Rainwater Storage Systems and Household Agriculture for the Sustainable Provision of Food & Water in Developing and Developed Countries

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BTech (Civil), BEng Hon class 1 (Civil)

A thesis submitted in fulfilment of the requirement for the degree of

Doctor of Philosophy

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February, 2021

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Statement of authentication

This thesis contains no material that has been accepted for the award of any other degree or diploma and that, to the best of my knowledge and belief, this thesis contains no material previously published or written by another person, expect when due reference is made in the text of this thesis.

Signature ....[redacted].. **Date** ...2.../...2.../...2021

Dedication

I dedicate this work to God: Father, Son and Holy Spirit, Mysteriously One God even as light is both particle and wave simultaneously, yet one light; to the thirsty and hungry in body, soul and spirit throughout the world, and to my family and friends. May we all play our part in helping others experience a taste of a paradise lost in anticipation of finding it renewed in the world to come.

"And he shewed me a ***pure river of water of life, clear as crystal,*** *proceeding out of the throne of God and of the Lamb. In the midst of the street of it, and on either side of the river, was* ***there the tree of life, which bare twelve manner of fruits, and yielded her fruit every month: and the leaves of the tree were for the healing of the nations****."*

Revelations 22: 1, 2 (emphasis mine)

Acknowledgements

I acknowledge God at the first and last who has given us air to breath, water to drink, and food to eat. I also acknowledge my own sin and corruption, which many times has led to the hurt of others or caused me to be ineffective or negligent when I could have done something good, something better. I thank my old man, Keith Mitchell for his patient proof reading and correction of my could-be-better English. I thank my wife, family and friends for their continued support and patience.

I acknowledge the financial support by Western Sydney University, and thank my supervisors. Particularly I would like to give a special thanks to my principal supervisor, the now professor, Ataur Rahman for his continued support, enthusiasm and timely guidance during this project. I would also like to congratulate him on the professorship which he received, and thank him for the friendship which we have developed through our many conversations since he first taught me as an undergraduate in 2003. I also thank my co-supervisors, Associate Professor Ming Zhao (WSU), and other staff and co-research students at WSU who have offered their advice and guidance in many and various ways.

I would like to thank my co-supervisor Professor John Gathenya Jomo Kenyatta university of Agriculture and Technology (JKUAT), Nairobi Kenya. I would like to thank the Commonwealth Scientific and Industrial Research Organisation (CSIRO) for their official affiliation during this study and for my co-supervisor, Dr Fazlul Karim of CSIRO. I would like to thank Klaus Joehnk (my team leader at CSIRO), Danial Stratford, and Mohammed Mainuddin at CSIRO Land and Water. I would also like to thank may others at CSIRO who have given me valuable insight to professional research standards. I would also like to thank my other co-authors who have provided valuable insight working side by side. Eran Friedler of Technion Israel Institute of Technology, Andre Renzaho and Isaac Lynes of Western Sydney University, Mahin Al Nahian and Ali Ahmed of International Centre for Diarrhoeal Disease Research, Bangladesh (icddr,b), and Dr Amir Ahmed of Daffodil university, Bangladesh All deserve special mention. I would also like to thank the many anonymous reviewers for their constructive comments and suggestions, their value in helping improve the quality of my work cannot be ignored.

I would also like to thank the many people and communities who have welcomed me and shared wonderful insights into the reality of what is happening from day to day in their communities. The Kayole Mtaa Safi Initiative (www.kayolemtaasafi.weebly.com) and the people of Kayole, a suburb in Kenya's capital are acknowledged for the time spent with them and the knowledge learned. I would like to thank Peder Pedersen of The Charitable Foundation (TCF) (www.thecharitablefoundation.org) for putting me in touch with Sotheycan (www.sotheycan.org) and others. I would also like to thank Cassandra Treadwell, Keri Chittenden, and particularly James Wabara of sotheycan for answering my many pestering questions about Miti Mingi Village, Nakuru, Kenya. In Bangladesh Dr. Md. Sabur Khan, Hon'ble Chairman of Daffodil International University for his kind support in DIU, Dr. Kazi Ali Azam, former Additional Chief Engineer of Dhaka's Water Supply and Sewerage Authority, Engr. A H M Kausher, Former Chief Engineer of Bangladesh's Water Development Board, Mahin Al Nahian, and Ali Ahmed of icddr,b deserve a special mention for their support and valuable insights into water related health issues in the coastal regions of Bangladesh. The Institute for Coastal Development ICD and its founder Asikuzzaman deserve special mention for help in local arrangements and for their enthusiasm for the seminar held there. I would also like to thank Darimi Barshat from North South University for helping in translating and transcription from Bengali to English. I would also like to acknowledge the Local people of Koyra who welcomed me with such enthusiasm.

Engineers without Borders (EWB) Australia are thanked for the valuable insights I learned from them about international work and in helping me make my research applicable at the ground level. Particularly I would like to thank Anna Cain who worked with me in establishing a university EWB chapter, and consequently a staff and alumni based EWB advisory panel at Western Sydney University. At the time of writing she was residing on the *front line* in Cambodia working as a clean energy entrepreneurship mentor for EnergyLab. I

also thank Dr Ee Loon Tan for working with me in establishing the club and who runs the EWB challenge at Western Sydney University. Other Staff and students are also to be acknowledged but are too many to mention here.

I acknowledge the Meteorology Bureaus of Australian, Bangladesh, and Kenyan for providing rainfall and climate data. Also, the NASA Langley Research Center POWER Project funded through the NASA Earth Science Directorate Applied Science Program, the climate hazard group for their Climate Hazards Group InfraRed Precipitation with Stations (CHIRPS) data, and SILO Data for providing the same. The Water Development and Management Unit and the Climate Change and Bioenergy Unit of FAO is acknowledged for their provision of data through the software CLIMWAT. Queensland Department of Environment and Science (DES), the Queensland Government and the Australian Bureau of Meteorology (BoM) sponsored by the Land and Water Resources Research and Development Corporation, are acknowledged for the provision of SILO climate data for Australia. Sydney Water, and other organisations for sharing their water use and price data.

List of Papers made from this study

Following is a list of publications made from this study which may be accessed via the following author profiles:

- ORCID:

  https://orcid.org/0000-0003-3387-2107

- Google Scholar:

  https://scholar.google.com.au/citations?user=WCmrvh8AAAAJ&hl=en

- Publions (also includes verified peer work for high quality Journals)

  https://publons.com/researcher/3474884/caleb-amos

- Web of Science ResearcherID:

  AAH-9697-2020

The papers may be available as preprint versions, etc. as appropriate to the publisher's conditions, from the following repositories:

- WSU repository: https://researchdirect.westernsydney.edu.au/
- CSIRO repository: https://publications.csiro.au/publications/

Scholarly book chapters (peer reviewed)

1. Amos, C.C., Lyne, I., Rahman, A. (2021) Harvested Rainwater as a Solution for Marine Pollution and Contaminated Groundwater, In: Encyclopedia of the UN Sustainable Development Goals, UN SDG: 6, Editor-in-chief: W. Leal Filho, Springer Nature

Refereed journal articles (ERA ranked/ISI listed journals)

1. Amos, C. C., Rahman, A., Karim, F., Gathenya, J.M. (2018). A Scoping Review of Roof Harvested Rainwater Usage in Urban Agriculture: Australia and Kenya in Focus, Journal of Cleaner Production, 202, 174-190. [**Impact factor: 6.395, SJR Quartile: Q1]**

2. Amos, C. C., Rahman, A., Gathenya, J.M. (2018). Economic analysis of rainwater harvesting systems comparing developing and developed countries: A case study of Australia and Kenya, Journal of Cleaner Production, 172, 196-207. [**Impact factor: 6.395, SJR Quartile: Q1]**

3. Amos, C. C., Rahman, A., Karim, F. (2019). The Influence of Irrigation Area and Roof Size on the Economics of Rainwater Harvesting use in Urban Agriculture: A Case Study in Sydney, Australia, International Journal of Engineering, Construction and Computing (IJECC), 48-58. **[Peer reviewed]**

4. Amos C.C., Amir, and Ataur Rahman A. (2020). Sustainability in Water Provision in Rural Communities: The Feasibility of a Village Scale Rainwater Harvesting Scheme, Water Resources Management. **[Impact factor: 2.644, SJR Quartile: Q1]**

5. Amos, C. C., Rahman, A., Gathenya, J.M., Friedler, E., Karim, F., Renzaho A. (2020). Roof Harvested Rainwater use in Household Agriculture: Contributions to the Sustainable Development Goals, Water: an open access journal. **[Impact factor: 2.52, SJR Quartile: Q1. Awarded "Editor's Choice" (https://www.mdpi.com/journal/water/editors_choice)]**

Full length refereed conference papers

1. Amos, C.C., Rahman A., Karim, F. (2017). As Impact of Residential Irrigation Area and Roof Size on the Economics of Rainwater Harvesting Systems, Proceedings of the 1st International Conference on Water and Environmental Engineering, pp. 7-14, 20-22 Nov 2017, Sydney, Australia.

2. Amos, C.C., Rahman, A., Karim, F., Gathenya, J.M. (2019). Sustainable Development: Economic and Feasibility Analysis of Roof Harvested Rainwater Use in Urban and Peri Urban Agriculture Comparing Developed and Developing Nations, 1st International Conference on Sustainability in Natural and Built Environment (iCSNBE-2019), 19-23 January 2019, Dhaka, Bangladesh, 4 pp.

3. Amos, C. C., Rahman, A., Karim, F. ,Gathenya, J.M., Friedler, E. (2019) Addressing the Sustainable Development Goals: Roof Harvested Rainwater use in Household & Village Agriculture for Increased Nutrition and Education in Developing Nations: A Case Study of a Kenyan Orphanage, Proceedings of the International Conference on Advancements in Engineering Education (iCAEED-2019), 24-28 Nov 2019, Sydney, Australia.

4. Amos, C. C., Rahman, A., Gathenya, J.M., Friedler, E., Karim F., A. Renzaho (2020) Improving Household Agriculture with Roof-Harvested Rainwater: Towards building resilience for food security and nutrition through sustainable housing practices. Sustainable Research and Innovation (SRI) Conference, Main Campus, Jomo Kenyatta University of Agriculture and Technology, Nairobi, Kenya. **[Accepted but subsequently cancelled due to the coronavirus]**

Extended abstract refereed conference papers

1. Amos, C.C., Rahman, A., Karim, F., (2020) Roof Rainwater Harvesting System: A Sustainable Tool for Clean Water Provision in Rural Area, International Conference on Resource Sustainability, June 30-July 2, 2020, University College Dublin, Dublin, Ireland.

Other publications indirectly related

The following papers and book chapter contribution were published as a direct result of the PhD. They also include an understanding of the need for Engineering to embrace a more integrated approach to learning and this is particularly relevant in addressing the sustainable development goals. They may be accessed via the author profiles and repositories mentioned above.

1. **Book Chapter Contributions:** Rahman, T., Amos, C.C., Rahman, A. (2018). Upgrading Australian engineering curriculum to enhance communication skills of engineering students. In: Blended Learning in Engineering Education: Recent Developments in Curriculum, Assessment and Practice, CRC Press (Taylor & Francis Group), edited by A. Rahman and V. Ilic, 26 pp.

2 **Full length refereed conference paper:** Amos, C., Rahman, A., Karim, F., Gathenya, J. (2018). Teaching and learning aspects of literature review as a component of Doctoral study: A case for Western Sydney University, International Conference on Advancements in Engineering Education (iCAEED-2018), 03-06 Dec 2018, Sydney, Australia, p. 38-43.

3. **Full length refereed conference paper:** Rahman, T., Amos, C., Rahman, A. Writing of a higher degree research thesis: perspectives of a student, supervisor and thesis, International Conference on Advancements in Engineering Education (iCAEED-2018), 03-06 Dec 2018, Sydney, Australia, p. 146-150.

4. **Full length refereed conference paper:** Rahman, T., Amos, C.C., Rahman, A. (2016). How to Enhance Technical Writing Skills of New Generation Engineering Students? In Proc. International Conference on Engineering Education and Research, 21-24 Nov 2016, Sydney, Australia.

Preface

I began this thesis shortly after returning from six months stay in Kenya working alongside underprivileged Kenyans who lack basic infrastructure, and consequently health. Ironically, we had arrived the day before the then American President, and we left the day before the arrival of the Pope of Rome, which squarely fixes our time there. My experiences in Kenya helped cement my understanding of the need for adequate food and water provision, and ideally infrastructure. Much of our time was taken up bucketing water and carrying it upstairs to ensure we had enough to clean our hands, flush the toilet adequately, and do our laundry. Food was available at local markets, but was quite restrictive in terms of variety, and cost is prohibitive to many people.

The recent Coronavirus has been the feature in world news that marks the final stages of writing this thesis and I am now living in relative isolation completing the final touches and reflecting on the work. Although the virus sadly hindered my attendance at a conference in Kenya where I hoped to promote the work and further its impact, being isolated to complete the work is really a blessing in comparison to the troubles it has and will cause others. The virus serves as a case in point for this study that focuses on household agriculture and rainwater harvesting systems. While on the one hand gardening can be a very social pastime, on the other hand in times of necessity it will only advantage a household to have access to some fresh fruit and vegetables at home. This could help minimise contact with others when purchasing supplies and particularly of fresh fruit and vegetables which are handled by staff before being purchased.

Another recent milestone in history that recently, that should be a starting point for philosophical thinking and reflection, is the 50th anniversaries of the circumnavigation of the moon and subsequent landing in Dec 1968 and July 1969 respectively. For me these have a personal relevance. Space and rockets are a dream for any young boy, and I was no exception. In my childhood I dreamed of being an astronaut working for NASA, and this dream guided my early decisions to study Physics and Astrophysics at Cardiff University in

Wales whilst at the same time perusing physical fitness through athletics. Having taken a gap year, which turned into two, I travelled extensively first to Australia from the UK and then through South East Asia, China and through Russia and Mainland Europe. More importantly during this time I became a student of the Judeo-Christian Scriptures and came under the influence of the teachings of Jesus. This made it increasingly more difficult to be content with just travelling and sightseeing, when many of those sights included people living in extreme poverty. Particularly the famous passages of Jesus came to mind,

"Thou shalt love the Lord thy God with all thy heart, and with all thy soul, and with all thy mind. This is the first and great commandment. And the second is like unto it, Thou shalt love thy neighbour as thyself. On these two commandments hang all the law and the prophets."

Matthew 22:37-40

also, the Beatitudes, which form the opening part of what is arguably Jesus' most famous teaching, the Sermon on the Mount (Matthew Chapters 5-7),

"Blessed are the poor in spirit: for theirs is the kingdom of heaven.
Blessed are they that mourn: for they shall be comforted.
Blessed are the meek: for they shall inherit the earth.
Blessed are they which do hunger and thirst after righteousness: for they shall be filled.
Blessed are the merciful: for they shall obtain mercy.
Blessed are the pure in heart: for they shall see God.
Blessed are the peacemakers: for they shall be called the children of God.
Blessed are they which are persecuted for righteousness' sake: for theirs is the kingdom of heaven."

Matthew 5:3-10

My eyes ceased to gaze into space so much and increasingly I became more aware of the needs "down here". To cut a long story short this eventuated in me leaving Astrophysics and later taking up Civil Engineering as a more down to earth pursuit. So, it is with great joy that I have been able to commit my research time to doing a doctorate that is focused on these two very pressing areas of need in the world today: Food and Water. And the timing could not have been better as universities and research organisations around the world sign agreements to teach the sustainable development goals (SDGs).

The readings from the Apollo 8 astronauts in the first manned circumnavigation of the moon, and the reading aloud of the opening verses of Genesis (King James Version) by the astronauts Anders (verses 1-4), Lovell (verses 5-8), and Borman (verses 9-10), can give us a glimpse the significance of our planet (Oliver 2013). The transcript was as follows.

William Anders

"We are now approaching lunar sunrise, and for all the people back on Earth, the crew of Apollo 8 has a message that we would like to send to you.

> *In the beginning God created the heaven and the earth. And the earth was without form, and void; and darkness was upon the face of the deep. And the Spirit of God moved upon the face of the waters.*
>
> *And God said, Let there be light: and there was light. And God saw the light, that it was good: and God divided the light from the darkness"*

James Lovell

> *"And God called the light Day, and the darkness he called Night. And the evening and the morning were the first day.*
>
> *And God said, Let there be a firmament in the midst of the waters, and let it divide the waters from the waters. And God made the firmament, and divided the waters which were under the firmament from the waters which were above the firmament: and it was so. And God called the firmament Heaven. And the evening and the morning were the second day."*

Frank Borman

> *And God said, Let the waters under the heaven be gathered together unto one place, and let the dry land appear: and it was so. And God called the dry land Earth; and the gathering together of the waters called he Seas: and God saw that it was good.*

And from the crew of Apollo 8, we close with good night, good luck, a Merry Christmas – and God bless all of you, all of you on the good Earth”

To many people this highlights the uniqueness of the earth in the universe, as you can imagine that the Astronauts felt as they watch the earth coming into view.

Earthrise, a colour photograph of the Earth and Moon by William Anders (Anders 1968)

Indeed, the moon, in the foreground, lacks the three things basic to mankind’s existence: Food, Water and Air. This image itself should put things in perspective and cause us to question, what are we doing down here? It should be an encouragement that we have achieved the unachievable, what wolf howling at the moon could ever hope to reach it, let alone land there and receive communion as Buzz Aldrin did (Oliver 2013)? The encouragement should be that having achieved the unachievable up there we should set our focus on achieving the unachievable “down here”: adequate food and water for all! At the beginning of the space race there was a perception that the aid program could not be used as a satisfactory substitute race with Russia (Rechtin 1959). That was a shame, and perhaps if it had been, then that good will may have reaped abundant fruit in international relations and the world would be at a greater state of peace and health than it is today.

I am glad that the universities have started to play more of a role in the realisation of these goals and I can only hope that this will increase. There is a real opportunity for good research to be done that can benefit developing nations while simultaneously improving the quality of research conducted at the universities. Much like the “space race” this challenge needs to be met with a multidisciplinary effort. In fact, the challenge may be even more multidisciplinary as it has a large social aspect, which the moon is missing – a world population of approximately 7 billion people! A recent Engineers Australia Create Magazine featuring Dr Pablo Juliano’s work at CSIRO emphasises the roll that engineers can play in improving food security (Balinski 2020).

Engineers without Borders (EWB) - Australia, founded in Australia inspired by the international organisation founded in Canada, is aware of the need for a multidisciplinary and broad ranging approach. Having first heard of EWB in Kenya, most likely the UK or American Branch, when I returned to Australia, I became involved with them in Sydney. Finding that there was no club in Western Sydney University I founded a university “chapter” with support from others, notably Anna Cain, the then NSW chapter president, and Ee Loon Tan, a pro-active WSU Lecturer who was already running EWB Challenge as part of the engineering degree. Realising the issue with student leaders only serving for one or two years, to help the EWB university chapter grow in strength, I established a predominantly staff and alumni based “EWB WSU Advisory panel” to help guide the chapter and advise and train student leaders. It is my hope that EWB at WSU will be a training ground and an encouragement for Engineers to engage with the major challenges facing us today, and particularly with the provision of safe food and water. I also hope that given the location in the West of Sydney that the club will engage with the local refugee population, acknowledging also the insights that they can give the sheltered Australian engineer to the real world out there in developing countries that lack stable governments, good infrastructure and consequence food and water. I am glad to have been able to be involved in this, it helps to make my point that research needs to also be involved and engaged to be in touch with reality and the needs of society.

A final milestone for me during this thesis has been the birth of my fourth child. A great joy, and I can only hope that children the world over can experience the provisions he is able to experience here in Australia. It is my understanding that equality can only be realised by sharing as one person differs from the next in both natural and acquired abilities and assets: the strong need to help the weak, the intelligent need to help the disadvantaged, the rich the poor, and so on. To those who have laboured through this preface, may you find the grace to be merciful in reflection of The Father, Who sends His rain on the just and on the unjust (Matthew 5:45).

Abstract

Food and water are at the heart of every community, form significant aspects of cultural identity, and must be in good supply for healthy and sustainable development. Not surprisingly, food and water feature directly as part of the recent UN sustainable development goals (SDGs) as Goal 2, Zero Hunger, and Goal 6, Clean Water and Sanitation. Household agriculture (HA) and rainwater storage systems (RSS) have grown in popularity in recent years and have the potential to increase yields and supplement household nutrition. Yet there is a significant lack of research into this potential. Domestic RSS studies usually focus on water savings rather than on crop production. There is also little research on the economic analysis of RSS systems in developing countries where home gardens often fail due to insufficient rainfall and water supply. Promoting green cities in general, begs the question of whether there is enough water available to support it. The recent COVID-19 crisis and keeping safe by isolation at home only strengthens the argument for HA. This study investigates the potential of using RSS in water, sanitation and hygiene (WASH) and particularly for HA. It also looks at economic issues associated with RSS, which are particularly relevant to developing countries. The work focuses mainly on Australia, Bangladesh, and Kenya, but is relevant to most other regions.

An economic analysis tool, called ERain, was developed to combine daily performance analysis of RSS with life cycle cost analysis for use in economic evaluation. ERain provides a realistic framework for establishing sustainable RSS solutions. ERain analyses detailed daily climate data to evaluate evapotranspiration and calculate expected irrigation demand for agricultural production. The relationship between the benefit cost ratio (BCR), net present value (NPV), reliability and efficiency (the percentage of available water used) are discussed. It is found that there is a considerable potential to supply water for both WASH and HA using RSS.

RSS systems in Kenya are found to be economically beneficial, if installed without reticulation. The recent tendency towards smaller tanks in Australia is shown to be a poor

choice economically. For tank sizes ranging from 1-7 kL results show that excluding outdoor use, the benefit cost ratio (BCR) increases with roof size along with reliability, while efficiency decreases. Interestingly, the larger roof area has the most significant effect in terms of reliability on the smaller tanks. Including outdoor use reduces reliability overall but increases both the efficiency and BCR indicating that it is better financially to use the RWH system for outdoor use when reliability is not a concern (e.g. mains top up is connected). The larger NPVs and BCRs occur with the larger irrigation areas as this increases water use and hence monetary water savings. Within the 1-7 kL tank range, the 7 kL tank is the most favourable when outdoor irrigation use is connected. However, in Kenya, reliability is found to be a financial issue as alternative sources are expensive, and connecting outdoor use is not economically beneficial when the value of crop production is excluded.

High annual rainfall in monsoonal delta regions surrounded by saline and, or arsenic contaminated groundwater makes rainwater harvesting attractive. Village scale rainwater harvesting plants for a cluster of houses consisting of 100 or so families are proposed. It was found that a village treatment plant with RSS 3 m deep 100 m by 100 m could supply 100 L/p/d for 85% of the year whilst simultaneously being the catchment. Their capacity and feasibility are compared with systems for individual houses. Advantages of the village scale include the opportunity for improved management and water quality monitoring, and the potential for public-private partnerships. One advantage of the individual household scale is access to water at home during the wet season when it is difficult to travel, but cost is restrictive.

A socio-economic context is built around Miti-Mingi orphanage in the semi-humid region of Nakuru, Kenya. Comparisons are made with the semi-arid region of East Pokot. A 225 kL closed masonry tank and a 1 ML open reservoir with an additional 8 kL/day of recycled water entering are analysed for various roof sizes. The 225 kL RSS connected to 1000 m^2 of roof and irrigating 1000 m^2 could increase yields from 1850 to 4200 kg/year in Nakuru.

Overall results highlight the need for innovation, and reduction in capital and on-going costs associated with RSS. This is in preference to increasing the price of water to increase their economic viability. In developing countries, particularly among the poor, RSS will generally require external financing, either by NGO or government support. RSS can have a considerable impact on increasing HA and food production and hence nutrition, particularly of women and children and may also contribute to household finances. The findings of this study, and the consequent publications are intended to serve as a key reference on modelling and economic aspects of RWH in urban agriculture and greening of cities. They are expected to be useful to modellers and researchers, water engineers, environmentalists, town planners, and policy makers concerned with sustainable development and dealing with integrated water management and the water-energy-food-ecosystem nexus by bringing together knowledge gaps and potential solutions. It is hoped that the challenge of providing food and water for all be met with the same vigour as was the space race, circumnavigation of and landing on the moon.

Keywords

- Sustainable development goals (SDGs); water, sanitation and hygiene (WASH); socioeconomics; developing countries; urban; village; delta regions; Australia; Bangladesh; Kenya;
- Household agriculture (HA); urban agriculture (UA); evapotranspiration; irrigation scheduling, crop yield;
- Rainwater storage systems (RSS); rainwater harvesting (RWH); rainwater tank; tank size; roof area; village scale schemes;
- Drinking water; agricultural water uses from harvested rainwater;
- Economic analysis; modelling.

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Abbreviations

AS/NZS	Australian/New Zealand Standards
AQUACROP	Software that simulates crop production under different irrigation regimes produced by FAO
BASIX	Building and sustainability index
BCR	Benefit Cost Ratio
BOM	Bureau of Meteorology
BOQ	Bill of quantities
CF	Cash flows
CROPWAT	Crop production simulation software uses soil, climate and crop data to calculate crop water and irrigation requirements on a monthly basis produced by FAO
CSIRO	Commonwealth Scientific and Industrial Research Organisation
Ecotopes	Areas with same physical and socio-economic characteristics
ERain	Economic tool developed in FORTRAN and R-Script as part of this study
ET	Evapotranspiration
FAO	Food and Agricultural Organization
GFC	Global financial crisis
GR	Green roofs
GWR	Ground water recharge
HA	Household agriculture

IJECC	International Journal of Engineering, Construction and Computing
INEA	Italian Institute of Agricultural Economics
IWM	Integrated water management
JKUAT	Jomo Kenyatta University of Agriculture and Technology
JKUAT-RWH	Performance Calculator Software developed by JKUAT - a daily time-step model using daily rainfall data to analyse various configurations of RWH systems.
LC	Levelised cost
LCC	Life cycle cost
LCCA	Life cycle cost analysis
MDGs	Millennium development goals
NASA	National Aeronautics and Space Administration
NPV	Net Present Value
NSW	New South Wales, Australian state
PP	Payback period
PV	Present value
RSS	Rainwater storage systems
RWH	Rainwater harvesting
RWT	Rainwater tank
SIR	Supplementary irrigation requirements
SF	Storage fraction

SUD	Sustainable urban design US equivalent to WSUD
TRMM	Tropical Rainfall Measuring Mission
UNESCO	United Nations Educational, Scientific, and Cultural Organization
VGMS	Vertical greenery modular systems
WASH	Water, sanitation and hygiene
WSUD	Water sensitive urban design
SDGs	Sustainable development goals
UA	Urban agriculture
YAS	Yield after spillage
YBS	Yield before spillage
ZFarming	Zero acreage farming

Chapter 1
Introduction

Chapter 1 Introduction

1.1 Overview

In this chapter a brief background is given followed by an outline of the research questions which were addressed in this study. A summary of the research undertaken is then given followed by an outline of communities engaged, the relevance of the work, and whom it is intended to impact. Finally, a brief outline of each chapter in the thesis is presented.

1.2 Background

The need to supply food and water is as ancient as history itself. Cultures can often be identified by the way they meet these needs. If we talk about drawing water from deep wells, this may speak to us of the ancient nomadic patriarchs of the Middle East, Abraham, Isaac and Jacob, or Joseph being thrown in a well (Genesis). If we talk about hand pumps, or tube wells we might imagine Africa or the Indian subcontinent with streaks of coloured cloth. If we talk about fish and chips one might think of a traditional English shop, rice and fish would give us a different picture. A meat pie and BBQ are Australian staples, while bread is almost as universal as water. There are records that the Australian Aboriginals used to make a kind of bread or “damper” from spinifex seed long before European settlement. Many of these cultural and social preferences can have a direct impact on the sustainability of water use and food production. In this way coming to sustainable solutions requires more than just an engineering or agricultural analysis of the problem. It also needs to include an appreciation of, and sensitivity towards cultural, social, and economic issues. Therefore, developing safe and sustainable solutions demands a multidisciplinary approach bringing together expertise from engineers, scientists, health professionals, teachers, social scientists, religious leaders and more.

Today the world is changing. Advancements in science and technology built upon "*the shoulders of giants*" are the starkest change. However, more pertinently we are sustaining a population on earth larger than anything ever known before. Population growth, urbanisation, and ultimately population concentration, have increased the world over. This has led to increasing concerns over food and water security in developed and developing countries alike. The sustainable development goals (SDG) published by the UN highlight that there are many people in developing countries that lack nutrition and access to clean water. Food and water feature directly as SDG Goal 2, zero hunger, and Goal 6, clean water and sanitation. The recent COVID-19 crisis has seen stable foods being rationed out by supermarkets all over the world and a supply chain that could not meet demand. The tactic of keeping safe by isolation at home only strengthens the argument for household agriculture. Having some food supply at home can only be an advantage in such situations. Food related problems range from lack of food to too much food, and in both cases a lack of a healthy balance. Water related problems include lack of water and contaminated water.

It seems like grace rained down from above that at this time of increased need, we have increased technology to help us meet that need. It is up to us to work with that grace, but sadly we have been too keen to dream about the moon, and not keen enough to supply to neighbour's needs. The 16th of July 2019 11:32 pm GMT+10 marks 50 years since 'man on the moon', a great technological achievement no doubt (Williamson 2002) as was the Apollo 8 first manned circumnavigation of the moon the December before (Oliver 2013) in which the opening verses of Genesis were read aloud by the astronauts as they saw the earth rise. The availability of such high-level technology over 50 years ago highlights that the water issue is not just technological but also socioeconomic. At the beginning of the space race there was an acknowledging that the aid program could not be used as a satisfactory substitute race with Russia (Rechtin 1959) and that preoccupation with cold war issues was hampering aid (Prentice 1960). The problems remain with us today and many people on earth are having a moon like experience: lacking food and water. The UN SDGs, previously the millennium development goals (MDGs), World Bank, and World Health Organisation report this lack in abundance. There are still many people in developing countries that lack basic nutrition and access to clean water for drinking and sanitation (van Welie et al. 2019). In other areas overabundance is leading to obesity and a paralleled malnutrition. It is a discredit to advanced societies that the technological achievement of putting man on the moon has not been paralleled by the simple provision of food and water. It has long been recognised that sustenance and shelter are the basic requirements for health, wellbeing and contentment (First Timothy 6:8-10) and hopefully peace. Provision of safe drinking water is much easier in terms of existing technology than the space race, yet the problems remain. There is need for increased innovation (Cohen and Ilieva 2015), a focus on, and care about the basic needs of mankind.

Household agriculture (HA) and rainwater storage systems (RSS) are both ancient practices gaining a high level of modern interest. They are both potentially sustainable practices and directly address food and water security. In developing countries HA supplies important nutrition and an income to many families. However, crops often fail due to lack of water, RSS can help provide the water needed to avoid that failure. The advancements in technology and history of climate record keeping over the last 100 years of the "*instrumental age*" (Zillman 2001), and access to satellite data since the 1980s could be used to assist the design of combined RSS – HA systems that are sustainable. Currently however, most research has focused on RSS and HA separately. Where research has looked at using RSS in HA it has not been based on a detailed analysis of agricultural water use, but based on simplifications, or on limited case studies of a particular system's performance. Towards this goal this study focuses on the analysis and feasibility of RSS in HA in both developing and developed countries. For convenience reference is made to the SDGs however, the issues have been prevalent for a long time before the SDGs or MDGs were formulated.

The integrated practice of HA and RSS can contribute to many of today's global issues. The SDGs provide a useful framework for demonstrating that contribution. Understanding the underlying nexus that needs to be addressed is important to realizing that potential. HA and RSS can contribute to at least eight of the 17 SDGs; on an individual level, particularly Goals 2 to 6, and on a more community and global level, Goals 11, 12, and 15. The fact that it can contribute to food security, improved nutrition, sustainable agriculture, and sustainable water management practices (Goals 2 and 6) needs little explanation. In terms of Goal 3, good health and well-being, many researchers have also reported a variety of other benefits to practicing HA, including reductions in depression, anxiety, and body mass index, and increases in life satisfaction, quality of life, and sense of community, (Genter et al. 2015; Marsh and Spinaze 2016; Soga et al. 2017). It is understood to enhance well-being (Galhena et al. 2013), improve physical and mental health (Milligan et al. 2004), and reduce diabetes by providing a diet less based on often imported and highly processed food. In the republic of Nauru in the Pacific, this is exactly what has happened as populations have shifted towards purchasing cheap imported food and away from producing their own, resulting in high levels of obesity and diabetes (Hamilton et al. 2014). HA in itself also provides a medium for physical activity (Peeters et al. 2014) and is often prescribed for therapeutic and mental health benefits, as well as for its use in the treatment of obesity (Heise et al. 2017). Whilst providing nutrition, it can also help in educating children about nutrition (Christian et al. 2014; Davis et al. 2014), and it is increasingly forming part of the educational curriculum (Keatinge et al. 2012). The state of New South Wales in Australia, for example, has just this year released a new syllabus for teaching Agriculture at primary school level k-10 (NSW Education Standards: Teaching Agriculture 2019). The Food and Agricultural Organization (FAO) has a number of publications to specifically assist with this; for example, a toolkit for setting up and running a school garden (FAO 2009) and program lessons for “Integrating agriculture and nutrition education for improved young child nutrition” (FAO 2016). In this way, Urban Agriculture (UA) is integral to Goal 4, quality education: Ensure inclusive and equitable quality education and promote lifelong learning opportunities for all. This addresses Goal 5, gender equality: Achieve gender equality and Empower all women and girls. Firstly, because it is women who predominantly engage in HA and household water management (Hossain and Rahman 2017), they are the primary benefactors. If collecting water from a distant RSS can save time when collecting water, this can produce more time for other things, such as education. If HA produce is also sold, this will also mean that the women are contributing to the household income, while the children start their education at home through their participation.

Sustainable cities and communities, which make cities and human settlements inclusive, safe, resilient and sustainable (Goal 11), can be addressed by a change in lifestyle and healthier living, and HA in the urban environment also means greener cities. Cuba, a world leader in UA (Hamilton et al. 2014), due to trade embargoes, developed a system called organoponics that relies on neither diesel nor chemical fertilizer. The food is grown close to where it is consumed, and organic material is used to fertilize garden beds. The potential reduction in “food miles” and change in consumer consumption patterns addresses Goal 12, responsible consumption and production: Ensure sustainable consumption and production pattern. Finally, it contributes to Goal 15, life on land: Protect, restore and promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification, and halt and reverse land degradation and halt biodiversity loss. HA can increase the biodiversity of plants and insects (Lin et al. 2015). Organisations such as “Garden Organics” in the UK have set up a “heritage seed” library, which encourages individuals to grow forgotten plant varieties in the face of a homogenizing market. For example, in the US, 90% of the 7000 varieties of apples that used to exist have all but disappeared (De Wit 2016). Vegetables cultivated all over the old city in Andernach, Germany, are known to maintain “forgotten varieties” (Eigenbrod and Gruda 2015). Therefore, extensive home gardening can help maintain genetic diversity and the wealth of the world’s collective seed bank, whilst commercial large-scale agriculture tends to focus on a narrow selection of high-yield varieties (Altieri et al. 1987).

While we have only discussed the positives here, there are some negatives and challenges. One particularly malignant issue that warrants serious consideration is the potentially increased risk of malaria due to mosquito breeding grounds associated with urban agriculture (Boelee et al. 2013; Hamilton et al. 2014) and RSS systems (Jongman and Korsten 2016). This will need to be mitigated by RSS design (Moglia et al. 2016) and open containers are not generally recommended (Helmreich and Horn 2009). Another is diarrhoea associated with using wastewater to irrigate and human waste as fertilizer (Hamilton et al. 2014). Jongman and Korsten (2016) investigated water quality in rural villages in South Africa in 80 rainwater tanks and concluded that the use of untreated rainwater in crop irrigation or domestic use poses a potential health risk, especially in areas with a high population of immunocompromised individuals, so they advocate treatment before use. A little consideration will also show that to fully realize the potential, there are several barriers. For example, the crop yield is highly variable and dependent not only on resources, but on the gardener's skill. Through an in-depth literature review (Chapter 2) the following research questions were developed.

1.3 Objectives

The objective of this study is to assess the potential of using rainwater storage systems (RSS) and household agriculture (HA) to provide food and water in a sustainable way in line with the UN sustainable development goals and applicable to both developed and developing countries. This includes, not only an assessment of the capacity of various systems, but also of current socioeconomic issues.

1.4 Research questions

The research questions that this study addresses can be categorised into three broad questions. Firstly, what is the economic feasibility and social acceptability of rainwater storage systems (RSS)? Secondly, what is the capacity of RSS to supply or supplement general domestic water use and or drinking water? Thirdly, what is the capacity of RSS to support household agriculture (HA)? These questions are considered in the context of both developing and developed countries.

1.4.1 Economic feasibility

1. Are RSS economically beneficial from a life cycle cost analysis perspective?
2. Are RSS affordable?

1.4.2 General domestic water and/or drinking water supply

1. What is the capacity of alternative RSS configurations?
2. Is there an optimum design for RSS?

1.3.3 Water supply for household agriculture

1. What quantity of water is available for irrigation?
2. What quantity of food can be produced with the available water?
3. Is there an optimum design for a combined RSS and HA system?

