Min of Jihad-e-Sazandegi, Tehran, Iran, pp.3-9.

[14] Ariyabandu, R. de S. (1998). Study of Exsiting rainwater harvesting technology. Report prepared for the Lanka Rainwater Harvesting Forum, unpublished.

[15] Ariyabandu, R. de S. and Aheeyar, M.M.M. (2000). Evaluation the effectiveness of rainwater as a domestic water source in rural Sri Lanka. Unpublished report prepared for the Lanka Rainwater Harvesting Forum.

[16] Ariyananda, T. (2004). Overview of Rainwater harvesting in Urban Areas. Awareness programme on rainwater harvesting for urban and industrial sector, unpublished.

[17] Arnell, N.W.,(1999), “Climate change and global water resources - a new assessment,” Global Environmental Change, Volume 9, Issue 1001, Pages S31-S49.

[18] Atwater, M. A., Ball, J.T. (1978), “A numerical solar radiation model based on standard meteorological observations,” Solar Energy 21: 163-170.

[19] Australian Bureau of Meteorology. Australian Rainfall. Retrieved March 18, 2008. from http://www.bom.gov.au/v.

[20] Australian Bureau of Statistics. Water account Australia 2005-2005. Australian Government;2006.

[21] Bandara, M. A. C. S, “ Analysis of Quality and consumer preference for harvesting rainwater in Anuradhapura district”, Tropical Assessment research, Vol 18.

[22] Bany, J., Applebaum, J. (1979), “Performance analysis of DC motor photovoltaic converter system – 1, Solar Energy, 122:439-45.

[23] Barnett, J.,(2003), “Security and climate change,” Global Environmental Change, Volume 13, Issue 1, Pages 7-17.

[24] Behr, H.D. (1997), “Solar radiation on tilted south oriented surfaces: validation of transfer models,” Sol. Energy. 6: 399-413.

[25] Bennet, I. (1969), “Correlation of daily insolation with daily total sky cover, opaque sky cover and percentage of possible sunshine,” Solar Energy 13: 391-393.

[26] Bindi, M., Miglietta, F., Maracchi, G. (1991), “Estimating daily global radiation from air temperature and rainfall measurements,” Boll. Geof., VI: 141-147.

[27] Bird R., Hulstrom R.L. (1981), “Review evaluation and improvement of direct irradiance model,” J. Sol Energy Eng, 103-183.

[28] Black, J. N., Bonython, C. W., Prescott, G. A.(1954), “Solar radiation and the duration of sunshine,” Q.J.R. Meteorol. Soc. 80: 231-235.

[29] Black, J.N., (1961), “Some aspects of climatology of solar radiation,” Paper presented at UN conference on New Sources of Energy, Rome.

[30] Black, J.N.,(1956), “The distribution of solar radiation over the earth’s surface,” Arch. Meteorol. Geophys. Bioklim., B7, 165-189.

[31] Blaney, H.F, Criddle, W.D. (1950), “Determining water requirements in irrigated areas from climatological and irrigation data,” USDA/SCS-TP 96.

[32] Branvall, G., Eriksson, M., Johansson, U., Svensson, P. (1999), “Physical and monetary data connected to abstraction, use and discharge of water in the Swedish NAMEA,” Statistika Centralbyran (Statistics Sweden).

[33] Bristow, K. L., Campbell, G. S.(1984), “On the relationship between incoming

solar radiation and daily maximum and minimum temperature," Agric. For. Meteorol. 31: 159-166.

[34] British Petroleum Energy, statistical review, 2006.

[35] Brown, R., 2009. Practitioner percepttions of social and institutional barriers to advancing a diverse water source approach in Australia. Water Resour. Dev. 25 (1), 15-28.

[36] Butler, D. (1993) "the influence of dwelling occupancy and day of the week on domestic appliance wastewater discharges", Building and Environment, 28(1): 73-9.

[37] Butler, D., Memon, F.A., Makropolous, C., Southall A., Clarke L., 2010.WaND: Guidance on water cycle Management for new developments. CIRIA report C690. CIRIA, London ISBN9780860176909

[38] Cano, D., Monget, J. M., Albuisson, M., Guillard, H., Regas, N., Wald, L.(1986) "A method for the determination of the global solar radiation from meteorological satellite data," Solar Energy 37: 31-39.

[39] Cengiz, H.S., Gregory, J. M., Sebaugh, J. L. (1981), "solar radiation prediction from other climatic variables," Trans. A.S.A.E. 24(5):1269-1272.

[40] Central Bank of Sri Lanka, Annual Report, 2005.

[41] Centre for the Analysis and Dissemination of Demonstrated Energy Technology (CADDET) (1999), "Combined and stepped use of energy in Sumida City office".

[42] Chakravorty, U., Roumasset, J., Tse, K.,(1997), "Endogeneous substitution among energy resources and global warming," J.Ploitical Econ., 105, 1201.

[43] Chang, M., McBroom, M.W., Breasley, R.S., 2004. Roofing as a source of nonpoint water pollution. J. Environ. Manage.73,307-315.

[44] Chen, C. L., Chan, C. Y., Chen, C. L. (2005), "empirical approach to BIPV evaluation of solar irradiation for building applications," renew. Energy, 6: 1055-1074.

[45] Chilton, J.C., Midment, G.G., Marriott, D., Francis, A., Tobias, G. (1999), "Case study of a rainwater recovery system in a commercial building with a large roof", Urban Water; 1(4): 345-54.

[46] Chiu, Y. R., Liaw, C.H., Tsai,Y.L., 2009. Harvesting Rainwater, an innoative approach to easing urban water energy dilemma. In: Proceedings of the 14th international Conference on rainwater Catchment System, Kuala Lumpur.

[47] Collarez, Pereira, M., Rabi, A., Solar Energy 22, 195 (1979).

[48] Collin, M.L., Melloul, A.J. (2001), "Combined land-use and environmental factors for sustainable groundwater management," Urban Water, Elsevier Science Ltd.

[49] Collins, W.D. et al. (2001), "Simulating aerosols using a chemical transport model with assimilation of satellite aerosol retrievals: Methodology for

INDOEX," J. Geophys. Res.,106 D, 7313-36.

[50] Coombes PJ, Kuczera G, Kalma JD. Dunstan HR. Rainwater quality from roofs, Tanks and hot water systems at Figtree place. In: The third International Conference Hydrology Symposium; 2000b. P. 1042-

[51] Coombes PJ, Kuczera G, Strategic use of storm water, BDP environmental design guide, sustainable water use. The Royal Australian Institute of Architects;2001

[52] Coombes, P. (2002), "Rainwater tanks revisited. New opportunities for urban water cycle management." PhD Thesis, University of NewCastle, Australia.

[53] Coombes, P.J., Kuczera, G., 2003. Analysis of the Performance of rainwater tanks in Australian Capital Cities. 28th International Hydrology and water resources Symposium, Wollongong. Http://www.eng.newcastle.edu.au/~cegak/Coombes/Coombes51.pdf (accessed 10.12.10)

[54] Coombes, P.J., Kuczera, G., Kalma, J.D Argue, JR 2002. An Evaluation of the benefits of source control measures at the regional scale. Urban Water 4, 307-320.

[55] Coulson, K.L., (1975), "Solar and terrestrial radiation, Methods and measurements," pp. 242, Academic Press, New York., London.

[56] CSIRO (2005), Commonwealth Scientific & Industrial Research Organization Department of Atmospheric Research, FAQ, Greenhouse: Questions and Answers, "How will Australia's climate change in future? www.dav.csiro.au/publications.