1.5 Research methodology

Firstly, an in-depth literature review was performed, and it became apparent that there is a lack of studies specific to RSS use in HA. A critical review of existing literature was therefore difficult. Therefore, a scoping review methodology following the five basic steps outlined by Arksey and O'Malley (2005) and Levac et al. (2010) as shown in Figure 1.1, was deemed more appropriate. This was also justified by the broad nature of the water-food-energy-ecosystem nexus, under which nexus food and water security sits. The multidisciplinary nature of this research also meant that if too narrow an approach was adopted important factors, particularly economic, would be neglected. The scoping review approach aided the synthesis of relevant areas of research in the search for realistic and sustainable solutions. It also helped in the development of ERain and in laying a foundation for future research in this relatively new and important area.

Figure 1.1 The five basic steps of a scoping review

The literature review process continued through the research, but with more of a focus on comparison of results with existing literature where it could be found and on new developments.

Secondly in order to analyse the research questions a detailed model called ERain was developed in FORTRAN with R_Script being used for data preparation, control and presentation of results. Figure 1.2 shows a schematic of ERain.

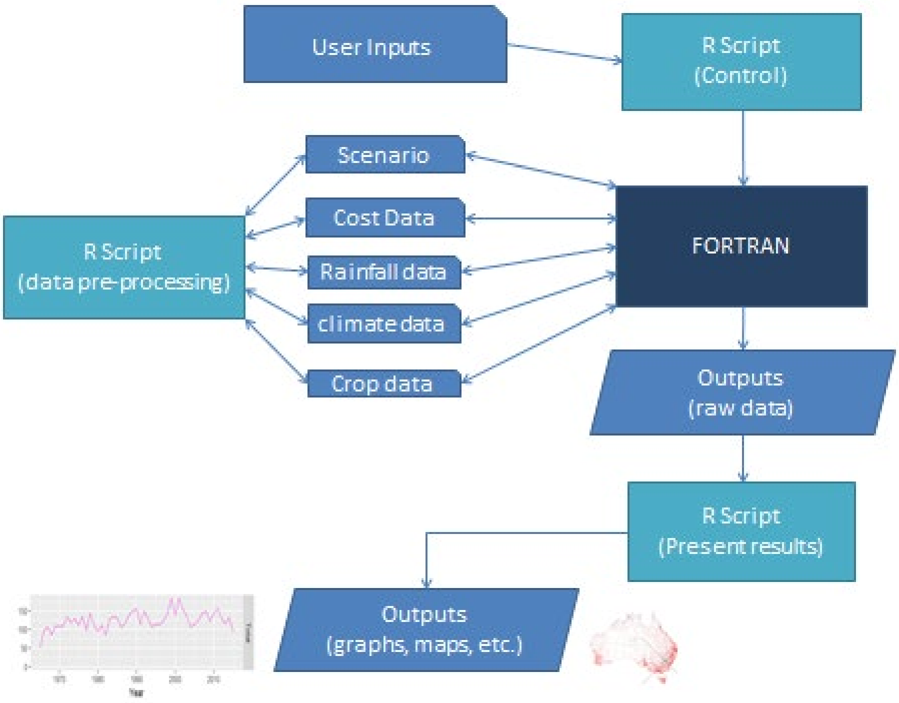

Figure 1.2 Schematic of ERain

ERain combines a yield after spillage water balance model with detailed evapotranspiration equations from the UN’s food and agriculture authorities’ (FAOs) publication on evapotranspiration, commonly referred to as FAO 56 (Allen et al. 1998). ERain also performs life cycle cost analysis based on AS/NZ Standard AS4536 “Life Cycle Costing – an Application

Guide" (Standards Australia 2014). Input parameters to ERain include: scenario data (number of occupants, tank size , roof area, system losses (roof loss, mass loss, first flush), initial water storage, garden size, water demand profile, rainfall and climate data; FAO 56 data requirements including: planting date, factors for irrigation, mulch factor, catchment, infiltration, soil type, soil texture, evaporation depth, crop development stage lengths (days), max crop height, max root depth, crop coefficients (Kc), depletion factors; FAO 33 yield response factor; detailed costs (capital, and ongoing costs for all elements). Outputs include system reliability, water use/savings, crop yield, and economic measures including benefit cost ratio (BCR) and the net present value (NPV).

Thirdly, after verification and testing, ERain has been used in several socio-economic scenarios in developed and developing countries, primarily in:

- Australia;
- Bangladesh; and
- Kenya.

This broad spectrum of analysis means that results are expected to be applicable in several scenarios throughout many regions of the world. In each case a multidisciplinary approach was taken in consultation and engagement with health professionals, social professionals, water engineers, local politicians, local community leaders and local community members.

1.6 Research impact

The research has been dynamic and published high impact journal papers, in conference proceedings, and in a book chapter under review. It has been presented and discussed at conferences, presentations and meetings. Each paper has been developed in the framework of direct community involvement and consultation to fulfil the socioeconomic aspect of the work. The work is intended to have high impact bringing focus attention on the potential that combined RSS and HA have on improving nutrition and health. It directly addresses

Western Sydney Universities' responsibility to *"to equip the next generation of leaders, innovators and thinkers to understand the global challenges facing the world and the role they can play in rising to meet these challenges"* – as promised in the March 2017 educational signatory to the Pacific Initiative. Particularly, point 2 "*Undertake research that provides solutions to sustainable development challenges".* This research has paved the way for similar research addressing the SDGs.

The design has been to not only to do research for research's sake but also to provide solutions to important questions and to engage and promote instigation of projects so that the research will become beneficial in real terms. It is hoped that the work will be of direct advantage to the communities in Nairobi and in Miti Mingi Village in Kenya, and to those in Koyra, Bangladesh where the community was introduced to the advantages of RSS and the acceptability of RSS in Australia. Australia is a key reference point for RSS uptake, the success and the lessons learned can be of benefit the world over. One principle followed in this research is that Australia as a developed country, with a high level of research can produce knowledge and share experience that will be of benefit to developing countries in a neighbourly fashion.

It is hoped that developments in Australia can contribute particularly towards meeting SDG Goal 2 zero hunger, and Goal 6, clean water and sanitation, in developing countries. It is expected that the findings and discussion in this study will be of benefit to decision makers in NGOs and government positions able working in the water, sanitation and hygiene (WASH) area. It will also be of interest to modellers and researchers, water engineers, environmentalists, and town planners, and policy makers concerned with sustainable development and dealing with integrated water management, the water-energy-food-ecosystem nexus by bringing together knowledge gaps and potential solutions. It is expected that the findings of this study will both be of assistance to the village and relevant to community- and school-size projects internationally considering the use of HA and RSS.

1.7 Structure of the thesis

The research undertaken in this doctoral study is presented in 8 chapters. The first chapter is an introduction, while the second chapter provides an in-depth literature review of RSS use in HA. Chapters 3 and 4 cover economic aspects of RSS. Chapter 5 focuses on RSS capacity for drinking water provision, while chapter 6 focuses on provision of water for HA. Chapter 7 presents the key findings and conclusions of the study. The chapters are as follows.

Chapter 1 – Introduction

This chapter provides an overview of the research undertaken and sets the background for the work. It also identifies the objectives and scope of the work and provides a layout of the study.

Chapter 2 – Literature Review of Rainwater Storage Systems Usage in Household Agriculture

This chapter is a partial reproduction of the journal article: Amos, C. C., Rahman, A., Karim, F., Gathenya, J.M. (2018). A Scoping Review of Roof Harvested Rainwater Usage in Urban Agriculture: Australia and Kenya in Focus, Journal of Cleaner Production, 202, 174-190 (Impact factor: 6.395, SJR Quartile: Q1)

Chapter 3 – Economic analysis of rainwater harvesting systems comparing developing and developed countries

This chapter is a partial reproduction of the following journal article: Amos, C. C., Rahman, A., Gathenya, J.M. (2018). Economic analysis of rainwater harvesting systems comparing developing and developed countries: A case study of Australia and Kenya, Journal of Cleaner Production, 172, 196-207 (Impact factor: 6.395, SJR Quartile: Q1)

Chapter 4 – Economics of Rainwater Harvesting use in Urban Agriculture: The Influence of Irrigation Area and Roof Size

This chapter is a partial reproduction of the journal article: Amos, C. C., Rahman, A., Karim, F. (2019). The Influence of Irrigation Area and Roof Size on the Economics of Rainwater Harvesting use in Urban Agriculture: A Case Study in Sydney, Australia, International Journal of Engineering, Construction and Computing (IJECC), 48-58. Peer reviewed.

Chapter 5 – Rainwater storage systems capacity to provide clean drinking water at the village and individual household scale

This chapter is a partial reproduction of the journal article: Amos C.C., Ahmed, Amir, and Rahman A. (2020) Sustainability in Water Provision in Rural Communities: The Feasibility of a Village Scale Rainwater Harvesting Scheme, Water Resources Management Impact factor: 2.644, SJR Quartile: Q1.

Chapter 6 –Roof harvested rainwater use in household agriculture: contributions to the sustainable development goals

This chapter is a partial reproduction of the journal article: Amos, C. C., Rahman, A., Gathenya, J.M., Friedler, E., Karim, F., Renzaho A. (2020) Roof Harvested Rainwater use in Household Agriculture: Contributions to the Sustainable Development Goals, Water, MDPI (Impact factor: 2.52, SJR Quartile: Q1) Awarded “Editor’s Choice”.

https://www.mdpi.com/journal/water/editors_choice

Chapter 7 Summary, conclusion and recommendations

This chapter summarises the various findings in the study and reports the major conclusions. It also shows how the research questions were answered point by point and what aspects of each question remains. The chapter also includes recommendations for further research.

Chapter 2

Literature Review of Rainwater Storage Systems Usage in Household Agriculture

Chapter 2 Literature review of rainwater storage systems usage in household agriculture

This chapter is a partial reproduction of the following refereed journal paper:

Amos, C. C., Rahman, A., Karim, F., Gathenya, J.M. (2018).

A Scoping Review of Roof Harvested Rainwater Usage in Urban Agriculture: Australia and Kenya in Focus,

Journal of Cleaner Production, 202, 174-190.

Impact factor: 6.395, SJR Quartile: Q1

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2.1 Overview

This review investigates the potential of using roof harvested rainwater to support urban agriculture. Among the important issues, we concentrate on system configuration, modelling and economic analysis while comparing research from both developed and developing countries. Urban agriculture contributes notably to food and nutrition in many developing nations, and is receiving increasing attention in developed countries due to a cultural shift towards sustainable living coupled with increasing demand and food prices. Domestic rainwater harvesting (RWH) from rooftops increasingly forms part of integrated water management strategies and has seen a considerable amount of research on modelling and economics, as has water use in agriculture. However domestic RWH usually focuses on in-house usage such as toilet flushing and washing, while there has been very little research specific to its use in food production. In developing countries home gardens often fail due to insufficient rainfall and water supply. In general, promoting urban agriculture and the greening of cities begs the question of whether there is sufficient water available to support it and where additional water will come from.

A scoping review following five step criteria is adopted here to understand the extent to which roof harvested rainwater can be used to support urban agriculture and what are the associated economic implications. In view of the broad scope of the water-food-energy-ecosystem nexus, under which this research fits, this scoping review is deemed better suited (in absence of an ample body of literatures) to the synthesis of relevant researches than a systematic review. The major contributions of this review are to highlight the lack of initiatives to utilise harvested rainwater in urban agriculture, to explore the obstacles and to lay a foundation for new areas of research within the sustainable urban development paradigm. Furthermore, the comparison between developed and developing countries helps bring to light cultural, socio-economic and political obstacles to improving sustainability and healthier living in the urban environment. The impact of history and traditions on crop choice, growing methods and consequently water consumption rates are also discussed.

This review is particularly relevant to three of the United Nations’ sustainable development goals (i.e. Cleaner and Sustainable Cities; Health and Wellbeing and No Hunger). It is found that there is a considerable potential to supply water to urban agriculture using customised roof RWH system designs. For example, one study reports that up to 41% of urban horticulture sites in Rome could be sustained by water harvested from local roofs. Irrigating a small garden (20 m^2) with harvested rainwater can increase the yield by about 20% meeting the caloric requirements of a typical Indian household. Further research is needed on the integration of roof rainwater harvesting and urban agriculture to maximise its contribution to food production and sustainability.

2.2 Introduction

Adam, who for many was the first man, was a gardener or a farmer (George et al. 2013) described as living in a Garden of Paradise called Eden. The Garden of Eden is described as being abundant with a great variety of fruit trees watered by a huge river system (Genesis 1:11, 2:10). Eden continues to be an object of contemplation and a reference point for many writers both romantic and scientific. In the British Food Journal, McKee (1995) titles his work, "East of Eden" and argues that you cannot separate history and traditions from food consumption. History and culture affects crop choice which in turn has one of the highest impacts on water consumption (Raz et al. 1987; Woltersdorf et al. 2015). Gardening for food and aesthetic purposes has been practiced for thousands of years (Wang and Clark 2016) and still has its appeal. In Australia, partly due to water limitation, there is a movement towards native plants which naturally tend to have low water consumption (Josh Byrne & Associates 2013). Urban agriculture has many definitions but can be defined simply as "agriculture within an urban or peri-urban setting" (Hamilton et al. 2014). It may include trees, bees, vegetables, pulses, may also be done in conjunction with animal production, especially chickens and sometimes fish (Orsini et al. 2013). Food and water, along with air, are the basic necessities of mankind. For many people urban agriculture represents food security, nutrition and economic stability. For others gardening means a healthy lifestyle, for others it may be purely therapeutic, and another may get involved as a medium for social interaction, or as part of an education program at school. However there is heavy competition over the use of water and arable lands traditionally used for agriculture within city limits all over the world, owing to pressure from increased urbanisation and a growing world population (Corbould 2013). In light of this, promoting urban agriculture begs the question of where the additional water required to support it will come from.

In this regard, this study presents a scoping review of rainwater harvesting practice, primarily from roof catchments, in view of its potential to support urban agriculture. In the early stages of the review, it became apparent that there is a sparseness of definitive studies on the specific area of roof harvested rainwater use in urban agriculture. On this premise, a scoping review methodology is adopted rather than a systematic review. Systematic reviews are designed to focus on a narrow range of studies that answer a specific question, whereas scoping studies address a broader topic (Arksey and O'Malley 2005). Considering the need to supply additional water for green sustainable cities, the broader question we ask is, to what extent can roof harvested rainwater be used to support urban agriculture and what are the economic implications of its use in either developed or developing nations. In this study, various relevant issues are synthesised to explore this relatively new area of research in modern sustainable development. Among the important issues, we concentrate on urban agricultural forms, economic analysis, system configuration, and the modelling aspects of rainwater harvesting for urban agriculture. Developing and developed countries are compared and there is a special focus on Australia and Kenya.

Developed countries are commonly envisioned as the world leaders in technology and innovation, however there is a case for developing countries to lead the way in innovation. Slums in Kenya demonstrate that rainwater harvesting is a viable supply for urban agriculture through practicing it. Increased food prices in Australia is seeing a growing trend in Urban agriculture with increased popularity of urban farms (Russ Grayson 2017) and roadside gardens (Marshall 2017). This practice is encouraged by many local councils who may provide guidelines (Sydney 2017). Across the world, Mexico City already produces up to 20% of its own food, and there in a desire to increase this by reintroduce pre-Hispanic practices of Chinampas or Floating gardens (Dieleman 2016). Cuba has become a world leader in “organoponics” (raised seed beds) due to the breakdown of supply chains and trade isolations (Eigenbrod and Gruda 2015; Orsini et al. 2013). In developing countries home gardens are often used to supply the family with food and income (Jayasuriya et al. 2014). Many authors recognise that increased urbanisation results in loss of arable land and see a need to find new places and ways to grow food within city limits (Corbould 2013; Eigenbrod and Gruda 2015; Orsini et al. 2013; Suparwoko and Taufani 2017). America hosts cities known as “food deserts” (Beaulac et al. 2009; Horst et al. 2017; Walker et al. 2010), where urbanisation has increased to such an extent that it is difficult to buy fresh fruit and vegetables locally (Eigenbrod and Gruda 2015; Smith et al. 2013). In Kenya it is performed variously and often supplements household nutrition (Gallaher et al. 2013a). Both developed and developing countries are found to come short of the sustainable development goals (SDGs) set by The United Nations in regard to Goal 11 Cleaner and sustainable cities, and Goal 3 Health and wellbeing. Food and water security, tied into Goals 2 and 6, are a problem for many developing countries. It is a shame that the technical achievement of putting man on the moon in 1969, nearly 50 years ago, has not been matched in providing the basic needs of man. Innovation is a key component in the water industry in general (Gabrielsson et al. 2018) so also in RWH techniques, agricultural water use (Kongo and Jewitt 2006) and in the process of greening the urban environment (Germer et al. 2011; Specht et al. 2016; Thorn et al. 2015). Innovation affects the system configuration which is relevant to economic analysis and adds complexity to it (Gabrielsson et al. 2018; Getnet and MacAlister 2012; Melville-Shreeve et al. 2014).

Rainwater harvesting (RWH) in the urban domestic context usually refers to water harvested from a roof area and stored in a tank before it is used for irrigation or household. In agricultural literature RWH usually refers to runoff from catchment areas, such as field and mountain sides, and stored in dams (Boers and Ben-Asher 1982; Helmreich and Horn 2009). More broadly it is defined as, "*a method of inducing, collecting, storing, and conserving local surface runoff for subsequent use*" (Rahman 2017). Here RWH is used to refer specifically to rainwater harvesting from rooftops. RWH has seen a substantial amount of research over the last 15 years (Campisano et al. 2017; DeBusk and Hunt 2014; Gwenzi and Nyamadzawo 2014; Lade et al. 2011; Mankad and Tapsuwan 2011; Sharma et al. 2016). The harvested rainwater is commonly used for toilet flushing, laundry and irrigation. Although not advising it, Environmental Health (2010) recognizes that in peri urban and rural areas of Australia it is often the main source of domestic water being also used for drinking and cooking, as is the case in many countries. Many authors recognise the potential improvements in food security that RWH systems offer (Helmreich and Horn 2009; Kahinda et al. 2007; Morgan 2007; Wachira 2015). Stout et al. (2017) investigate three ecosystem services for RWH in India, including indoor use and food production and also add groundwater recharge (GWR). Rainwater harvesting is often quoted as a potential solution to minimise the effect of increased runoff from urban landscapes (Coombes and Barry 2012;

Gwenzi and Nyamadzawo 2014; Ishida et al. 2011). Although lacking research (DeBusk and Hunt 2014), likely benefits from RWH system installation include both delaying stormwater and water main's supply infrastructure (Melville-Shreeve et al. 2014). Using RWH systems in small-scale domestic gardens particularly can improve nutrition among women and children who would have direct access to the produce (Gwenzi and Nyamadzawo 2014; Ngigi et al. 2005). It is not expected that urban agriculture is the complete solution to food security, as rainwater harvesting is not a complete solution to water security. Further investigation is needed to identify their potential position within the water-food-energy-ecosystems nexus (Vanham 2016) and to delineate the extent of the contribution that both can make to water and food security (Abdulla and Al-Shareef 2009; Lupia et al. 2017).

Economic analysis of RWH systems frequently includes calculation of water savings using a daily time step model with historic rainfall data as an input and the water savings as an output. The water demand profile, tank and roof size being important system variables (Amos et al. 2016). The water demand profile is difficult to quantify (Willis et al. 2013), depending on the number of occupants and their water use habits it merges into a socio-economic issue. Water use for irrigation is probably the most difficult to predict (Gato-Trinidad and Gan 2014), with some owners not irrigating at all, others occasionally watering lawns and others maintaining extensive gardens both ornamental and for food production. Plumbing reticulation and pumping costs are one of the main factors that make RWH financially non-viable (Amos et al. 2018a). The use of pumps in RWH systems particularly has been considered to make them environmentally unfriendly due to power consumption and large quantities of small motors (Vargas-Parra et al. 2013; Vialle et al. 2015; Vieira et al. 2014) leading to a search for innovative systems (Melville-Shreeve et al. 2014). Using water for irrigation only therefore may be the most beneficial economically and environmentally if it can be achieved without the use of a pump. Stout et al. (2017) conclude that irrigation to a small garden with the overflow to a drywell for ground water recharge produced maximum benefits in India. Also, if food is produced from the water, which may not otherwise be available, then there is also a financial benefit from the food. The concept of food miles, if the net distance the food has to be transported from growth to consumption is another economic and environmental consideration (Wiltshire and Azuma 2000). A review paper on "Garden Kits" in Africa found that water management technologies used in home gardens has seen minimal research particularly in regards to economic outcomes and sustainability (Merrey and Langan 2014). The various garden configurations, such as use of greywater or clay pots, bag gardens, keyhole gardens, and trench gardens, etc. are rarely considered. In this review little research was found on combined RWH and urban agricultural systems and so other generally types of RWH are considered where appropriate. Increasing the green areas of the urban environment is one way of reducing environmental impacts that has seen growing attention in recent years. Green roofs, which are also becoming a growing trend, have been found to reduce building heat (Liaw et al. 2015) and promote the removal of atmospheric pollutants (Monteiro et al. 2016; Wang et al. 2017). Rooftop RWH gardens have also been found to have a cooling effect reducing building temperatures by more than 1.3°C (An et al. 2015). Researchers recognising that this increases potable water use are considering RWH as an option for reducing mains water consumption. Liaw et al. (2015) investigate using rainwater to mitigate this effect and state that the design method for using RWH systems in conjunction with green roofs is not well developed.

Research in economic analysis and modelling of roof harvested RWH in relation to in-house use of harvested rainwater has increased in recent years (Amos et al. 2016). There is also significant research on rainfall runoff stored in dams for agricultural systems. However, limited research was found specific to using roof harvested rainwater for urban agriculture and for food production. Hence, this study reviews papers relevant to combined RWH and urban agriculture and the current state-of-the-art of economic analysis and modelling of RWH that could be adapted to include urban agriculture and identifies the areas of further research. Firstly, economic analysis of urban agriculture and RWH systems is discussed followed by a review of system configurations, water sources, water use, and modelling methods. Finally, future research tasks are identified. This study is intended to serve as a key reference on modelling and economic aspects of RWH in urban agriculture and greening of cities and will be useful to modellers and researchers, water engineers, environmentalists, town planners, and policy makers concerned with sustainable development and dealing with integrated water management and the water-energy-food-ecosystem nexus by bringing together knowledge gaps and potential solutions.

2.3 Review methodology

In the early stages of reviewing this subject, it became apparent that there is a lack of studies specific to roof harvested rainwater use in urban agriculture and food production, making a systematic review of definitive literature difficult. The broad nature of the water-food-energy-ecosystem nexus, under which nexus the sustainable cities and urban agriculture sits, means that if a too narrow approach is adopted, important factors can easily be neglected, particularly economic aspects. A scoping review approach was therefore preferred to aid the synthesis of relevant areas of research in the search for realistic and sustainable solutions and to lay a foundation for future research in this relatively new and important area.

In this study we followed the five basic steps of conducting a scoping review outlined by Arksey and O'Malley (2005) and Levac et al. (2010) as shown in Figure 2.1.

Figure 2.1 The five basic steps of a scoping review

Promoting urban agriculture begs the question, where will the additional water required to support it come from. The research question we ask is thus, to what extent can roof harvested rainwater be used to support urban agriculture and what are the economic implications of its use. Studies covering both RWH and urban agriculture were deemed the most relevant, while studies covering only one aspect were deemed necessary due to the lack of research on combined systems. For example, Merrey and Langan (2014) state that there has been *"very little research on the actual use of these water management technologies"* in economic outcomes and sustainability of their use in home gardens and Amos et al. (2016) found that, "the *use of RWH systems in water management strategies for small-scale domestic gardens and their financial benefit through crop production warrant further research"*. Research on RWH that does include irrigation usually does not incorporate in-depth analysis of potential crop production but only estimations based on basic parameters such as lawn area (Jones and Hunt 2010; Sample and Liu 2014). Previous studies were selected by searching for the keywords (rainwater harvesting, urban agriculture, green roofs, green walls) in scientific database (Scopus, Web of Science, Science Direct, Google Scholar and CSIRO's research repository, and the Food and Agricultural Organization's (FAO's) repository). Initially we found over 1000 articles. Some additional papers were found by searching references in papers that were of particular relevance and also by looking at papers that quoted them. Papers were categorised with the help of further keywords (Australia, Kenya, gardening, wick bed, tank, modelling, economics, nexus, water, and food) and screened by title and abstract. Irrelevant and less important articles were excluded from the list. The remaining 600 or so were then collated and finally over 160 articles were retained and used to write this review paper.

2.4. Urban agricultural forms

2.4.1 The state of urban agriculture

Where urban agriculture occurs can be conveniently segregated into developing and developed countries which can help identify drivers particular to these categories. In developing countries urban agriculture plays a significant role in providing food security and in many cases also income (Corbould 2013; Hamilton et al. 2014). Developed countries generally lack the desperate need for food, and income from small scale agriculture is minimal and so the motivation has been more ideological (Corbould 2013; Mok et al. 2014). What this categorisation misses however is the cultural diversity of various nations. Trends in a countries economics and infrastructure may not be reflective of the agricultural insights that have become embedded in various cultures throughout their history. For example, Dieleman (2016) discusses Mexico City's desire to reintroduce pre-Hispanic practices of Chinampas or Floating gardens in the context of balancing social and symbolic value with economic and ecological realities. Chinampas were established by the Aztecs around the year 1350 to overcome land shortages and feed the growing population. In nineteenth-century Japan rice, heavily water dependant, was grown in paddies interspersed among residential areas (Mok et al. 2014). Germany has traditional city areas, such as in Andernach, where old vegetable varieties are cultivated and anyone can come and pick and eat them (Eigenbrod and Gruda 2015). Interestingly it is the less developed old Eastern part of Berlin that was found to have a higher density of fruit trees which. Larondelle and Strohbach (2016) attribute to the legacy of the separation and the different political, social and cultural systems that existed. Perhaps in an environment of warm friends rather than cold war there is opportunity for mutual learning. In London extensive areas of greenhouses produce nearly their entire city's demand for cucumbers (Mok et al. 2014). While some of these differences will be partly circumstantial and allowed or limited by the local economy, climate (esp. rainfall and temperature), soil types, and local plant varieties cultural preference and history plays a larger role than mere economics. McKee (1995), in East of Eden, briefly discusses the history of fruit and vegetable consumption and argues that you cannot separate history and traditions from food consumption. He states that among the poor cost and distribution are the prime considerations, but notes that traditions and habits also have an influence.

Cuba, in the heart of the Caribbean neighbouring Haiti-Dominican republic where Columbus first saw some of today's most world-renowned crops, deserves a special mention as it is heralded as a world leader in urban agriculture. Isolation due to trade embargoes and the collapse of the USSR, stopped many imports notably fuel and fertilisers pushing Cuba to invest in an urban agriculture reliant on neither. (Eigenbrod and Gruda 2015). Promotion of Organoponics, raised bed systems, described in more detail in section 3, by the Cuban government helped increase yields by 17% between 1994 and 2001 (Hamilton et al. 2014). Their effectiveness and simplicity mean they could easily be appropriately replicated in many countries. This push ahead in urban agriculture in times of crisis is not isolated to Cuba, but is simply more recent. Less than 100 years ago during World War 2, America and the UK both had highly successful gardening programs known as victory gardens in the US, and dig for victory in the UK. The many allotment gardens in the UK (Saunders 1993) continue this tradition to some degree (Genter et al. 2015). These campaigns were successful in alleviating the demand on commercial food supply chains allowing it to be directed to troops (Mok et al. 2014). Since those times it has declined and now America hosts cities known as "food deserts," where urbanisation has increased to such an extent that it is difficult to buy fresh fruit and vegetables locally (Eigenbrod and Gruda 2015; Smith et al. 2013). Community gardens have become a way to help address this issue (Mok et al. 2014) as well as being a popular past time.

Along with urbanisation has come Innovation in both developing and developed countries alike. Green infrastructure is finding a path in developing nations (Adegun 2017) due to poverty. In the slums of Nairobi, for example, people are using simple sacks filled with topsoil to grow vegetables (Gallaher et al. 2013a; Thorn et al. 2015). Plants such as kale may be planted in both the top and the sides of the sacks to maximise the use of space (Gallaher et al. 2013b). This implies that urban agriculture can be economically viable. In a bid to balance between ecological, economic, social and symbolic value Mexico City, which already produces 20% of its own food, is looking to urban agriculture. Symbolism is important in Mexico and urban agriculture is not only culturally acceptable but is seen by some to tie in with the country’s pre-Hispanic history and represents a restoration of Aztec practices. At the centre of this are the Floating gardens or Chinampas that fell out of practice during colonization (Dieleman 2016). In developed nations a concern for ascetics and the trend towards environmental awareness and sustainability has contributed to a desire for a greener environment including Architectural design of green buildings (Mi 2013). This has led to concepts such as green roofs (Oberndorfer et al. 2007) and walls (Wilkinson et al. 2017), vertical farming (Despommier 2011) and high-rise farms (Marris 2010), Zero acreage farming or “ZFarming”(Thomaier et al. 2015). Urban agriculture is an ancient practice that should not be left behind by modern urbanisation, but should be promoted by legislation and supported by scientific research to maximise its sustainable implementation particularly in regard to water consumption. This will be an important step towards sustainable cities, health and well-being as well as food and water security, as reflected in the UN sustainable development goals.

2.4.2 Urban agricultural system configurations

Also, we might consider that there are considerations peculiar to urban agriculture that may not be so widely considered in traditional agricultural practices which the FAO papers are designed for such as:

- Building envelope may introduce shade
- Competition with trees shade and root systems
- Reduced wind may be an advantage, reducing evapotranspiration (ET) rates
- Heat island effect may increase temperature and ET rates
- Small areas may be easier to improve soil quality or bring in garden soil

- Reduced soil depth in pots may reduce soil moisture storage.

To calculate water-use in urban agriculture it is necessary to understand the various urban agricultural forms as this will impact water consumption. The Cuban National Urban Agriculture Group recognises four main production methods, namely, patios (basic home gardens) , parcelas, huertas intensivas, and organopónicos (Koont 2011). Parcelas are small parcels of land for basic production while the latter two are structured rows of soil without and with walls. Mok et al. (2014) in a review of urban agriculture in the developing world defines 3 scales of urban agriculture namely, small commercial farms or community-supported agriculture, community gardens, and backyard gardens. The first two are both plots of land with community gardens generally being subdivided for individual use. The last is possibly where the most innovation occurs as it often involves integration with the building itself and even if just a standard garden, the location of the surrounding buildings is an important issue due to shade, wind, etc.

In-ground gardens

In-ground gardens may include allotments, patios, parcelas, community gardens, community-supported agriculture, and probably most forms of basic home gardens or patios. These are in many ways comparable to commercial rain-fed or irrigated agriculture but on a smaller scale. Rain-fed agriculture refers to crop production without irrigation relying on “green water”, soil moisture available to plant growth, common in farming large areas where irrigation is impracticable. Irrigated agriculture is usually a combination of rained agriculture complimented by irrigation, using “blue water”, liquid water in water bodies, as rivers, lakes and aquifers (Falkenmark 1995). In the urban environment however, these may be watered by treated town water rather than by untreated water stored in farm ponds, etc. In developing countries it is not uncommon to use raw sewage or whatever untreated water is available to water (Hamilton et al. 2014), which carries heath issues with it. In the urban environment however, these may be watered by treated town water rather than by untreated water stored in farm ponds, etc. In the urban area obvious disadvantages are the space that they take up, and location may be more restrictive with respects to shaded areas around the building envelope. The natural soil type has a large impact on the quality of the garden, but being smaller scale than large farms it may be easier to improve by adding organic matter and working the ground, etc. In-ground gardens have the advantage of soil depth and access to a larger pool of “green water” or soil moisture than pots or planter boxes. The soil depth may be an advantage depending on the preferred root depth of the intended crop.

Tower Gardens

Tower garden, also called bag or sack gardens (Figure 2.2) have the advantage of being space saving, portable, and water saving. A supported or unsupported bag is filled with a soil and manure mix with a plastic bottle or pipe in the middle, which is used to water the sack garden with, usually, recycled water. These are popular in developing countries and have been promoted all over Africa and have contributed significantly to household nutrition in Kibera, a slum in Nairobi (Gallaher et al. 2013a), however there are health risks associated with its practice, chemical from heavy metals in the soil used and to a lesser degree biological because of the lack of sanitation systems in the slums (Gallaher et al. 2013b) .

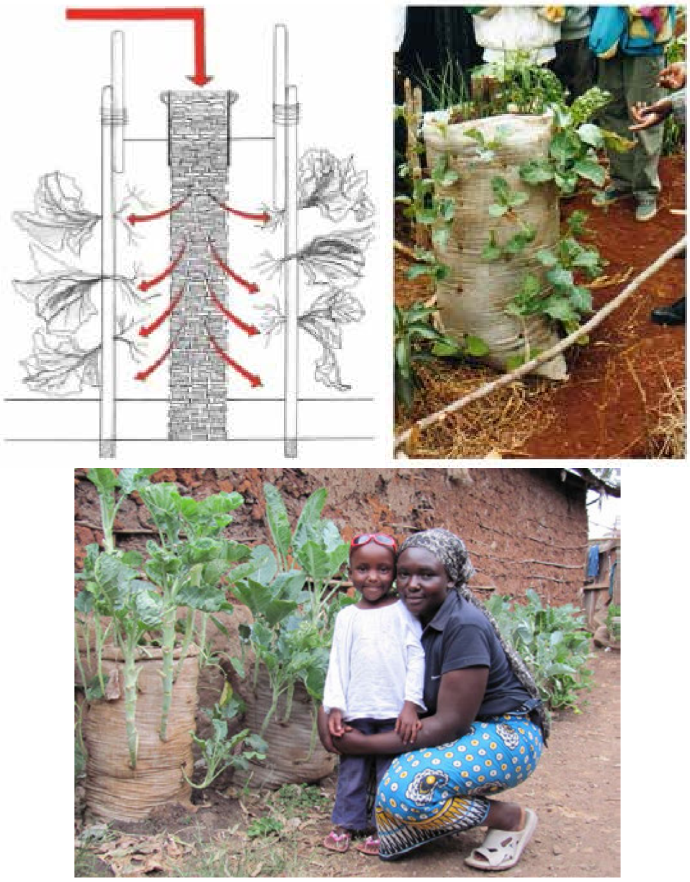

Figure 2.2 Vegetable tower garden, sack garden. Source Merrey and Langan (2014), and Gallaher et al. (2013a).

Keyhole gardens

Keyhole gardens (Figure 2.3) are similar to the sack gardens but is a more permanent and larger structure allowing multiple layers of compost. The central shaft is usually made of sticks and leaves allows for deep watering with minimal surface evaporation. They can also be used in dry semi-arid climates with poor soil. They are popular all over Africa including in schools (Merrey and Langan 2014).

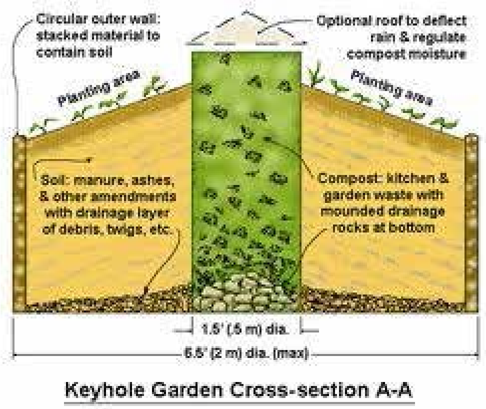

Figure 2.3 Keyhole garden. Source Merrey and Langan (2014).

Trench gardens

Trench gardens (Figure 2.4) are similar to keyhole gardens except that they involve digging deep into the soil and filling up with compost layers rather than building up the sides. The advantage is that they require fewer materials than keyhole gardens whilst still having the same advantages of fertility and moisture retention. They are simple and have been used for many years.

Figure 2.4 Trench gardens. Source Merrey and Langan (2014).

Organopónicos In the Cuban classification of garden systems huerta intensive and organopónicos (Figure 2.5) are both raised cultivation bed systems. They are similar to the keyhole and trench gardens popular in Africa. The former is simply rows of mounds of soil while the latter is made of walled cultivation beds roughly 1 m wide and 15–30 m long (Koont 2011) with a mix of soil and organic matter (Eigenbrod and Gruda 2015). Organoponics are used where natural soil is poor and there is limited access to fertilisers.

Figure 2.5 Organopónicos in Havana, Cuba. Source Hamilton et al. (2014).

These are also used for individual consumption and for schools and are suitable for developing countries due to their low cost. They are also seen as an ecologically friendly practice due to the lack of chemical input and so the concept has much to offer developing countries seeking sustainable urban agriculture.

Wick Gardens

Wick gardens or wick beds (Figure 2.6) are a form of sub surface irrigation. Externally they may appear similar to a simple raised garden bed but underneath the soil Layer, typically 300 mm, they have a water reservoir separated from the soil by a layer of geo-fabric. The reservoir may be in the form of an aquifer made of loose pebbles or scoria, or may be an open space if there is another means for supporting the soil above. A 300 mm soil depth is often advised and performs better than 600 mm depth for growing tomatoes, but reservoir depth appears to have no or little influence. Recent research in South Australia has shown that Wick bed systems perform as well or better than precision surface irrigated pots finding a significant improvement in yield and tomato quality as well as water use efficiency (Semananda et al. 2016). Wicking beds do not require any hi-tech components, are scalable and appear to be a good solution to improve water management in urban agricultural settings. Once build they require less frequent watering than conventional gardens which is also an appeal in the urban environment where owners may be busy with other activities.