[57] Cunliffe DA, Guidance on the use of rainwater tanks. National environmental Health Forum, Territorial Health services, Commonwealth Depatment of Health and services, Community Health Services, Queensland Health, Human services, Department of Health and Community Care NSW Health Department, Health Department of Western Australia: 1998.

[58] Cunliffe, D.,(2004), "Guidance on use of rain water tanks," National Environmental Health Forum Monograph," Health Council, Water Series No. 3, pp 29.

[59] Da Mota, F.S., Beirsdorf, M.I.C., Acosta, M.J.C., (1977), "Estimates of solar radiation in Brazil," Agricultural Meterology., 18, 241-254.

[60] Daneshyar M. (1978), "Solar radiation statistics for Iran," Sol Energy,21: 345-9.

[61] Davey (2005), Davey Products Pty Ltd, "Rainbank" Switching System, www.davey.com.

[62] De Jong, B., (1973), "Net radiation received by a horizontal surface at the earth," Monograph, Delft University Press.

[63] DeBoer D.W., Olson D.I., Skonard C.J. (2005), "Evaluation of solar radiation estimation procedures for eastern South Dakota," J Proceedings of the South Dakota Academy of Science, Vol.84: 265-275.

[64] Dennler, G., Bereznev, S., Fichou, D., Holl, K., Ilic, D., Koeppe, R., Krebs, M., Labouret, A.; Lungenschmied, C., Marchenko, A., Meissner, D., Mellikov, E., Meot, J., Meyer, A., (2007), "A self-rechargeable and flexible polymer solar battery," Solar Energy, Volume 81, Issue 8, Pages 947-957.

[65] Department of the Environment and Welsh office (1992), "Using water wisely", HMSO, London.

[66] Diak, G.R., Gautier, C., Masse, S.(1982), " An operational system for mapping insolation from GOES satellite data," Solar Energy 28: 371-376.

[67] Dillaha, T. A., Zolan, W.J., 1985. Rainwater catchment water quality in Micronesia. Water Res. 19(6), 741-746

[68] Dixon, A., Butler, D., Fewkes, A.(1999), "Computer simulation of domestic water reuse systems: investigating greywater and rainwater in combination", Water Science Technology, 21(2), 99-106.

[69] Dixon, A., Butler, D., Fewkes, A., 1999. Water saving potential of domestic water reuse systems using greywater and rainwater in combination. Water Science and Technology 39(5), 25-32.

[70] Dogniaux, R., Lemoine, M. (1982), "Classification of radiation sites in terms of different indices of atmospheric transparency in Palz. W.", Solar radiation data. Series F. Vol.2, Reidel Publishing Company, Dordrecht, p. 94-105.

[71] Duffie, J.A., Beckman, W.A. (1991), "Solar Engineering of thermal process," 2nd ed. New York: Wiley.

[72] Dungumaro,E.W., Madulu,N.F., (2003), "Public participation in integrated water resources management: the case of Tanzania," Physics and Chemistry of the Earth, Parts A/B/C, Volume 28, Issue 20-27, Pages 1009-1014.

[73] EC, (1997), Energy for the future: Renewable Sources of Energy, White Paper, European Commission, DG XVII.

[74] Economic & Social Commission for Asia & the Pacific (ESCAP) (1989), "Rainwater Harvesting Techniques and Prospects for their application in Developing Island Countries." In Water resources Developments in Asia and the Pacific: Dam safety Evaluation and Monitoring, Water tariffs & Rainwater Harvesting, Bangkok pp 101-108,

[75] Edmonds, J., Reilly, J., (1983), " A long-term global economic model of carbon dioxide release from fossil fuel use," Energy Econ., 5,74.

[76] Edwards RA, microbiological investigation into the degree of contamination of water in-domestic rain water storage tanks with residents of Noosa Shire solely supported by tank water: In: The 54th Annual State Conference of the Australian Institute of Environmental Health p

[77] Edwards, D., Keller, K. (1984), "A workshop design for rainwater catchment systems (Training Guide) & appendix. "Rainwater Harvesting for Domestic Water Supply in Developing Countries," La Paz, UNESCO/ROSTLAC, UNICEF.

[78] Erlykin, A.D., Gyalai, G., Kudela, K., Sloan, T., Wolfendale, A.W.,(2007), "On the correlation between cosmic ray intensity and cloud cover," Journal of

Atmospheric and Solar-Terrestrial Physics.

[79] Etuk, E., Akpabio, L. E. (2002), "Modeling global radiation for a tropical location: Onne, Nigeria," turk. J. Phys. 29: 63-69.

[80] Excell, R.H.B.,(1981), "A mathematical model for solar radiation in South-East Asia, (Thailand)," Solar Energy 26, 161-168.

[81] Farreny R, Guisasola A, Morales-Pinzón T, Tayà C, Rieradevall J, Gabarrell X (2011b) Roof selection for rainwater harvesting: quantity and quality assesment. Water res. Doi:10.1016/j. watres.2011.03.036

[82] Fayez, A. A. et.al; "Rainwater harvesting system for household water supply in Gardens" (zw6) Desalination, 243, 195, 207

[83] Ferenc, K., Jozsef, B., Marianna, V.,(2002), "Changes in solar radiation energy and its relation to monthly average temperature," Acta Montanistica Slovaka J., 7, 164-166.

[84] Feuermann, D., Zemel, A.(1992), "Validation of models for global irradiance on inclined planes," Sol. Energy. 1: 59-66.

[85] Fewkes, A. (1999a),"Modeling the performance of rainwater collection systems towards a generalized approach", Urban water, 1, 323-333.

[86] Fewkes, A. (1999b), "The use of rainwater for WC flushing: The field test of a collection system", Building & Environment, 34, 765-772.

[87] Flowe DJM, Mitchell VG, Codner GP (2007) Urban water systems: drivers of climate change? In: Proceeding of the rainwater and urban design 2007, IRCSAXIII Conference, Sydney, Australia.

[88] Folke, C.,(2006), "Resilience: The emergence of a perspective for social-ecological systems analyses," Global Environmental Change, Volume 16, Issue 3, Pages 253-267.

[89] Forster, J. (1991),"Roof runoff pollution". In: Grottker, M., Schilling, W., editors: Proceedings of second European Junior scientist Workshop, Kastienbaum, Switzerland, pp. 145-58.

[90] Fragkou M, Gabarrell X, Vicent T (2008) Artificial water flow accounting in a Mediterranean coastal region. In: Malhotra G (ed) Development issues of environmental groeth. Macmillan India, New Delhi.

[91] Frantzeskaki, N., Gekas, V., Tsoutsos., (2002), "Environmental implications from the use of solar systems; Examples of the potential impact mitigation in a sustainable perspective," 7th National Conference for Solar Energy Sources, Patras, 6-8, November 2002.

[92] Fritz, S., McDonald, T.H., (1949), "Average solar radiation in the United States," Heating and Ventilation, 46, 61-64.

[93] Frulla, L. A., Gagliardini, D. A., Grossi, G., Lopardo, R., Tarpley, J. D. (1988),"Incident solar radiation on Argentina from the geostationary satellite GOES: comparison with ground measurements," Solar Energy 41: 61-69.

[94] Fthenakis, V.,(2000), “End-of-life management and recycling of PV modules,” Energy Policy 28, 1051-1058.

[95] Fuller CO, Martin TJ, Walters RP. Quality aspects of water stored in domestic rainwater tanks, a preliminary study. Engineering and water supply department, South Australia, Australian Government; 1981

[96] Furumai, H., (2008), “Rainwater and reclaimed wastewater for sustainable urban water use,” Physics and Chemistry of the Earth, Parts A/B/C, Volume 33, Issue 5, Pages 340-346.