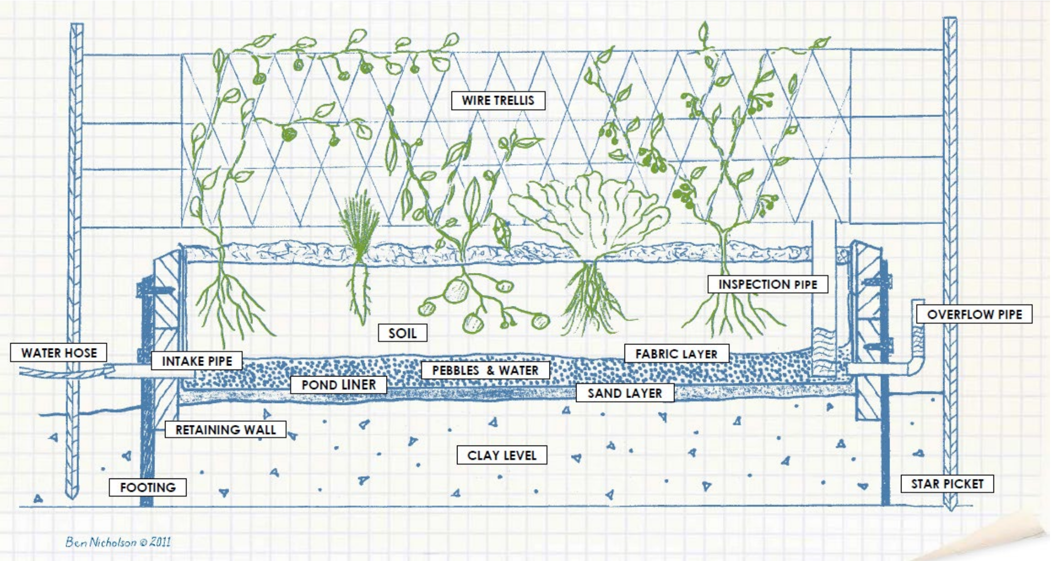

Figure 2.6 Wicking bed design and concept. Source Nicholson and Samuel (2011).

Pots and planter boxes

Pots and planter boxes have the advantage of being able to be placed in any location, and can be of various sizes. They can be used to grow vegetables on windowsills, balconies, front porches and in City Streets (Figure 2.7). Roadside gardens are also becoming popular in Australia (Marshall 2017) with the practice being encouraged by many local councils who in some cases provide guidelines (Sydney 2017). One disadvantage with growing in pots however is the frequent watering they require because of drying out. Many modern pots do incorporate a wicking bed type system with the bottom layer acting as a reservoir, although being small it is only so effective.

Figure 2.7 Human size pots in Brussels. Source Eigenbrod and Gruda (2015).

Green roofs

One way of minimising some of the environmental problems of urban centres is to increase the green areas of cities by implementing Green roofs (Figure 2.8). Stratigea and Makropoulos (2015) Investigate the role of green roofs (GR), rainwater harvesting (RWH) and greywater reuse in integration at the building level. Their research reports a significant decrease of total runoff volumes for rainfalls of medium-to-small return periods; a significant impact of latent heat peaking during the months of June and July as do other studies (Monteiro et al. 2016). They also find that results are significantly influenced by the type of vegetation used for the green roof ("plant factor") has on water requirements. Wang et al. (2017) note that green roofs are also a potential source of pollutants and propose a Dual-substrate-layer that can prevent pollutants leaching out and be effective at retaining rainfall. Another issue noted by Liaw et al. (2015) is that green roofs tend to increase potable water use and having negative environmental effect. They investigate using rainwater as a preferred option and note that the design method is not well developed. Another important issue is the structural integrity of the building, especially for a soil based green roof if retrofit, and the additional structural expense in new design.

Figure 2.8 Green roofs. Source Nyuk Hien et al. (2007).

Wilkinson et al. (2017) propose and investigate retrofitting not only roofs but also walls and balconies with vegetation particularly for thermal insulation, improving air quality, stormwater attenuation, and increased biodiversity. They compare retrofitted timber constructions in Sydney, Australia and Rio de Janeiro, Brazil. Others are designing "vertical greenery modular systems" (VGMS) for use in architectural design strategies for improving both the outdoor and indoor building climate (Serra et al. 2017) whilst maintaining an aesthetic appearance. While some of these strategies sound modern, they have been practiced for thousands of years in various ways, and are common practice in some developing countries, for example turfed mud roofs, and ivy growing on historical houses.

In an attempt to balance ecological, economic, social and symbolic value in Mexico City, floating gardens or Chinampas have been popular (Dieleman 2016). Chinampas are enclosures filled with mud and decaying vegetable matter and are watered by a canal system. They are used for vegetation and used for cultivation of mainly vegetables and aromatic flowers. In many ways they are a precursor to hydroponics, based on a nutrient rich water medium (de Anda and Shear 2017). They are usually rectangular and 100 to 850 m^2 in size. Effective use of seed beds allows continuous cultivation. The only existing canal systems remaining are in Xochimilco, a suburb of Mexico City and have been registered as a World Heritage Site by the United Nations Educational, Scientific, and Cultural Organization (UNESCO) since 1987 (Dieleman 2016).

There are various other gardening methods, some ancient such as hanging gardens, vineyards, orchards and some not so ancient such as green houses and some quite modern, or at least dressed in modern clothing such as Raingardens, Hydroponics, Aquaponics, sky farming, vertical farming, Zfarming, etc. The soilless culture of plants was popularized in the 1930s which the modern Hydroponics practice has grown from. Aeroponics, also based on these principles, has exposed roots in a controlled moist environment into which nutrients are added (de Anda and Shear 2017). Vertical farming focuses on growing crops on the sides of buildings and may use aquaponic principles which can increase yield up to 20% (Corbould 2013). Zero acreage Farming or “ZFarming” is an initiative in Berlin, Germany aiming at energy efficient production of local food. The proponents identify roof top gardening as having the best potential for farming in Berlin without the need for additional land for agriculture (Specht et al. 2015).

Not all innovations are modern of course, the hanging gardens of Babylon (Britannica 2017) and other Innovative agricultural techniques such as UNESCO world heritage listed rice terraces of the Philippine Cordilleras which may be as much as 2000 years old are examples (UNESCO 2016). Classical authors describe the hanging gardens as roof terrace and balconies with an exceptional irrigation system. They were waterproofed using layers of lead, reeds, bitumen, etc. (Britannica 2017). This description could easily fit in with some of today’s modern green buildings such as Sydney’s latest in central park which boasts the tallest vertical gardens in the world (NIEA 2013). This move towards building integrated agriculture (Gould and Caplow 2012) comes with its own challenges, selection of plant varieties that can thrive under the given conditions is important (NIEA 2013). Also, if the produce is intended for sale then appropriate plants need to be selected to meet market demand, and this is a complex issue and the challenge of any farmer. A deeper scientific understanding of the various urban agricultural forms is needed, particularly in regard to economics, productivity and water consumption to maximise sustainable development in a way that suits various cultural preferences.

2.4.3 Impact on water demand

Design and Innovation is a contributing factor to the uncertainty of economic analysis of RWH systems generally (Melville-Shreeve et al. 2014). With urban agriculture this is expected to be true to an even greater extent with various types of growing methods, as discussed above, such as in ground, raised beds, wick gardens, pots being considered for urban agriculture including various hi-tech systems with controlled lighting and water use, also concepts such as sky farming (Amos et al. 2018a; Germer et al. 2011), ZFarming (Zero acreage farming) (Specht et al. 2016) Aquaponics each having various water requirements and system setups, or low-tech systems such as the various garden Kits used in Africa (Merrey and Langan 2014).

The water delivery system also adds another dimension, drip irrigation requires pressure which implies a pump which is a large contributing factor to RWH systems being financially non-viable (Amos et al. 2018a; Germer et al. 2011), Irrigation without pumping is preferable. Merrey and Langan (2014) presented various garden kits that don’t require pressurised irrigation and are suitable for developing countries and also minimise energy use. The types and varieties of plants grown will also have a huge impact on water consumption. Woltersdorf et al. (2015) found that in Namibia the most promising adaptation measures to sustain yields and revenues are to change to high water efficient crops. They found that this has a higher impact on irrigation requirements than the change in rainfall patterns.

Different researchers have modelled water use in household gardening and urban agriculture in different ways. How much water is required depends on a number of factors as noted below:

- Installation type (design and innovation)
- Irrigation type
- Sprinkler
- Drip irrigation
- Subsurface irrigation
- Hose, watering can, etc
- The crop being produced (type and variety)
- Climate
- Rainfall
- Temperature
- Wind
- Evapotranspiration
- Available green water (ground moisture)
- Soil type
- Mulching.

It will be important to know the efficiency of the various garden types and irrigation methods in order to calculate the reliability of RWH systems. The cost of implementation and the implied manual labour attached to each system, comparing for example, using a watering can with drip irrigation, must be considered. The acceptability of various systems will vary with culture and economics. A combined RWH and urban agricultural analysis tool could be used to optimise existing systems, and assist in the design of new and sustainable systems.

2.4.4 Water sources

The relationship between water and crop production is well known to farmers, and irrigation scheme designers. Rain-fed agriculture refers to crop production without irrigation relying on “green water”, soil moisture available to plant growth, common in farming large areas where irrigation is impracticable. Irrigated agriculture is usually a combination of rained agriculture complimented by irrigation, using “blue water”, liquid water in water bodies, as rivers, lakes and aquifers (Falkenmark 1995), to increase yield, or make cultivation possible in arid climates. (Ran et al. 2017). Urban agriculture may implement either method (Lupia and Pulighe 2015). Home gardens, often rain-fed systems, are used to supply food and provide income particularly in many developing countries. However, in many areas they suffer problems with the variable and unreliable nature of rainfall. The method and water source alternatives available will impact the relative cost and the economic viability of using a RWH system to supply water. Where there is abundant and cheap water available from other sources RWH systems are likely to be less viable. The following alternative sources may be considered for irrigation:

- Mains water
- Dam water (far dams, large reservoirs, etc.)
- River water
- Spring water
- Ground water / Bore water
- Natural aquifers
- Recharged aquifer schemes
- Upside-down dams
- Recycled water
- Black water (often used untreated in developing countries)
- Greywater
- Desalination
- No irrigation: ground moisture and rain-fed only.

The Australian Bureau of Statistics (2013) report that in the state of New South Wales (NSW) approx. 48% of people use mains water to irrigate, 26% do not water or rely on rainfall, while 12% use RWH systems. Figure 2.9 shows the water sources used in Australia for gardening state by state, as can be seen, in 2013, mains water is by far the most popular, with rainwater being the second most excluding a rain-fed only system. Australia wide, mains water is by far the most popular irrigation source in urban areas, with harvested rainwater being the second most popular excluding a rain-fed only system. There is therefore great potential to increase rainwater harvesting use in urban agriculture even in Australia, which is quite advanced in terms or RWH. Research by Jayasuriya et al. (2014) indicates that tanks from 2 -10 m^3 can have a significant impact on home garden productivity and that tanks of 10 m^3 offer a reliability of up to 95% for a home garden plot of 500 m^2 in Sri Lanka, which has a monsoonal rainfall pattern. The variables that affect urban agriculture and rainwater harvesting are diverse, particularly climate. Tools are needed that can determine the appropriateness of RWH to supply water to a given urban agricultural system in any climate and circumstance. An integrated water management approach that considers the wide range of factors can lead to the most sustainable solutions in each case.

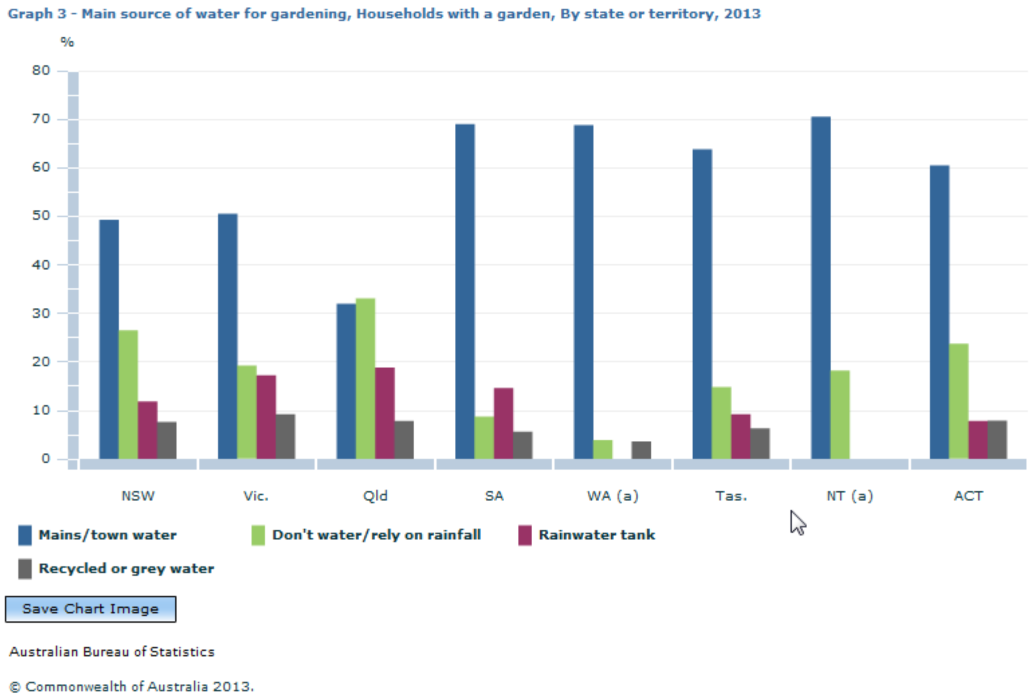

Figure 2.9 Australian Water Sources for Gardening. Source Australian Bureau of Statistics (2013).

2.5 Economic analysis

Economic analysis is an important aspect of making sustainable development a reality. The water sector commonly uses the life cycle cost (LCC) analysis method. In Australia and New Zealand AS/NZS 4536:1999 defines the proper process of conducting a LCC analysis (Australian Standard 2014). Due consideration of costs must be given over a product's entire lifecycle, including acquisition (often called capital costs), use and maintenance (often called maintenance and operational costs), renewal and adaption, and finally the cost of the products disposal. Following a LCC guideline is very useful in ensuring that costs are not neglected as they appear to be in the research on economic analysis (Mitchell and Rahman 2006; Roebuck et al. 2012; Ward et al. 2012a) . LCC considers both costs and benefits cash flows (CF), relative to the time they occurred by adjusting the value according to a discount rate producing the present value (PV) of the CF as in equation 1.

$$\text{Discount rate} = \frac{1}{(1+\mathrm{i})^{\mathrm{t}}}\ \mathrm{PV} = \frac{\mathrm{CF}}{(1+\mathrm{i})^{\mathrm{t}}} \tag{1}$$

Where (i) is the interest rate (i) and (t) the year in which the cash flow occurred. The PVs are then used to produce various economic measures, such as the net present value (NPV), benefit cost ratio (BCR) and payback period (PP). The NPV is calculated by summing the annual net cash flows over the number of years, N, as in equation 2.

$$NPV(\mathrm{i},\mathrm{N}) = \sum_{\mathrm{t}=0}^{\mathrm{N}} \frac{\mathrm{CF}_{\mathrm{t}}}{(1+\mathrm{i})^{\mathrm{t}}} \tag{2}$$

The BCR is the ratio of costs (C) to benefits (B) and is calculated as in equation 3.

$$BCR = \frac{\sum_{\mathrm{t}=0}^{\mathrm{N}} \frac{\mathrm{C}_{\mathrm{t}}}{(1+\mathrm{i})^{\mathrm{t}}}}{\sum_{\mathrm{t}=0}^{\mathrm{N}} \frac{\mathrm{B}_{\mathrm{t}}}{(1+\mathrm{i})^{\mathrm{t}}}} \tag{3}$$

The payback period (PP) is "the time required to recover an investment or loan" (businessdictionary.com 2015; investinganswers.com 2015). If the project does not present a PP, the NPV is negative, or the BCR is less than one the project will not create a profit. There is some debate over the economic measures used, some argue that being a ratio the

BCR does not present the actual benefit or cost clearly (Cbabuilder, 2016) and suggest that presenting both the BCR and the NPV together is preferred. Gato-Trinidad and Gan (2014) state that while the PP is easy to understand it gives no measure of the benefits after the PP period.

Table 2.1 presents a summary of selected articles that address the LCC analysis issue and also use a selection of modelling tools that will be referred to later. It also includes works done in modelling small scale rural farms that is relevant to urban agriculture.

Table 2.1 A selection of results from article on rainwater harvesting systems and urban agriculture

Location & Ref	Modelling Methods	MAR	Roof Area	Tank Size	Irrigated area	What is irrigated	Methods	Quantity produced	Reliability	Costs	Benefits	Pay-back period	NPV
		mm	m^2	m^3	m^2				%			Years	
Laikipia District Kenya (Ngigi, Savenije et al. 2005)	Hydro-economic analysis	280-1100	5000	30, 100 ponds	2000	Maize	Drip irrigation	4000–5000 kg/ha, showing an increase of 1000 kg/ha.	67-80 (during rainfall seasons)	Dam, drip irrigation system	market price maize net benefit of US$ 150 per season	1-2	
India (Stout et al. 2017)	RWH - Water mass balance method ET - Penman-Monteith (FAO)	492 - 1605	21	0.75, 1.9	20	Tomatoes and lettuce	not specified	2.75 kg of tomatoes and 1.05 kg of lettuce	30 - 60, 60 - 90	construction 1363 - 2082 INR, and maintenance	0 - 1550 INR/ yr for water 2605–4522 INR/ yr for vegetable production	none, 1 - 12	21,764–38,851 INR
Rome Italy Lupia, F. and G. Pulighe (2015)	Irrigation areas estimated from geodatabase Irrigation water requirement (IWR) formulation		100	assume 60% of rainfall		Horticulture, mixed crops, orchards, vineyard.	Surface and Drip irrigation	not specified	18 - 41 of horticulture sites could be sustained	no specific economic analysis			
Namibia (Woltersdorf et al. 2015)		400-500	100	30	60-104	various crops	Drip irrigation and rainfall garden plot	?					

Sydney Australia & Nairobi Kenya (Amos et al. 2018)	"ERain" water balance model combined with life cycle cost analysis	964 Aus 891 Ken	Aus - 200 Ken – 120	1-7, 10,15	Aus - 120 Ken - 60	lawn	sprinkler supple-menting rainfall	ornamental, no produce	Aus 47-100 Ken 20 - 94	Acquisition Aus 3251-5319 Ken 386 - 1444 Ongoing Aus 1062-1158 Ken 37 - 390	Water savings, rebate, hedonic price and	none, or	US$ Aus 18484 cost to small benefit Ken 6208 cost to 1248 benefit
Western Australia (Yang et al. 2009)	"AQUACYCLE" Water mass Balance Method. Greywater and rainwater compared.	490	249	1-300	not specified	lawn	not specified	ornamental, no produce	62-100	no specific economic analysis			
Brisbane Australia (Cook et al. 2013)	"Urban Vol. and Quality" (UVQ) water mass balance: 6 min time step, case study (retirement village)		10700 for 46 house-holds	400, 40 for treated water				ornamental, no produce	90%				

Published literature in the field of roof RWH for use in urban agriculture are limited in Australia and developing countries. Research on domestic irrigation is focused on water savings and does not consider food production or nor discuss the condition of ornamental gardens. In developing countries there is some, but limited research. In India Stout et al. (2017) found that irrigating a small garden (20 m^2), with overflow (40% of site rainfall) used for ground water recharge (GWR), could pay for itself within a year (PP = 1 year). The garden meets the caloric requirements of the typical Indian household and excess food is sold. However, the paper does not explain if the savings from the food produced could also have been made if low cost mains water, were used instead. In Kenya (Ngigi et al. 2005) performed a hydro-economic analysis of using rainwater harvesting to improve domestic crop yields, but they considered runoff and dam storage and not roof harvested rainwater. The dam could be considered equivalent to a rainwater tank at 30 and 100 m^3 but the runoff catchment area is far larger than an average roof size. They propose a similar a PP period to Stout et al. (2017) of 1-2 years for a dam and drip irrigation system by increased maize production. Woltersdorf et al. (2015) found that a 30 m^3 tank and a roof area of 100 m^2 in a semi-arid region of Namibia could irrigate between 66 and 104 m^2. Interestingly they found that the crop variant cultivated had more impact on production than the predicted climate change. They propose increasing the roof size to increase water harvest. They also suggest that at present water prices it would still be profitable to irrigate with water from the public supply. They admit that while it is a bad option for agriculture generally, for small scale home gardens it might be viable as a supplementary to the RWH system. However, they note that if tap water prices increase, as expected, this could change, and could also lead to inequity within the community.

2.6. State of the art modelling methods

2.6.1 Input data

Increased access to data has also contributed to developing models capable of assessing the data. Consider that the instrumental age is only considered to be the last 100 years (Zillman 2001). Coombes and Barry (2012) proposes that all the detailed local inputs need to be analysed to create successful solutions including “demographic profiles, human behaviour and climate dependent water demands, and linked systems that account for water supply, sewerage, stormwater and environmental considerations”. The majority of water balance models discussed in this review relies on daily rainfall data. However, in many parts of the world this data is not available. In these cases estimated rainfall data from satellites (Ciabatta et al. 2015; Li et al. 2015; Munzimi et al. 2015; Prakash et al. 2015) or simulated data may be used in its place. In a water balance approach to analysing RWH in India Stout et al. (2017) used 3 hourly satellite rainfall data from NASA Tropical Rainfall Measuring Mission (TRMM). This publicly available data was gathered by the Japanese Aerospace Exploration Agency and NASA (NASA 2013). The data was calibrated with ground based measurements. Lupia and Pulighe (2015) acquired data from WorldClim (Hijmans 2005) which provides climate grids with a spatial resolution of 1 km^2 and rainfall in 6-min time intervals. These can be integrated into GIS raster grids using programs like ArcGIS. Gridded climate data (0.05^o) is also available from the Australian Bureau of Meteorology (BOM 2017).

2.6.2 Modelling combined systems

There are only a few studies area available on RWH system modelling combined with urban agriculture. Stout et al. (2017) investigated ecosystem services regionally throughout India, using a water mass balance model with a daily time step (cf. Table 2.1). The inputs for the RWH model are daily rainfall data and tank volume, while the input is the water demand. Seasonal evapotranspiration (ET) rates were calculated using FAO's Penman-Monteith method, described by Smith et al. (1991), for each city. Crop yield was based on the production of tomatoes and lettuce, rates obtained from an urban design lab (Ackerman 2011), multiplied by the garden area. Household vegetable consumption rates, based on a national survey (NSSO 2007), with any remaining crop is then sold at local rates. Cost analysis was based on mains water price, acquisition, use and maintenance costs and the vegetation supplementation potential. The regional cost of tomatoes and lettuce were obtained from Ackerman (2011). NPVs are calculated over an 11-year life cycle. It is not clear if any cost of sales was deducted from the profits, such as time, transport to markets, etc. It is also questionable if the any profit from vegetable sales should be attributed directly to the RWH system if the water could equally have been sourced from elsewhere. It does not seem that any monetary value was fixed to the groundwater recharge of the optimum system. It also appears that their MATLAB model was restricted to the RWH system itself while the crop production and LCC analysis was calculated separately. The assumed irrigation method is not discussed as it is by Jayasuriya et al. (2014) who consider both pot and drip irrigation methods.

Ngigi et al. (2005) model a small dam and groundwater runoff in semi-humid and semi-arid areas in Kenya (see Table 2.1), which may be considered similar in principal to a RWH system, perform a hydro-economic analysis focusing on bridging dry spells for increasing crop production. The work is done from the perspective of agricultural investments for small scale farms (<2ha) which have become more common since the end of colonisation in the 1960's and thus falls into the scope of urban agriculture. Firstly, historical rainfall records from the regions were analysed to assess the probability of meeting crop water demands. Planting dates were staggered according to rainfall onset window obtained from combining information from FAO and other reports using FAO methodology (FAO 1978). The work is done from the perspective of agricultural investments for small scale farmers and thus falls into the scope of urban agriculture. Light, moderate and severe droughts were reported as well as seasonal dry spells considering crop water requirements for maize and soil moisture balance. A drip irrigation system was assumed and relevant parameters for maize production including root depth, crop efficiency, and planting times used. A daily time-step water balance approach to soil moisture balance was used to calculate supplementary irrigation requirements (SIR). SIR is estimated based on the effective rainfall, P_e (including surface runoff stored in reservoirs and used as irrigation and that used through infiltration within the root zone), and the crop water requirements, E_c (estimated from evaporation (ET) data and crop type) and the soil moisture deficit, D. The soil moisture balance is calculated for each time-step, t, as in equation 4.

$$\frac{S_t - S_{t-1}}{\Delta t} = P_e - E_c \tag{4}$$

Where S_t = soil moisture storage per unit surface area at time t, S_{t-1} = soil moisture storage per unit surface area at time, t-1. Δt = the time interval. Supplementary irrigation requirements, SIR, are then calculated as in equation 5.

$$SIR = max\begin{cases} 0, \\ D - \dfrac{S_t - S_{t-1}}{\Delta t} \end{cases} \tag{5}$$

If there is more rainwater than required to meet the soil moisture deficit (D) and the crop water requirement (E_c) then the soil moisture reserve (S) is replenished. If the soil reaches its maximum capacity S_{max} deep percolation (D_p) occurs. However, was generally assumed that excess water is drained off at each step. The effective rainfall was estimated with empirical equations from FAO Irrigation and Drainage Paper No. 25 (Dastane 1974) No. 56 (Allen et al. 1998) and a training manual put out by FAO and the World Meteorological Organization (WMO), (FAO and WMO Undated).

Woltersdorf et al. (2015) analysed the impact of climate changes on small-holder horticultural production in a semi-arid region of Namibia. They used a software program called CROPWAT for calculating crop water requirements in accordance with their Irrigation and Drainage Paper No. 56 (FAO 1988). FAO produce many technical papers related to agricultural production (FAO 2018) and other software programs such as AQUACROP that simulates crop production under different irrigation regimes (Khov et al. 2017). CROPWAT uses soil, climate and crop data to calculate crop water and irrigation requirements on a monthly basis. Woltersdorf et al. (2015) use results from CROPWAT to find garden irrigation requirements which then becomes the outflow in a monthly time-step RWH system model. They justify the monthly time-step with reference to the storage fraction (see equation 10). They consider a 30 m^3 Ferro-cement tank, 100 m^2 roof area and four different garden scenarios produced by varying the crop choice, water requirement, garden size, crop production and market revenue. The philosophies behind the garden variants were subsistence, low water, cash and super-cash (maximise revenue). The first three options included a tree, while the last option did not. The risk of harvest failure was then assessed, and they found that adaption measures would be necessary with temperatures increase and rainfall decreases. Planting dates were optimised using FAO's Crop Water Requirements and Irrigation Scheduling manual (Savva and Frenken 2002). This considers time needed for sowing, transplanting and preparing the land for the next crop as well as climate conditions. The best time for planting is during periods of high rainfall and low evapotranspiration which in their case was Jan-Feb while the worst time is in the preceding two months due to high temperatures and low humidity. They found operating the gardens with one growing period per year starting in the wet season was more efficient than two growing seasons. Gardens were optimised such that the harvested rainwater would be sufficient for 3 out of 4 years as deemed sufficient for irrigation schemes by FAO (Critchley 1991). The interaction between the tree root system and crops is not discussed and neither is the effect of the building envelope on shade, etc.

Lupia and Pulighe (2015), provoked by recent increases in urban agriculture, assess the potential of using RWH for irrigating residential kitchen gardens in Rome, Italy (Table 2.1). Their approach is quite unique and worth considering. They used a spatial data set produced by the Italian institute of Agricultural economics (INEA) from high resolution google earth imagery. The data set includes information about urban agricultural sites throughout Rome such as land use (horticulture, mixed crops, orchards, vineyards and olive groves) and size. This data was used to estimate irrigation water requirements (high and low) for each plot using the method described in FAO Irrigation and drainage paper 56 (Allen et al. 1998) using common Mediterranean crops. The water demand was then compared spatially with nearby roofs that have potential for RWH. Water harvested was calculated using a simple equation based on the MAR, roof area, and a harvesting efficiency of 60%. Monthly precipitation and evapotranspiration data was used from the web portal WorldClim (available at http://www.worldclim.org/) which provides information over a 1 km grid resolution (Hijmans 2005). Due to lack of information on building envelopes a roof area of 100 m^2 was assumed. However, they concluded that irrigated urban horticulture is sustainable. One limitation of this study was that inner-city residential gardens were not included.

2.6.3 General RWH system modelling

Stout et al. (2017) paper on ecosystem services from RWH and Ngigi et al. (2005) hydro-economic evaluation of surface runoff dam storage systems for Farmers investment options are a good representatives of the distinct types of analysis found in the literature. The former paper while considering urban agriculture still focuses more on the RWH system analysis while the later provides more detailed analysis of crop production expected from an agricultural perspective. Many of the models used for RWH system analysis do not consider seasonal variation in irrigation demand (Mitchell 2007).

In many disciplines computer simulation and modelling has taken precedence over formulation. RWH and agricultural analysis is no exception with water balance models finding preference over formulation. AquaCrop, developed by FAO (Khov et al. 2017) is one example of this in agriculture used to predict plant growth relative to soil moisture, presently being calibrated for peanut growth in remote areas such as Laos. In a controlled experiment Ward et al. (2012b) compared the actual performance of a RWH system with findings from a theoretical and a model based analyses, the latter was found more accurate. Londra et al. (2015) compare a dry period demand method with and conclude that RWH systems are strongly influenced by local variables and cannot be formulated, and prefer the daily water balance method. Mitchell (2007) considered the importance of the computational analysis method to the accuracy of model-based analysis focusing on the behavioural method, time step and number of years of analysis.

There are two RWH system behavioural models often discussed, these are supply/yield after spillage (YAS) and supply/yield before spillage (YBS). Fewkes (1999) developed the concept based on earlier work by Jenkins et al. (1978) and used it in combined RWH and greywater system analysis (Dixon et al. 1999). They are described mathematically by Fewkes and Butler (2000) as shown for yield after spillage in equations 6, and for yield before spillage in equation 7.

$$YAS: \qquad Y_t = min\begin{cases} D_t \\ V_{t-1} \end{cases} \qquad V_t = min\begin{cases} V_{t-1} + Q_t - Y_t \\ S - Y_t \end{cases} \tag{6}$$

$$YBS: \qquad Y_t = min\begin{cases} D_t \\ V_{t-1} + Q_t \end{cases} \qquad V_t = min\begin{cases} V_{t-1} + Q_t - Y_t \\ S \end{cases} \tag{7}$$

Where t = time interval (min hours or days), Y_t = yield, or water use, from store in the interval, D_t = water demand in the interval, V = volume in the store (tank) during interval t or t-1, Q_t = rainfall runoff during interval, S = store capacity (tank size). The basic difference between the two methods is that with the YAS the rainfall fills the tank (storage) after the water is used (demand) and so there is no access to the rainwater that fell in that time interval, whereas YBS assumes that the rainfall comes before the tank is used and is therefore available for use. Both Mitchell (2007) and Fewkes and Butler (2000) advise using YAS as it is more conservative and this is the method most commonly used. For their water mass balance model Stout et al. (2017) chose a yield after spillage (YAS) method rather than yield before spillage (YBS) because of work done by Schiller and Latham (1987) who also finds YAS conservative. Hajani et al. (2013) found that YBS could overestimate the water savings by 10%–15%. However, Mitchell (2007) found that the degree of overestimation is dependent on the time step. Finding that with a 6 min time step over 50 years of data the difference between YAS and YBS was negligible. They admit that in some cases with a 24-hr time step the long-term yield can be significantly underestimated by the YAS model. In most cases a daily time step is considered quite accurate. Not much difference in accuracy was found between 10 and 50 year simulations but 1 year simulations not recommended. Fewkes and Butler (2000) proposed a measure called storage fraction (SF), shown in equation 8, for deciding acceptable time-steps for a given system configuration.

$$SF = {}^{S}/_{AR} \tag{8}$$

Where S = storage capacity/ tank size (m^3), A = roof area (m^2), and R = annual rainfall (m). hourly data can be used for SF below or equal to 0.01, daily data for SF between 0.01 and 0.125, and monthly only for SF greater than 0.125. This means that for a roof area of 200 m^2 and an annual rainfall of 1000 mm, daily data would be acceptable for analysing tanks from 2 to 25 m^3 and for larger tanks monthly data would also be acceptable. However daily rainfall data is the most commonly collected time series rainfall data. Maheepala et al. (2013) found using daily data as opposed to hourly only overestimated the yield by 2%. Devkota et al. (2013) used a monthly life cycle-based model called “*EEAST*” which overestimate the size of tank needed.

In Australia *Aquacycle* is a daily time-step model produced by CSIRO (Mitchell et al. 2001). It models water flow through the urban water supply, stormwater and wastewater systems. Aquacycle was built with the concept of integrated water management and getting away from the history of fragmented water systems. Mitchell et al. (2001) noted that the, “*interaction between the potable water supply–wastewater discharge network, and the rainfall–stormwater runoff network, is rarely considered within the same modelling framework*”. Later Zhang et al. (2010) use *Aquacycle* to investigate greywater reuse and rainwater harvesting using daily rainfall data they were able to determine reduction in mains water use and stormwater reductions for both systems. A model called "*Urban Volume and Quality*" or *UVQ* is also a daily time-step built by enhancing Aquacycle but also incorporating wastewater quality (Farley 2000) referred to in Marleni et al. (2011) in the context of sustainability seeking to source water and re-use wastewater locally and source management practices (SMPs). Recognising issues with reduced flow in sewer systems such as odour and corrosion they use UVQ to simulate water and wastewater flows for 6 different scenarios including greywater recycling and using a RWH system for toilet flushing. The *UVQ* also estimates the wastewater quality. Cook et al. (2013) use *UVQ* as their water balance model to track flow paths and contaminant levels and explore the reliability of a communal residential RWH system supplying a 46-home retirement village development near Brisbane, Australia. *ERain* was produced at Western Sydney University, Australia based on an extensive review of RWH in both developed and developing nations (Amos et al. 2016). *ERain* is also a daily time step water balance model but integrates LCC analysis into the model. *ERain* was used assess rainwater harvesting potential in Sydney, Australia (Amos and Rahman 2016) and to compare the economics of RWH in both developed and developing countries. *ERain* was used to analyse the impacts of roof size and irrigation area on RWH systems economic (Amos and Rahman 2017) but this did not include crop production. Extensive LCC analysis data is used and calculated on a yearly time step with annual water savings being aggregated from the daily savings.

In Kenya The water supply services practice manual provides some simple formulas for sizing RWH systems (Belgium Study and Consultancy Fund 2005). These methods and similar ones used in the UK (Government 2010; Standards 2009; UK Department for Communities and Local Government 2010) and have been found to be inaccurate compared more advanced methods models (Roebuck et al. 2012; Ward et al. 2012b) . Jomo Kenyatta University of Agriculture & Technology (JKUAT) developed the *"JKUAT-RWH Performance Calculator*" which is a daily time-step model using daily rainfall data to analyse various configurations of RWH systems. Gathenya et al. (2010) used the model to develop "nomographs" that plot tank size against roof area for a given reliability. The nomographs can then be used for financial decisions based on the designer's preference for increasing either the roof or tank size to acquire the same expected reliability. Results from the *JKUAT-RWH Performance Calculator* were compared with the "*Warwick Calculator*" developed in the UK by Warwick University (Engineering 2015) and results were found comparable even when using monthly rainfall data to do the analysis. The "Warwick Calculator" is a daily time-step model that uses monthly data to generate a pseudo daily sequence using an algorithm that gives a daily sequence similar to historic records (Warwick University 2018).

In Spain Morales-Pinzón et al. (2015) developed *Plugrisost* (standing for pluvials, greys and sustainability) to contribute to urban water planning and smart city development. It was built in a software program called "*Stella*" that can model dynamic systems. *Plugrisost* analyses RWH and greywater systems at a daily time-step and uses daily rainfall data as an input. The novelty of *Plugrisost* is that it integrates system analysis with not only financial but also environmental analysis. Similar to Cook et al. (2013) use of *UVQ for* a retirement village, earlier work by Morales-Pinzón et al. (2012) found that the for large-scale and high-density development RWH at the neighbourhood scale was preferable. Then Morales-Pinzón et al. (2014) found that the most profitable arrangement for RWH systems was groups of houses and apartments rather than individual. It is worth noting that currently in Australia there is a push for increasing medium to high-density infill with transport and green space access (Jackson et al. 2017). *Plugrisost* was developed with the concept of analysing various development types such as individual household, retirement village or high-density development, etc. Analysis using *Plugrisost* found that the apartment scale is financially preferable to the single house scale in Spain (Morales-Pinzón et al. 2015).

There are a number of other daily time-step water balance model models that have been developed such as *RainCycle* (SUD Solutions 2005) used by (Farreny et al. 2011). *EEAST* which performs both environmental and cost life cycle analysis of RWH systems and composting toilets (Devkota et al. 2013). These models have been developed in the context of an increased awareness of the need for a sustainable approach to water management in Cities. Integrated water management (IWM) and water sensitive urban design (WSUD), called sustainable urban design (SUD) in the US, and increased environmental awareness. Towards this goal Kahinda et al. (2007) divided regions of South Africa into "ecotopes" (areas with same physical and socio-economic characteristics). They Stout et al. (2017) make use of ArcGIS to determine average roof sizes. Not only is integrated water management coming into focus but also integration of the water, food and energy nexus (Belinskij 2015). All this requires an increased calling for modelling tools that can process a large amount of data becoming available to us.