[97] Gardner, T., Miller, G., Hyde, R. (2003), “The healthy Home: A step towards sustainable suburbs”, paper published in the proceedings of the 2nd national water Recycling Conference, Brisbane Sept. 2003, Australian Water Association and Stormwater Industry Association.

[98] Ghisi, E., Lapolli Bressan, D., Martini, M 2007.Rainwater tank capacity and potential for potable water savings by using rainwater savings by using rainwater in the residential sector of southeastern Brazil, Build. Environ. 42, 1654-1666

[99] Glover, J., McCulloch, J.S.G.,(1958), “The empirical relationship between solar radiation and house of sunshine,” Quart. J.R. Met. Soc. 84, 172-175.

[100] Gordon, G., Adam, L., Bubnis, B., 1995 Minimizing chlorate ion formation. J. Am, Water works Assos. 87, 97-106

[101] Gould J, Niessen- Peterson E (1999) Rainwater catchment systems for domestic supply: design, construction and implementation. Intermediate Technology, London.

[102] Gould, J.E. , Rainwater catchment systems technology: Recent development in Africa and asia. Proc. Science and Technology in the Third World Development Conference, University of Strathclde, Glasglow, 1993.

[103] Grant T, Hallmann M (2003) urban domestic water tanks: life cycle assesment. Water, August 2003:22-27

[104] Green, M.A.,(2003), “Crystalline and thin-film silicon solar cells: state of the art and future potential,” Solar Energy, Volume 74, Issue 3, Pages 181-192.

[105] Green, M.A.,(2004), “Recent developments in photo voltaics,” Solar Energy, Volume 76, Issue 1-3, Pages 3-8.

[106] Gregory S. (1993), “Statistical methods and geographer,” New York: Wiley.

[107] Griggs JC, Shoulder MC, Hall J (1997) Water conservation and the built environment. 21 Adwater: architectural digest for the 21st century. Oxford brookes University, Oxford.

[108] Hammer, A., Heinemann, D., Hoyer, C., Kuhlemann, R., Lorenz, E., Muller, R., Beyer, H. G. (2003), “Solar energy assessment using remote sensing technologies,” Remote Sens. Environ., 86, 423-433.

[109] Hargreaves, G.H, Samani, Z.A. (1985), “Reference crop evapotranspiration from temperature,” Transaction of ASAE 1(2): 96-99.

[110] Hargreaves, G.H. (1994), “Simplified coefficients for estimating monthly solar

radiation in North America and Europe," departmental paper, dept. of boil. and Irrig. Engrg., Utah State University, Logan, Utah.

[111] Haurwitz, B. (1948), "Insolation in relation to cloud type," J. Meteorol. 5: 110-113.

[112] Hay, J. E., Suckling, P. W.(1979), "An assessment of the networks for measuring and modeling solar radiation in British Columbia and adjacent areas of Western Canada," Canadian Geogr., 23: 222-238.

[113] Head L., 2008. Nature, networks and desire: changing cultures of water in Australia. In: Troy,P. (Ed.), Troubled waters. Confronting the Water Crisis in Australia's Cities. ANU E Press. The Australian National University, Camberra, Australia, pp67-80

[114] Healthy Home (2005). Queensland Department of Natural Resources and Mines and Environmental Protection Agency., Healthy Home Project, www.healthyhomeproject.com.

[115] Hermann, T., Schmida, U. (1999),"Rainwater utilization in Germany: efficiency, dimensioning, hydraulic and environmental aspects", Urban water, 1, 307-316.

[116] Hestnes, A.G.,(1999), "Building integration of solar energy systems," Solar Energy 67, 181-187.

[117] Hills, S., Birks, R., McKenzie, B. (2001)"The Millennium Dome water Cycle experiment: To evaluate water efficiency and customer perception at a recycling scheme for 6 million visitors". Proceedings of the IWA second World water congress, Berlin.

[118] Hitz, S., Smith, J.,(2004), "Estimating global impacts from climate change," Global Environmental Change, Volume 14, Issue 3, October 2004, Pages 201-218

[119] Hodges, T., French, V., LeDuc, S. (1985), "Estimating solar radiation for plant simulation models," AGRISTAR Technical Report, USC 20239.

[120] Hoel, M., Kverndokk, S.,(1996), "Depletion of fossil fuels and the impact of global warming," Resource Energy Econ., 18,115.

[121] Hontaria, L., Aguilera, J., Zufiria, P., "A new approach for sizing stand-alone photovoltaic systems based in neural networks," Sol.Energy, 2005, 78:313-9

[122] Hoogenboom G.(2000), "Contribution of agro-meteorology to the simulation of crop production and its applications," J agriculture and forest meteorology, 103: 137-157.

[123] IPCC, 2007. In: Solomon, S., Qin, D., Manning M., Chen, Z., Marquis, M., Averyt, K.B., Tignor, M., Miller, H.L., (Eds), Climate Change 2007: The Physical science Basis, Contribution of working Group I to the fourth Assesment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NT, USA.

[124] Iqbal M. (1983), "An introduction to solar radiation," London: Academic Press.

[125] Iziomon, M. G., Mayer, H.(2002), "Assessment of some global solar radiation

parameterizations," Atmos. Solar Terres. Phys., 64, 1631-1643.

[126] Jafarpur, K., Yaghoubi, M.A. (1989), "Solar radiation for shiraz, Iran," Sol. Wind Technol. 6(2): 177-179.

[127] Jagtap, S.S. (1991), "Spatial pattern of reference evapotranspiration in Africa," ASAE paper no.91-2644, ASAE national meeting, Chicago, IL.

[128] Jayasinghe, M.T.R., Jayawardene, A. I., Attalage, R. A. (2001) "Concepts for sustainable residential developments for urban and suburban areas in Sri Lanka", Engineer, Journal of Institution of Engineers, Sri Lanka, vol xxxiv, No.2, pp 63-77.

[129] Jenkins, D., Pearson, F., Moore, E., Sun J.K., Valentine, R. (1978), "Feasibility of Rainwater Collection Systems in California", Contribution No. 173, Californian Water Resources Centre, University of California.

[130] Jewitt, G., (2002), "Can Integrated Water Resources Management sustain the provision of ecosystem goods and services?" Physics and Chemistry of the Earth, Parts A/B/C, Volume 27, Issue 11-22, Pages 887-895.

[131] Justus, C. G., Paris, M.V. (1985). "A model for solar spectral irradiance and radiation at the bottom and top of a cloudless atmosphere," J. Appl. Meteorol, 24(3): 193-205.

[132] Kaelin, M., Rudmann, D., Tiwari, A.N,(2004), "Low cost processing of CIGS thin film solar cells," Solar Energy, Volume 77, Issue 6, Pages 749-756.

[133] Kaika, M., 2005. City of Flows: Modernity, Nature and the City. Routledge. Taylor ans Francis Group, New York.

[134] Kambezidis, H. D., Psiloglou, B. E., Guaymard, C. (1994), "Measurements and models for total solar irradiance on inclined surface in Athens, Greece," Sol. Energy. 2: 177-185.

[135] Kandirmaz, H. M., Yegingil, I., Pestemalci, V.,Emraglu, M.,(2004), "Daily global solar radiation mapping of Turkey using Meteosat satellite data," Int. I. J. Remote Sense., 25, 21592168.

[136] Kasten, F., Czeplak, G.(1980), "Solar and terrestrial radiation dependent on the amount and type of cloud," Solar Energy, 24: 177-189.

[137] Keulan, H., Van, S., Van, H. D. J.(1986), "Meteorological data," Wageningen, p. 35-46.

[138] Kim RH, Lee S, KimYM, Lee JH, Kim SK, (2007) Design for Rainwater management system for eco- housing complex: In: Proceedings of the Rainwater and Urban Design Conference, 21-23 August, Sydney, Australia.

[139] Kim RH, Lee S, KimYM, Lee JH, Kim SK, Kim JG (2005) Pollutants in rainwater runoff in Korea: their impacts on rainwater utilisation. Environ Technol 26: 411-420

[140] Kimura, K., Stephenson, D. G.,(1969),"Solar radiation on cloudy days," ASHRAE Trans., 75: 227-234.

[141] Klein S.A. (1994), "Calculation of monthly average insolation on tilted

surfaces," Sol Energy, 43(3): 153-68.

[142] Knapp, C. L., Stoffel, T. L. (1980), "Insolation solar radiation manual," Solar Energy Research Institute, Golden, Colarado, p. 281.

[143] Kondo J, Nakamura T, Yamazaki T. (1991), "Estimation of the solar and downward atmospheric radiation," Tenki, 38: 41-48.

[144] Lowa, D., Saun, D., (2011) " A comparative approval of the use ofrainwater harvesting in single and multistory buildings of Metropolitan area of Barcelona (Spain) Social Experience, drinking water savings and economical costs" Journal of cleaner productions. 19 (598-608)

[145] Lanka Rainwater Harvesting Forum (2004), "Rainwater Harvesting in urban areas."

[146] Larsen, G.A., Pense, R.B.,(1982), "Stochastic simulation of daily climatic data for agronomic models," Agronomy Journal, 74, 510-514.

[147] Lastovicka, J., (2009), "Global pattern of trends in the upper atmosphere and ionosphere: Recent progress," Journal of Atmospheric and Solar-Terrestrial Physics, Volume 71, Issue 14-15, Pages 1514-1528.

[148] Latham, B., Schiller, E.J.(1987), "A Comparison of Commonly used Hydrologic Design Methods for Rainwater Collectors", Water Resources Development, 3:165-70.

[149] Laut, P., (2003), "Solar activity and terrestrial climate: an analysis of some purported correlations," Journal of Atmospheric and Solar-Terrestrial Physics, Volume 65, Issue 7, Pages 801-812.

[150] Law, A.M., Vincent, S.G., (1003), Unifit II Users guide, Averill M. Law Associates, Tuscon.

[151] Le Mouel, J.-L., Blanter, E., Shnirman, M., Courtillot, V., (2005), "Empirical analysis of the solar contribution to global mean air surface temperature change," Journal of Atmospheric and Solar-Terrestrial Physics.

[152] Leggett DJ, Brown R, Brewer D, Stanfield G, Holliday E (2001) Rainwater and Greywater use in buildings: best practice guidance. CIRIA reports C539, CIRIA, London.

[153] Li, F., Ramanathan, V. (2002), "Winter to summer monsoon variation of aerosol optical depth over the tropical Indian ocean," J. Geophys. Res., 107D, doi:10,1029.

[154] Li, Z., Garand, L. (1994), "Estimation of surface albedo from space: A parameterization of global application," Journal of Geophysical Research, Vol. 99, pp.8335-8350.

[155] Liaw, Chao-Hsien., Tsai, Yao-lung.,(2004), "Optimum storage volume of rooftop Rain water harvesting system for domestic use", journal of American Water Resources Association.

[156] Lijuan, L. and Gouyou, Z. (1997) Different purpose of rainwater catchment in China and their environmental effects. *Proceedings of the 8th International*

Conference on Rainwater catchment Systems, IRC-SA/Min of Jihad-e-Sazandegi, Tehran, Iran, pp.378-382.

[157] Liu, B.Y.H., Jordan, R.C.,(1960), "Solar Energy," 4(3), 1.

[158] Lof, G.O.G., Duffie, J., Smith, C.O.,(1965), "World distribution of solar radiation," Engineering station report No. 21, University of Wisconsin, Madison.

[159] Lorenzo, E., Narvarte, L., (2000), "On the usefulness of stand-alone PV sizing methods," Prog. Photo voltaics Appl. 8:301-40.

[160] Lucke, F. K. (1999)"Process water of potable quality; sense or non-sense", Mark Moodie, Newham, UK.

[161] Lumb, F. E. (1964), "The influence of cloud on hourly amounts of total solar radiation at sea surface,"Q.J.R. Meteorol, Soc. 90:383.

[162] Lundie S, Peters GM, Beavis P, (2004) Life cycle assesment for sustainable metropolitan water systems planning. Environ Sci Technol 38 (13) :3465-3473

[163] Madungwe, E., Sakuringwa, S., (2007), "Grey-water reuse: A strategy for water demand management in Harare?" Physics and Chemistry of the Earth, Parts A/B/C, Volume 32, issue 15-18, Pages 1231-1236.

[164] Magal, B. S.(1993), "Solar Power Engineering," Tata McGraw-Hill Publishers.

[165] Mahmoud, E., Nather, H. (2003), "Renewable energy and sustainable developments in Egypt, Photovoltaic water pumping in remote areas," Applied Energy, 74 Elsevier.

[166] Mani, A., Chacko, O., Iyer, N.V.,(1973), "Atmospheric turbidity over India from solar radiation measurements," solar Energy 14, 185-195.

[167] Mani, A., Chacko, O., Krishnamurthy, K., desikan, V.,(1967), "Distribution of global and net radiation over the Indian ocean," Arch. Met. Geoph. Bioklm. B 15, 83-98.

[168] Mantovan, P., Pastore, A., Szpyrkowicz, l., Zilio- Grandi, F., 1995. Characterization of rainwater quality from the Venice region network using multiway data analysis. Sci. Total Environ. 164, 27-43

[169] Maracchi, G., Miglietta, F. (1988), "Estimating daily global radiation from air temperature and rainfall measurements," Boll. Geof., VI: 141-147.

[170] Marion, W., George, R.(2001), "Calculation of solar radiation using a methodology with worldwide potential," Solar Energy, 71, 4: 275-283.

[171] Marion, W., Urban, K.(1995), Users manual for TMY2s-typical meteorological years derived from the 1961-1990 National Solar Radiation Data Base, NREL/SP-463-7668, National Renewable Energy Laboratory, Golden, CO.

[172] Massie, D. D., Kreider, J. F., (2001), "Comparison of and discrepancies between TMY and TMY2S predictions for simple photovoltaic and wind energy simulations," Trans. ASME, 123: 6-9.

[173] Maxwell, E. L.(1998), "METSTAT- The solar radiation model used in the production of the NSRDB," Solar Energy, 62.4: 263-279.

[174] McCaskill, M. R. (1990), " Prediction of solar radiation from rain day information using regionally stable coefficients," Agric. For. Meteorol., 51:247-255.

[175] McDough, M.S., whiting, P.F., Wilson, P.M., Sutton, A.J., Chestnutt, I., Cooper, J., Misso, K., Bradley, M., Treasure, E., Kleijnen, J., 2000. Systematic review of water flouridation. Br. Med J. 321, 855- 859

[176] McGeever, B. and Thomas, T.H. (1997) Underground storage of rainwater for domestic use; including construction details of a low-cost cistern and pumps. Working Paper 49, DTU, Warwick University.