2.7 Discussion

RWH from roof catchments has been predominantly limited to in-house use and outdoor cleaning, but there is a strong potential to boost agricultural production within urban territory by changing the design of RWH systems and with more understanding of crop selection, climatic effects, water requirements, and economic aspects of RWH systems. In Australia it is common to use RWH systems for toilet flushing. A more sustainable approach may be to use waterless composting toilets that produce fertilizer, e.g., the "Clivus Multrum" (Incorporated 2015). In peri-urban and rural areas of developing countries particularly the fertilizer can produce an income or enhance crop production (Morgan 2007) in conjunction with the harvested water. Harvesting excess runoff in RWH systems and using it in urban agriculture combines the sustainability benefits of both having potential to improve sustainable living in multiple ways:

1. Improved nutrition, especially among the poor;

2. Reducing "food miles" and hence fuel used in transportation, greenhouse gas emission, and costs through local food supply;

3. Socio-economic benefits such as social interactions and education;

4. Reducing the urban heat island effect through increased green spaces;

5. Mimicking the natural water cycle by local water retention;

6. Results in cleaner water ways because less pollutant wash-off; and

7. Reduced flooding risk.

There is increased demand for urban water (Jackson et al. 2017) but greater efficiency of water use, and improved water storage and recycling facilities counteracts this to some degree. To address pressure on the water supply in many Australian cities there has been a strong policy to reduce the water demand for urban use by changing consumer behaviour, increasing efficiency of water use, and improved water storage and recycling facilities. There is mounting concern in many developed nations with competition over water resources expected to increase globally (Flörke et al. 2018; Proskuryakova et al. 2018; Tularam and Murali 2015). The availability of a safe and reliable water supply is a well-known problem in many developing nations (Stout et al. 2017). In urban centres there can be a play off between minimising and maximising water use. Maximising mains water use, when it is available, is more profitable for the water companies, but they have a responsibility to ensure it doesn’t run out. Minimising water use overall can increase water security, but maximising rainwater use results in higher water savings (and apparent financial benefit in economic analysis) and also is likely to have a bigger effect on minimising stormwater runoff (Amos et al. 2016), except in cases where reliability has a financial effect, for example by triggering purchases of bottled water at higher prices when the RWH system fails (Amos et al. 2018a). The concept of using as much water as possible to produce as much food as possible therefore satisfies both these criteria: where there is more water available more food can be produced while reducing urban runoff.

The sustainability of using treated tap water for irrigation is questionable and proposing to increase urban agriculture to make “green” cities only compounds the issue. Is it ecologically sound or viable to use treated tap water to irrigate urban agriculture, if not, then where will the water come from? In many cities the domestic water supply is already strained without adding to it the burden of extensive urban agriculture. If more dams need to be built to supply the increased demand for urban irrigation water, then this would need to be considered in any LCC analysis as a benefit to using RWH instead. The use of RWH for domestic use such as irrigation, laundry and toilet flushing has been considered favourable despite many, but not all, researchers showing it to be financially non-viable (Campisano et al. 2017; Ishida et al. 2011; Kumar 2004; Roebuck et al. 2011; Stec et al. 2017). This is probably because other benefits are recognised that are not easily quantifiable in a LCC analysis. For example Zhang et al. (2015) state that real estate agents recognise RWH systems as an “eco-friendly feature” and estimated that they increase a property’s value by US$14,160 in Perth, Australia. A RWH system may not be subject to water restriction as tap water is and so it may be possible to maintain a garden where others cannot. This is a significant point for urban agriculture warranting consideration by the individual, but also by legislators and governments looking at the cities. In Australia RWH has been encouraged by rebates (Gato-Trinidad and Gan 2011; Gato-Trinidad and Gan 2014) and also enforced through various legislation such as Building Sustainability Index (BASIX) in NSW, Australia (BASIX 2016b).

Water for agriculture is also a present and increasing problem globally. For example, in South Africa there are 200 000 ha of backyard gardens in rural homesteads representing half irrigated land, these are extremely important for resource-poor households. However, Baiyegunhi (2015) reports that home garden programmes often fail due to lack of water particularly in the semi-arid regions. Consequently, in Sri Lanka Jayasuriya et al. (2014) find that they are often neglected due to scarcity of water during cropping seasons and investigate RWH as a solution. Rainwater harvesting has already been found to significantly improve agricultural productivity in arid and semi-arid regions (Unami et al. 2015). The potential improvement in food security that RWH systems offer is well recognised (Helmreich and Horn 2009; Kahinda et al. 2007; Morgan 2007; Wachira 2015). Moreover, it is known that using RWH systems in small-scale domestic gardens improves women and children’s nutrition (Gwenzi and Nyamadzawo 2014; Ngigi et al. 2005). Even if systems are not strictly economically viable, the question could be rephrased as, is it worth spending money on women and children’s nutrition? What is needed is design, and implementation plans that are feasible and within the given constraints. Although this merges into a socio-political issue correct design is also important, and for this reason it is necessary to model various options and consider their implications. One thing that is not often recognised is that water treatment and supply is a large consumer of power and hence CO_2 emissions, and chemicals for treatment. The relationship between water, food and power, known as the water-energy-food nexus (Europe 2016) is coming into focus internationally along with the increased concern over both water and food security. Biodiversity and environmental concerns add ecosystems to the equation putting urban agriculture well within the scope of the water-food-energy-ecosystems nexus (Vanham 2016). Urbanisation also takes a heavy toll on biodiversity (Plummer et al. 2017) tree planting is seen as a way to minimise the urban heat island effect and reintroduce some biodiversity (Marinoni et al. 2017).

Economic analysis of RWH systems used in conjunction with urban agriculture is important for developing and recommending affordable and realistic solutions particularly in developing countries. If produce is intended for sale as part of household income then appropriate plants need to be selected to meet market demand, and this is a complex issue and the challenge of any farmer. System set up cost come into focus particularly for the individual. Parker et al. (2013) reviewed tank costs for domestic rainwater harvesting in East

Africa find that where there is no reticulation and pump the tank represents the major cost of a RWH system and therefore reducing tank costs is important. They find that constructed tanks are cheaper than prefabricated tanks and conclude that in many cases water from community sources such as communal hand pumps is 10 times cheaper than water from rainwater tanks although admit that a RWH system has certain advantages over a communal source. Amos et al. (2018a) found that financial viability issues were common to both Australia and Kenya influenced primarily by capital costs, replacement costs, water price and subsidiary benefits such as the hedonic price and rebates. Adding urban agriculture to the picture is expected to increase the complexity of the economic feasibility question. In its favour, a whole countries economy may also be boosted by widespread adoption of RWH systems by creating an industry and providing jobs. Herrmann and Schmidt (1999) state that “The market for rainwater usage related products is booming and of increasing economic importance.” Combined RWH and urban agriculture may further boost this important market.

In a broader context a through economic evaluation should consider a wide range of factors and not simply the net present value of a project which is an economic measure that should not be taken as economic conclusions (Australian Standard 2014). Many authors consider RWH in the broader context of a multi criteria analysis (Domènech et al. 2013; Lü et al. 2013; Melville-Shreeve et al. 2016; Singh et al. 2017) and have called freshwater the backbone of socio economic development and the lifeblood of the biosphere (Jha et al. 2014). Multi criteria analysis (MCA) is a technique that does not necessarily rely on monetary valuations produced by a life cycle cost analysis (Dodgson et al. 2009). Food and water security particularly should be a high priority at any “cost”. The fruit of the antithesis is well expressed by the renowned Native American Indian proverb that, only when the last tree is cut down, the last fish eaten, and the last stream poisoned, will we realize that you cannot eat money (Speake 1983). Michael mobs, famous for his Sydney inner city sustainable house, pointed out, the main barrier to sustainable living in Sydney is food, simply because of the water required to produce a daily meal (Mobbs 2012). Moving towards more sustainable cities will require innovative thinking checked by scientific analysis. The development of modelling tools appropriate to new innovations will form an important part of this analysis as we develop along the road of sustainability.

2.8 Summary

This review confirms that both rainwater harvesting (RWH) from rooftops and urban agriculture are important and emerging practices holding potentially significant cultural and economic value. The sustainable production of basic human needs, and particularly of food and water, within the urban environment is an important and current concern. Inability to supply sufficient food and water has been the root cause of many famines and death for millennia. Sadly these issues still remain and are a prominent feature in the current United Nations sustainable development goals (SDGs), in Goals 2 and 6. Independently both urban agriculture and RWH are reported to increase nutrition, particularly among women and children in developing nations, and to increase water security in both developing and developed countries. They have also been shown to contribute towards other pressing issues documented by the SDGs which Australia and other so-called developed countries do not meet, namely, Goal 11 - Cleaner and sustainable cities, and Goal 3 - Health and wellbeing. In terms of sustainability, all countries should be seen as developing. The potential that roof RWH systems can supply water to urban agriculture has been demonstrated in the literature, for example one study reports that irrigating a small garden (20 m^2) with harvested rainwater can increase the yield by about 20% meeting the caloric requirements of a typical Indian household. Another research indicates that for a large 500 m^2 home garden plot in Sri Lanka even a 2 m^3 tank can have a significant impact on productivity, and that a tank of 10 m^3 offers a reliability of up to 95%. On a city wide scale another study found that 41% horticulture sites in Rome could be sustained by water harvested from local roofs that already exist in close proximity to the sites.

The current practice of urban agriculture in developing countries is economically viable in many circumstances but often fails or falls short of efficient production due to water shortages. Independently increasing urban crop production via urban agriculture and promoting green infrastructure will increase the burden on existing water supply networks. Moreover, using water treated to drinking standards for urban agriculture is unnecessary and not environmentally sound as water treatment has a high carbon footprint. The combined use of RWH and urban agriculture may therefore be an important step towards sustainability, where locally harvested rainwater generates locally produced food while reducing urban runoff and flooding and restoring the natural water cycle, encouraging increased nutrition, social activity, health, wellbeing, and overall, more sustainable cities.

The main obstacles to accomplishing sustainability through rainwater harvesting and urban agriculture found in this review are a lack of knowledge, a lack of design methods, and a lack of initiatives to use roof harvested rainwater in urban agriculture. The latter of these merges with socio-economic and political issues that vary both internationally and regionally. RWH and urban agriculture do not traditionally form part of urban water management strategies and both practices, although not new, are emerging independently. The lack of initiatives to combine roof rainwater harvesting with urban agriculture and the accompanied want of scientific research in the specific area of using harvested rainwater for urban agriculture is a major obstacle. The lack of understanding and access to technical tools and models that can inform stakeholders inhibits the development of creative and productive sustainable solutions. Moreover, it is difficult to assess the sustainability of given solution, and to quantify its potential contribution to an integrated water management strategy. This want of knowledge is apparent across the literature and is seen across the various forms of urban agriculture being noted by several authors. The extent of urban agriculture that RWH can support is unknown. The economic outcomes and the sustainability of water management technologies used in home gardens have not been researched. The design method for using RWH systems in conjunction with green roofs is not well developed, and there is very little research on combined RWH and urban agricultural systems. While there are plenty of tools available to model and analyse RWH systems independently, and plenty to analyse various kinds of agriculture, there are few that are specifically designed to analyse urban agriculture. No tools were found that integrate RWH and urban agriculture into one model in any depth. There are difficulties in accommodating various parameters. The form of urban agriculture, the crop varieties grown and the region in which it is practiced are significant influencing factors which have been highlighted in this article. Analysis is necessarily regional, especially if economics are to be taken into consideration. In this article we have highlighted the barriers and brought together the state of the art in modelling of RWH systems to help the reader appreciate the potential benefits and the hurdles that must be jumped in order to achieve sustainability.

The benefit of a scientific approach in utilising rainwater to enhance agricultural productivity within urban territory around the world is ultimately more sustainable cities.

Understanding the potential and limitations of using roof harvested rainwater to sustain or increase production in urban agriculture will be greatly beneficial to increasing food security in a sustainable way. Developing countries particularly could benefit from implementing or increasing irrigation to urban agriculture and maximising crop production thereby reducing malnutrition and dependence on aid. In Australia and other developed nations where there is sufficient food and water supply it can still improve the sustainability of cities and contribute towards a healthier, more satisfying, and sustainable lifestyle.

To achieve this goal a paradigm shift will be needed, from the current practice of designing RWH systems primarily for toilet flushing and in-house washing and cleaning to designing them in conjunction with urban agricultural systems. This will require reference to crop selection, crop water requirements, irrigation methods and economic analysis. Some lessons in sustainability can be learned from developing countries, notably Cuba's forced experience of local production induced by a lack of access to fuel and fertilizer. If the developing countries can continue to move along the search for sustainability and follow the mindset and make the paradigm shift and increasing technical and scientific understanding, the scientific knowhow and technical knowledge can filter back to the developing countries and help them improve their sustainability whilst the developed countries also improve theirs. The growing trend in urbanisation makes it necessary to also increase sustainable solutions. Modellers and researchers need to provide tools that water engineers, environmentalists, town planners, and policy makers can easily access to design and implement solutions on both an individual and sector wide scale. To understand the potential of combined systems a comprehensive model should be formulated for developing solutions that will be sustainable. The integration of RWH with urban agriculture is an important area for future research in integrated water management and in the broader context of the water-food-energy-biodiversity nexus for both developed and developing nations experiencing increasing levels of urbanisation. Therefore, further research is recommended into combined RWH and urban agricultural systems with a specific focus on potential food production, water savings and contributions to nutrition.

Chapter 3
Economic Analysis of Rainwater Storage Systems Comparing Developing and Developed Countries

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Chapter 3 Economic analysis of rainwater storage systems comparing developing and developed countries

This chapter is a partial reproduction of the following refereed journal paper:

Amos, C. C., Rahman, A., Gathenya, J.M. (2018).

Economic analysis of rainwater harvesting systems comparing developing and developed countries: A case study of Australia and Kenya

Journal of Cleaner Production, 172, 196-207.

Impact factor: 6.395, SJR Quartile: Q1

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3.1 Overview

Rainwater is a naturally occurring potentially clean source of water. There has been an increased interest in rainwater harvesting (RWH) in both developing and developed nations. RWH can alleviate the effects of accelerated urbanisation and improve their water security in the face of uncertain future climate patterns. Australia's management of her millennium drought has proved the effectiveness of RWH systems. Success in Australia is promising for developing countries with inadequate water supply for drinking and sanitation and unreliable centralised water supply systems. However, there is little research on the economic analysis of RWH systems in developing countries. Here we have developed an economic analysis tool, called ERain, to combine daily performance analysis of RWH systems with life cycle cost analysis for use in economic evaluation. ERain has shown that the recent tendency towards smaller tanks in Australia is a poor choice economically, that RWH systems in Kenya can be economically beneficial if installed without reticulation, and that reliability (the percentage of days that the demand is met) can be a financial issue. ERain provides a realistic framework for establishing sustainable RWH solutions. The relationship between the benefit cost ratio, reliability and efficiency (the percentage of available water used) is discussed as well as discrepancies between the benefit cost ratio (BCR), and net present value (NPV) as economic indicators. Results highlight the need for innovation and reduction in capital and on-going costs associated with RWH systems in preference to increasing the price of water to increase their economic viability. The impact of paying elevated prices for water purchased from street vendors on the other hand demonstrates the dependency of RWH system economic viability on regional freshwater cost. Results also show that a rebate that matches tank size would be a good initiative to encourage the installation of larger tanks and increase water security, while relying on customer perspective of value will tend towards installation of smaller tanks and a superficial water security.

3.2 Introduction

Rainwater is a naturally occurring relatively clean and abundant source of water in many locations. Rainwater Harvesting (RWH) system involves capturing the rain before it becomes surface water minimising pollution and capturing its potential energy. Being available over large areas it does not need extensive reticulation nor to be pumped from deep wells, over hills and across valleys. RWH systems also provide a defence against failure of centralised water supply (e.g. due to natural disasters, terrorist attacks or simply system inadequacy or failure) and have come into favour with local decision-makers, city council managers and environmental groups because of their self-sufficiency (Domènech et al. 2013). A RWH system is a simple structure that does not necessarily need pumps or difficult to maintain parts. It may also defer augmentation of mains water infrastructure, reduce the size of downstream storm-water infrastructure (Coombes and Kuczera 2003; Palla et al. 2017), relieve pressure on natural reservoirs (Nápoles-Rivera et al. 2015) and may present environmental savings (Devkota et al. 2015; García-Montoya et al. 2016; Morales-Pinzón et al. 2015; Stec et al. 2017). An average annual rainfall of only 300 mm falling on a house roof 10 m long and 6 m wide captured without losses could hypothetically supply 50 L of water per day on average. This is more than the daily consumption of many individuals in developing countries (Fry and Martin 2005; IRC 1983; Watkins 2006). RWH has been practiced from ancient times (Cowan 2014) and its advantages have come into focus again in very recent years, as nations look for water security solutions to accommodate an ever-increasing world population in the face of uncertain future climates (Morales-Pinzón et al. 2015; Singh et al. 2017).

Australia is a highly developed country and still experienced the effect of a subtle change in climate during the millennium drought in early 2000's (Beatty and McLindin 2012). Water restrictions were enforced and RWH systems mandated to help alleviate the water stress (Gardner and Vieritz 2010). Since the drought eased, Sydney's inner-city urban areas have shown a tendency towards installing smaller rainwater tanks to meet legislative requirements. This can be observed in the Building and Sustainability Index (BASIX) records from 2005 to 2015 (BASIX 2016a). This tendency developed quickly as dam level rose and the millennium drought eased. Australia has already been criticised for its weak water security planning (Beatty et al. 2009; Burton et al. 2015). Reducing tank size is not the best choice in preparing for future droughts and dry spells (Haque et al. 2016). This study investigates whether or not this is the best choice economically. People commonly purchase mobile phones for their children's security, extra locks for their doors, pay insurance for everything from house to health. Should not water security be a top priority before droughts hit again?

Kenya is a developing country that experiences problems with water supply both in urban and rural areas. Just after completion of this study there was an extreme drought in Kenya that lead to a national emergency and a five-fold increase in water prices in some areas (Kahinga 2017). This is a case in point of the need to improve water security as well as demonstrating the unpredictable nature of water prices. Yet existing Legislation in Nairobi, the nation’s capital, does not encourage RWH and the public health act is restrictive (Act of Parliament - Kenya 2012). Most suburbs have limited supply and some only have water on tap for one day a week. Although RWH is in use in some of the slums (Thorn et al. 2015), generally it is hardly practiced in a scientific and regular manner (Dickson et al. 2015). A number of international bodies and NGOs are focusing on using RWH systems to meet the water needs of developing countries:- Africa Now, World Vision, and CARE Kenya are some of these (Owuor and Foeken 2009). International institutions such as the Organization for Economic Co-operation and Development (OECD) and The World Bank argue that it is unrealistic to base financial planning of water services on full cost recovery of investment costs, proposing sustainable cost recovery instead (Banerjee et al. 2010; TEAM 2009). The use of handpumps in Bangladesh has adversely affected up to 70 million people with skin cancer and other health problems caused by the natural arsenic contamination in the ground water (Islam et al. 2010). The benefits from using RWH systems in preference, if it were possible, would have been untold. Similarly, along the rift valley in Kenya and into Ethiopia fluoride levels in the groundwater are causing fluorosis in both adults and children. RWH is a potential solution to these problems (Moturi et al. 2002). Some work has been done to optimise RWH system design in developing countries such as the production of “Nomographs” of roof area-tank size for financial decisions (Gathenya et al. 2010). However a thorough life cycle analysis is necessary to avoid instigating infrastructure that cannot reasonably be maintained as has been experienced with many of the village handpump projects throughout Africa (Parry-Jones et al. 2001). Broader issues such as training communities, establishing cost recovery mechanisms, and supply of spares also come into focus. Economic evaluation is an important aspect of this research if governments and NGO’s are to make informed decisions. The existing literature presents conflicting results on water supply projects, with some costs and benefits often neglected

Economic analysis attempts to “measure in monetary terms the private and social costs and benefits of a project to the community or economy” (www.businessdictionary.com 2016). Economic evaluation, according to the AS/NZ Standard AS4536 “Life Cycle Costing – an Application Guide” (Standards Australia 2014), considers the financial viability of a product or installation via a detailed life cycle cost analysis (LCCA). LCCA results are presented in the form of economic measures such as a payback period (PP), benefit cost ratio (BCR), and net present value (NPV). Where there is a payback period, a BCR less than one, or a positive NPV the project is considered financially viable. The majority of researchers find RWH systems to be financially non-viable (Amos et al. 2016; Gao et al. 2015; Ishida et al. 2011; Kumar 2004; Mitchell and Rahman 2006; Rahman et al. 2007; Roebuck et al. 2011; Roebuck et al. 2012). Roebuck et al. (2011) go as far as to state that any research that finds a RWH system can provide a PP should be thoroughly examined, having found that systems in the UK are not likely to present any. However work by Gato-Trinidad and Gan (2014) find that RWH systems in Melbourne Australia can be paid back between 12 to 47 years for householders and 1 to 12 years for the Victorian Government (who paid a rebate). In Spain Morales-Pinzón et al. (2014) calculated a PP of 5-204 years for apartment scale installations, but for single houses positive results were dependant on a significant increase in water prices (Morales-Pinzón et al. 2015). In Brazil Lopes et al. (2017) present a positive NPV and a payback of less than 17 years depending on the demand – roof area ratio and tank size. In Nairobi, Kenya Essendi (2014) present a PP of 25 years. Conflicting results may be due to the varying financial assumptions and various modelling parameters used such as the local cost of water (benefits), materials and labour (costs). A negative financial viability does not necessarily equate to a negative economic viability. The results of a LCCA give economic measures not economic decisions. The economic evaluation should take into account broader considerations such as the definition of need, and indirect benefits such as improving health through water, sanitation and hygiene (WASH), (Alexander et al. 2014), which have a socio-economic impact that is often difficult to measure in financial terms. The economic question may be how much will this amenity cost to build and maintain and what will it do for us, rather than, will it provide an income? Benefits for the whole society may be of more value than the costs involved as Domènech and Saurí (2011) found was the case in Spain, and as wide spread installation in Australia demonstrates (Beatty and McLindin 2012).

Research on the economic viability of RWH systems rarely focuses on developing countries. Comparison of a developed country with a developing country has the potential to highlight converging and diverging economic factors that influence the viability of RWH systems. For example, the developing country may learn from the experiences of the developed and the developed may learn from the innovations of the developing country (Thorn et al. 2015). Yet in the literature review upon which this work is based (Amos et al. 2016), no studies were found to directly compare RWH systems in a developing country with those in a developed country. It was also found that few studies examined the benefit-cost associated with the RWH systems in detail, but often overlook several factors such as maintenance and replacement costs.

This study fills the above research gap and provides important insight into factors affecting the financial viability of RWH systems common to diverse economies by comparing hypothetical RWH systems situated in Australia and Kenya. To achieve this objective a detailed model called ERain was first developed which combines financial analysis with performance analysis using daily rainfall data and economic inputs. The financial analysis in ERain was built by incorporating the detailed costs and benefits found in the literature following the guidelines of the Australian Standard AS4536 on life cycle costing. Outputs include the BCR and NPV as economic measures. ERain's performance analysis is based on a yield after spillage analysis of daily rainfall data and has "efficiency" (percentage of available water used) and "reliability" (percentage of days that the demand was met) of the RWH system as outputs. This enables evaluation of the LCCA outcomes in view of the systems performance and highlights areas of potential improvement. ERain was then applied to single occupancy residential houses using detailed cost information and rainfall data collected on location in Nairobi, Kenya during the time that elapsed between the American President and the Pope's visit to Kenya in 2015 and at the same time in Parramatta, a region of Sydney, Australia.

3.3 Material and Method

A base scenario of two hypothetical single occupancy residential houses using a RWH system for toilet and laundry use with or without irrigation/outdoor water use were considered (section 3.3.1). The base scenario considers the benefit of mains water savings alone, while other scenarios include additional benefits such as saving water purchase from street vendors (section 3.3.1). Outdoor use varies depending on the number of consecutive days of rain. The RWH system includes a roof area (catchment), a tank, first flush device and a mains top up system (set at 5% in this study) and overflow is lost to the stormwater system (Figure 3.1). Two locations were chosen, one in Nairobi, Kenya and the other in Sydney, Australia. The specific characteristics considered that distinguish the two countries are the economic data and the rainfall data. The availability of water in the respective locations has not been considered directly, but the lack of availability in Kenya, and other developing countries, contributes to the increased prices that are experienced, particularly at the street vendor level. Poor availability is commonly due to lack of water distribution infrastructure, as is the case in the eastern suburbs of Nairobi. Historical daily rainfall data, information about the water demand profile, and detailed financial data were obtained for both locations (see section 2.2).

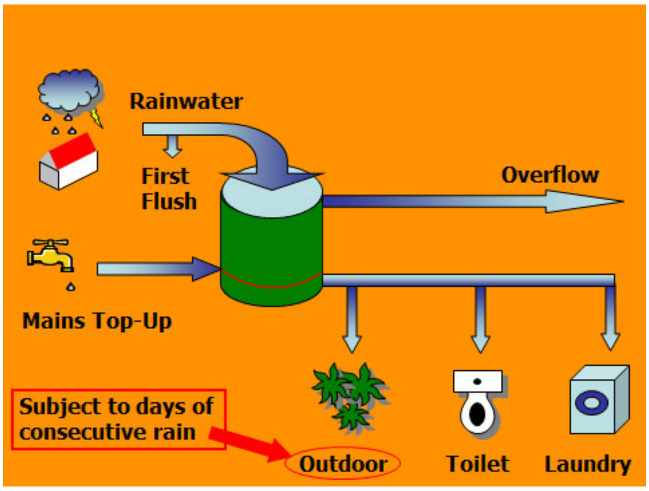

Figure 3.1 ERain basic parameters model

An analysis tool called ERain was developed in this study (described in section 2.3). ERain enables daily rainfall data to be analysed and checked for quality and then used as an input to a yield after spillage model (YAS) which Fewkes and Butler (2000) concluded to be more conservative than a Yield before spillage model. The model calculates daily water savings based on daily demand as well as the reliability and efficiency of the system. The financial data is also processed by ERain and benefits and savings calculated according to their present value at the time of their expenditure or benefit, which in the case of a replaced pump may be in 5 years’ time. Benefit cost ratios and Net present values are then calculated considering a 60-year life cycle. ERain then combines the performance and economic results into various charts (see figures 3.2 - 3.5) that allow evaluation of economic measures together with system performance.

3.3.1 Scenarios

For both Kenya and Australia, a single occupancy house is considered with 2, 4 or 6 occupants in line with Sydney Water's Water Efficiency Targets (Sydney Water 2016b) Rainwater is used for the toilet and laundry, with or without irrigation and outdoor use. 1-7 m^3 tanks are based on sizes commonly installed to fulfil or exceed the Australian BASIX legislation requirements (BASIX 2016a). The site dimensions chosen for Sydney are similar to those used in previous studies (Hajani et al. 2013; Rahman et al. 2012) with a total site area of 400 m^2 divided between a roof area of 200 m^2 , a landscaped area of 120 leaving 80 m^2 for driveways, etc. For Nairobi, a smaller plot of 200 m^2 is chosen reducing these values to 120, 60 and 20 m^2, respectively. Losses of 1 mm per m^2 of roof area including 0.5 mm/ m^2 of roof for a first flush are considered and a mains top up level of 5% of the tanks volume is adopted. The system is considered over 60-year life cycle with various parts being replaced and maintained.

3.3.2 Data

Rainfall data

The daily rainfall data used is summarised in Table 3.1, obtained from the Australian and Kenyan Bureaus of Meteorology.

Table 3.1 Summary of daily rainfall data

Country	Location	Type	Rainfall station	Period of rainfall record	Average annual rainfall (mm)	5th Percentile (mm)
Australia	Parramatta	Urban	066124	1965 - 2015	964	612
Kenya	Nairobi	Urban	Wilson Airport	1959-1988	891	536

Water demand profile

The water demand profile is one of the most unpredictable inputs. As noted by Willis et al. (2013) knowledge of water use and especially water savings can only be acquired with high resolution water consumption data "disaggregating water use for showers, toilets, clothes washers and garden irrigation etc." In this study the water demand profile is modelled on disaggregated water use assumptions based on Reece Sustainable Bathroom Guide (Reece 2016) and calibrated using Sydney Water's daily consumption estimates to give a reasonable correlation between the model and the statistical data available. Sydney Water obtained its estimates by simply dividing the total water consumption by the population giving 297 L/person/day (Sydney Water 2016c). This is necessary due to the lack of empirical data giving specific use for each part of the demand profile. Reference was also made to Sydney Water's efficiency targets (Sydney Water 2016b) for household total use and the water profile presented by Kuczera et al. (2003). This profile was adapted to produce the Kenyan considering outdoor use and laundry done by hand to be less consuming. This was then calibrated using the average multiple tap house connection value given by the IRC (1983) at 150 L/person/day. Consideration was also given to the first author's experience of living in a 2-bedroom flat in Kenya, with 6 occupants. Practicing some simple greywater recycling their consumption was between 900 and 1500 L per week (36 L/person/day). Sydney Water suggest water efficiency targets of between 106 and 267 L/person/day depending on household size, lot size and season (Sydney Water 2016b). Statistics for Average Daily Water Use by Property Development give 623 L/dwelling/day (Sydney Water 2016a). The assumptions in this study have led to consumption of 172 L/person/day for indoor use and a maximum of 1233 L/d/hh for outdoor use (per household regardless of occupants) depending on climatic condition. The assumptions are based on 3 star rated appliances (an average rating) as follows.

Bathroom:

- Toilet full flushed twice a day per person and half flushed once per day giving 23.5 L/person/day.
- Shower 8 L/min for 4 min per person per day (m/p/d) (Reece 2016) resulting in 32 L/person/day.
- Tap 18 L/min for 2.5 min/person/day for shaving, washing hands, and brushing teeth (Reece 2016) resulting in 45 L/person/day.

Kitchen:

- Tap 9 L/min for 5 min/person/day for cooking, washing dishes, etc. resulting in 45 L/person/day.
- Dishwasher 18 L/load at 1 load for every 2 people per day resulting in 9 L/person/day.

Laundry:

- Tap 9 L/min for 0.8 min/person/day resulting in 7.2 L/person/day.
- Washing machine 50 L/load at 3 loads for every 2 people each week, resulting in 75 L/person/week or approximately 10.7 L/person/day.

Outdoor use includes irrigation at 10 mm depth of irrigation multiplied by the irrigation area (generally 120*10 mm = 1200 L/household/day). This seems high when comparing the average water use per person of 297 L but if only 50% (approximately) of people use mains water to irrigate (Australian Bureau of Statistics 2013) then we would expect those people who do use it to have a considerably higher water consumption than the average . The value is also comparable with assumptions used in other studies (Hajani et al. 2013; Rahman et al. 2012). A sprinkler may use 1000 L/hr (Dupont and Shackel 2006) so 2 sprinklers running for 36 min/day is also 1200 L/household/day. Seasonal variation of irrigation is based on information from Sydney Water (2016b). Car washing is included at one car per household, washed every 2 week at 180 L/wash (Sydney Water 2016c).Washing hard surfaces is included for 8 min/week at 18 L/min, (20 L/day) assuming its often done in conjunction with watering the garden or washing the car.

In Kenya, non-star rated toilets were assumed at 3 flushes of 9 L per person per day giving 27 L/person/day. 16 L/person/day was allowed for showers.18 L/person/day was allowed for the hand basin. 45 L/person/day was allowed for the kitchen tap, assuming it may be used for various purposes. 15 L/person/day was allowed for the laundry, assuming hand washing (105 L/person/week). Irrigation is estimated to be a minimal amount of 5 mm over 60 m^2 of lawn = 300 L per day per household incorporating all types of outdoor use, with ET effects adjusted to the Kenyan seasonal pattern.

Economic Data

Retailers supplied the detailed cost information. Australian prices were compared to estimates given by recognised cost estimate guides particularly Cordell Housing Building Cost Guide (Solutions 2015), Rawlinsons Australian Construction Handbook (Rawlinsons 2015b), and Construction Cost Guide for housing, small commercial and industrial buildings (Rawlinsons 2015a). Although Cordell offers an estimate for a complete rainwater tank installation (p184), detailed information was preferred to facilitate distinction between installation type, to account for replacement and repair of various parts at various stages of the life cycle (the cost guides focus on capital not ongoing costs), and to create a more flexible model adaptable to new and innovative designs. The dollar value of the water saved represents the primary benefit. Rebates (total acquisition/capital cost) and the hedonic price ($18000), proposed by Zhang et al. (2015) as an increase in real estate value due to installation, were also considered. A summary of the costs, water prices (Water 2016), interest and inflation rates (Independent Pricing and Regulatory Tribunal (IPART) 2016; TradingEconomics 2016; Water 2016) used are given in Table 3.2. It should be noted that the water price changes from city to city and from country to country, and therefore the outcomes of this study need to be interpreted in relation to the water price at other locations of interest.

Table 3.2 Economic inputs

	Australia	Kenya
Exchange rate[*1]	US$1	59.01 KSH
Interest rate	4.50%	11.50%
Inflation	2.50%	6.80%
Water inflation	2.50%	6.80%
Water charge (/m^3)	$1.78/$m^3$	$0.59/$m^3$
Nominal service charge	$88.95/yr	$15.6/yr
Water purchased in 20L jerry cans	NA	US$5.3
Tank cost alone (1 - 7m^3)	$622 - 2114	$132 - 454
A) Total acquisition costs	$3251 - 5319	$731 - 1444
A) Total acquisition costs (Yard)[*2]	-	(386 - 1072)[*2]
B) Average annual use and maintenance costs[*3]	$1062 - 1158	$369 - 390
B) Average annual use and maintenance costs (Yard)	-	(37 - 57)[*2]

Notes:

[*1] Used to convert to American dollars. [*2] Values in brackets are the costs of a yard type installation without pump and plumbing. [*3] These values are average annual real costs over the life of the system (including the inflation but not the reduced value of future money due to interest).

AS4536 categorised costs into 4 life cycle phases, considered here over a 60-year cycle. Acquisition includes definition of need, design, legal issues, and capital costs. Use and maintenance support includes maintenance, repair, replacement, management, and impact (e.g. running costs such as electricity). Table 2 includes summary values used for these. Analysis did not include renewal and adaption, or disposal. A brief explanation of the model used to analyse the data follows, while the supplementary section provides an example of detailed life cycle cost data input.

3.3.3 Development of economic analysis tool, "ERain"

ERain is a comprehensive spreadsheet-based model that combines the analysis of a RWH system's performance, using daily rainfall data, with its life cycle cost. It includes all aspects of a product's life cycle (as per AS4536) in conjunction with information from an extensive literature review on RWH (Amos et al. 2016). The main economic measures ERain presents are the benefit cost ratio (BCR), and net present value (NPV) standardised to Australian Dollars (US$). Both BCR and NPV use present values (PV) of the dollar calculated using the discount rate as shown in equation 1:

$$\text{Discount rate} = \frac{1}{(1+i)^t} \quad \text{PV} = \frac{\text{CF}}{(1+i)^t} \tag{4}$$

Where *i* is the interest rate, and t is the year in which the cash flow (CF) occurred. The sum of PVs over the project life defines the NPV, calculated as shown in equation 2:

$$\text{NPV}(i, N) = \sum_{t=0}^{N} \frac{\text{CF}_t}{(1+i)^t} \tag{5}$$

Where N is life cycle in years, and here CF is the difference between cash out flow and inflow reduced by the discount rate appropriate to the time (t) of transaction. The benefit-cost ratio (BCR) is simply the sum of discounted costs (C) divided by the sum of discounted benefits (B) as they occur at time (t) over the lifetime of the project N as shown in equation 3:

$$\text{BCR} = \frac{\sum_{t=0}^{N} \frac{C_t}{(1+i)^t}}{\sum_{t=0}^{N} \frac{B_t}{(1+i)^t}} \tag{6}$$

Put simply BCR is a ratio of benefits to cost, whereas NPV is the sum of benefits minus the costs when interpreting these results. Comparing these some analysts say that BCR can give inaccurate results because being a ratio it does not present the overall monetary value of the costs and benefits (Cbabuilder 2016).

ERain also presents information on the RWH system's physical performance in terms of "efficiency" (percentage of available water used) and "reliability" (percentage of days that the demand was met). It also includes additional benefits from not needing to purchase water at elevated prices from the standing pipes in 20 L jerry cans. The cost of water from a street vendor is about 20 ksh per can (US$5.3 per m^3). Based on purchasing 2 cans on average per week additional water savings are calculated as:

$$\text{Additional Water savings} = 52 \times 2 \times \frac{20}{59.01} \times \text{Occupants} \times \text{Reliability}$$

Where each can cost 20 ksh each (59.01 is the exchange rate in US$). This is only saved when the RWH system is meeting the demand and so is multiplied by the reliability.

3.4 Results

3.4.1 Base scenario

In the base scenario, no benefits are included other than the price of mains water. Figure 3.2 shows that the BCR is less than 1 in all cases for the base scenario in both Kenya and Australia agreeing with the majority of research reviewed (Amos et al. 2016).

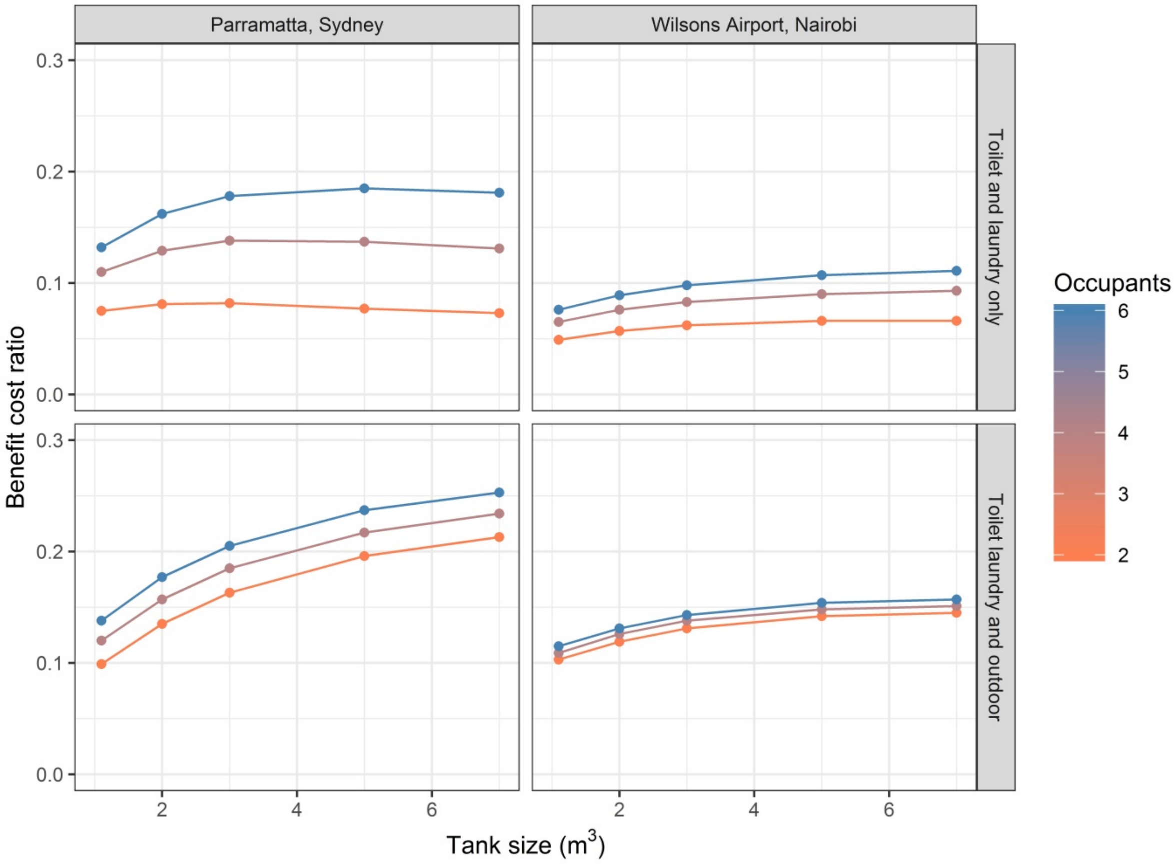

Figure 3.2 Benefit cost ratio against tank size for 2-6 occupants, laundry and toilet installation with and without irrigation based on Wilson Airport, Nairobi and Paramatta, Sydney rainfall data

In all cases the BCR increases with the number of occupants, however, the tank size that produces the highest BCR varies with the number of occupants, connection type and region. For Parramatta, excluding outdoor use, the 5 m^3 tank returns the highest BCR for 6 occupants, while the 3 m^3 does for fewer occupants. Including outdoor use improves the BCR overall and changes the pattern so that BCR increases with tank size for all sizes within the range such that the 7 m^3 tank returns the highest BCR. Kenyan BCR's are lower than in Australia but unlike Parramatta, the BCR improves with tank size in all cases regardless of occupants or connection type. This is probably due to the lower cost of the tank relative to the pump. Including outdoor uses improves the BCR, but not greater than in the Australian context. Plotting BCR with efficiency and reliability (Figure 3.3 and 3.4) helps to highlight the relationships.

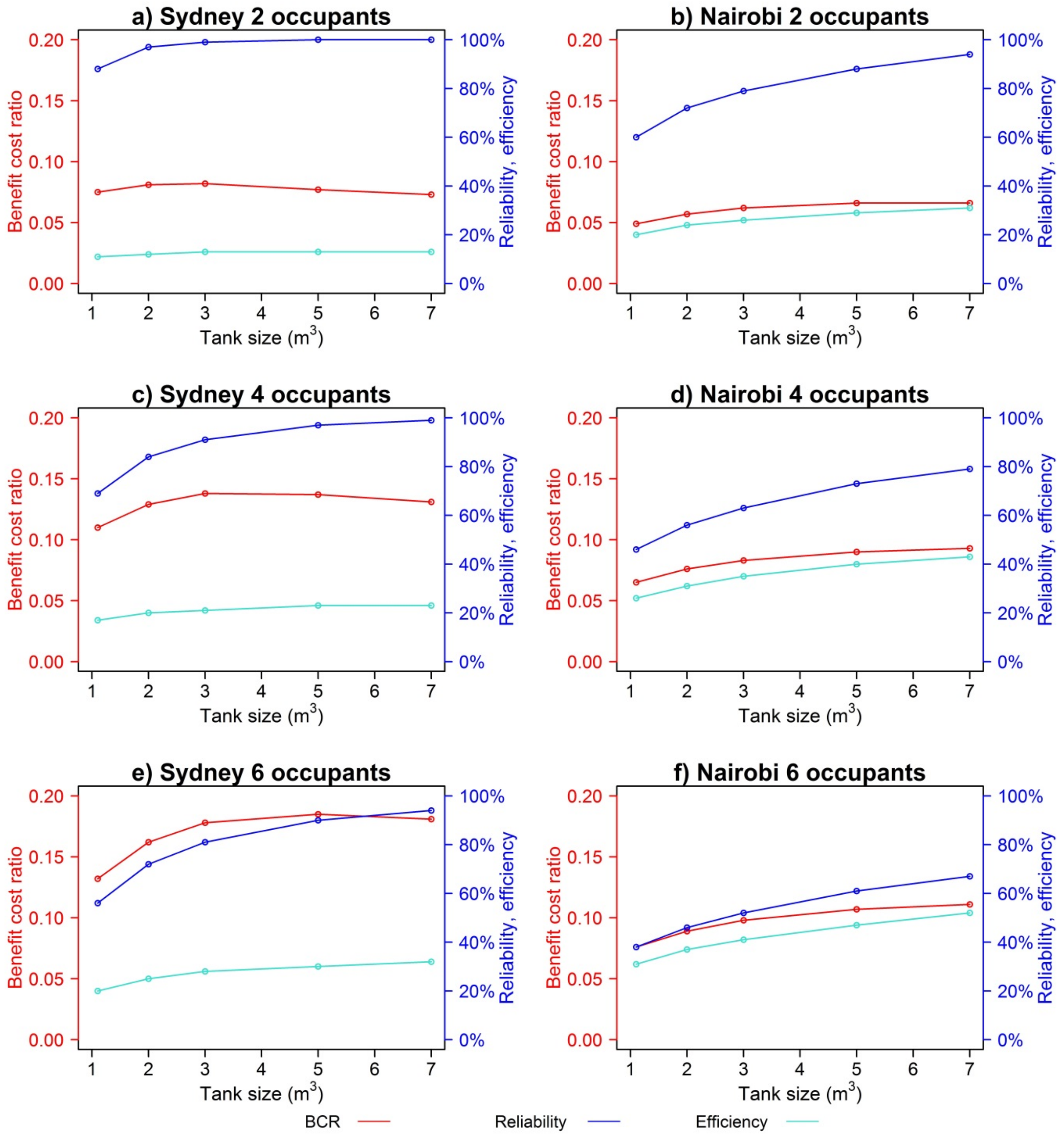

Figure 3.3 BCR, reliability and efficiency against tank size for 2, 4 and 6 occupants, laundry, and toilet only installation based on Wilson Airport, Nairobi and Paramatta, Sydney rainfall data

For toilet and laundry installation (Figure 3.3), in Australia for 2 occupants, efficiency does not increase much with tank size. Reliability is 99% with a 3 m^3 tank and so there is little advantage in having a larger one. With 4 occupants there is a slight increase in efficiency up to the 3 m^3 tank, and reliability up to the 5 m^3 and their BCRs are competitive. With 6 occupants reliability continues to increase up until the 7 m^3 tank although 90% is already achieved by the 5 m^3 tank. In Kenya, the reliability is lower, and efficiency is higher. A lack of star rated toilet and washing machine increasing consumption and smaller roof sizes in decreasing available water would contribute to this. Reliability, and BCR, continues to improve with tank size. For example, with 6 occupants, maximum reliability is only 68% (Australia 95%) and efficiency over 50% (Australia 32%). The BCR reaches a maximum of 0.11 (Australia 0.18) due to the high capital costs in relation to the cost of water. Tank prices are about 32% of the Australia (although there are questions when comparing quality), and water only about 22% at 50 c/m^3. The pump, pressure vessel and town-main controller however make up a substantial portion of the capital costs at $284, (40% of the cost in Australia of $681).

Connecting outdoor uses, as shown in Figure 3.4, improves the BCRs. In both Kenya and Australia, reliability and efficiency increase with tank size as does the BCR and a tank larger than 7 m^3 may be even better. However, adding outdoor use decreases the reliability overall and reduces the effect of increasing occupants. For example, in Australia, reliability is 63.5% with 6 occupants and 68.4% with 2. The assumption that irrigation use is the same regardless of occupants would contribute to this. Efficiency is still quite low at a maximum of 41% in Australia but is 73% in Kenya. Kenyan BCRs (max 0.16) are again noticeably smaller than Australian (max 0.25) although neither present a BCR greater than 1.

The Net present values (NPV) for all base scenarios in Australia and Kenya are negative, indicating a cost, which is consistent with a BCR of less than one. However, in a number of cases the tank size that returns the least negative NPV is not the same as the one that returns highest BCR. For example, for a toilet and laundry only installation with 6 occupants in Australia the 5 m^3 tank returns the highest BCR, while the 3 m^3 tank returns the least negative NPV. Kenyan NPVs are less negative that in the Australian scenarios, due to the lower costs, and the pattern is often different. For the equivalent installation in Kenya, the smallest tank (1 m^3) returns the least negative NPV, while the largest tank (7 m^3) produces the highest BCR. Reliability is low with the 1 m^3 tank at 37% compared to 67% for a 7 m^3 tank. For comparison, the tank with the least negative NPV in the Australian scenario (3 m^3) has a reliability of 81% compared to 56% and 94% for the 1 and 7 m^3 tank. This suggests that reliability has a larger influence on, or is a better indicator of which tank size is economically the best in Australia than it does in the Kenyan scenario. Costs are high relative to the price of water (and the average income) and so the increased water savings do not cover the cost of increasing the tank size. Including outdoor uses increased the tank size that has the highest BCR to the largest tank and still has not peak within the 1-7 m^3 tank range, but the least negative NPV is with a 3 m^3 tank for the whole range of occupants. Figure 3.5 shows an example of NPV and BCR plotted together with the corresponding PV of costs and benefits for an installation including outdoor use for 6 occupants. Examining the example in Figure 3.5 can help understand the different patterns seen between the BCR and the NPV.

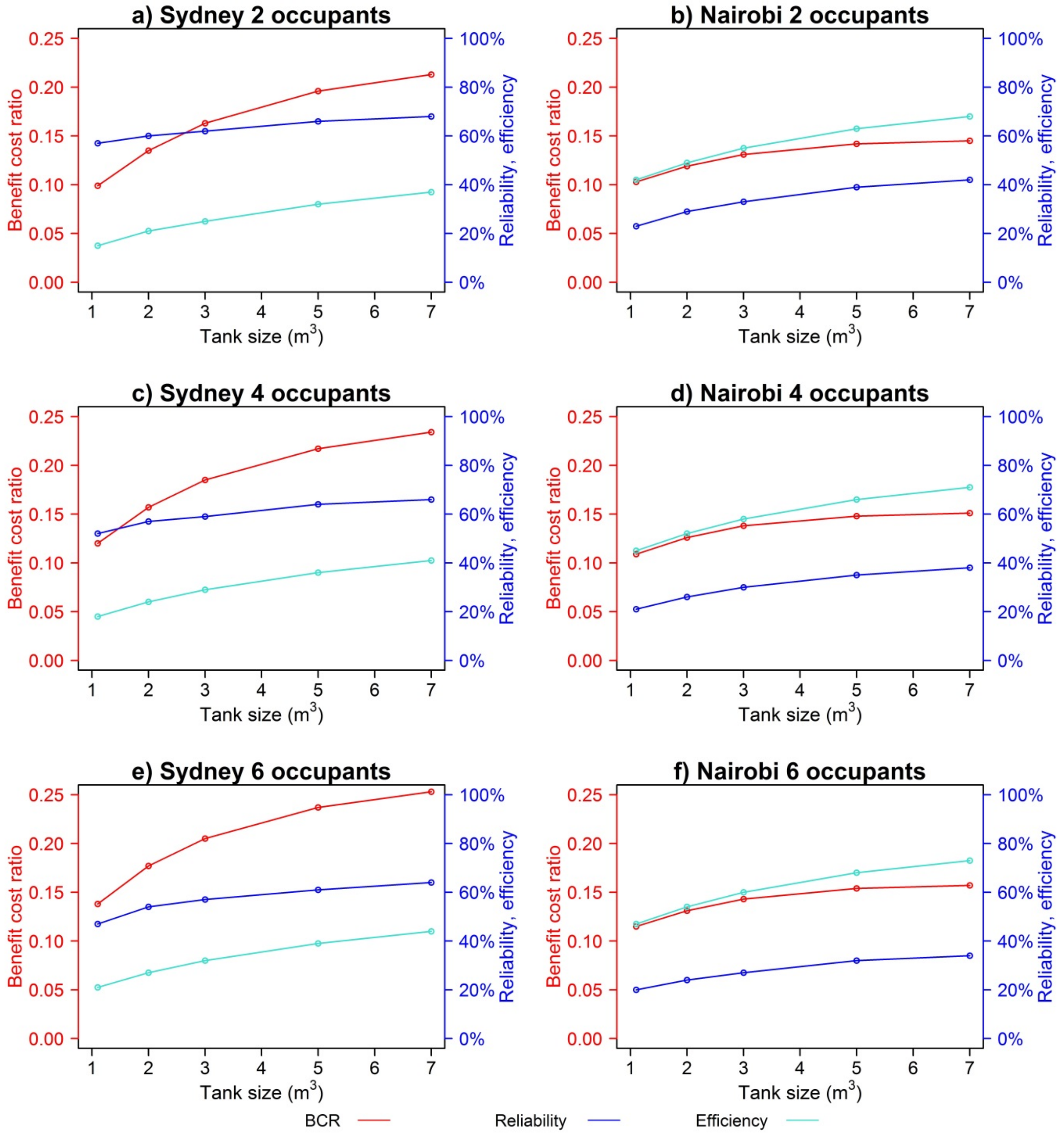

Figure 3.4 BCR, reliability and efficiency against tank size for 2,4 and 6 occupants, laundry, toilet and outdoor installation based on Wilson Airport, Nairobi and Paramatta, Sydney rainfall data.

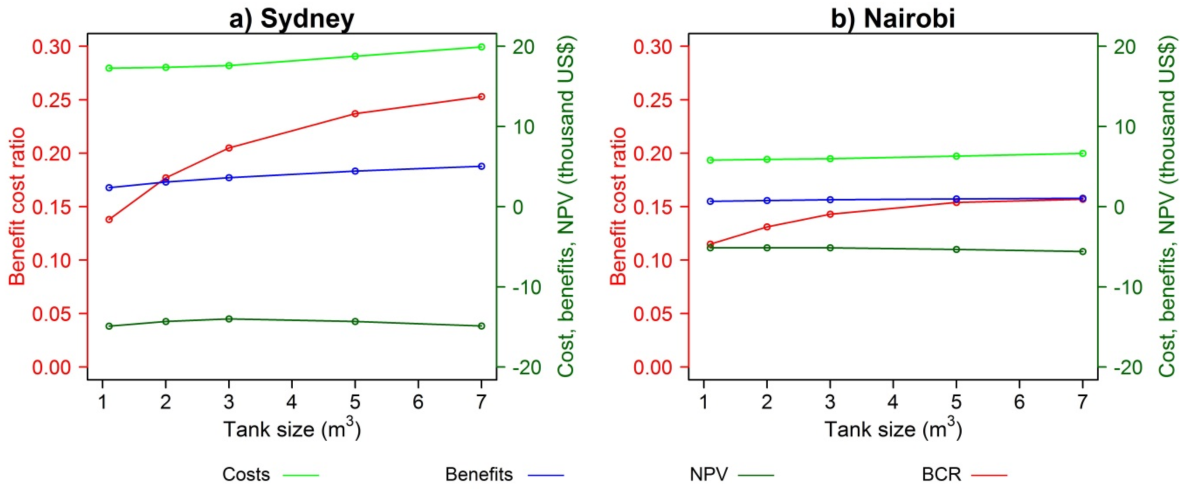

Figure 3.5 NPV, BCR, costs and benefits against tank size for 6 occupants, laundry, toilet and outdoor installation based on Wilson Airport, Nairobi and Paramatta, Sydney rainfall data.

In the Australian example, the BCR has not peaked, but the NPV is most positive (least negative) at the 3 m^3 tank. Both costs and benefits increase with tank size, however, the benefits increase at a greater **rate** than costs for the 1-3 m^3 tanks, while, perhaps because of the quantity manufactured, the costs increase at a slightly greater **rate** than benefits for the 3-7 m^3 tanks. Therefore, the difference between the benefits and the costs (giving the NPV) increases in favour of benefits up to the 3 m^3 tank and decreases thereafter. In contrast, the BCR continues to increase for the whole range because both benefits and costs are increasing. It implies that the user is paying more for less increase in benefit when changing from a 3 to a 5 m^3 tank compared to choosing between a 1 and 3 m^3 tank, although in both cases there is an increase in the BCR. This may be easier to see by examining the results in tabular form as given in Table 3.3.

The Kenyan example shows a similar pattern although there is less of a defined peak in the NPV at the 3 m^3 tank. The NPVs are again less negative than the Australian equivalent, but not positive in any case. The Kenyan scenario was rerun in ERain using the Australian interest and inflation rates to observe their effect on the results and both the BCR and NPV improved.

Table 3.3 Economic differences between proposed base scenarios

		Sydney				Nairobi			
		no irrigation				no irrigation			
Occ*[1]	Tank	NPV	BCR	Reliability	Efficiency	NPV	BCR	Reliability	Efficiency
2	1.1	$(15,985.06)	0.075	88%	11%	$(5,515.31)	0.049	60%	20%
2	2	$(15,977.32)	0.081	97%	12%	$(5,564.86)	0.057	72%	24%
2	3	$(16,166.92)	0.082	99%	13%	$(5,612.97)	0.062	79%	26%
2	5	$(17,309.63)	0.077	100%	13%	$(5,887.70)	0.066	88%	29%
2	7	$(18,484.29)	0.073	100%	13%	$(6,203.13)	0.066	94%	31%
4	1.1	$(15,384.11)	0.110	69%	17%	$(5,427.21)	0.065	46%	26%
4	2	$(15,138.70)	0.129	84%	20%	$(5,455.99)	0.076	56%	31%
4	3	$(15,181.52)	0.138	91%	21%	$(5,486.38)	0.083	63%	35%
4	5	$(16,192.74)	0.137	97%	23%	$(5,733.29)	0.09	73%	40%
4	7	$(17,317.44)	0.131	99%	23%	$(6,027.85)	0.093	79%	43%
6	1.1	$(14,987.08)	0.132	56%	20%	$(5,361.83)	0.076	38%	31%
6	2	$(14,571.32)	0.162	72%	25%	$(5,378.79)	0.089	46%	37%
6	3	$(14,468.98)	0.178	81%	28%	$(5,398.60)	0.098	52%	41%
6	5	$(15,293.33)	0.185	90%	30%	$(5,628.46)	0.107	61%	47%
6	7	$(16,325.19)	0.181	94%	32%	$(5,907.68)	0.111	67%	52%
		with Irrigation				with Irrigation			
Occ	Tank	NPV	BCR	Reliability	Efficiency	NPV	BCR	Reliability	Efficiency
2	1.1	$(15,569.81)	0.099	57%	15%	$(5,202.68)	0.103	23%	11%
2	2	$(15,040.40)	0.135	60%	21%	$(5,198.38)	0.119	29%	12%
2	3	$(14,732.47)	0.163	62%	25%	$(5,199.16)	0.131	33%	13%
2	5	$(15,093.81)	0.196	66%	32%	$(5,406.29)	0.142	39%	13%
2	7	$(15,683.94)	0.213	68%	37%	$(5,679.12)	0.145	42%	13%
4	1.1	$(15,203.66)	0.12	52%	18%	$(5,168.01)	0.109	21%	17%
4	2	$(14,654.76)	0.157	57%	24%	$(5,161.49)	0.126	26%	20%
4	3	$(14,347.48)	0.185	59%	29%	$(5,160.35)	0.138	30%	21%
4	5	$(14,689.52)	0.217	64%	36%	$(5,366.34)	0.148	35%	23%
4	7	$(15,271.50)	0.234	66%	41%	$(5,638.97)	0.151	38%	23%
6	1.1	$(14,899.00)	0.138	47%	21%	$(5,135.50)	0.115	20%	20%
6	2	$(14,313.54)	0.177	54%	27%	$(5,128.12)	0.131	24%	25%
6	3	$(13,994.27)	0.205	57%	32%	$(5,126.02)	0.143	27%	28%
6	5	$(14,325.53)	0.237	61%	39%	$(5,329.80)	0.154	32%	30%
6	7	$(14,890.66)	0.253	64%	44%	$(5,602.11)	0.157	34%	32%

Notes: *[1] Occ = number of occupants

3.4.2 Beneficial scenarios

The base scenario is limited and ignores several important economic considerations. In Australia, from the owner’s perspective, this includes the hedonic price (increase in real estate value of a property with a RWH system) and government rebates. In Kenya the fact that the centralised water system is not reliable resulting in water purchase from street venders, and that a simpler installation without reticulation (i.e. pumps and plumbing) would be quite acceptable to many Kenyans. These considerations make the RWH system financially beneficial in many cases. It should also be noted that these scenarios still do not include other potential subsidiary benefits such as reducing downstream storm water infrastructure.

In Australia, introducing a hedonic price of $14,040 increases the BCR to just above 1 for 4 or more occupants but has the effect of making smaller tanks look more viable. Conversely, Including a rebate that covers the capital costs of the tank makes the larger 7 m^3 tanks look the most viable (with a BCR of 0.47). Thus, a rebate that matches tank size would be a good initiative to encourage the installation of larger tanks and maximise water security, while relying on customer perspective of value will tend towards installation of smaller tanks and a superficial less robust water security.

In Kenya, the main beneficial scenario was for a RWH system installed without pumps and plumbing and including savings from not needing to purchase water in 20 L jerry cans. In this scenario, the BCR for almost all tank sizes & occupants is above 1, with a maximum value of 2.56 for a 3 m^3 tank installed for 6 occupants. The NPV are also mostly positive, but the last negative NPV occurs with a 5 m^3 tank for 6 occupants and shifts to the to 3 m^3 for fewer, whereas the highest BCR occurs with the 3 m^3 tank in all cases. Interestingly, rather than increasing the BCR adding outdoor use decreases it. The BCR is still more than one in many cases and highest for the 3 m^3 tank in all cases, at 1.78 for 6 occupants. The NPV also decreases but follows the same pattern as when excluding outdoor uses. This tendency towards better economic result for a larger tank size in the NPV is opposite to that in the base scenarios.

3.4.3 Factors of influence

This study has shown that the financial viability issues are not phenomena peculiar to the Australian context. Both countries examined face similar issues relating predominantly to the cost of installation, replacement of parts, and the current price of water. Using results from ERain it was possible to categorise factors of financial influence according to the degree of influence. Although the relationships and boundaries between these factors have not been defined the following categorisation is proposed.

Factors having a high level of influence:

- Capital Costs (esp. Plumbing Reticulation and pumps)
- Replacement costs (esp. if a pump is installed)
- Water Prices
- Consideration of subsidiary benefits (e.g. Hedonic price)
- Rebates (if large enough).

Factors having a medium level of influence:

- Relationship between tank size & water demand profile, including:
- The number of occupants
- The types of water use allowed
- Type of tank (round, slim line, and underground tanks especially)
- Roof area
- Rainfall (In some extreme cases this might be a primary influence)
- Maintenance (other than replacement).

Factors having a low level of influence:

- Maintenance (other than replacement)
- Interest and inflation rates.

This list is by no means exhaustive; other things that could be considered include the cost of designing the system if professionals (e.g. engineer, architect, etc.) were used, and water treatment. Subsidiary benefits of installing rainwater tanks are difficult to quantify in monetary terms.

3.5 Discussion

The base scenario showed that presently the life cycle costs of a fully reticulated RWH system with pumps cannot be paid back in the lifetime of a RWH system purely by the value of mains water they can save in either Australia or Kenya. These results are in line with the majority of research (Amos et al. 2016; Campisano et al. 2017; Ishida et al. 2011; Kumar 2004; Mitchell and Rahman 2006; Rahman et al. 2007; Roebuck et al. 2011; Roebuck et al. 2012; Stec et al. 2017). Larger tanks of 3-5 m^3 are generally better financially than 1 or 2 m^3 tanks. This is in contrast to Lopes et al. (2017) who present a benefit, and expect the maximum benefit to be with a 2 kL tank, although they also admit that larger tanks may still be preferable with uncertain future economics. If outdoor use is considered, tanks of 5 to 7 m^3 sizes are better financially. A shift towards smaller tanks in Sydney is not positive either financially or practically in terms of water savings. The definition of need has been making RWH systems an essential part of urban development in many cities around the world. Reducing installation and maintenance costs focusing on pumps and plumbing is a more reasonable way to improve the economic viability of RWH systems rather than increasing the price of water. This will naturally occur if there is increased acceptance as manufacturing costs, for example, usually reduced unit cost (Campisano et al. 2017). Including the hedonic price, in the Australian context, however they do become economically viable in agreement with Zhang et al. (2015). One issue with the hedonic price is that economically it tends to favour the smaller tanks. This is because the hedonic price represents a greater portion of the benefit than the actual water savings. In other words, the prestige in having a tank counts for more than the water savings. Interestingly this result mirrors the tendency towards installing smaller tanks in Parramatta (BASIX 2016a). If someone is truly interested in saving water, it would be better to pay the small amount extra for a larger tank. Including a rebate, that covers the capital costs of the tank, makes the larger tanks look the most viable and may encourage this. Governments should be concerned about increasing water security and should not rely on customer perspective of value to do this. So far Australian installation of RWH systems can be considered a success story with the highest adoption of any country in the world at 34% of households (Gardner et al. 2015).

In Kenya, it is quite realistic to consider a yard type connection with no pump or plumbing reticulation and to include savings from the cost of purchasing water from the street vendors. A significant portion of population, especially lower income earners would see the extra burden of bringing water into the house from a tank as less of a burden than buying from vendors. For those who can afford it, they would go for the fully reticulated installation. Rainwater harvesting in slums (Kahariri 2014; Owuor and Foeken 2009; Thorn et al. 2015) demonstrates its potential economic viability and their social acceptability to some extent. Considering the rise in Diabetes even in developing countries such as Kenya and the known connection to physical activity (WHO 2014) one could be forgiven for thinking that a certain amount of manual labour in daily life has benefits. Not having a full connection also reduces water consumption (IRC 1983). There are other benefits that are hard to quantify including the amenity that RWH system can bring in a city that has an unstable and irregular water supply. These added benefits and attraction can quantify as a hedonic price. Also the introduction of a RWH system industry can help strengthen the country's economy by creating an industry and jobs as experienced in Germany (Herrmann and Schmidt 1999; Owuor and Foeken 2009). Kenyan scenario analysed using with Australian interest and inflation rates improved the financial viability of the RWH system indicating that the overall economic situation in a country affects the analysis. The relationship between interest rate and inflation will have an effect on the analysis because product costs increase with inflation while the Present Value of the dollar decreases annually by the interest rate. This is in line with the conclusion from Khastagir and Jayasuriya (2011) , that low inflation and high discount (interest) rates are more favourable to RWH systems.

One of the most interesting results from the Kenyan analysis was when including the cost of purchasing water from street venders. Contrary to the Australian scenario adding outdoor decreases the BCR rather than increasing it. This is because it reduces the reliability forcing the owner to buy more water from the standing pipes. Reliability becomes a financial issue and not just water savings alone. The lower levels of water security in urban Kenya make reliability a financial issue. A similar scenario may also be present in peri-urban and rural Australia where there is no mains reticulation and tanker deliveries are the only alternative source of water. In reality people may tend to forget irrigation and outdoor uses if water is not easily available. However, if the water is for urban food production, maintaining the supply becomes more of an issue than convenience. Climate variability also plays a role in the economics and three or four months of water rationing happening once or twice every five years may have other economic implications making RWH even more beneficial. This may also vary within a city even as Nairobi's Eastland's and Westland's have very different rainfall patterns as do Ryde and Campbelltown in Sydney (Hajani and Rahman 2014) . The rainfall data in this study is from central locations within each city warranting more analysis in different parts of the cities.

Unpredictable future climates challenge the assumption that past rainfall data can be used to project into the future. The future price of water is unpredictable, and this is a major issue as it is the main form of benefit considered. The broader economic assumptions may also be subject to criticism. Economies can collapse and can be unstable as Germany's hyperinflation showed in 1923 where it is said that a loaf of bread cost a wheelbarrow full of money (Keynes 2009), and the more recent Global Financial Crisis (GFC). In this scenario, the concept of privately owned RWH systems may become more beneficial than we can now imagine. Australia's experience with RWH systems in the rural and urban environment should be of great interest to nations considering widespread implementation. For practical purposes, it will be wise for other nations to look at the economic factors that will affect implementation and the benefits from having widespread installation of RWH systems. One benefit of widespread installation that is coming into focus is RWH potential to relive pressure on natural reservoirs (Nápoles-Rivera et al. 2015). This should be incorporated into the economic evaluation if not somehow into the financial analysis along with the potential to defer mains water supply infrastructure and downstream stormwater infrastructure. The place that RWH systems have in the up and coming more modern developments of Nairobi remains a question. Certainly Kenya is on the Green pathway and has just started enforcing the installation of solar water heaters this year (Lugaria 2017; Systems Administrator 2017). One question that remains for Kenya if is to follow the example of Australia is, where the financing will come from. This research will be beneficial to forming a realistic government policy that will improve the water security and hopefully the economy. Future research should focus on refining the data, expanding to regional analysis and scaling up costs for mandating installation across whole cities.

After completion of this analysis Nairobi experienced extreme drought that lead to a national emergency and a five-fold increase in water prices in some areas (Kahinga 2017) giving a case in point of insecure water security issues and the unpredictability of water prices. Although not considered here, the frequent rationing in Nairobi due to drought increased cost of water when one has to buy water from vendors or bowsers. At a time of extreme drought, such as early this year, water price increases, especially that purchased from standing pipes, which would have influenced the conclusions of this study in favour of RWH. This drought heightened Kenya's interest in RWH, especially in the rural areas as the long rains are now falling (Kairu 2017; Purcell 2017). Now is the time for Kenya to consider investing in a RWH program. Investigations should focus on the cost of installations and not the fact. Australia should cultivate its strong RWH policy and Kenya should learn from Australia's experiences to help improve its water security in hope of also improving its economy.

3.6 Summary

Economic evaluation of RWH systems including the Hedonic price in Australia or a yard type (without pump and reticulation) connection with additional savings from water bought from street venders in Kenya produced favourable economic results. The base scenario, considering the value of mains water saved alone, on the other hand does not. The effect that the elevated price paid in Kenya to water vendors has on analysis highlights that the economic viability of the RWH system is heavily affected by regional freshwater cost.

The Kenyan yard connection, including benefits from not purchasing from street vendors, returns the highest BCR at 2.5, with a NPV of $1248 benefit for a 3 m^3 tank without outdoor use. The use of RWH systems in some of Kenya's slums confirms this finding. Interestingly, connecting outdoor uses decreases both the BCR and NPV (less beneficial) because it reduces reliability and triggers the need to purchase more water from the street vendors, which outweighs the additional water savings. A small reduction in installation costs would make the yard type connection beneficial without including savings from purchasing water from the street vendors.

Adding a pump and fully reticulating the system increases the costs considerably. For 3 m^3 tank, capital costs increase from $480 to $1213 and the operation and maintenance costs increase from $39 /yr (real cost) compared to $371 /yr. The BCR, excluding outdoor use, decreases from 2.5 for a 3 m^3 tank to 0.11 for a 7 m^3 tank. The NPV decreases from $1248 benefit to a cost of $5382 for a 3 m^3 tank.

Introduction of the hedonic price or a rebate in Australia makes the RWH system financially viable with a BCR just over 1. Other subsidiary benefits are difficult to quantify, and an economic evaluation should keep other benefits in perspective while also considering the LCC results. Reducing installation costs (and especially pumps and plumbing) and maintenance costs, rather than increasing the price of water, seems to be the way forward for making RWH systems more economically viable in a wider range of circumstances. Economic viability of RWH systems improves with the number of occupants. Kenyan BCRs are lower than Australian, but due to the lower cost involved the NPVs are less negative. However, for the consumer this needs to be measured against the average wage.

Chapter 4

Economics of Rainwater Storage System use in Household Agriculture

Chapter 4 Economics of rainwater storage system use in household agriculture: the influence of irrigation area and roof size

This chapter is a partial reproduction of the following refereed journal paper:

Amos, C. C., Rahman, A., Karim, F. (2019).

The Influence of Irrigation Area and Roof Size on the Economics of Rainwater Harvesting use in Urban Agriculture: A Case Study in Sydney, Australia

International Journal of Engineering, Construction and Computing (IJECC)

Peer reviewed

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4.1 Overview

Urban agriculture and Rainwater Harvesting (RWH) have grown in popularity in recent years. The economic viability of RWH systems has been reported with various outcomes. The water demand profile is complex and of all domestic demands, outdoor irrigation use is the most variable and potentially the largest domestic use of potable water. Water for

gardening, toilet and laundry does not need the high level of treatment that drinking, and cooking water requires. The amount of water a RWH system can supply for these uses is influenced by the rainfall pattern, tank size and roof area. A versatile economic evaluation tool named ERain has been developed to analyse the economics of various RWH system arrangements. ERain combines performance analysis using daily rainfall data with life cycle cost analysis. Here ERain has been used to assess the effects of varying roof size or irrigation area on the economic viability of RWH systems for tank sizes ranging from 1-7 kL. Results show that excluding outdoor use, the benefit cost ratio (BCR) increases with roof size along with reliability, while efficiency decreases. Interestingly, the larger roof area has the most significant effect in terms of reliability on the smaller tanks. Including outdoor use reduced reliability overall but increases both the efficiency and BCR indicating that it is better financially to use the RWH system for outdoor use when reliability is not a concern. This is particularly true if, as in most urban cases, mains water is connected to the tank as a backup. If reliability is a concern however, and a threshold reliability of 75% is required for irrigation then an irrigation area of 50 m^2 will require a tank size of at least 5 kL. The larger NPVs and BCRs occur with the larger irrigation areas as this increases water use and hence monetary water savings. Within the 1-7 kL tank range, the 7 kL tank is the most favourable when outdoor irrigation use is connected.

4.2 Introduction

Rainwater harvesting (RWH) from roof tops as a result of the millennium drought has become a significant feature in Australia (van Dijk et al. 2013). About 34% of households in Australia have adopted RWH systems which is the highest adoption rate in the world (Beatty and McLindin 2012). With this has come a significant amount of research and installation guidelines from various sectors including universities, government and other research organisations such as Commonwealth Scientific and Industrial Research Organisation (CSIRO). For example, in 2008 the Master Plumbers and Mechanical Services Association of Australia (2008) developed and published a Rainwater Tank Design and Installation Handbook (HB 230-2008) for regulatory authorities, installation professionals and homeowners. In 2010 the Environmental Health Committee produced a timely revision of the 2004 Guidance on use of rainwater tanks (Environmental Health 2010) in response to the ongoing interest in using RWH systems. Various rebate schemes were introduced which have now been reviewed by several authors and government departments (Gato-Trinidad and Gan 2014; Hall 2013). RWH reports were prepared for the prime minster and cabinet. In many cases, RWH systems have been mandated for new constructions. In NSW, for example, they were included in Building Sustainability Index (BASIX) requirements. Now we are starting to see reviews of RWH system used globally (Amos et al. 2016; Campisano et al. 2017; Sharma et al. 2016). Since the drought has eased in Australia, and in Sydney particularly, there appears to be a reduced interest in RWH systems, and the desalination plant has also lost its spotlight. BASIX compliance records from 2005 to 2015 (BASIX 2016a) reveal this current trend. However, internationally there is heightened interest in RWH systems and Australia has been criticized for its weak water security (Beatty et al. 2009; Burton et al. 2015), so it is likely that RWH systems will continue to grow across Australia.