[177] McMahon, T.A. and Mein, R. (1978) *Reservoir Capacity and Yield,* Elsevier, Netherlands.

[178] McMahon, T.A., Mein, R.G. (1978), "Reservoir Capacity and Yield, developments in Water Science", Amsterdam Elsvier.

[179] McQuigg, J.D., Decker, W.L.,(1958), "Solar Energy, A summary of records at Columbia, Missouri," Mon. Agr.Exp. Sta. Bull. 671.

[180] Meinel A.B., Meinel M.P. (1977), "Applied solar energy," New York: Addison-Wesly Publ.inc.

[181] Mikkelson, P. S., Adeler, O. F., Albreshton H. J. & Henzeth.,(1999), "Collected rainfall as a water source in Danish households: What is the potential? What are the costs"? Water Science & Technology, 35(5), 49-56.

[182] Miller, G., Yu, Bofu., Gardner, T. (2003), "Rainfall catch efficiency for domestic water supply," 28th International Hydrology and water resources Symposium, Wollongong, NSW, Australia, Institution of Engineers, Australia.

[183] Mills, D., (2004), "Advances in solar thermal electricity technology," Solar Energy, Volume 76, Issue 1-3, Pages 19-31.

[184] Ministry of Urban Development and Water Supply; Government of Sri Lanka 2005.

[185] Mirandola, A., Stoppato, A., (2003), "A variable approach to the optimization of energy systems," Int J Appl Thermodyn; 6(4):157-67.

[186] Moran, P.A.P. (1978), "The Theory of Storage", London:Methuen.

[187] Mottier, V., Bucheli, T., Kobler, D., Ochs, M., Zobrist, J., Amman, A., Eugster, J., Mueller, S., Shoenenberger, R., Sigg, L., Boller, M. (1990),"Qualitative aspects of roof runoff: In: Eighth Junior European workshop-Urban Rainwater resourcefully used"; Deventer, The Netherlands.

[188] Mou,H. (1995) rainwater Utilisation for sustainable development in North China, *Waterlines*, **14** (2), 19-21

[189] Mujumdar, P.P., (2008), "Implications of climate change for sustainable water resources management in India," Physics and Chemistry of the Earth, Parts A/B/C, Volume 33, Issue 5, 354-358.

[190] Muneer, T. (2004), "Solar radiation and daylight models," 2nd ed,. Amsterdam, Elsevier Ltd, p. 36-37.

[191] Murase, M. (2003),”Promoting rainwater utilization based society for sustainable development in urban areas”. www.ircsa.org website visited on 15th Aug 2006.

[192] Mustow, S. and Grey, R. (1997) Greywater and Rainwater systems: Recommended UK Requirements. Rept. 13034, Build Services Res & Info Assoc, Bracknell.

[193] Mwenge Kahinda, J.m., Taigbenu, A.E., Boroto, J.R.,(2007), “Domestic rainwater harvesting to improve water supply in rural South Africa,” Physics and Chemistry of the Earth, Parts A/B/C, Volume 32, Issue 15-18, Pages 1050-1057.

[194] Namal, E. D., Jayasekara, C.B. (2003) “Domestic energy usage in Sri Lanka” Engineer, Journal of Institution of Engineers, Sri Lanka, vol xxxvii, No.3, pp 43-54.

[195] Ndomba, P., Mtalo, F., Killingtveit, A., (2008), “SWAT model application in a data scarce tropical complex catchment in Tanzania,” Physics and Chemistry of the Earth, Parts A/B/C, Volume 33, Issue 8-13, Pages 626-632.

[196] Nicholls, R.J., (2002), “Analysis of global impacts of sea-level rise: a case study of flooding,” Physics and Chemistry of the Earth, Parts A/B/C, Volume 27, Issue 32-34, Pages,1455-1466.

[197] Nolde E (2007) Possibilities of rainwater utilisation in densely populated areas including precipitation runoffs from traffice surfaces. Desalination 215 (1-3):1-11

[198] Nordhaus, W.D.,(1979), “The efficient use of energy resources,” Yale University Press, New Haven, CT.

[199] Norton, B., Eames, P.S., Lo, N.G.,(1998), “Full-energy-chain analysis of greenhouse gas emissions for solar thermal electric power generation systems,” Renewable Energy, 15, 131-136.

[200] Nunez, M.(1987), “A satellite-based solar energy monitoring system for Tasmania, Australia,” Solar Energy, 39: 439-444.

[201] OECD/IEA,(1998), “Benign energy? Environmental implications of renewable international energy agency,” www.iea.org.

[202] Olanike, O., et al;(2010) “ Assessing the potential of Rainwater Harvesting”, water resource manage, 24; 2129-2137.

[203] Olmo, F. J., Vida. J., Foyo, I., Castro-Diez, Y.(1999), “Prediction of global irradiance on inclined surfaces from horizontal global irradiance,” Energy. 24: 689-704.

[204] O'Neill, S.J., Hulme, M.,(2009), “An iconic approach for representing climate change,” Global Environmental Change, Volume 19, Issue 4, Pages 402-410.

[205] Pacey, A. and Cullis, A. (1986) *Rainwater Harvesting: The collection of rainfall and runoff in rural areas*. Intermediate Technology Pubs, UK.

[206] Page, J.K., (1961)., “The estimation of monthly mean values of daily total short wave radiation on vertical and inclined surfaces from sunshine records for latitudes 40^0N to 40^0S, ” paper presented at the UN conference of New sources of Energy, Rome.

[207] Paltridge, G. W., proctor, D. (1976), “Monthly mean solar radiation statistics for Australia,” Sol. Energy, 18: 235-43.

[208] Parkinson J, Schütze M, Butler D (2005) Modelling the impacts of domestic water conservation on the sustainability of the Urban seweage system. Water environ J 19 (1): 49-56

[209] Parry, M.L., Rosenzweig, C., Iglesias, A., Livermore, M., Fischer, G.,(2004), “Effects of climate change on global food production under SRES emissions and socio-economic scenarios,” Global Environmental Change, Volume 14, Issue 1, Pages 53-67.

[210] Perenc, K., Jozsef, B., Marianna, V. (2002), “Changes in solar radiation energy and its relation to monthly average temperature,” Acto Montanistica Slovaca J.,7: 164-166.

[211] Perez, R., Ineichen, P., Seals, R.(1990), “Modelling daylight availability and irradiance component from direct and global irradiance,” Sol. Energy. 5: 271-289.

[212] Perez, R., Seals, R.(1987), “A new simplified version of Perez diffuse irradiance model for tilted surface,” Sol. Energy. 3: 221-231.

[213] Pinfold, J.V., Horan, N.J., Wirojanagud, W., Mara, D., 1993. The bacteriological quality of rainjar water in rural Northeast Thailand. Water res. 27(2), 297- 302

[214] Polo, J., Zarazalejo, L. F., Ramirez, I., Espinar, B.,(2006), “Iterative filtering of ground data for qualifying statistical models for solar irradiance estimation from satellite data,” Solar Energy, 80, 240-247.

[215] Pratt, C.J., Parker, M.A. (1987), “Rainfall loss estimation on experimental surfaces”, The 4th International Conference on Urban Storm Drainage, Lausanne.

[216] Punyawardena, B.V.R., Kulasiri, D.,(1996), “Stochastic simulation of solar radiation from sunshine duration in Sri Lanka,” Centre for computing and Biometrics, Lincoln, ISSN 1173.

[217] Randel, D.L, Thomas, H., Vonder, H., Mark, A. (1996), “A new global water vapor dataset,” Bull.Amer.Meteor.Soc., 77(6):1233-1246.