Urban agriculture is also on the increase in Australia due to the increasing cost of food and other social trends (Russ Grayson 2017). Local councils are encouraging the practice and providing guidelines on how to do practice forms urban agriculture in various ways (Sydney 2017) and gardens along roadsides are becoming popular in the inner city (Marshall 2017). Urban agriculture may be defined as “agriculture within an urban or peri-urban setting” (Hamilton et al. 2014). As well as vegetables and fruit trees, it can also encompass bees and animal production, such as chickens, and fish in Aquaponics (Orsini et al. 2013). Various countries have already been quite successful in urban agriculture. Cuba has become a world leader in urban agriculture and has developed a system called “organoponics” (Eigenbrod and Gruda 2015; Orsini et al. 2013), Mexico City produces 20% of its own food (Dieleman 2016). In many developing countries, home gardens supply family their food, and important nutrition (Gallaher et al. 2013a), and to some extent - income (Jayasuriya et al. 2014). There are growing demands to increase urban agriculture (Corbould 2013; Eigenbrod and Gruda 2015; Orsini et al. 2013; Suparwoko and Taufani 2017) to avoid the “food deserts” present in some American cities (Beaulac et al. 2009; Horst et al. 2017; Walker et al. 2010) where fresh vegetables simply aren’t available locally (Eigenbrod and Gruda 2015; Smith et al. 2013). Measuring up against Goal 11 of the United Nations’ sustainable development goals (SDGs), cleaner and sustainable cities, most - if not all countries - will come short. Australia, although a developed country, does not meet Goal 3 (health and well-being) due particularly to increased diabetes. Urban agriculture as a healthy pursuit can help alleviate this by increased activity, healthier foods and building awareness. Concurrently, in recognition of water shortages, there is a trend in Australia towards using native plants that naturally have a lower water use than many imported ornamentals (Josh Byrne & Associates 2013). Urbanisation, population increase and changing climates are increasing competition over water resources and arable land worldwide (Corbould 2013). Urban Agriculture can alleviate the food demand to some degree, but as with the concept of greening cities, this will also increase the water demand. Roof RWH in urban areas may then be able to meet some of this increased water demand. An important question is to what extent can roof RWH provide this water and what are the economic implications of using it to do so.

The economic viability of RWH systems has been reported with various different outcomes, predominantly at a cost, however some report a positive financial evaluation. Assessing the viability of RWH systems faces a number of challenges. Firstly, proper evaluation of the lifecycle costs particularly of the maintenance and replacements costs which are often neglected. Secondly modelling the systems performance is difficult and often based on various assumptions about water consumption, and a standardised site (roof area and tank size particularly). Irrigation and outdoor use are potentially the most variable household water use, with some owners using virtually no water outdoors, to others using large amounts, especially when there are no restrictions in place. The quantity of water available for harvest is influenced especially by roof area supplying the RWH system (its catchment). Roof area can vary considerably with the size of the house, or because parts of the roof are unsuitable for harvesting (e.g. due to overhanging trees or the practicality and/or cost of the guttering arrangement). The rainfall pattern, tank size and water demand profile will also affect how much water can be harvested. Irrigation use particularly will be influenced by the rainfall and the season.

Most studies use a standard roof size and quantity of water used for irrigation. The Australian Bureau of Statistics (2013) reported that in NSW approximately 48% of people use mains water to irrigate. Here we have developed a versatile economic evaluation tool named ERain to investigate the effect of varying roof size and irrigation water use on RWH system performance and the economic viability. ERain combines performance analysis using daily rainfall data and various water demand profile data with a detailed life cycle cost analysis based on AS/NZ Standard AS4536 “Life Cycle Costing – an Application Guide”

(Standards Australia 2014). Model outputs include both performance and economic indicators which can be compared. Economic measures reported include the benefit cost ratio (BCR) and net present value (NPV) and performance indicators include reliability (% of days the demand is met) and efficiency (% of available water used – i.e. not lost to overflow). ERain is designed to be flexible and to be able to account for all the aspects of costs involved, anticipating that innovation will be an ongoing feature of RWH system design and urban agricultural methods for some time to come (Kongo and Jewitt 2006). System configurations will be greatly affected by Innovation and this will have a direct impact on economics (Gabrielsson et al. 2018; Getnet and MacAlister 2012; Melville-Shreeve et al. 2014). One of today's challenges is to make RWH economically viable. It is hoped that developments in Australia can contribute towards meeting SDG Goal 2 zero hunger, and Goal 6, clean water and sanitation, in developing countries. The technological achievement of putting man on the moon 50 years ago in 1969, should be matched with providing the basic needs of man.

In this study ERain has been used to assess the economic implications of varying the roof size, and the irrigation area of RWH systems with tank sizes ranging from 1-7 kL. Parramatta, the geographical centre of Sydney, Australia, has been used as the study site.

4.3 Materials and Method

4.3.1 Scenarios

This study considers a single occupancy house in Parramatta with 4 occupants. Site dimensions are similar to those used in previous studies (Hajani et al. 2013; Rahman et al. 2012). In order to reflect the tendency towards smaller lot sizes, the overall site area is reduced from 450 m^2 to 400 m^2 and the nominal landscaped area from 150 to 120 m^2. However, a variety of landscape areas, namely 40, 80, 120, 160 and 200 m^2, are modelled to account for variation in water use. In Sydney currently, while plot sizes are decreasing, house sizes are increasing and so an average roof area of 200 m^2 was chosen and a variety of roof areas, namely 100, 150, 200, 250 and 300 m^2 were modelled to account for variation in the roof sizes and connection.

The RWH system is commonly used for the toilet and Laundry, with and without irrigation, and outdoor use. Tank sizes ranging from 1-7 kL were considered for toilet and laundry type connections and tanks sizes up to 15 kL when irrigation use is included. This size range reflects the tank sizes commonly installed to fulfil or exceed the BASIX legislation requirements. The majority of tanks are in the 0-2 kL, and 2-3 kL range, with a few being larger than 10 kL in the Parramatta area. For cost analysis, “Slimline” tanks have been assumed as these are the most common in urban areas where space is limited. Losses of 1 mm per square meter of roof area, a first flush volume equivalent to the first 0.5 mm of rain and a mains top up level of 5% of the tanks volume are adopted.

4.3.2 Rainfall Data

The Rainfall data from 1965 – 2015 for Parramatta (Station No. 066124), was used in this study (Table 4.1).

Table 4.1 Summary of daily rainfall data

Country	Location	Type	Rainfall station	Period of rainfall record	Average annual rainfall (mm)	5th Percentile (mm)
Australia	Parramatta	Urban	066124	1965 - 2015	964	612

4.3.3 Water Demand Profile

The profile chosen in this research was designed around looking at each specific water use and calculating estimates for each starting with quantities obtained from the Reece Sustainable Bathroom Guide and the distribution of water use between uses reported by Kuczera et al. (2003). The overall usages that these specific values yielded were then compared with the averages given by Sydney water, 297 L/p/d (litres per person per day). This resulted in an average consumption of 172 L/p/d excluding outdoor use (which varies and is ultimately shared between the occupants) and a maximum outdoor use of 1233 L/household. Toilet use is based on two full flushes and one half flush of a 3 star toilet per person/day, resulting in 23.5 L/p/d. Laundry use is based on 3 loads for every 2 people each week in a 3 star washing machine, resulting in 150 L/p/week or approximately 10.7 L/p/d. Outdoor uses include washing one car per household every 2 weeks, at 180 L/wash, and a low estimate for washing hard surfaces of 8 min per week (at 18 L/min), resulting in 20 L/day, assuming that some people may also water the garden or wash the car at the same time. Irrigation use is calculated at 10 mm depth of irrigation per household per day multiplied by the irrigation area assumed for the property (generally 120 m^2) giving 120 m^2 times 10 mm = 1200 L/household/day, which is comparable with assumptions used in other studies (Hajani et al. 2013; Rahman et al. 2012). A sprinkler may use 1000 L/hr so it is not unreasonable to think that a property may have 2 sprinklers running for 30-40 min per day which would result in approximately the 1200 L of water as assumed in this study. Irrigation is assumed to stop when there are consecutive days of rain. Variation in irrigation use between users is modelled by changing the area of irrigation considering 40, 80, 120, 160 and 200 m^2.

4.3.4 Economic Inputs

Interest and inflation (other than water) were considered as 4.6% and 2.5% respectively from the WACC biannual update report for the water industry produced by Independent Pricing and Regulatory Tribunal (IPART). The primary benefit of the RWH system is the monetary value of the water saved. This is calculated using the annual average amount of water saved, found by the daily analysis and summary modules, multiplied by the current water price of \$2.28 /kL (including a service charge of \$114.04). Prices were obtained from Sydney water's prices for customers 2015 and compared with a recent water bill. The water inflation rate was taken from prices for customers between 2016-2020. Costs have been categorised according to AS/NZ 4536:1999 Life cycle costing - An application guide (Australian Standard 2014). Predominantly the Acquisition and Use and Maintenance Support categories were considered while renewal and adaption and disposal were not. Although there are arguments to include various subsidiary benefits from HA, the only benefit from HA considered is the water savings.

4.3.4.1. Life Cycle Phase A – Acquisition

The variety in types of RWH installation leads to a number of complex issues when it comes to costing. For example, the level of advice that may be used to design the system is a costing issue that is often neglected. In this analysis the focus has been the effect of tank size on the economic viability of the system. For this reason, an average price was adopted for most aspects of the system while special attention was given to costs that vary with different size tanks. Prices were obtained from various suppliers and compared with Cordell and Rawlinsons (Rawlinsons 2015a; Solutions 2015) where they had comparative pricing. The hourly rates for the various trades were taken as the average values given in "Payscale"

- an online guide for trade rates. An example of some of the capital costs are shown in Table 4.2, labour costs are included elsewhere. The red highlighted section shows the values that vary with tank size.

Table 4.2 Acquisition costs

Cost Code	Details	units	per unit	Total
	<u>Catchment and Drainage System</u>			
1104	Roof Treatment to adequate standard		-	
1104	Downpipes to tank	1	$43	$43
1104	Guttering		-	
	<u>Tank</u>			
	Tank volume (kl)= m^3)	3		
	Tank slab area	2.2		
3101	Cost of land /m^2	2.2		
3102	Levelling ground (m^2)	2.2	$13.87	$32.89
3103	Concrete base for tank (exc. labour) (m^2)	2.2	$104.22	$247.16
3104	Tank Cost	1	$910	$0.00
	<u>Water Treatment</u>			
1104	Gutter and downpipe screening	1	$15.00	$15.00
1104	Tank and inlet screening, passive treatment, outlet height			
1104	First Flush device	1	$17.00	$17.00

4.3.4.2. Life Cycle Phase B – Use and Maintenance Support

Dividing the RWH system into separate sections helps identify the various maintenance issues. These costs occur on a scheduled basis rather than at acquisition. Repair and replacements are considered to carry more cost to the owner than general maintenance which the owner is assumed to do himself. The pump is assumed to run for 2 hrs/day using 0.9 KW/h at $0.2122 per kWh.

4.3.5 Method: "ERain" analysis tool

ERain combines performance analysis with economic analysis using daily rainfall data, economic data and scenario inputs. It was originally developed as a spread sheet model and has been upgraded using FORTRAN and R Script programming in conjunction, with information from extensive literature reviews on both RWH (Amos et al. 2016) and Urban Agriculture (Amos et al. 2018b). The basic model parameters are shown in Figure 4.1. ERain uses the yield after spillage model (YAS) which Fewkes et al. (2000) deem to be more conservative than a yield before spillage model.

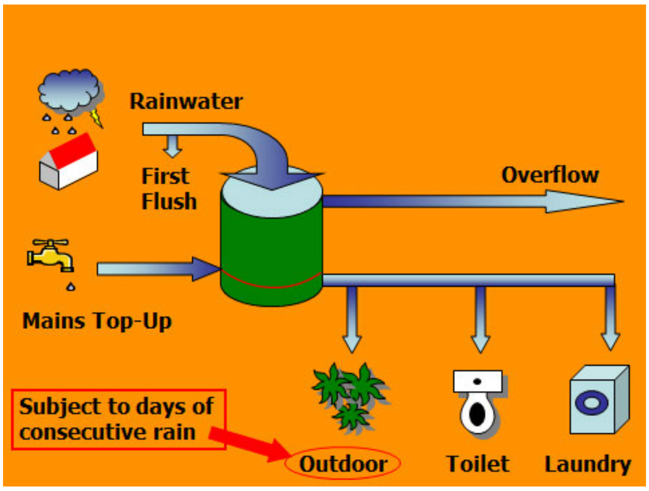

Figure 4.1 ERain basic parameters model

Following the guidelines in AS/NZ 4536:1999 Life cycle costing - An application guide (Australian Standard 2014) ERain includes all aspects of a product's life cycle and presents the benefit cost ratio (BCR), and net present value (NPV) standardised to Australian Dollars (AU$), using the concept of Present Value (PV).The PV is calculated as shown in equation 1:

$$\text{Discount rate} = \frac{1}{(1+\mathrm{i})^{\mathrm{t}}} \quad \mathrm{PV} = \frac{\mathrm{CF}}{(1+\mathrm{i})^{\mathrm{t}}} \tag{7}$$

Where, CF is the cash flow, i the interest rate, and t the year in which it occurred. The NPV is defined as the sum of PVs over the project and is calculated as shown in equation 2:

$$\mathrm{NPV}(\mathrm{i},\mathrm{N}) = \sum_{\mathrm{t}=0}^{\mathrm{N}} \frac{\mathrm{CF}_{\mathrm{t}}}{(1+\mathrm{i})^{\mathrm{t}}} \tag{8}$$

Here CF is the difference between cash inflow and outflow reduced by the discount rate appropriate to the time (t) of transaction. N is life cycle length (years). Equation 3 shows how the benefit-cost ratio (BCR) is the sum of discounted costs (C) divided by the sum of discounted benefits (B) as they occur at time (t) over the project lifecycle length N:

$$\mathrm{BCR} = \frac{\sum_{\mathrm{t}=0}^{\mathrm{N}} \frac{\mathrm{C}_{\mathrm{t}}}{(1+\mathrm{i})^{\mathrm{t}}}}{\sum_{\mathrm{t}=0}^{\mathrm{N}} \frac{\mathrm{B}_{\mathrm{t}}}{(1+\mathrm{i})^{\mathrm{t}}}} \tag{9}$$

In summary the NPV is the sum of benefits minus the sum of costs over the project's lifecycle. BCR is a ratio of the benefits and costs. The BCR being a ratio is sometimes considered by analysts to be inaccurate (Cbabuilder 2016). A basic understanding of basic economics is required to understand the implications of BCR and NPV.

The two main measures of system performance reported by ERain are reliability and efficiency. Reliability is defined as the percentage of days that the demand was met. Efficiency is defined as the percentage of available water used. Among other things, the Efficiency indicates if a greater tank size could help yield more water from the given roof area.

4.4 Results and discussion

4.4.1 BCR of roof size for a toilet and laundry only installation

Results from varying roof areas for the various tank sizes are shown in Figure 4.2. For the 3 kL tank, the reliability and BCR increase with roof size while the efficiency decreases. Even with a small roof area, only 30% of the available water is being used with this type of installation. With larger roof areas the efficiency decreases to only 10%, however the system is quite reliable at over 70%.

The increase in roof area has the largest effect on efficiency when the tank is small. For example, a 1.1 kL tank's reliability increases by 10.6% from a minimum of 61.4% to max of 72%, while for a 7 kL tank the equivalent increase is only 4.5% from 95.1% to 99.6%. This influences the NPV and BCR results. For example, the NPV of a smaller tank (1.1 kL) with a large roof (300 m^2) has a less negative NPV than a larger tank (3 kL) with a smaller roof (100 m^2).

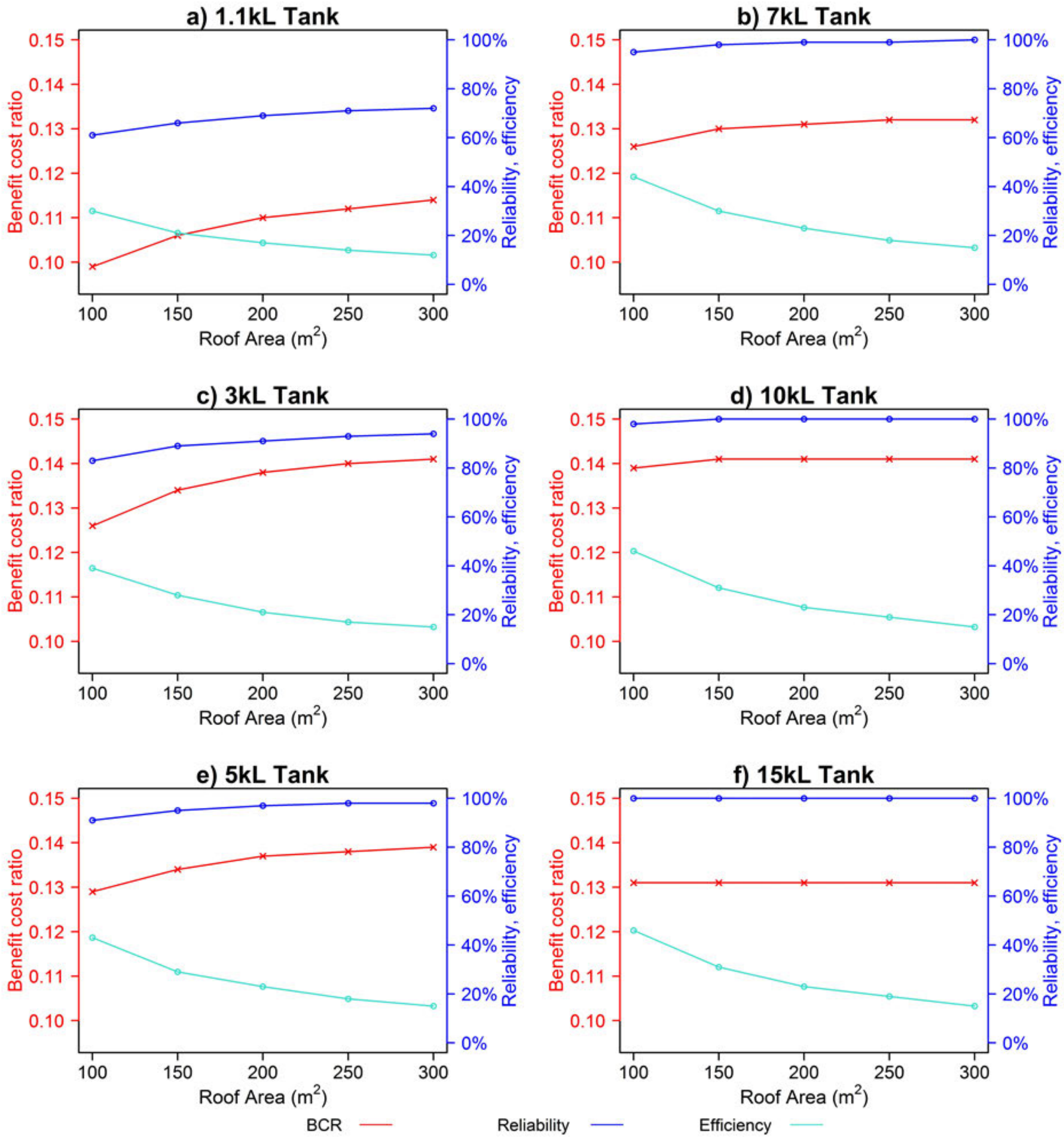

Figure 4.2 Roof area vs. BCR, reliability and efficiency for toilet and laundry use based on Paramatta, Sydney rainfall data.

4.4.2 BCR of roof size for a toilet, laundry and outdoor installation

As expected, system reliability is reduced by connecting irrigation while the efficiency increases and so does the BCR, as seen in Figure 4.3. Therefore, financially, it is an advantage to use the harvested rainwater for irrigation, particularly when mains water is connected as a backup, as it usually is in the urban environment, and where reliability is not an issue.

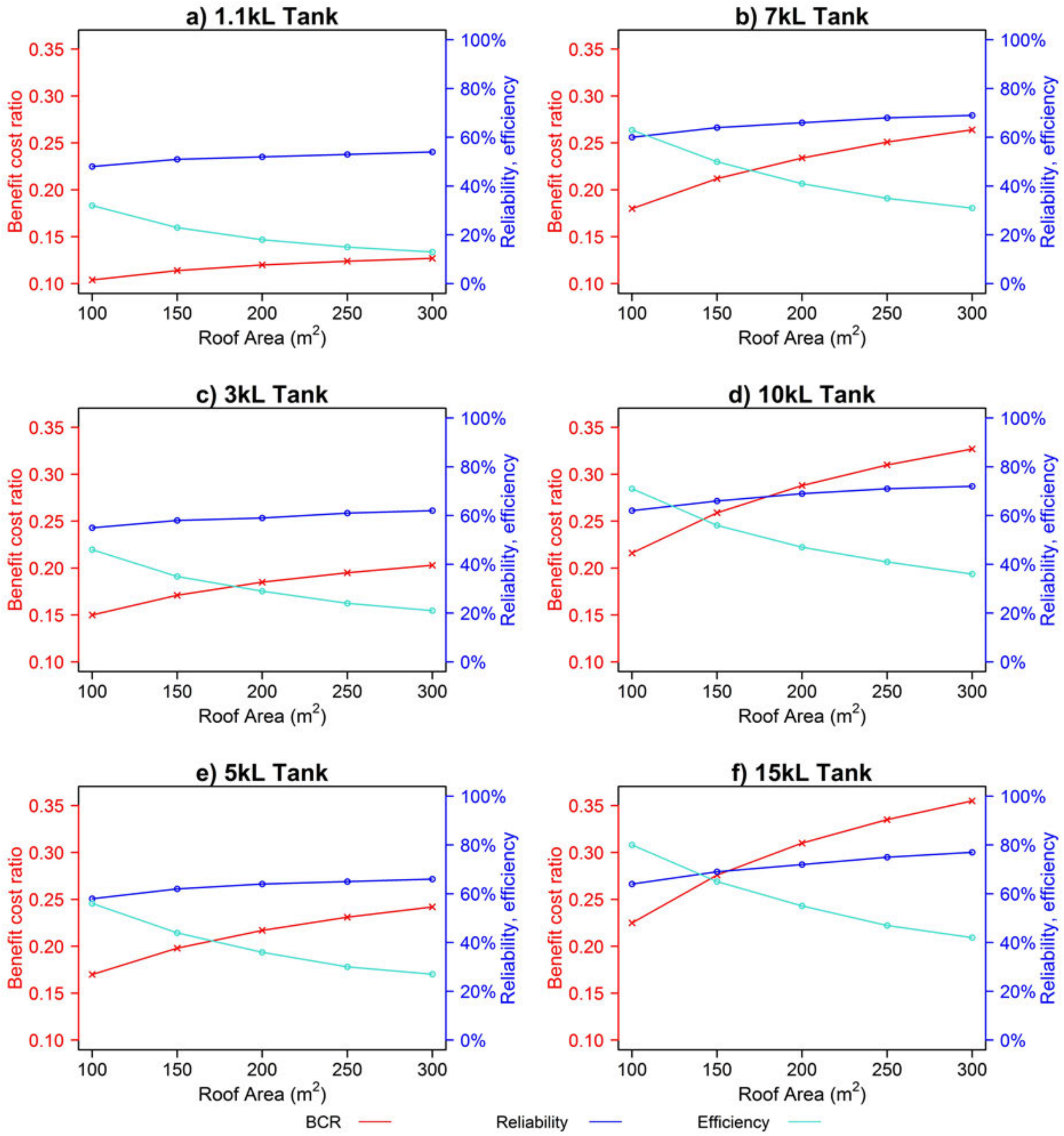

Figure 4.3 Roof area vs. BCR, reliability and efficiency for toilet, laundry and outdoor use based on Paramatta, Sydney rainfall data.

The larger roof catchment means that the smaller rainfall events harvest a more substantial quantity of water and help refill the tank, increasing reliability. The efficiency decreases mainly due to increased overflows, and particularly with the larger rainfall events. If we again compare the results for the 1.1 kL tank and 300 m^2 roof with a 3 kL tank and 100 m^2 installation, we find that NPV is now more negative where for the toilet and laundry only installation above the opposite was true. For a toilet and laundry only installation, reliability is quite high even with a smaller tank, and so a larger tank does not increase reliability much. Once outdoor use is connected however, reliability reduces, leaving room for greater increases in reliability with a larger tank size. The highest NPV is still negative ($16,657) and the BCR less than 1. Interestingly the highest (least negative) NPV occurs with a 10 kL tank, while the highest BCR is 0.355 with a 15 kL tank. It appears that compared to the NPV, the BCR will generally imply that a larger tank size is more economically viable.

4.4.3 Various irrigation areas for a toilet and laundry and outdoor installation

Results for varying irrigation area with a set a roof area of 200 m^2 are shown in Figure 4.3.

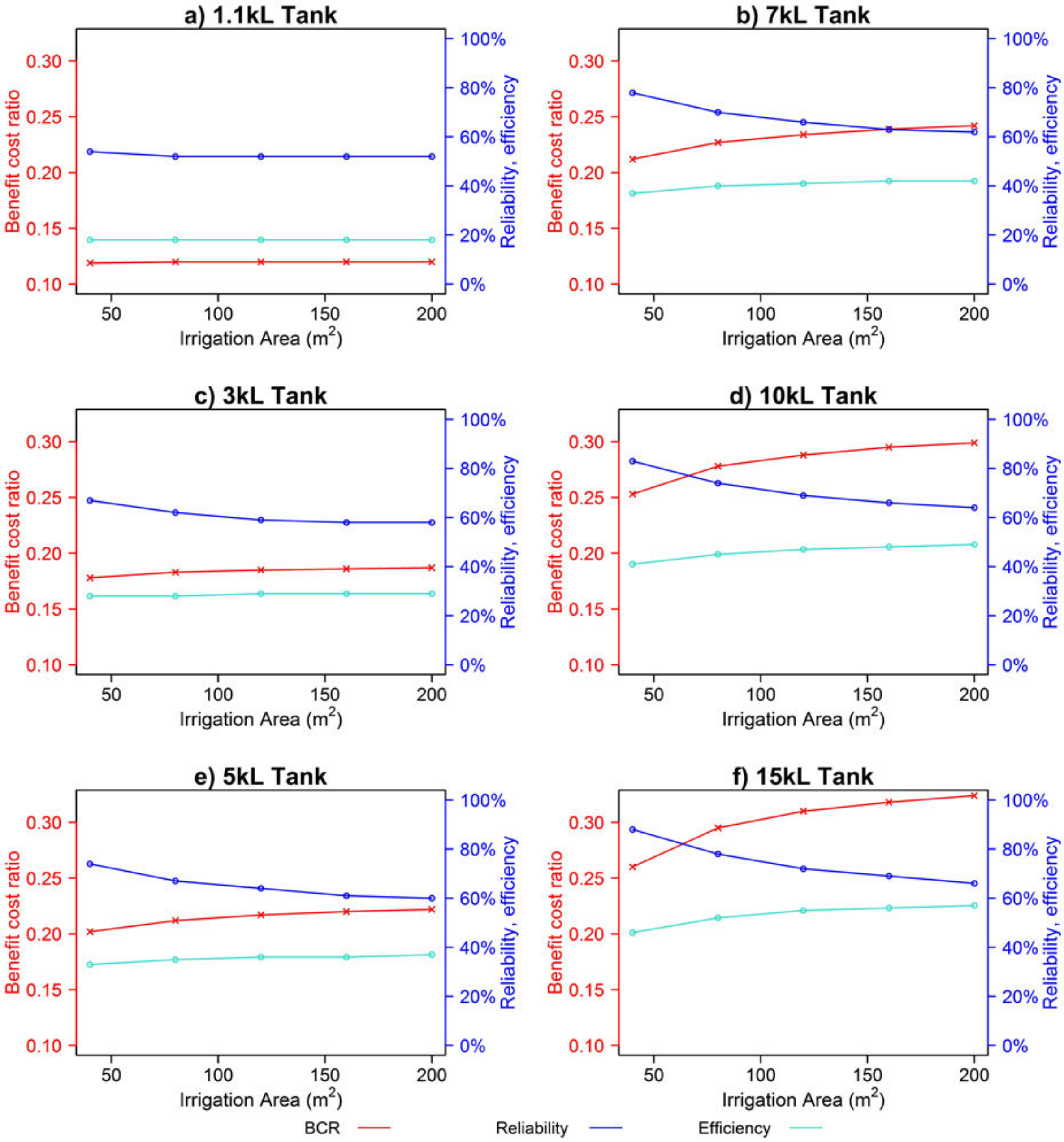

Figure 4.4 Irrigation area vs. BCR, reliability and efficiency for toilet, laundry and outdoor use based on Paramatta, Sydney rainfall data.

For the smallest tank, there is a slight increase in the BCR when increasing the irrigation area from 40 to 80 m^2, but for larger irrigation areas there is no significant increase. The efficiency and reliability are virtually unchanged implying that the RWH system has already reached its capacity to supply water with a small area being irrigated. The larger 3 kL tank has a higher BCR for any irrigation area, and also shows a greater increase in BCR with irrigation area. Efficiency increases only slightly to a maximum of 30%, again implying that the system is already at its capacity to supply water at the lower irrigation areas, while reliability declines to 60% with the larger irrigation areas. The low efficiency means that lots of water is being lost to overflow. The 5 kL tank has higher BCR than both the 1.1 and 3 kL tanks for all areas of irrigation and corresponding higher efficiencies and reliabilities. The relatively small increase in efficiency, and low reliability, implies that the 5 kL tank system is again close to capacity to supply water. Exploring larger tank sizes' results showed that larger NPVs and BCRs occur with the larger irrigation areas as this increases water use and hence monetary water savings. The highest BCR was found with a 15 kL tank; while the highest (least negative) NPV occurs with a 10 kL tank. These results could be affected if future rainfall patterns do not reflect the historical data that is available for, only, the last 100 years or less (Haque et al. 2016).

A 5 kL tank was found preferable to a 2 or 3 kL tank by Rahman et al. (2012) when used for toilet, laundry and outdoor in terms of water savings, reliability and financial viability. Reliability was reduced from an average of 97% to 57% when outdoor use was added. This compares similarly with results found in this analysis. Notably in this analysis the BCR values are all below 1, which also suggests that there is no payback period possible. This is in agreement with the majority of literature (Amos et al. 2016; Gao et al. 2015; Ishida et al. 2011; Kumar 2004; Mitchell and Rahman 2006; Rahman et al. 2007; Roebuck et al. 2011; Roebuck et al. 2012). However it is in conflict with some significant publications such as Gato-Trinidad and Gan (2014) find that RSS systems to have a PP of 12 to 47 years. Roebuck et al. (2011) conclude that any research that finds an RSS system can provide a PP should be thoroughly examined. Reasons for the conflict are often due to improper consideration of expenses and hence the use of a vigorous model such as used here is emphasised.

The only benefit from HA considered is the water savings, there are arguments for including subsidiary and non-quantifiable benefits to using RSS to HA. These may include the improved quality of vegetables produced at home. Reduction in "food miles" from reduced trips to purchase vegetables (Wiltshire and Azuma 2000). Increased real estate value (hedonic price) due to maintained gardens. Noting that under certain restrictions gardens cannot be watered using mains water, but can be from rainwater tanks.

4.5 Summary

Increase in roof area for a toilet and laundry only installation increases both the reliability and BCR while efficiency decreases. For a 3 kL tank only 30% of the available water is used with the smallest roof area (100 m^2). This decreases to 10% with the largest roof area (300 m^2) while reliability increases to over 70%. Interestingly it is with smaller tanks that the increased roof area has the biggest effect in increasing the reliability. This implies that if there is a larger catchment available the tank size can be reduced.

Increase in roof area has a greater effect for an installation that includes outdoor usage. The decreased reliability means that there is greater potential for increasing reliability with a larger tank or roof area. This changes the pattern of BCR and NPV. Without outdoor use, attached reliability is already high with a small tank and so a larger tank offers little increases in reliability. The lower efficiency at larger roof areas compounds the increase in reliability with increasing tank sizes. Without outdoor uses attached, the NPV of a 1.1 kL tank with a roof area of 300 m^2 is more favourable than the 3 kL tank with a roof area of only 100 m^2. When outdoor uses are attached this is no longer the case, and the 3 kL tank becomes more favourable than the 1.1 kL tank.

Including outdoor use considerably reduces the reliability overall while the efficiency and BCR increase. This indicates that it is financially advantageous to use the RWH system for outdoor use where reliability is not a concern. This is particularly true if, as in most urban cases, mains water is connected to the tank as a backup. If reliability is a concern however, and a threshold reliability of 75% is required for irrigation then an irrigation area of 50 m^2 will require a tank size of at least 5 kL. Reliability could feasibly be improved through irrigation water management and seasonal plantings sensitive to water demand. Increasing the irrigation use increases the NPVs and BCRs as this increases water use and hence monetary water savings. The highest BCR occurs with a 15 kL tank; while the highest (least negative) NPV occurs with a 10 kL tank. The BCR of smaller tanks do not increase much with larger irrigation areas because the RWH system has already reached its capacity to supply water even with a small area of irrigation. Crop failure due to decreased reliability however may still be an issue if the water supply is not supplemented with mains water.

This study highlighted a number of areas for further research. This study only presented a simplistic method of modelling irrigation use and a more in-depth study focusing on irrigation use would be useful. Some say that, with respect for gardening, a rainwater tank is empty when it is needed most. To address this, the reliability and efficiency of RWH systems in relation to irrigation use could be explored in more depth. Particular attention should be paid to evapotranspiration, water requirements, and yield. Relationships between monthly and seasonal variation in rainfall, rainfall categories, total water available in the various regions of Australia and their influence on reliability and efficiency of RWH systems should also be explored to deepen the understanding of roof RWH's potential use in urban agriculture and the contribution it can make to greener cities and the SDGs.

Chapter 5

Sustainability in Water Provision in Rural Communities

Chapter 5 Sustainability in water provision in rural communities: the feasibility of village scale rainwater harvesting schemes

This chapter is a partial reproduction of the following refereed journal paper:

Amos C.C., Ahmed, Amir, and Rahman A. (2020)

Sustainability in Water Provision in Rural Communities:

The Feasibility of a Village Scale Rainwater Harvesting Scheme

Water Resources Management (Under Review)

[**Impact factor: 2.644, SJR Quartile: Q1**]

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5.1 Overview

Groundwater resources are often the main source of drinking water for remote communities, but they are increasingly found to be unsuitable, and a source of ill health in many parts of the world. High annual rainfall in monsoonal regions makes rainwater harvesting an attractive alternative, but lack of infrastructure for capturing and storing sufficient quantities is often restrictive. This study focuses on the coastal region of Bangladesh where groundwater supplying tubewells are progressively found to contain arsenic and high salinity, and where cyclones are a common cause of damage to infrastructure. The aim of this study is to evaluate the potential of a village scale rainwater harvesting scheme as a solution to water security concerns. Analysis of various size rainwater storage systems (RSS) is conducted using daily rainfall data from Khulna Station in Bangladesh. It was found that a village scale RSS with 3 m deep and 100 m by 100 m surface area could supply 100 L/p/d for 85% of the year. The reliability could feasibly be increased to 100% with seasonal water restrictions. The village scale RSS is compared with an individual household level RSS. Advantages of the village scale RSS include the opportunity for improved management and water quality monitoring, and the potential for public-private partnerships. The proposed methodology can be adapted to other monsoonal delta regions to enhance water supply.

5.2 Introduction

Access to safely managed drinking-water services is often limited by the availability of suitable water sources. About 15% of the world population do not have access to clean water. In many developing countries, the main source of drinking water is untreated groundwater. However, unless properly managed, groundwater is not a sustainable resource (Shahid and Hazarika 2010). In rural groundwater supply, pump failure can also be a major issue leading to use of whatever low quality water is at hand, and increases incidents of diarrhoea (Thompson 2020). Contaminants present in groundwater may undermine the water supply such as high salinity, especially in coastal regions, fluoride, such as in the rift valley, and arsenic such as in Bangladesh (Rakib et al. 2020). Large dams may not be viable in absence of suitable topography. Desalination is expensive and has a high energy demand (Shamsuzzoha et al. 2018). Filtered pond water, bottled water and roof harvested rainwater storage systems (RSS) are some of the remaining options. Monsoonal rains in the delta regions with high annual rainfall, surrounded by saline waters make rainwater harvesting an attractive option. It also means that the water is most available at times when transport is most difficult due to monsoonal floods. The main issue is whether the quantity of water required can be provided by an RSS.

In one of most densely populated countries in the world, Bangladesh, only 56% of people have access to safely managed drinking-water services (WHO 2019). It is a delta region with a Tropical Monsoon climate (Köppen Am category) and has an annual rainfall of approximately 2000 mm. For drinking water, Bangladesh relies heavily on groundwater where a hand-pump known as a tubewell is widely used. However, the tubewells are becoming increasingly unsuccessful in coastal areas of Bangladesh. Pond sand filters, introduced as an alternative to arsenic contaminated tubewells, have also regularly failed (Hoque et al. 2019). In the coastal region, issues are compounded by frequent cyclones. For example, Cyclone Aila in 2009 caused widespread destruction, and major disruption to water supplies (Sadik et al. 2018). In stead of the usual 500 m, women and children, had to travel over 5 km to fetch drinking water during the cyclone. Many tubewells remain damaged and people often just drink untreated pond water (Saha, 2019, Pers. Com., 27 Jan). There is also arsenic contamination, that affects much of the groundwater in Bangladesh (Rahman et al. 2018), and health issues linked to salinity have also been reported (Ahmed et al. 2018). In the rural areas of Bangladesh, there is no regular testing or monitoring of the quality of the various and scattered water sources. Health records are limited to the hospitals, with little or no records from local doctors and so it is difficult to monitor the health effects of the water people are drinking (2019, Pers. Com., 31 Jan). Uncertain future climate and the expected rise in the sea level will only compound these issues (Rezaie et al. 2019) with low lying delta regions like Bangladesh being particularly vulnerable (Kabir et al. 2016). Hence, it is important to identify reliable fresh water sources for countries like Bangladesh. In this study, the feasibility of an RSS is examined for coastal region of Bangladesh where groundwater has a high level of arsenic and salinity.