[218] Raptis, F., Sachau, J., Kaspar, F.,(1995), “Assesment of the external costs of the photovoltaic and wind energy life cycle-national implementation in Germany, report, DG XII, JOULE, ISET, Kassel, Germany.

[219] Ravfeim, K.J.A.,(1981), “Estimating solar radiation income from bright sunshine records,” Quart. J.R. Met. Soc. 107, 427-435.

[220] Reddy, S. J. (1971), “An empirical method for the estimation of total solar radiation, “Sol. Energy 13: 289-91.

[221] Remund, J., Salvisberg, E., Kunz, S. (1998), “On the generation of hourly short wave radiation data on tilted surfaces,” Sol. Energy. 5: 331-344.

[222] Rianawati, E., Balasubramanian, R., (2009), “Optimization and validation of solid phase micro-extraction (SPME) method for analysis of polycyclic aromatic hydrocarbons in rainwater and storm water,” Physics and Chemistry of the Earth, Parts A/B/C, Volume 34, Issue 13-16, Pages 857-865.

[223] Richardson, C.W, (1981), “Stochastic simulation of daily precipitation, temperature and solar radiation,” water Resour. Res., 17(1): 182-190.

[224] Rimoczi-Paal, A. (1983), “Determination of global radiation from satellite pictures and meteorological data,” Solar Energy, 31: 79-84.

[225] Robledo, L, Soler, A.(1998), “Modelling irradiance on inclined planes with an anisotropic model,” Energy. 3: 193-201.

[226] Roebuck RM, Ashley RM (2006) Predicting the hydraulic and lifecycle cost performance of rainwater harvesting systems using a computer based modeling tool. In: Proceeding if the 4th International Conference on Water Sensitive Urban Design, Apr. 2-7, Melbourne, Australia, pp 699-706

[227] Roebuck, RM, 2008. A whole life costing approach for rainwater Harvesting system. Unpublished PhD Thesis, School of Engineering, design and technology, University of Bradford, Bradford.

[228] Ruíz F, Briz J (2010) Estudio de los efectos de la Azotea Ecológica Aljibe sobre el ahorro Energético. Investigación desarrollada a escala natural en un edificio experimental construido al efecto (Proyecto Módulos I) [Study of the effects of the Ecological Roof Cistern on Energy Conservation. Natural Scale investigation developed in an experimental building constructed for that prupose. (Project Module I)] INTEMPER. http://www.intemper.com/pdfDt/ProyectoModulosI_20100301.pdf. Accessed June 2010

[229] Ruiz, E., Soler, A., Robledo, L.(2002), “Comparison of Olmo model with global irradiance measurement on vertical surface at Madrid,” Energy. 27: 975-986.

[230] Rycroft, M.J., Israelsson, S., Price, C., (2000), “The global atmospheric electric circuit, solar activity and climate change,” Journal of Atmospheric and Solar-Terrestrial Physics, Volume 62, Issue 17-18, Pages 1563-1576.

[231] Sabbagh, J., Sayigh, A. A. (1977), “Estimation of the total solar radiation from meteorological data, “Sol. Energy, 19: 307-11.

[232] Samani, Z., Bawazir, A. S., Bleiweiss, M., skaggs, R., Tran, V.D.(2007), “Estimating daily net radiation over vegetation canopy through remote sensing and climatic data,” J. Irrig. Drainage Eng., ASCE, 133: 291-297.

[233] Samimi J.(1994), “Estimation of height dependent solar irradiation and application to the solar climate of Iran,” Sol Energy, 52: 5401-9.

[234] Samuel, T.D.M.A. (1991), “Estimation of Global radiation for Sri Lanka,” Solar Energy, 47(5): 333-337.

[235] Samuel, T.D.M.A., Srikanthan, R.(1982), “Solar radiation estimation for Sri Lanka,” transactions of the Institution of Engineers, Sri Lanka, pp.15-19.

[236] Sazakli E, Alexopolous A, Leotsinidis M (2007) Rainwater Harvesting, quality Assesment and Utilisation in Kefalonia Island, Greece. Water Res. 41:2039-2047

[237] Scharmer, K., Greeif, J.,(2000), “European solar radiation atlas,” Les Presses de I’Ecole des Mines, Paris, France.

[238] Schultz, R.E.,(1976), “A physically based method of estimating solar radiation

from suncards," Ibid. 16, 85-101.

[239] Sendanayake S., Miguntanna N.P., Jayasinghe M.T.R, "Predicting solar radiation for tropical islands from rainfall data" Journal of Urban and Environmental Engineering(JUEE), 2015, Vol 9, No. 2, p.109-118, ISSN: 1982-3932.

[240] Sendanayake, S. (2007), MSc. Thesis, University of Moratuwa, Sri Lanka.

[241] Sendanayake, S., "Development of an optimized integrated rainwater harvesting model for multi-storey houses"., PhD Thesis, University of Moratuwa, Sri Lanka, 2010, http://dl.lip.mrt.ac.lk/handle/123/2033.

[242] Sendanayake, S., Jayasinghe, M.T.R, "Cost effective cascading multi-tank rainwater harvesting systems for multi-storey buildings" International Journal of Advances in Engineering Research (IJAER), (2016c), Vol 11, No. 5, pp 49-55, e-ISSN: 2231-5152, p-ISSN: 2454-1796.

[243] Sendanayake, S., Jayasinghe, M.T.R, "Energy requirement of multi tank rainwater harvesting systems with uneven loading" Ideal Journal of Engineering and Applied Sciences (IJEAS), (2016d), Vol 2, No. 2, ISSN: 2067-7720.

[244] Sendanayake, S., Jayasinghe, M.T.R, "Estimation of retention volumes to mitigate overflow of rainwater harvesting systems in tropical islands" Ideal Journal of Engineering and Applied Sciences (IJSRIT), (2016g), Vol 3, No. 7, pending, ISSN: 2313-3759.

[245] Sendanayake, S., Jayasinghe, M.T.R, "Multi tank model for energy efficient rainwater harvesting" Ideal Journal of Engineering and Applied Sciences (IJEAS), (2016a), Vol 2, No. 2, pp 52-55, ISSN: 2067-7720.

[246] Sendanayake, S., Jayasinghe, M.T.R, "Performance of two tank rain water harvesting models for tropical houses" International Journal of Scientific Research and Innovative Technology (IJSRIT), (2016f), Vol 3, No. 5, pp. 92-101, ISSN: 2313-3759.

[247] Sendanayake, S., Kumara, K.J.C, "Impact of the variation of storage volumes in cascading multi-tank rainwater harvesting systems" International Journal of Advances in Engineering Research (IJAER), (2016e), Vol 12, No.1, pp. 56-64, e-ISSN: 2231-5152, p-ISSN: 2454-1796.

[248] Sendanayake, S., Kumara, K.J.C, "Optimizing the pumping requirement in rainwater harvesting systems" International Journal of Scientific Research and Innovative Technology (IJSRIT), (2016b), Vol 3, No. 7, ISSN: 2313-3759.

[249] Sendanayake, S., Miguntanna, N.P., Jayasinghe, M.T.R, "Estimating incident solar radiation in tropical islands with short term weather data" European Scientific Journal(ESJ), January 2014 edition, Vol 10, No. 3, ISSN: 1857-7881.

[250] Sendanayake, S., Miguntanna, N.P., Jayasinghe, M.T.R, "Validation of Design Methodology for rainwater harvesting for tropical climates" Asian Journal of Water, Environment and Pollution(AJWEP), Vol 11, No. 1 (2014), pp. 87-93.

[251] Short, T. D., Burton, J. D. (2003),"The benefits of induced flow solar powered wate pumps", Solar Energy, 74, Elsevier Science Ltd.

[252] Simmons, G., Hope V., Lewis, G., Whitmore, J., Wanzhen, G., 2001. Contamination of potable roof collected rainwater in Auckland, New Zealand.

Water Res. 35(6), 1518-1524

[253] Sims, R.E.H,(2004), "Renewable energy: a response to climate change," Solar Energy, Volume 76, Issue 1-3, Pages 9-17.

[254] Skinner, B. (1995) *Ferrocement water storage tanks, Sustainablity of Water & Sanitation Systems*, Proceedings of 21st WEDC conference in Kampala, WEDC, Loughborough, pp. 241-244

[255] Smit, B., Wandel, J.,(2006), "Adaptation, adaptive capacity and vulnerability," Global Environmental Change, Volume 16, Issue 3, Pages 282-292.

[256] Soga, K., Akasaka, H., Nimiya, H.(1998), "A comparison of methods to estimate global irradiance on tilted surfaces from horizontal global irradiance," J. Archit. Plann. Environ. Eng. AIJ. 512: 17-24.

[257] Spencer J.W. (1971), "Fourier series representation of the position of the sun," Search 2(s): 172.

[258] Spinks, A.T., Dunstan, R.H., Coombes, P..Kuczera, G. A. (2003),"Water quality. treatment processes and health implications of using harvested rainwater in the urban environment." In: 28th Hydrology and Water Resources symposium, Institution of Civil Engineers, Australia, Wollongong.

[259] Squires, M.F.(1995), "The demographics of worldwide weather data," ASHRAE Transactions, Vol.1, Part 1, pp. 484-490.

[260] Stanhil, G.,(1965), "A comparison of four methods of estimating solar radiation," In methodology of plant eco-physiology., pp 55-61. Proc. Montpellier Symposium, UNESCO, Paris.

[261] Stokes J, Horvath A (2006) Life cycle energy assesment of alternative water supply systems. Int J Life Cycle Assess 11(5): 335-343

[262] Stringer, E.T.,(1972), "Techniques in climatology," pp 200, W.H. Freeman and Company, San Fransisco, USA.

[263] Sturm, M., Zimmermann, M., Schutz, K., Urban, W., Hartung, H., (2009), "Rainwater harvesting as an alternative water resource in rural sites in central northern Namibia," Physics and Chemistry of the Earth, Parts A/B/C, Volume 34, Issue 13-16, Pages 776-785.

[264] Suckling, P.W.(1985), "Estimating daily solar radiation values in selected mid-latitude regions by extrapolating measurements from nearby stations," Solar Energy, 35: 491-495.

[265] Suppiah, R.,(1989), "Relationship between the southern oscillation and the rainfall of Sri Lanka," International Journal of Climatology, 9, 601 – 618.

[266] Surendran, S., Wheately, A. (1998),"Grey-water reclamation for non-potable re-use", J. CIWEM, p 406-13.

[267] Svensmark, H., Friis-Christensen, E., (1997), "Variation of cosmic ray flux and global cloud coverage--a missing link in solar-climate relationships," Journal of Atmospheric and Solar-Terrestrial Physics, Volume 59, Issue 11, Pages 1225-1232.

[268] Tabata, S. (1964), “Insolation in relation to cloud amount and sun’s altitude,” In. Yohida K., Studies on oceanography, University of Tokyo., pp.202-210.

[269] Tarpley, J.D.(1979), “Estimating incident solar radiation at the surface from geostationary satellite data,” J. Appl. Meteorol., 18: 1172-1181.

[270] Thomas, T.,(1998) “ domestic water supply using rainwater harvesting” Building research & implementation, 26:2, 94-101, ISSN:0961-3218

[271] Thomas TH, Martinson DB (2007) Roofwater harvesting: a handbook for practitioners. Technical paper series, no 49, IRC International Water and Sanitation Center Delft, The Netherlands, 160 pp.

[272] Tiwari, G.N. (2002), “Solar Energy: Fundamentals, Design, Modeling and applications,” Alpha Science Publishers.

[273] Tomas, M. (2000), “Solar Electricity,” 2nd ed. New York: Wiley. p. 5-18.

[274] Tonui, J.K., Tripanagnostopoulos, Y. (2008), “Performance improvement of PV/T solar collectors with natural air flow operation,” Solar Energy, Volume 82, Issue 1, Pages 1-12.

[275] Trenberth KE, Jones PD, Ambenje P, Bojariu R, Easterling D, Klein Tank A, Parker D, Rahimzadeh F, Renwick JA, Rusticucci M, Soden B, Zhai P, (2007) Observations: Surface and atmospheric climate change. In: Solomon S, quin D, Manning M, Chen Z, Marquis M, Averyt KB, Tignor M, Miller HL (eds) Climate Change 2007: the physical science basis. Contribution of working group I to the Fourth Assessment Report of the Intergovernmental Panel on climate Change. Cambridge University Press, Cambridge, p238

[276] Tsoutsos, T., Frantzeskaki, N., Gekas, V. (2005), “Envirnmental impacts from the solar energy technologies”, Elsevier, Energy Policy 33: 289-296.

[277] Tsur, Y., Zemel, A.,(1992), “Stachastic energy demand and the stabilization value of energy storage,” Natural Resource Model, 6,435.

[278] Turner, W.D., Abdulaziz, M. (1984), “The estimation of hourly global solar radiation using a cloud cover model developed at Blytheville, Arkansas,” J. Appl. Meteorol., 23: 781-786.

[279] UN (2010) World Urbanization prospects: the 2009 revision. Http://esa.un.org/unpd/wup/documents/WUP2009_Highlights_Final.pdf. Accessed May 2010.

[280] UN- HABITAT (2005) Blue drop series on rainwater harvesting and utilisation. UN- HABITAT, Nairobi, Kenya, ((2006) Meeting development goals in small urban centres-water and sanitation in the world cities 2006)

[281] UNEP (2002) Rainwater harvesting and Utilisation; an environmentally soundly approach for sustainable urban water; an introductory guide to decision makers. http://www.unep.or.jp/Ietc/Publications/Urban/UrbanEnv-2/index.asp. Accessed Mar 2010.

[282] United Nations 2008. World Urbanisation Prospects. The 2007 Revision. Highlights. Http://www.un.org/esa/population/publications/wup2007/2007WUP_Highlights_

web.pdf(Accessed 8.02.10).

[283] United Nations Environmental Program-DTIE-EITC/Sumida City Government/People for promoting rainwater utilization (2002), “Rainwater harvesting and utilization, an environmentally sound approach for sustainable urban water management”, An Industry guide for decision makers, United Nations water resources series, No.63

[284] United Nations Population Fund (UNPFA) (2008) State of the world population, culture, gender and human rights, UNPFA,108 pp

[285] Vaes, G., Berlamont, J., 1999. The impact of rainwater reuse on CSO emissions. Water Sci. Technol. 39(5), 57-64.

[286] Vairavamoorthy, K., Gorantiwar, S.D., Pathirana, A.,(2008), “Managing urban water supplies in developing countries - Climate change and water scarcity scenarios,” Physics and Chemistry of the Earth, Parts A/B/C, Volume 33, Issue 5, Pages 330-339.

[287] Vale, R., Vale, B. (1995),”Water and sewage treatment in the autonomous house”, Plumbing magazine, NSW, Australia, p17-19.