The RSS has been used from millennia (Cowan 2014), and is becoming increasingly popular (Campisano et al. 2017). Australia has made installation of RSS mandatory for new developments in many areas (Gardner and Vieritz 2010). RSS are being mandated in Bangladesh, but predominantly in the capital city (Bashar et al. 2018). However, at the individual level without funding it is unlikely that the rural poor will be able to install an RSS due to the large financial investments required (Amos et al. 2016; Naus et al. 2020). Groundwater supplies by tubewells are often operated on a village scale and this may prove to also suit village scale RSS (Gurung and Sharma 2014; Newman et al. 2014), and particularly where individuals cannot afford their own RSS. It has been noted that the communal approach to RSS can provide a reliable supply of domestic water (Cook et al. 2013).

The purpose of this study is to evaluate the potential of a village scale RSS to provide sufficient quantity of drinking water in the coastal region of Bangladesh. We consider an RSS for clusters of 100 families to supply sufficient quantity of water and compare this with small household scale RSS. Small RSS are expected to be the cheapest at the individual scale and may even be in the form of “makeshift” tanks thus minimising the size and cost of the system. This study aims to address several of the United Nations’ sustainable development goals (SDGs), particularly Clean Water and Sanitation, focusing on drinking water. Therefore, the analytical results are discussed in a socio-economic context in order to highlight issues that will need to be addressed for successful implementation of the RSS. It is expected that the outcome of this study will be of benefit to water engineers, town planners, researchers and policy makers in government and NGOs working on water security. The developed methodology can be adapted to other monsoonal regions where there is a scarcity of drinking water.

5.3 Materials and methods

5.3.1 Study area

Bangladesh is selected as the study area, which is highly populated, being the most densely populated delta in the world with a population density of 1173 people per km^2 and a total of approximately 170 million (Worldometers 2019). The study area, Koyra Upazila a sub-district of the Khulna district, which is part of the Khulna division, is Bangladesh (Figure 1). The population of the Koyra Upazila was nearly 200,000 in 2011 and is dominated by a rural population of approximately 182,337 while the urban population is considerably smaller at 11,594 (BBS 2015). The Upazila has an area of 1775 sq. km. most of which, 951 sq. km, is Sundarbans forest (BBS 2015).

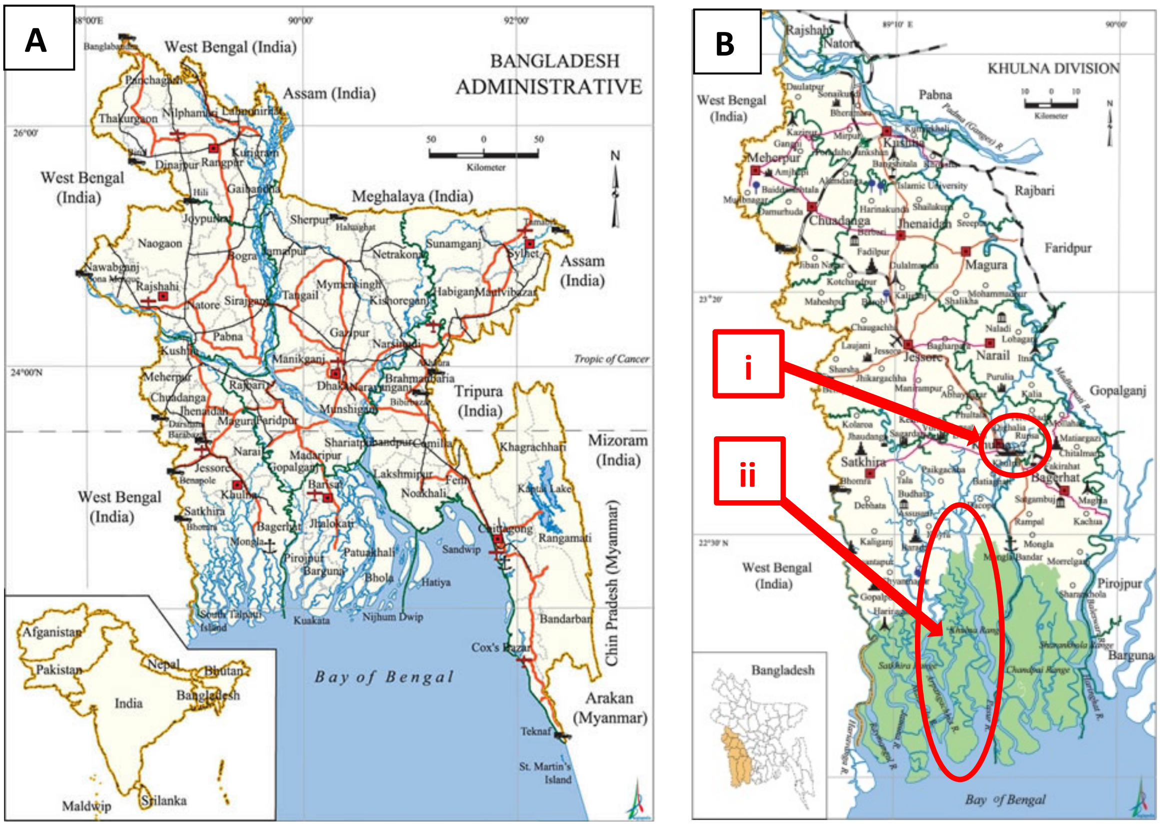


Figure 5.1 Location map: (A) Bangladesh , (B) Khulna Division showing location of (i) Khulna Rainfall station and (ii) Koyra Upazila (Banglapedia 2014)

5.3.2 Rainfall data

The climate is a Tropical savannah (Aw Köppen classification) with a wet summer and a dry winter. Daily and monthly rainfall data were obtained for Khulna station from the Bangladesh Meteorological Department (BMD 2019). Records from 1970 to 2016 show an average annual rainfall of 1728 mm with a standard deviation of 491 mm and 5th percentile of 962 mm. Monthly averages range from a minimum of 6.6 mm in December to a maximum of 335 mm in June. Evapotranspiration in the South West Coastal Region (SW-SC) of Bangladesh is high in winter months, when rainfall is low (Mac Kirby et al. 2014).

5.3.3 Scenarios

Scenarios are based on households of 5 people, rounded up from the national average of 4.5 (Population.un.org 2019). Three scenarios are considered:

Drinking Water only, 5 kL of water per person per day, for villages with 100, 200 or 300 families. With RSS of 50 - 20000 kL and roof catchment areas between 200 and 10000 m^2.

1. Higher daily consumption rates of 50, 100, 250 or 350 L/p/d for a wider range of

water uses to match middle income developing nations for villages of 100 families.

2. Larger RSS and catchment areas have been included, up to 100,000 kL, and 5000 – 100000 m^2 respectively, as 100% reliability was only found at these scales.
3. Individual houses of 5 persons, tank sizes from 1-7 kL, with roof catchment areas of 10-200 m^2. Average monthly reliability of the 1 kL tank with a roof area of 20 m^2 was investigated.

Losses of 1 mm for overflow and evaporation from the roof, and 0.5 mm for first flush were considered.

5.3.4 Water demand profile

The climate in the coastal region of Bangladesh is characterized by the average daily temperature of 26 °C (en.climate-data.org 2019) and so it is not a high temperature environment. A daily consumption ranging from 2 L/p/d to an extreme of 16 L/p/d for adults was advised by WHO in Table 6 , p24 Grandjean (2005). Physical activity and increased temperature influenced the upper limit considerably. For a temperate environment and sedentary activity levels the range is 2-4 L/p/d, an average of 5 L/p/d is therefore conservative. The 5 L/p/d is aimed primarily at supplying quality, contaminant free water for drinking to address the drinking water crisis.

In the first scenario, use would be monitored by the individual, and in the second, it would be by a governing body. In the third scenario, the consumption rates of 50, 100, 250 or 350 L/p/d were considered based on the IRC (1983), p40 which estimates a typical water use for a single tap connection in a house of 50 L/p/d, or a yard connection of 40 L/p/d (range of 20-80 L/p/d). A typical multiple tap connection is estimated at 150 L/p/d while 250 L/p/d was chosen to represent the upper limit of the range (given as 70-250 L/p/d). The 350 L/p/d was chosen to represent a developed country's consumption rate, based on Sydney (Sydneywater 2019). Evaporation from the storage area has not been considered quantitatively in the analysis.

5.3.5 Water balance modelling

The proposed RSS was analysed using a rainwater harvesting analysis tool called ERain (Amos et al., 2016) that has been developed specifically to analyse water balance in RSS. The minimum required inputs to ERain are:

- Daily rainfall data
- RSS sizes and catchment areas
- Water demand profile

The rationale behind ERain's development may be found in Amos et al. (2016) and an example of its application in Amos et al. (2018a). ERain uses the yield after spillage model (YAS), as described by Fewkes and Butler (2000), to analyse rainfall data over a daily interval (t) .

$$Y_t = min\begin{cases} D_t \\ V_{t-1} \end{cases} \qquad V_t = min\begin{cases} V_{t-1} + Q_t - Y_t \\ S - Y_t \end{cases} \tag{1}$$

Where Y_t is the actual water used (yield), and V is the volume of water in the RSS of size S. D_t is the demand, and Q_t = volume of rainwater, after losses, flowing into the RSS. The water flowing into the RSS is calculated as

$$Q_t = max\begin{cases} (I_t \times A) \ - L_t \\ 0 \end{cases} \tag{2}$$

Where I_t is the depth of rain, A is the effective catchment area, and L_t is the losses which includes evaporation and bulk losses. Reliability in ERain is defined as the ability of the RSS to meet the demand and is based on the number of days the demand is met over the year.

$$Reliability \ = \frac{days\ demand\ met}{365.25} \times 100\% \tag{3}$$

5.4 Results

Results for the three scenarios are presented below, firstly at the village scale for supplying drinking water only, then for domestic water, and finally at the individual household scale for drinking water only.

5.4.1 Village scheme RSS to supply drinking water

The potential of various sized village scale RSS schemes to supply 5 L/p/d of drinking water is shown in Figure 2.

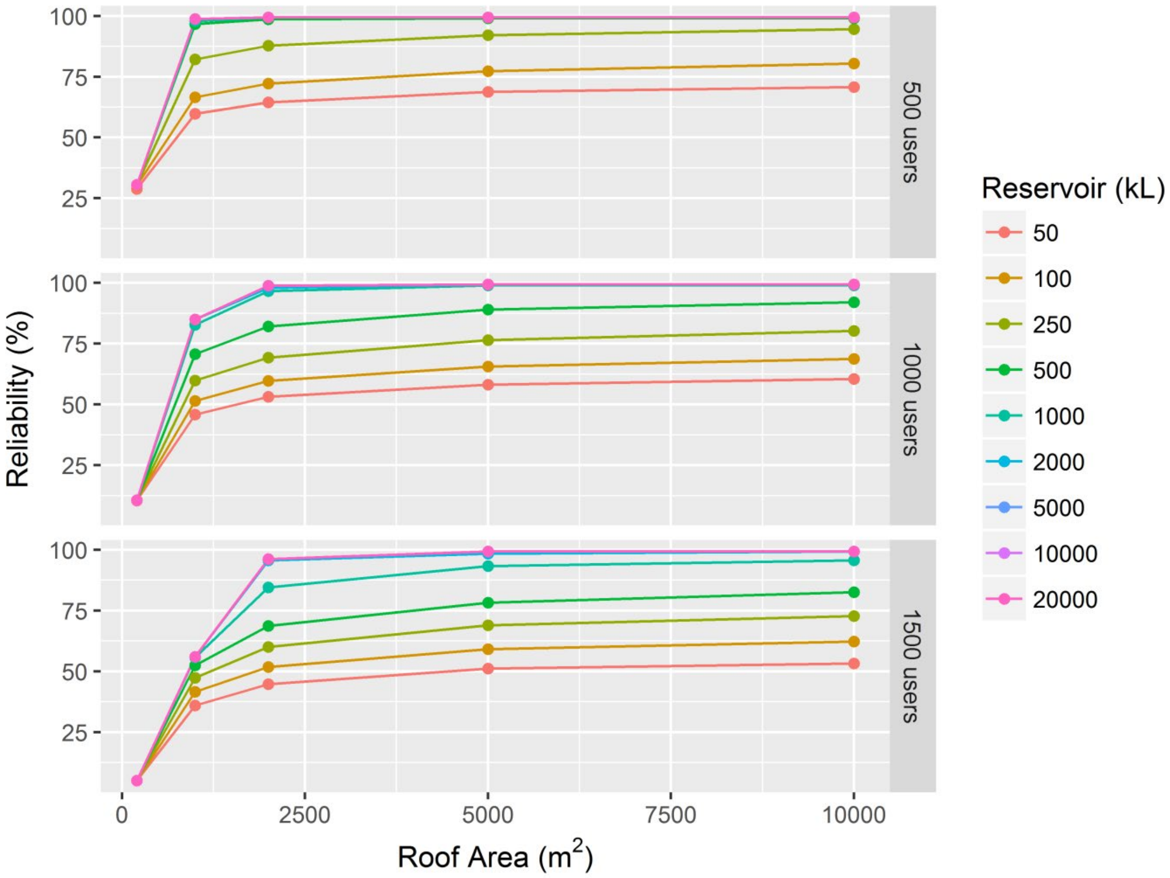


Figure 5.2 Reliability results from ERain program for 500, 1000 and 1500 users for systems with tank/storage sizes and roof areas based on Khulna Station Rainfall

For 500 users, or approximately 100 families, a reliability of 96.7% can be achieved with a storage system of 500 kL and a roof area of 1000 $m^{2.}$ Reliability close to 100% can be achieved for 1000 users with 1000 kL, and for 1500 users with 2000 kL. Interestingly this equates to approximately 1 kL of storage per person, which agrees with results for the individual house scale installations shown in Figure 4 where a 5 kL tank provides 100% reliability for 5 people with 20 m^2 of roof or more. There is no significant increasing in reliability for catchment areas larger than 2000 m^2.

5.4.2 Village scheme RSS to supply all domestic water supplies

The potential of community rainwater storage to supply domestic water at rates of 50, 100, 250 or 350 L/p/d with roof/catchment areas of 5,10,15,20,50 or 100 thousand m^2 is shown in Figure 3.

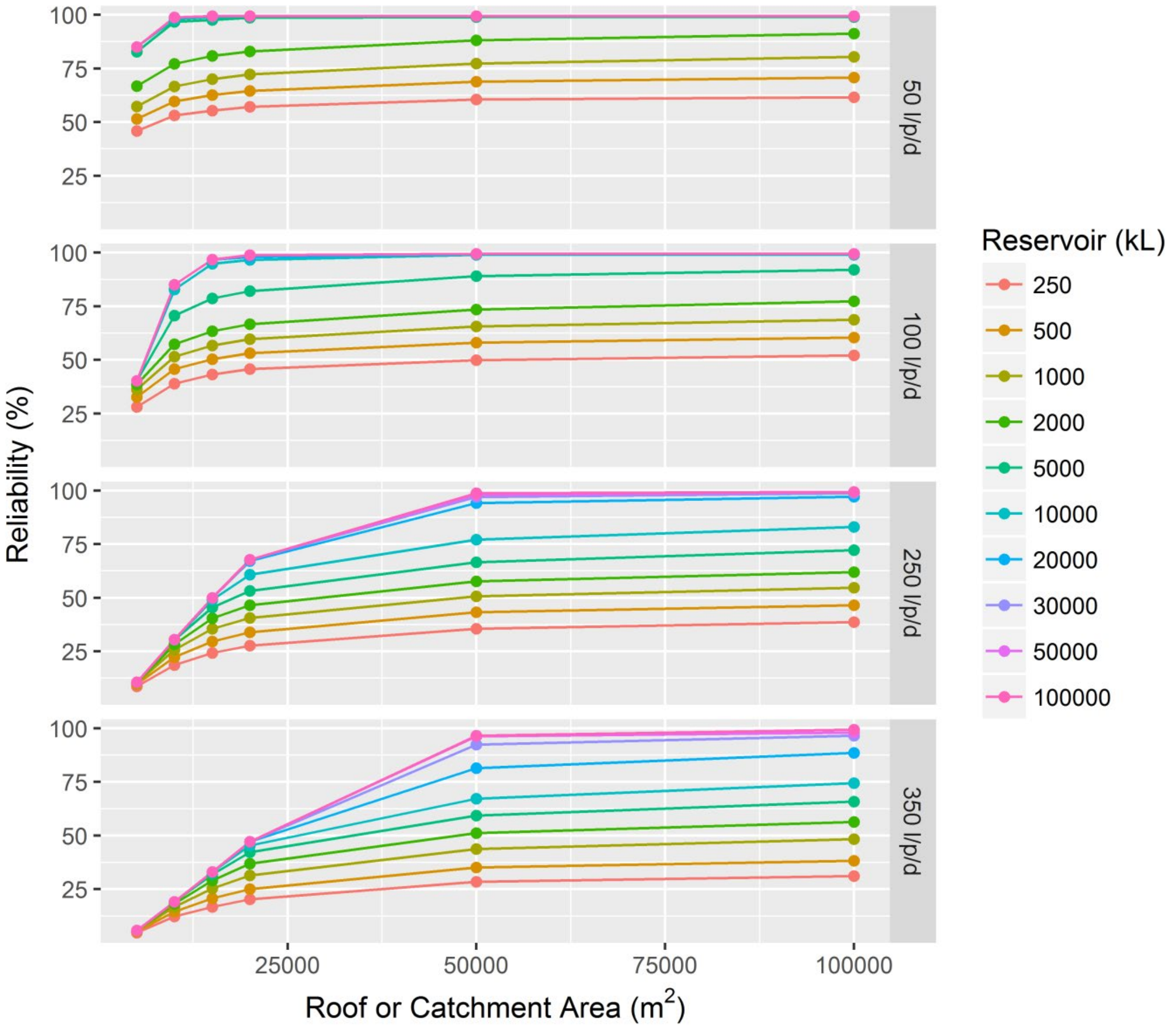


Figure 5.3 ERain reliability results for 500 users consuming 50, 100, 250 or 350 L/p/d for systems with various tank/storage sizes and roof areas based on Khulna Station Rainfall

With the higher usage, reliability continues to increase significantly with larger catchment areas, up to 50,000 m^2. To sustain a 100% reliability for a typical single tap household connection consuming 50 L/p/d, a catchment area of 10,000 m^2 and a reservoir of 5000 kL would be needed. However, for a demand of 350 L/p/d a 100,000 kL RSS would be required. Considering a 3 m deep RSS, then the 30,000 kL reservoir represents a 10,000 m^2 catchment area (e.g. 100 m by 100 m) if the rain falls directly into the RSS or on to a roof over the RSS. This would give a reliability of probably 100% for the 50 L/p/d consumption and a reliability of 85% for a consumption rate of 100 L/p/d which could feasibly tend towards 100% with seasonable water restrictions and or supplementary groundwater. These results are indicative only, and do not consider evaporation from open RSSs which would make a significant difference in the water storage if not controlled.

5.4.3 Individual household RSS for partial year supply

The potential of various RSS between 1 and 10 kL, with roof areas from 10 to 200 m^2, to supply a household of 5 with 5 L/p/d of drinking water is shown in Figure 4.

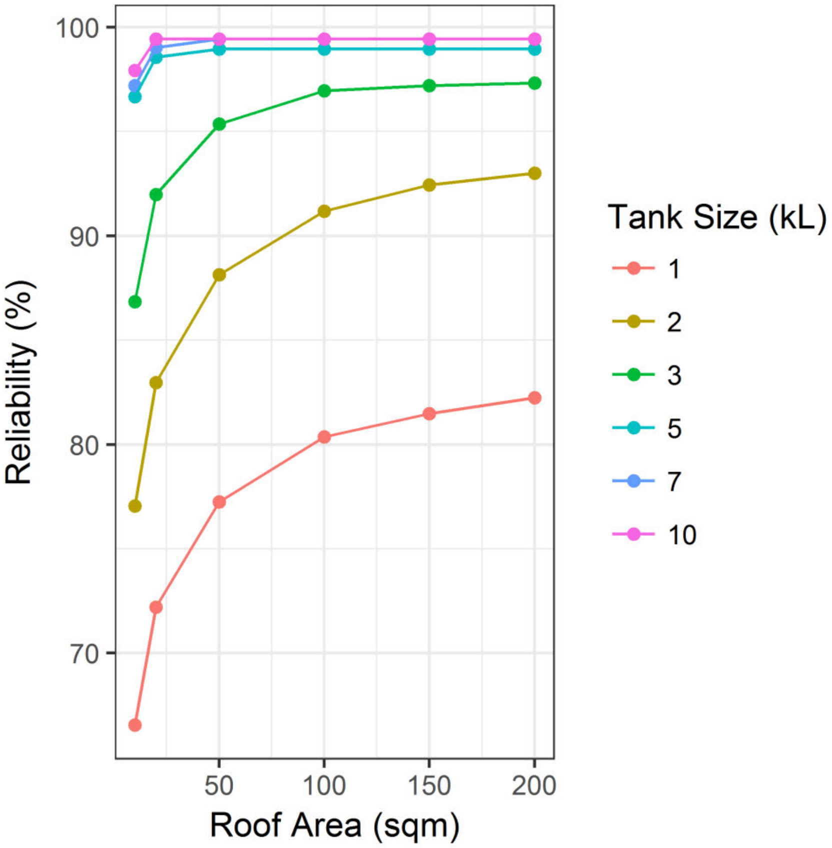


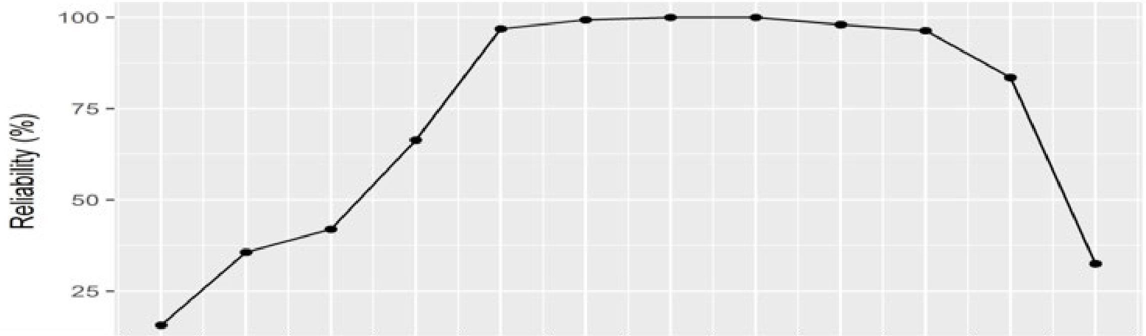
Figure 5.4 ERain reliability results for a family of 5 using 5 L per person per day for systems with tank sizes between 1 and 10 kL and roof areas from 10 – 200 m^2 based on Khulna Station Rainfall

A reliability approaching 100% can be achieved with a 5 kL tank and a roof area of 20 m^2. A reliability of 95% can be attained with the 3 kL tank with a catchment of 50 m^2.

Figure 5 shows the monthly reliability compared with the monthly rainfall averages and the % of the total rainfall that each month represents over the whole data set for a 1 kL RSS Tank and a roof area of 20 m^2 for a household of 5 people drinking 5 kL of water per day.

Reliability is nearly 100% for the 3 months from June to August and over 95% from May to October. Interestingly, May and October have a similar reliability, but October has only 7% (130 mm) of the annual rainfall while May has considerably more at 11% (200 mm). This is because the tank has more water in it at the beginning of October after the heavier rains in

September than in May after a dry February.



Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
Rainfall (mm)	13.3	52.1	44.4	87.5	200.0	335.6	329.8	323.5	254.7	129.8	32.1	6.6
% of total rainfall	0.7%	3%	2%	5%	11%	19%	18%	18%	14%	7%	2%	0.4%
Reliability	16%	36%	42%	66%	97%	99%	100%	100%	98%	96%	83%	32%

Figure 5 ERain Monthly reliability results whole data set compared to rainfall for a 1 kL RSS and a roof area of 20 m^2 for a household of 5 people drinking 5 kL of water per day. Based on Khulna Station Rainfall

A full 1 kL tank will still provide 25 L/d/hh for 40 days which implies that much of October's reliability is due to September's and perhaps even August's rains. The accumulated benefit of the earlier rains continues into December which has a very low rainfall but still has a reliability of 32%, while January has double the rainfall, but half the reliability. This demonstrates how storage size affects reliability of water supply. It should be noted that even the lowest reliability, 16%, means that for 4 days or more a month one would not have to walk to collect water. The tank could also be used to store delivered water in the dry season. A 1 kL tank could be made up of smaller storage systems, be more affordable and supply water for part of the year. This would be a great asset to a household. The main issues are water quality, management and particularly cost.

5.5 Discussion

Firstly, we discuss the village scale opportunities for either supplying drinking water only or domestic water generally. Secondly, we compare village scale with the household scale and seasonal water supply. Finally, the options are summarised and discussed.

5.5.1 Feasibility of village scheme RSS

The proposed village scale RSS are quite suitable to the area where the population is clustered in small villages. Such a system could provide a valuable alternative where the arsenic or salinity contamination is high in the tubewells. To supply drinking water only, metered at 5 L/p/d, for a village of 100 families (approximately 500 people), a reliability of 96.7% can be achieved with a storage system of 500 kL and a roof area of 1000 m^2. Proper management could conceivably increase this to 100%. The large roof area could be achieved by connecting several houses to the system, or a large building such as a school. 225 kL tanks have been installed in Kenya to supply clean drinking water for up to 400 people through the whole year (Innovations 2019; kiganda 2016).

A larger system designed to supply water for other domestic uses such as cooking, and sanitation is also feasible but challenging in terms of construction. To supply water at a rate of 50 L/p/d, a reservoir of 5000 kL with a catchment area of 10,000 m^2 would be needed. To supply water at 100 L/p/d for 85% of the year (average multiple tap connection), a storage volume of 30,000 kL and a catchment area of 10,000 m^2 could be required. A 3 m deep RSS 100 m by 100 m could both provide both the storage area of 30,000 kL and the catchment area of 10,000 m^2. Evaporation is a problem with such large surface area, however this could be mitigated using continuous floating covers that have a proven ability to reduce evaporation (Pittaway et al. 2018) while also being cost effective and the most appropriate method for this size storage. The semi-centralised system could allow for proper treatment, monitoring, and resource management to increase reliability. Seasonal water restrictions, and or groundwater supplementation, could be implemented. The remaining questions are, how can such a system be financed and administered, how water could be distributed, and how the poor would be benefited.

Public private partnerships (PPP) are one option for finance and administration. PPP are incorporated into the national water policy (PROB 1999), and stakeholder participation is increasingly being seen as the way forward to solving water issues (Kausher 2019) .The policy states that a committee should share the management of the system even if the private investor installs the technology. This helps avoid monopolies and ensures that the quality of the system is maintained in the common interest. The poor could also be accommodated by a government voucher system. Community training and resource mobilisation are often a barrier to ongoing maintenance and success of RSS (Behnke et al. 2017). This could be mitigated by Vocational Education and Training (TVET) to help build up the necessary skills in the community (Mouzakitis 2010). This will help avoid the problems that arise when the technologies advance faster than the support systems or when there is a mismatch in the labour market (Shelomentseva and Ifutina 2013). It will also help to strengthen the local community.

One option for distribution is producing branded bottled water at the local treatment plants. An enterprise to supply bottled drinking water from their own plant was achieved by Daffodil International University (DIU), Dhaka, Bangladesh for internal use at the university, staff and students with a student base of 25,000 people. The Bangladesh Rural Agricultural Development (BARD) was interested in their model and on the third author's invitation they visited DIU and decided to make a pilot of the project that they intended to popularise in rural areas. Based on the DIU experience this idea of selling water in the rural areas is quite promising. The water at DIU is simple filtered groundwater from reliable deep wells that are arsenic free, with no reverse osmosis, and the quality is assured because it is tested regularly. Water is often seen as something that should be equally available to all and not subject to commercialisation (Hawkins et al. 2015). However, there are other considerations at hand, such as water scarcity and quality. Preferably there would be some piping to local houses, and a van delivery service could be instigated for the more remote houses, or people could collect the water in jars as they currently do. There are ponds that are currently marked for re-excavation by the government that could potentially be used for the proposed project, or private lands could be sought.

While many important questions remain, this study has shown that there is enough water available locally through rainfall to supply people's needs. The underlying hypothesis here is that, there is such an abundance of high-quality rainwater falling on everybody's land, individuals or partnerships should capture that high-quality water for their own use and others.

5.5.2 Feasibility of Individual RSS for a partial year supply of drinking water

The concept of a partial year supply focusing on the wet season is quite attractive and offers several advantages. The system can be a relatively small, both in terms of storage size and roof catchment area, implying a lower capital cost. Village scale schemes would be in the village centres, and so in the rainy season difficult for the remote villagers to access via the wet, muddy, and slippery paths. In contrast, household installations supply water when and where it is most needed.

A small system could still bring a considerable advantage even in the dry season. After occasional rains (Figure 5), it could save on average at least one trip per week to collect water. It could also be used to store water that has been delivered or collected in larger amounts than usual. A 1 kL tank installation with a roof area of only 20 m^2, could supply drinking water for a family of 5 at 5 L/p/d reliably for nearly half the year. The average daily temperature is lower in the dry season at 20 °C (en.climate-data.org, 2019) and so less drinking water will be required (Grandjean 2005; Judith Marcin 2018), helping to improve reliability. A partial year RSS could easily be upgraded to a full year system by increasing the storage capacity to 5 kL or a 3 kL for a 95% reliability. Reliability could be increased by water rationing, careful management, and drinking water when away from home. As many people are walking to collect their water it is expected that they will be already quite capable of managing their water consumption in comparison to when it is ‘on tap’ (Wanyonyi 2000). A variety of management techniques could be employed such as storing water in 20 L bottles if they are available cheaply, acquiring water from other sources when convenient for example, if children are at school, parents at work or shopping.

The main hindrance is cost, as the rural poor tend to be the ones living at a distance from the village centres. Apart from the storage system itself, some of the main costs involve include the catchment system (including gutters, downpipes), and in some cases appropriate roofing materials (Amos et al. 2016). Traditional roof types are not suitable, although many of these have now been replaced with iron through government initiatives. The economic issues suggest that it is likely that for the poor this kind of installation will predominantly remain the initiative of the government and NGOs, although makeshift solutions may be possible.

5.5.3 Implementation

Rainwater is an underutilised resource that is available in abundance in Bangladesh, and many tropical regions, while groundwater is being over utilised and becoming increasingly saline in many coastal areas. There is currently both a freshwater and drinking water crisis in Koyra, and so the time is right to harness the potential of RSS. Diverse water sources should continue to be utilized for a sustainable solution resilient to the frequent cyclones and flooding. RSS, and also pond sand filters (PSF), were suggested nearly 15 years ago or more by Rahman et al. (2006), and while the PSF have seen increased use, use of RSS has not significantly increased. This is partly because it is not recognised as a healthy source of water, and the capital costs involved are also inhibitive. Future drinking water supply therefore should focus on maintaining and improving current water supplies and particularly on increasing rainwater use.

The main barriers to RSS implementation generally are social acceptability, the unfamiliar taste of the rainwater, community awareness, acceptability of the health of the rainwater, and economics. Successful solutions must address the synergy between society and engineering (Xavier and Holness 2019), and so community education will be needed. It is important to consider all the aspects of quality, reliability, sustainability, affordability and social acceptability of the various options (Azam 2019). Realistic solutions to the drinking water crisis also need to take into account these socio-economic factors, as important decisions are often made automatically and may be based on stereotypes or social norms (World Bank 2015) rather than on what may be a very appropriate solution.

The main advantage of a community-based approach to RSS, as compared to individual houses, is the capacity to monitor the water quality regularly and to incorporate professional training. The main advantage of household scale installations is that the water is available during the wet season when and where it is most needed avoiding the need to travel to collect water. The exact approach may be dictated by the funding available either by the government or individuals, and demographics. It is most likely that individual approach will continue to be suitable to the remoter homesteads, while the community approach may prove viable in the village centres.

The primary focus under the current conditions in Bangladesh should be simply ‘providing clean drinking water free of bacteria and harmful minerals' in a way that either is, or can become, socially acceptable and environmentally sustainable. This study has shown that a significant quantity of water could be made available through village scale RSS schemes. With the current situation in mind, increasing access to fresh quality water by all and every method possible is advised. The government and NGOs should continue funding individual RSS and work towards the implementation of village scale treatment plants. Further research should focus on the implementation of rainwater treatment plants in tropical delta regions both in terms of appropriate technology and community participation. A pilot scheme would be an excellent step forward.

5.6 Summary

This study examines the feasibility of a rainwater storage system (RSS) in coastal area of Bangladesh. AN RSS at Koyra, Bangladesh, that supplies drinking water to clusters of houses of 100 families (approximately 500 people) at a rate of 5 L/p/d for drinking water can be achieved with a roof or catchment area of 1000 m^2 with a tank or reservoir storage area of 500 kL if evaporation from the storage area can be controlled. Supply for other domestic uses such as cooking, and sanitation can also be achieved at a rate of 50 L/p/d by a reservoir of 5000 kL with a catchment area of 10,000 m^2.

To meet the bottom end expectation of an in-house multiple tap connection a 3 m deep RSS 100 m^2 would be needed to provide both the catchment area of 10,000 m^2 and the storage area of 30,000 kL required to supply 100 L/p/d for 85% of the year. The reliability could feasibly be increased to 100% if seasonal water restrictions and or groundwater supplementation were instigated. Issues with this scale of system include minimising evaporation, the distribution of water, financing, and management of the treatment plant.

At the individual household scale, a partial year supply of rainwater can be achieved with a relatively small system. AN RSS as small as 1 kL connected to only 20 m^2 of roof could supply water for a family of 5 at 5 L/p/d reliably for nearly 6 months over the wet season and for a month or so after it. Water management strategies such as drinking water when away from home, at school, etc. could increase this reliability considerably during the dry season when it is easier to travel. The advantages of this are lower capital costs due to the smaller tank, and a reliable supply of water at home in the wet season when it is difficult to travel across the wet and muddy tracks. Disadvantage is that it may still be relatively expensive for those whom it could most benefit, namely the poor living at remoter parts of the district.

A full year supply of rainwater can be achieved to over 95% reliability with a larger tank capacity and roof catchment. A 5 kL tank and a roof area of 20 $m^{2,}$ or a 3 kL tank with a 50 m^2 roof would be sufficient. Monthly results for reliability show that the RSS continues to supply water after the wet season as the tanks are full. This concept could also be applied to extending the growing season for household vegetable production by water being available into November and December when the rains have stopped.

Comparison of results for the individual and village scale agree that a rough estimate of 1 kL of storage and 4 m^2 of catchment is required to supply 5 L/p/d reliably all year around.

Future studies should focus on the economic and social feasibility, survey and proposed sites for the scheme. Due consideration should be given to population distribution, flooding during cyclones and access. Ideally a pilot scheme or trial should be monitored. The capacity of household RSS to increase household vegetable production, and hence nutrition, during the dry season should also be investigated.

Chapter 6

Roof-Harvested Rainwater Use in Household Agriculture: Contributions to the Sustainable Development

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Chapter 6 Roof harvested rainwater use in household agriculture: contributions to the sustainable development goals

This chapter is a partial reproduction of the following refereed journal paper:

Amos, C. C., Rahman, A., Gathenya, J.M., Friedler, E., Karim, F., Renzaho A. (2020)

Roof Harvested Rainwater use in Household Agriculture: Contributions to the Sustainable Development Goals

Water: an open access journal

[Impact factor: 2.52, SJR Quartile: Q1. ***Awarded "Editor's Choice"]***

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6.1 Overview

Food and water are at the heart of sustainable development. Roof-harvested rainwater kept in rainwater storage systems (RSS) and used in household agriculture (HA) has the potential to increase yields and supplement household nutrition. Combined systems may contribute to at least eight of the United Nations' 17 sustainable development goals (SDGs). In this study, a daily analysis tool, ERain, is used to assess what area of vegetables can be reliably irrigated by roof-harvested rainwater. A socio-economic context is built around an orphanage in the semi-humid region of Nakuru, Kenya. Comparisons are made with the semi-arid region of East Pokot. A 225 kL closed masonry tank and a 1 ML open reservoir with an additional 8 kL/day of recycled water entering are analysed for various roof sizes. The 225 kL RSS connected to 1000 m^2 of roof and irrigating 1000 m^2 could increase yields from 1850 to 4200 kg/year in Nakuru. If evaporation was controlled, the 1 ML RSS and recycled water system could support 4000 m^2 of land, yielding nearly 20,000 kg/year, which is enough to meet the WHO recommended vegetable dietary requirements of the orphanage. A combination of crops, some for consumption and some for sale, could be grown.

6.2 Introduction

The Garden of Eden, or Paradise, has long captured the heart and imagination. Many aspire to live in, and search for, such a paradise lost, often for more ascetic reasons. The Paradise of Eden, however, is described as not only beautiful, but also providing abundant food and being amidst a great river system, supplied with ample water (Genesis 1:11, 2:10). Gardening as an activity is known to be good for both physical and mental health (Soga et al. 2017), but the capacity for increasing household nutrition should not be overlooked. Yields from between zero (crop failure) to over 20 kg of vegetables per m^2 have been reported for small-scale agriculture (Rabin et al. 2012). This is particularly important in developing countries, where many people lack nutrition. Food and water are, and always have been, at the heart of a sustainable environment. Fifty years have passed since man landed on the moon (16 July 1969), but the challenge of providing what the moon cannot, food and water, remains. Zero hunger worldwide is a worthy, but historically unrealized, dream. The fact is that more than enough food is produced worldwide to feed everyone (Holt-Giménez et al. 2012). However, it is unevenly distributed, leading to a world where 1 in 9 people remain hungry and 1 in 4 children are stunted (United Nations 2015), while 1.9 billion adults are overweight (WHO 2018b). A report by the UN indicates that the food demand will double by 2050 (FAO 2017), whilst others suggest that it may only need to increase by 25%–75% (Hunter et al. 2017). If there is not enough food produced and distributed, the situation will only get worse. The problem is multidimensional, and there is a call for innovative systems and holistic approaches that build upon traditional knowledge and cultural preferences whilst also protecting the environment. Household agriculture (HA) or home gardening at a small scale bypasses the distribution issue and has the potential to significantly contribute to household nutrition, particularly that of women and children.