[288] Van Beers D, Bossilkov A, van Berkel R. A regional approach to advance sustainable water use: a case study using kwinna(Western Australia) Australasian journal of Environmental Management 2008:15(3) 149-58

[289] Villareal, E.L., Dixon, A. (2004), ”Analysis of a rainwater collection system for domestic water supply in Ringdansen, Norrkoping, Sweden”, Building & Environment, 40, Elsevier Ltd.

[290] Villarreal EL, Dixon A (2005) Analysis of rainwater collection system for domestic water supply in Ringdansen, Norrkoping, Sweden. Build Environ 49(9):1174-1184

[291] Vivian,W, Y, (2010), “Cost effectiveness& trade off on the use of rainwater tank: Am empirical study in Australian residential decision-making” Resources, conservation & recycling: 54: 178-186

[292] Waldau, A.J., PV status report 2005, EUR 21836 EN, 2005.

[293] Walsh, H. (1999), Private communication. Environment agency.

[294] Ward, S., 2010. Rainwater harvesting in the UK.: a Strategic framework to enable transition from novel to mainstrean. Publish PhD thesis, University of Exeter. Available at Http://hdl.handle.net/10036/106575 (accessed 20.07.10)

[295] Ward, S et al, (2012) “Performances of a large building rainwater harvesting system” Water research, V 46, 5127-5134.

[296] Wenxian, L., Wenfeng, G., Shaosuang, P., Enrong, L. (1995), “Ratios of global radiation on a tilted to horizontal surface for Yunan province, China,” Energy.8: 723-728.

[297] Wheeler D and Lloyd B.j. (1983) An investigation of some microbiological and physio-chemical aspects of rainwater harvesting, A report commissioned by the intermediate Technology Development Group, University of Surrey, England.

[298] White S, Campbell D, Giurco D. Caroline S, Kazaglis A, Fane S, Deen A, Martin J. Review of the Metropolitan water plan; final report, Institute for Sustainable futures, Sydney, ACIL Tasman and SMEC Australia: 2006

[299] White, G.F., Bradley, D. J. and White A. U. (1972) *Drawers of Water: Domestic water use in East Africa*, University of Chicago Press, Chicago

[300] WHO, Eastern Mediterranean Regional Office, Center of Environmental Health Activities, Guidelines on Technology for Water Supply Systems in Small Communities, CEHA Document No. TLM-05, Amman, 1993.

[301] Wijayatunga, P.D.C., Fernando, W.J.L.S. (2003), "Greenhouse gas emission mitigation in the Sri Lanka power sector supply side and demand side options". Pergamon, energy conversion and management.

[302] Xanthapoulas, C., Hahn,H. (1994), "Priority pollutants from urban storm water runoff In to the environment". Journal of European Water Pollutions Control, 4(5); 32-41.

[303] Y. Okada, Y., Yamamoto, A., Takamoto, T., Araki, K.,(2008), "Novel materials for high-efficiency III-V multi-junction solar cells," Solar Energy, Volume 82, Issue 2, Pages 173-180.

[304] Yaziz MI, Gunting H, Sapari N, Ghazali AW. Variations in Rainwater quality from roof catchments. Water Research 1989;23:761-5

[305] Zaizen M, Urakawa T, Matsumoto Y, Takai H (1999) The collection of rainwater from dome stadiums in Japan. Urban Water 1 (4): 335-359

[306] Zhang, D. Gersberg, RM, Wilhelm, C., Voight, M., 2009. Decentralized water management: Rainwater harvesting and greywater use in an Urban area of Brijing, China, Urban Water 6 (5) 375-385

[307] Zhang, Y., ChenD., Chen, L., Ashbolt, S., 2009. Potential for Rainwater use in highrise buildings in Australian cities. J. Environ. Manage. 91, 222-226

[308] Zhou, J., Yezheng, W. (2005), "General formula for estimation of monthly average daily global solar radiation in China," Energy Conversion Manage., 46: 257-68

[309] Zhu K, Zhang L, Hart W, Liu M Chen H (2004) Quality issues in harvested rainwater in arid and semi arid Loess Plateau of Nothern China. J Arid Environ 57(4):487-505

[310] Zobrist, J., Muller, S.R., Amman, A., Bucheli, T. A., Mottier, V., Ochs, M., Shoenenberger R., Engster, J., Boller, M. (2000), "Quality of roof run-off for Ground water infiltration", Water Resources, vol.34, No.5, pp 1455-1462.

[311] Bandara, M.A.C.S, "Analysis of quality & consumer preference for harvesting rainwater in Anuradhapura District"

[312] N. Alpaslan, N.B. Harmancioglu and V.P. Singh, Hydrol. J. IAH, 15 (1992)1-13,

[313] An introduction to rainwater harvesting-general description. Global Development Research Center, Osaka, Japan, 2002.

[314] Factsheet on sanitation, guideline for drinking-water quality, WHO/UNICEF

[315] UN World water Development Report (WWDR 2003)

[316] Kalika, M., 2005, City of Flows; Modernity, Nature and the city. Routledge. Taylor and Francis Group, New York.

[317] Vásquez, A., Costoya, M., Pena, R.M., Garcia, S., Herrero, C., 2003. A rainwater quality monitoring network: a preliminary study of the composition of rainwater in Galicia (NW Spain). Chemosphere 51, 375-386.

[318] Zaizen, M., urakawa, T., Matsumoto, Y., Takai, H., 1999. The Collection of rain water from dome stadiums in Japan. Urban water 1, 355-359.

[319] Konig, KW (2001) The rain water technology handbook: rain water harvesting in building. Wilo-Brain, Dortmund

[320] Falkenmerk & Lindt, Impacts, Adaptation and Vulnerability (UNDP/WMO) 2009

[321] Vaes, G., Berlamont, J., 1999. The impact of rainwater reuse on CSO emissions. Water Sci. Technol. 39(5), 57-64.

[322] Spinks, A. T. , Coombes, P., Dunstan, R.H., Kuczera, G., 2003. Water quality systems. In: proceedings of the 28th International Hydrology and water Resources Symposium, November 10-14, Wollongong, Australia

[323] Terpstra, P.M.J., 1998. Sustainable water usage systems: Models for the sustainable utilization of domestic water in urban areas. In: Proceedings of the International WIMEK Congress for closed water systems, Sustainable water management, March 11-13, Wageningen, The Netherlands.

[324] Evans, C.A., Coombes, P.J., Dunstan, R.H., 2006. Wind, rain and bacteria: the effect ofweather on the microbial composition of roof harvested rainwater. Water Res. 40 (1), 37-44

[325] Evison, L., Sunna, N., 2001. Microbial regrowth in household water storage tanks. J Am. Water Works Assos. 93 (9), 85-94.

ABOUT THE AUTHOR

Sisuru Sendanayake **Ph.D**

Sisuru Sendanayake is the Dean, faculty of engineering of South Asian Institute of Technology and Medicine (SAITM), Sri Lanka. He is a graduate of University of Moratuwa, Sri Lanka with B.Sc. Honors in Mechanical Engineering and later went onto obtain M.Sc. and Ph.D degrees also from University of Moratuwa.

Prior to entering academia, he had been a career engineer with extensive industry exposure, working at John Keells Holdings and Link Engineering as well as a consultant on machinery and equipment for local and foreign projects. He was also the Chairman of Bureau of Information Technology Education (BITE), a BOI company established in collaboration with the Ministry of Industries in Sri Lanka to propagate IT education in the provinces.

He has research interests in the diverse areas of solar power, rainwater harvesting, sustainable development, advanced materials and modern manufacturing.