Rainfed agriculture alone, particularly in arid or semi-arid regions, often proves to be unreliable and insufficient (Rockström et al. 2010) and an adequate water supply is essential to achieving such yields. However, with the already increasing concerns about water security and increased competition over fresh water resources (Strzepek and Boehlert 2010), where will the additional water come from? Modern building techniques favour impermeable surfaces, such as concrete driveways and roof coverings. The often negative effect of “paving paradise” (Frazer 2005) that includes the pollution of waterways and flooding, if overcome, could potentially mean that this approach could be used to provide the additional water sought for small-scale irrigation of household agriculture (HA). Roof-covered areas are particularly suitable for rainwater storage systems (RSS), harvesting the water before it becomes polluted by ground surfaces. The increased use of metal roofs over traditional grass roofs etc. in developing countries (Haines et al. 2013) means that more dwellings are becoming suitable for rainwater collection. In developing countries, RSS shows potential to support small-scale agriculture and in turn, to help provide important nutrition (Campisano et al. 2017; Stout et al. 2017), while also saving water (Lupia and Pulighe 2015; Muklada et al. 2016). To demonstrate the potential, consider a 100 m^2 roof used exclusively for HA in a semi-arid region with a mean annual rainfall (MAR) of 400 mm; if connected to a garden of the same size, the rainfall available would then double (800 mm). In practice, water is lost to deep percolation and surface runoff and the effective rainfall, at 70% of the total rainfall (FAO 2012), would only be 280 mm. An appropriately designed RSS system in this scenario could have a considerable impact on the yield. If the rainwater is polluted, e.g., from the collection system or air pollution, then it may not be the preferred source for drinking and potable uses (Friedler et al. 2017), but agricultural use is still acceptable. The non-uniform distribution of rainfall in arid and semi-arid regions causes droughts that are often the cause of crop failure (Yazar and Ali 2017), making the use of RSS and irrigation particularly advantageous. The focus region of this study, Nakuru, Kenya (MoALF 2016), is one such region.

Recent examples of RSS use in HA or home gardening include Australia’s “Water Smart Gardens and Homes Rebate Scheme” rebate scheme, specifically designed to encourage people to install rainwater storage systems (RSS) for household gardens and reduce pressure on the reticulated supply (Gato-Trinidad and Gan 2014). There have been a number of projects promoting small-scale agriculture and it is also becoming increasingly popular in developing countries (Mok et al. 2014). Chip Morgan, through the Africa Water Bank (AWB), has been installing 225 kL tanks in Kenya that are claimed to be able to irrigate 1350 m^2 greenhouses and grow vegetables to make a profit (Innovations 2019). The original concept of a project in Lesotho, South Africa, included the construction of 4 kL RSS to supplement the grey water being used in the garden (New Partnership for Africa’s Development (NEPAD) 2005). Another project, under the “Food for Assets” incentive, was quite successful in Lesotho, South Africa, with over 23,000 keyhole gardens being constructed between 2006 and 2013 (Billingsley et al. 2013). This kind of small-scale agriculture can also help to maintain “forgotten varieties” (Eigenbrod and Gruda 2015) and enhance biodiversity. This study is applicable to all forms of small-scale agriculture and the term HA is intended to include community- or village-scale agriculture used for the owners and so may also be applicable to community gardens and allotments (Genter et al. 2015; Marsh and Spinaze 2016).

The purpose of this study is to fill the current knowledge gaps in RSS-based HA. There is a lack of detailed analysis of RSS capacity with respect to evapotranspiration and the irrigation water demand at the HA scale and the capacity of RSS to meet that demand (Amos et al. 2018b). In particular, the aim is to determine what land area can be irrigated and what potential crop yield can be obtained from a given combination of HA area and RSS. ERain, a daily water balance analysis tool, is designed to analyse combined HA and RSS using daily climate data. For a realistic context, the study is based on conditions at Miti Mingi (“Many Trees”) Village in Nakuru, Kenya, an established orphanage that can house 120 children and 45 adults. This enables direct feedback on the results and the discussion includes insights about the practicality of the solution. A community’s acceptance of a system and their preferences will have a direct impact on the design and hence the analysis and results. Community engagement is often neglected in more technical research papers and so its importance and impact are highlighted here. It is expected that the findings of this study will both be of assistance to the village and relevant to community- and school-size projects internationally. It is expected to be a key reference for NGOs, environmentalists, researchers, town planners, water engineers, governments, and policy makers considering the use of HA and RSS in addressing the relevant sustainable development goals in various international contexts.

6.3 Materials and Methods

Climate data was analysed using ERain, a daily analysis tool first described in Amos et. al. (Amos et al. 2016; Amos et al. 2018a; Amos et al. 2018b), and which has now been updated to include evapotranspiration calculation. The main elements of ERain are a Yield-After-Spillage RSS analysis of daily rainfall data, and an analysis of daily climate data to calculate agricultural water use using FAO 56 and the crop yield in response to water availability using

FAO 33. The method employed in ERain was preferred over other tools available as it includes an analysis of not only rainfall data, but also climate data. Models that come from the agricultural sector have been found not to include a water tank balance model (Amos et al. 2018b). For example, Cropwat uses monthly data for its calculations and does not include a tank balance model (FAO 1988). Aquacrop, which in many respects supersedes Cropwat, although it is a good model for crop water use, also does not include a tank balance model (Raes 2016). Conversely, tools that focus on rainwater harvesting and domestic water use regularly include a daily time step analysis of tank balance, but do not include a detailed analysis of evapotranspiration and crop water use (FAO 1988). For example, AQUACYCLE (Mitchell et al. 2001; Zhang et al. 2010) and Urban Volume and Quality (UVQ) (Farley 2000; Marleni et al. 2011) do not include any detailed analyses of crop water use. The data requirements and a more detailed description of the method employed in ERain follow.

6.3.1 Data

6.3.1.1 Study Site

Two regions of Kenya are considered in this study: Nakuru and East Poket. According to the agro-climatic zone map of Kenya (Braun 1980), Nakuru is in zone III-5. The moisture zone (III) is thus semi-humid, with a rainfall value of 800 – 1400 mm/year and an Eo (annual average potential evaporation) of 1450 – 2200 mm/year (calculated using Penman's equation), with a high to medium potential for crop growth and a fairly low (5% – 10%) risk of failure of an adapted maize crop. The temperature zone (5) is considered cool-temperate, with a very rare incident of frost, and is considered to include lower highlands with an altitude of 1850 – 2150 m. East Poket, in comparison, is in zone V-2. The moisture zone (V) is thus semi-arid, with a medium to low potential for crop growth and a high risk of failure of an adapted maize crop. The temperature zone (2) is considered warm, with no incident of frost, and includes midlands. Further comparisons are detailed in Table 6.1.

Table 6.1 Agro-climatic zone definitions for selected locations

Location	Moisture Zone	Rainfall mm/ year	[1] E_o mm/ year	Crop Growth Potential	[2] Crop Failure	Temp Zone	Temp Mean Annual °C	Temp Mean Max. °C	Temp Mean Min. °C	Incident of Frost	Altitude
Nakuru	semi-humid	800–1400	1450–2200	high to medium	fairly low 5%–10%	cool-temperate	16–18	22–24	10–12	very rare	1850–2150
East Pokot	semi-arid	450–900	1650–2300	medium to low	high 25%–75%	warm	22–24	28–30	16–18	none	900–1200

[1] annual average potential evaporation [2] failure of an adapted maize crop.

6.3.1.2 Climate Data

Developments in the satellite estimation of rainfall data and climate data mean that analysis can be undertaken in areas where there is little or no recorded ground data available (Ciabatta et al. 2015; Li et al. 2015; Munzimi et al. 2015; Prakash et al. 2015). Much of Kenya has limited climate data, so daily agroclimatology data were obtained from the NASA Langley Research Center POWER Project (NASA 2019) for the Miti Mingi Village, Nakuru, Kenya, which has a latitude of −0.3534, longitude of 36.1628, and elevation of 2179 m. The data includes the following:

- Maximum temperature in °C;
- Minimum temperature in °C;
- Dew point temperature in °C;
- Wind run in m/s;
- Solar radiation in MJ/m^2/day; and
- Rainfall in mm/day.

The relative humidity needed for the FAO 56 calculations was calculated from the max., min., and dew point temperature. The data were analysed and compared (Figure 6.1) with averages for the closest station, Nakuru Airfield (lat. of 0.3, long. of 36.15) obtained from CLIMWAT (FAO 2019) and the World Meteorological Organization (WMO) (WMO 2019). Rainfall data for the area from the Climate Hazards Group InfraRed Precipitation with Stations (CHIRPS) data sets (CHC 2019; Funk et al. 2015) was ultimately preferred to the

NASA rainfall data for reasons explained under data integrity in the results section. Due to the lack of availability of alternative daily climate data, the NASA data was still used for temperature, wind, and solar exposure, while both NASA and CHIRPS data were used for precipitation for comparison.

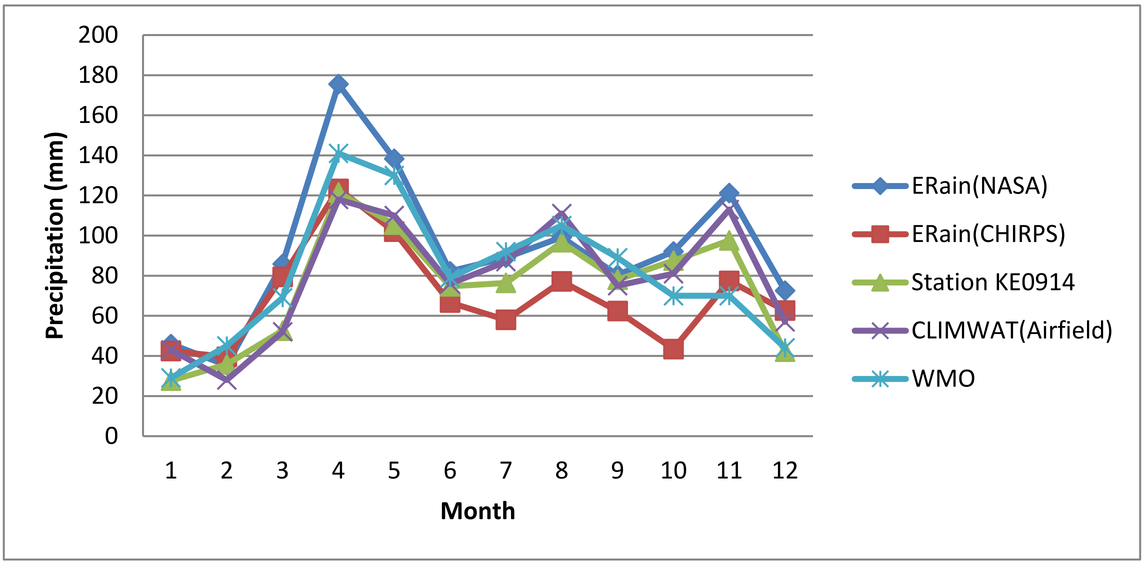

Figure 6.1 Comparison of monthly precipitation for Nakuru from various sources.

6.3.1.3 Yield, Water Use, and Nutritional Need

An average amount of vegetables that can be produced of 7.3 kg/m^2/year. was chosen, based on a study of 2608 mixed stand communities or home food gardens (Rabin et al. 2012), assuming three crops per year. The study does, however, report a massive variety in yields, from 0.44 up to 22 kg. This agrees quite well with the findings of Foeken et al. (2002) in Nakuru, who found a range of 0.22 to 20.17 kg, so crop failure should also be considered (Table 2). Importantly, they found a correlation between plot size and yield. The smaller plots generally had a higher productivity. This is because they are generally close to living quarters and thus get frequent attention and more personal care. It is not unreasonable to think that they are also better watered, in which case the water supply would also be a contributing factor to the higher yields. Under this hypothesis, if water could be supplied domestically for irrigation, then larger areas of land could realize a higher yield.

Water use is determined based on the methods employed in FAO 56 (Allen et al. 1998), and an average crop coefficient value (Kcb) of 1 is assumed for general vegetables. This study is only indicative, and plantings may vary somewhat from the averages used here.

Evapotranspiration inside the greenhouse is taken as a conservative 0.75 times that outside, towards the upper limit given in Carolina and Eduardo (2003). Scenarios for both greenhouses and open gardens were considered. It was assumed that no rain falls directly on the land inside the greenhouse.

Table 6.2 Yield comparisons for various plot sizes.

Location	Statistic	Plot Size (m^2)	Yield ($kg/m^2/year$)	Area (m^2) Req to Provide 1 Person [3]
Nakuru, Kenya [1]	mean	<10	20.17	7
Nakuru, Kenya [1]	mean	10–99	4.73	31
Nakuru, Kenya [1]	mean	100–999	0.51	286
Nakuru, Kenya [1]	mean	1000+	0.22	664
Nakuru, Kenya [1]	mean	All	0.31	471
New Jersey, USA [2]	Max.	Mixed stand	21.97	7
New Jersey, USA [2]	Upper	Mixed stand	6.35	23
New Jersey, USA [2]	Lower	Mixed stand	0.98	149
New Jersey, USA [2]	Min.	Mixed stand	0.44	332
New Jersey, USA [2]	mode	Mixed stand	7.32	20
Any location	Failure	All	0	-

[1] Source: Foeken et al. (2002); [2] Source: Rabin et al. (2012), assuming three harvests per year; [3] Based on the WHO recommendation of 400 g/p/d (146 kg/p/y) of fruit and vegetables.

Values for daily fruit and vegetable consumption were taken as those advised by the World Health Organization (WHO), at 400 g per adult per day and 200 g for smaller children (WHO 2018a). This can be compared to the Australian Government's National Health and Medical Research Council (NHMRC) guidelines (NHMRC 2013). NHMRC's serving size is 75 g (NHMRC 2015), and up to six servings of vegetables or 450 g/p/d for an adult. Assuming a ratio of three 80 g servings of vegetables to two of fruit, the WHO recommendation is 240 g of vegetables. This is considerably less than the NHMRC's 450 g, and this is partly because the WHO recommendation excludes starchy vegetables, such as potatoes and cassava, while NHMRC does not. These differences should be noted; however, for simplicity, in this study, we have compared the results to ¼ of the WHO amount of 400 g as it is expected that the garden will only be used to supplement household supplies. It is also assumed that some of the crop yield could also include fruits, such as strawberries, and possibly fruit trees. For comparison, 400 g/d equates to 146 kg/year, and at the chosen rate of 7.32 kg/m^2/year, this equates to 20 m^2 of growing area, which agrees with Iannotti (2019), who suggests that at intermediate yields, 18.5 m^2 is required to supply vegetables and soft fruits for an individual. If the yields in Table 2 could be realized, then an area of 10 m^2 would be sufficient for an individual, although variety may be an issue.

6.3.1.4 Scenario

Information about the circumstances at the orphanage were obtained from discussions with Sotheycan (Treadwell, Chittenden 2019), a charitable organization that promotes the principle that education is the best route to sustainable change (sotheycan 2019), and with the onsite Program Manager/Village Director, James Wabara (2019). The orphanage houses 120 children and 45 adults.

There is no reticulated water supplied to the orphanage, so water must be either sourced on site or purchased and delivered by truck at high prices. The primary water sources are therefore bore water and roof-harvested rainwater, while water is currently only purchased on rare occasions due to system failure. The bore is powered by mains electricity and yields up to 35 kL per day, which is pumped into an overhead tank. Approximately 8 kL/day of the domestic water is recycled and stored in a 1000 kL reservoir. The reservoir also has a roof catchment of 1400 m^2 flowing into it, and is analysed both with and without the recycled water inflow to assess performance. It is uncovered and subject to evaporation losses, which are modelled at 1.05 times the daily evapotranspiration (ETo) rate based on Allen et al. (1998), assuming that the reservoir depth is below 2 m. The evaporable surface is 20 by 25 m, or 500 m^2. A second tank of 225 kL has a roof catchment of 800 m^2 that is used to top up the overhead bore tank for domestic use if the bore fails. If both the bore and rainwater fail, water must be purchased from the local water bowser and delivered by truck at a cost of 4000 ksh (approximately AU$56) for 10 kL. In this study, we focus on the 1000 kL reservoir, which is used to irrigate a 240 m^2 of greenhouse crops. There is 4 acres of land available that could also potentially be irrigated. Miti Mingi Village is located in a semi-humid zone. The same scenario is analysed in East Pokot, which is a semi-arid area, for comparison. For both locations, the capacity of the 225 kL tank to support a garden was considered in more depth, as tanks this size are being installed cost effectively in Kenya by the Africa Water Bank (AWB) (Innovations 2019). As the setup can vary considerably, roof catchments varying from 20 to 2000 m^2 were considered. To examine the potential garden area that can be supported by the tank, a wide variety of cultivated areas from 10 to 20,000 m^2 were analysed.

6.3.2 Method

6.3.2.1 Tank Balance Model, Water Demand, Evapotranspiration, and Crop Yield

The performance of the RSS was analysed using a daily time step water balance simulation model. A Yield-After-Spillage (YAS) model was preferred for the analysis as it is generally agreed to give a more conservative estimate, which is more suitable for the design in this context (Hajani et al. 2013). The YAS model described in Fewkes and Butler (2000) was used.

The water demand is ultimately the evapotranspiration, and this was calculated on a daily basis based on the climate data obtained from NASA. The well-known FAO Penman–Monteith equation (Allen et al. 1998) was chosen as the NASA data provides the necessary data for this calculation, with the exception of relative humidity data. The relative humidity (RH) data (minimum and maximum) was calculated from the minimum and maximum temperature and the dew point temperature, as per Eccel (2012) (Equations (1–5)).

$$\mathrm{ea} = 0.6108 \times \exp\left((17.27 \times \mathrm{Tdew})/(\mathrm{Tdew} + 237.3)\right) \tag{10}$$

$$eo\_Tmax = 0.6108 \times exp((17.27 \times Tmax)/(Tmax + 237.3)) \tag{11}$$

$$eo\_Tmin = 0.6108 \times exp((17.27 \times Tmin)/(Tmin + 237.3)) \tag{12}$$

$$RHmin = 100 \times ea/eo\_Tmax \tag{13}$$

$$RHmax = 100 \times ea/eo\_Tmin \tag{14}$$

6.3.2.2 Definition of Reliability and Calculation of Crop Yield.

RSS reliability is a measure of the system’s ability to meet the demand. In the case of a garden, the demand is that required to maintain the vegetables’ maximum evapotranspiration (ETo max) at each respective stage of development. When the soil water content is reduced below the readily available water (RAW), the plant cannot transpire at its maximum rate and the actual evapotranspiration (ETo actual) will be less than the maximum (ETo max) (Allen et al. 1998). ETx is defined as the maximum possible ETo over the crop cycle (or plants life), assuming an unlimited water supply, while ETa is the actual total ETo over the crop cycle. Hence, ETa and ETx are accumulated over the plant's life. Reliability is then calculated as shown in Equation (6). Reliability was not calculated based on the "number of days the demand is met" for three main factors, as that would have complicated the calculation. Firstly, there will not always be a demand as the soil water storage will supply water when it is above the RAW. Secondly, when below the RAW, the plant's demand is still partly met, as ETo is reduced and not zero until the total available water (TAW) is reached. Thirdly, the soil water deficit may also be either partly or fully met on any given day, depending on the rainfall.

$$\text{Reliability} = \frac{ETa}{ETx} \tag{15}$$

The focus of this study is water use, so the maximum crop yield assumed (an annual average of 7.3 kg/m^2/year.) is reduced based on the ability of the RSS to supply the necessary irrigation water. Ultimately, this reduction was calculated using the method described in FAO 33 (Doorenbos and Kassam 1979) (Equation 7):

$$\left(1-\frac{Ya}{Yx}\right)=Ky\left(1-\frac{ETa}{ETx}\right)\left(1-\frac{Ya}{Yx}\right)=Ky\left(1-\frac{ETa}{ETx}\right), \tag{16}$$

where Ya and Yx are the actual and maximum crop yield, respectively; Ky is a yield response factor, taken as 1.1 in this analysis; and ETa and ETx are as above.

6.4 Results

This section presents results from the ERain analysis, proceeded by a comparison of the NASA climate data with other available data for the site.

6.4.1 Climate Data Integrity

The climate at Nakuru was found to be reported variously. Figure 6.1 shows a comparison of the average monthly precipitation according to the NASA data, CHIRPS data, CLIMWAT data, and data from a nearby rainfall station (KE0914). The MAR is given as 1116, 834, 896, and 951 mm/year, respectively.

The NASA rainfall data also seemed problematic as on closer analysis, it was found that it reported 354 days of rain per year, while the CHIRPS data reported only 57 days, which is much less than the WMO value of 132 days/year (WMO 2019) for Nakuru. Excluding rain below 1 mm, the NASA data still has an average of 221 days/year. to match the CHIRPS data days of rain, and any rainfall below 5.6 mm would need to be ignored, but this would give an MAR of only 594 mm. To match the CHIRPS MAR of 834 mm/year, NASA rainfall below 3.1 mm would need to be excluded from the data, still reporting 114 days of rain, which is considerably more than the CHIRPS data, but closer to the WMO value of 132 days. Therefore, the NASA rainfall data not only varies considerably from the CHIRPS and station data in terms of annual and monthly averages, but also from the CHIRPS in terms of the daily rainfall depth. The max. daily rainfall reported by NASA is 81 mm, compared to 104 mm by CHIRPS. This is important because actual evapotranspiration will be affected by the rainfall distribution, as well as the quantity. The water balance and performance of RSS will also be affected. Where the main catchment is a relatively impervious roof, small rainfall events, e.g., in this case, considered to be below 3.1 mm or 5.9 mm, will still supply water due to the relatively low losses. Another consideration is that the grid resolution of CHIRPS data has a much finer resolution at 0.05 deg. compared to the NASA data at 0.5 deg. With these considerations, the CHIRPS rainfall data was deemed to be preferable to the NASA data. A comparison of the monthly averages calculated in ERain with the NASA data for the min./max. temperature is shown in Figure 6.2.

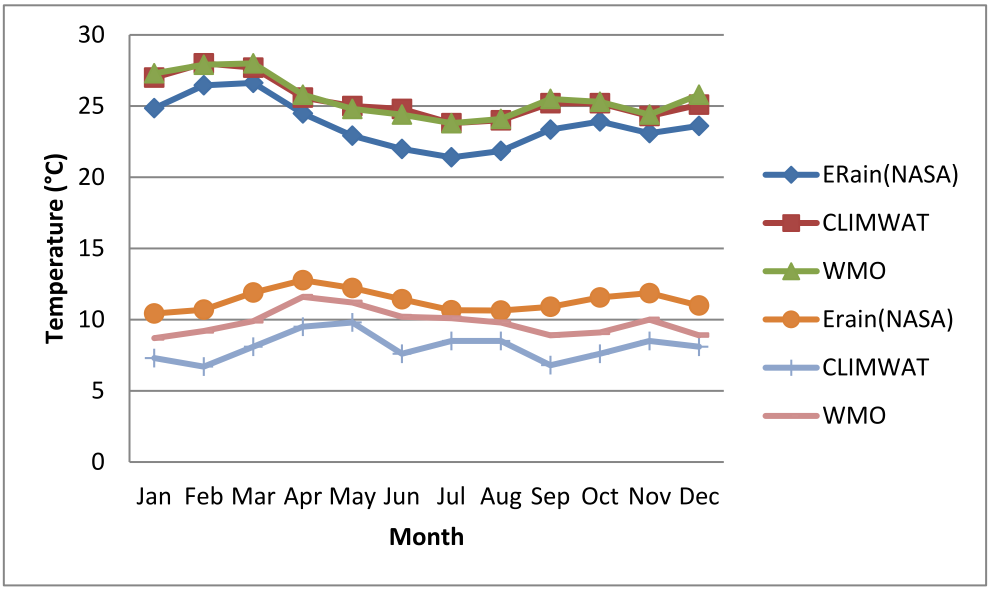

Figure 6.2 Comparison of monthly max./min. temperature for Nakuru from various sources.

The NASA data has a lower maximum and higher minimum temperature than most other sources report for Nakuru. Table 6.3 shows a comparison of average annual climate data for

Nakuru.

Table 6.3 Comparison of annual average climate data for Nakuru from various sources.

Source	Min. Temp	Max. Temp	Humidity	Wind	Rad	ETo	Rain	Rain
	°C	°C	%	km/day	MJ/m^2/ day	mm/ day	mm	Days
CLIMWAT (airfield)	8.1	25.5	71	161	19.3	3.94	951	-
ERain (NASA-MMV) *	11.33	23.69	-	181	20.27	3.81	1086	363
ERain (CHIRPS-MMV) *	-	-	-	-	-	-	833	57
WMO (Nakuru)	9.8	25.6	-	-	-	-	963	132
Nakuru Lanet Police Post (KE0914)	-	-	-	-	-	-	896	-

*** These values were calculated from daily data using ERain.**

For solar radiation, CLIMWAT reports an average of 19.3 MJ/m^2/day, whilst NASA exhibits a slightly higher value of 20.27 MJ/m^2/day; wind is, on average, 181 km/day compared to 161 km/day, respectively. Due to the lack of availability of alternative daily climate data, the NASA data was used to calculate ETo, while both NASA and CHIRPS data were used for precipitation and compared. As can be seen in Table 3, the average annual ETo calculated from the NASA data using ERain, 3.81 mm/day, compares quite well with the CLIMWAT value of 3.94 mm/day, although it is on the low side. ETo is discussed in more detail in the next section.

6.4.2 ETo Analysis

Figure 6.3 shows monthly ETo results for Nukuru. Figure 6.4 shows daily ETo results from ERain, demonstrating that the calculated ETo varies from approximately 2 to 6 mm/day. The annual averages for CLIMWAT are 3.94 mm/day or 1439 mm/year; from the NASA data, this was slightly lower, at 3.81 mm/day or 1392 mm/year (Table 6.3), which is expected to result in a lower water use from the RSS, and hence a reduced reliability. The value given in the agro-climatic zone map of Kenya (Braun 1980), 1450 – 2200 mm/year, is higher, but this value was Eo (annual average potential evaporation) calculated using Penman's 1948 equation for open water surfaces and it gives values higher than FAO 56's Penman–

Monteith equation used here.

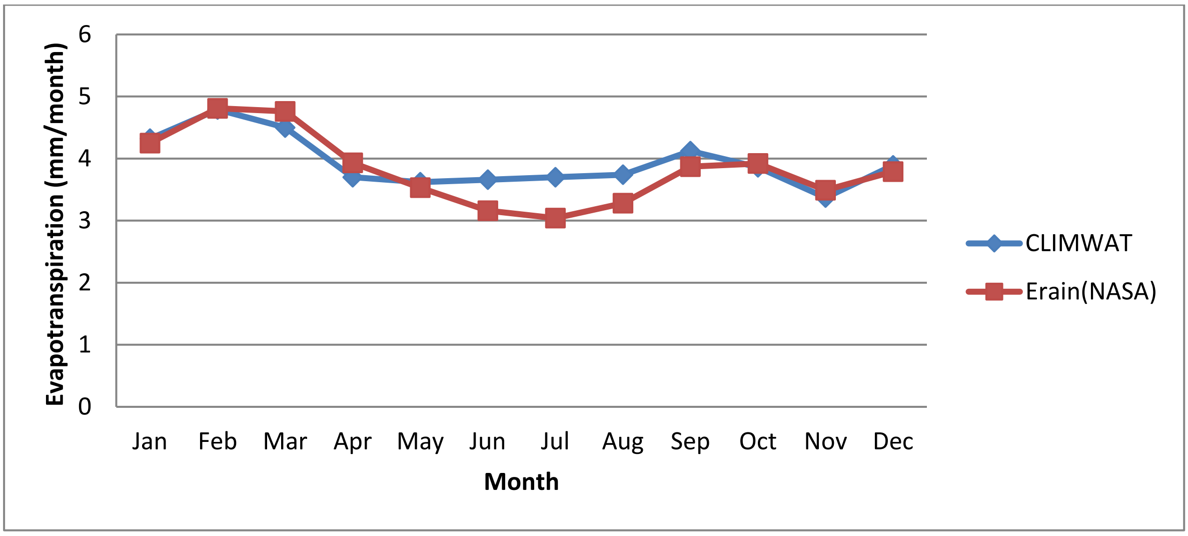

Figure 6.3 Monthly average evapotranspiration (ETo) for Nakuru, comparing CLIMWAT with ERain (NASA data)

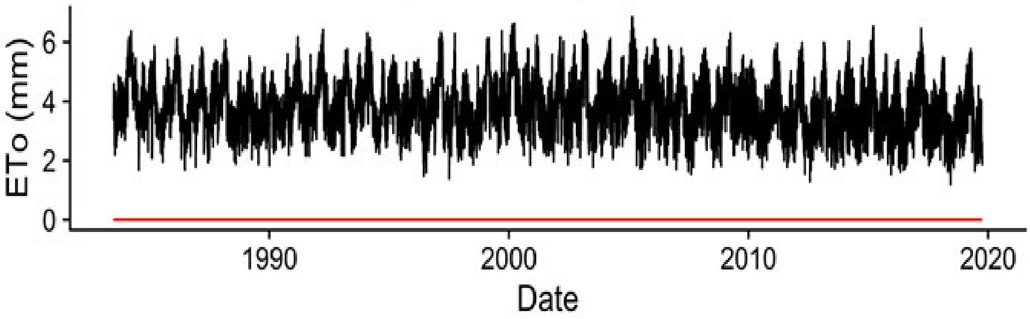

Figure 6.4 Daily ETo and RH results with input climate and rainfall data

In summary, there is considerable variability in the climate data and any results should be interpreted with this in mind. The NASA data serves as an upper limit of RSS performance as it reports rainfall at the higher end of the scale, and the climate data results in an ETo at the lower end, which tends to result in a higher system reliability than might be the case. The CHIRPS rainfall data is about average, while the ETo is still based on the NASA data, so a higher ETo is possible, which implies that the results will not be conservative and should be expected to be at the mid to upper range of potential reliability. Uncorrected NASA data has been used for crop simulation modelling, with some degree of success, but correction using at least 3 years of observed data is preferred (Van Wart et al. 2015). Details about the NASA data methodology can be found in Westberg et al. (2018). The climate may be even less favourable or more variable in the future, so any results based on historic data should be considered with a degree of uncertainty, and hence reasonable contingency plans can be developed. Nevertheless, a comparison with CLIMWAT results (Figure 6.3) indicates that the NASA climate data does provide a reasonable estimate of evapotranspiration and hence crop water requirements.

6.4.3 RSS reliability and crop yield

In this section, RSS reliability is discussed, this is, the ability of the RSS to supply water to the field and maintain the maximum evapotranspiration (ETx) that the crop requires at its growth stage. It is calculated from the actual evapotranspiration (ETa) as ETa/ETx.

6.4.3.1 The 1 ML reservoir in the orphanage scenario

Figure 6.5 shows a comparison of results using the NASA and CHIRPS rainfall data. ETo was calculated using the NASA data in both cases. “OF” represents an open field, as opposed to “GH” (greenhouse). In the “GH”, rain does not fall directly on the soil, so it relies exclusively on irrigation. The suffix “Evap” indicates that the RSS is open and subject to evaporation; otherwise, it is closed and is deemed to suffer from no evaporation loss. “Rcyl” indicates that the 8 kL of recycled water is included as daily inflow to the RSS, and as expected, this can support much larger areas of irrigation. “RF” indicates rain-fed only; in other words, it indicates how well the rainfall alone could supply the water needs all year around.

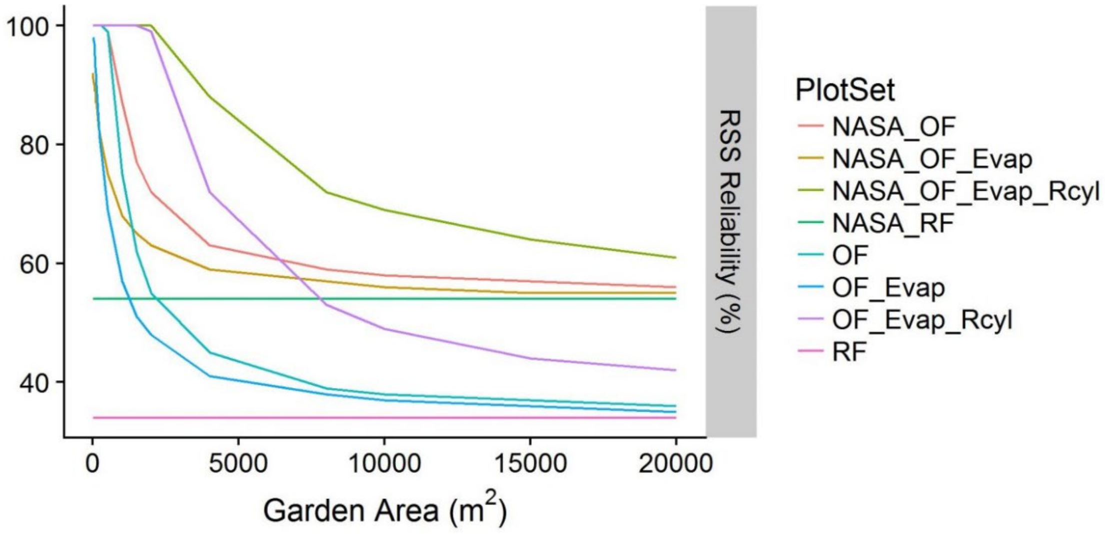

Figure 6.5 NASA vs. CHIRPS for various scenarios

Comparing the NASA_RF with RF (CHIRPS-NASA), it can be seen that the former reports a reliability of 54% and the latter reports a value 20% less, at 34%. For East Pokot, not shown here, the reduction was from 53% to 26%. Therefore, it appears that the NASA data shows little difference between the semi-humid region of Nakuru and the semi-arid region of Poket. The use of CHIRPS rainfall results in a more conservative estimate and we deemed the NASA data to be preferable, so the analysis from here on was conducted using a combination of CHIRPS rainfall and NASA climate data.

Figure 6.6 shows the CHIRPS analysis without the NASA data for a smaller range of garden areas and includes the analysis of a greenhouse (GH).

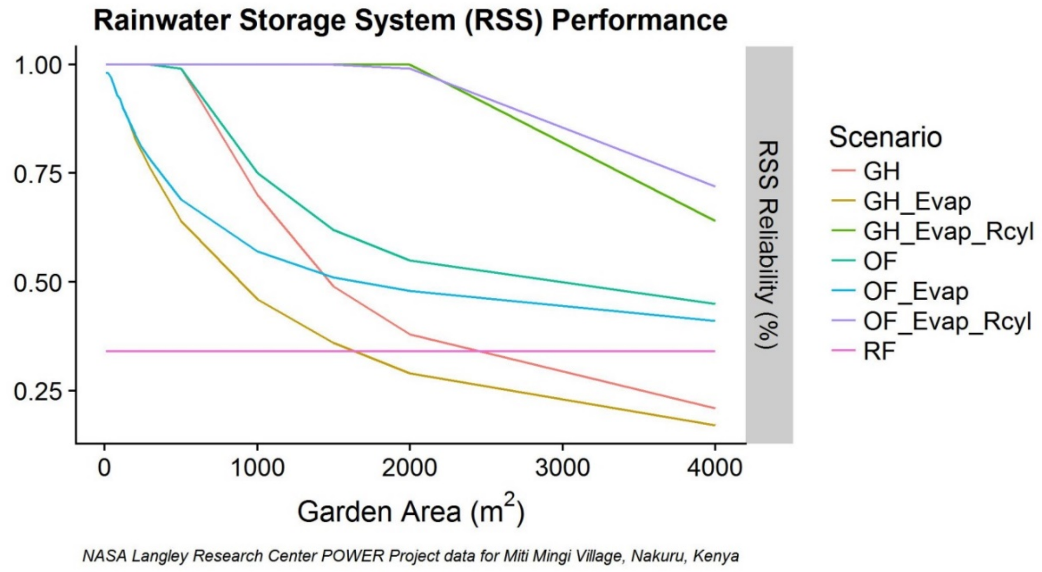

Figure 6.6 CHIRPS data only for small range of garden areas

With reduced evaporation (75%), despite no rain falling directly on the soil, the performance is good while there is water available in the RSS. If the recycled water is included, about 2000 m^2 of land can be reliably irrigated and 4000 m^2 with a 72% reliability in the open field, resulting in yields of 14,330 and 19,190, respectively. This would be more than enough to supply the orphanage with the WHO required daily vegetables/fruit for approximately 100 adults, with a value of 14,600 kg/year (0.4 × 365.25 × 100). In the greenhouse scenario, the respective yields are 14,420 and 16,860. For the larger area, the greenhouse has only a 64% reliability. Once the RSS is at capacity, the greenhouse reliability reduces steeply below the RF reliability and the open field becomes preferable. With careful water management and seasonal crop plantings, however, it may still be possible to get good returns from an acre of land (4046.86 m^2), which is considerably more than the current greenhouse size of 240 m^2.

However, if the recycled water is not included, and there is evaporation from the RSS (GH_Evap), then the current greenhouse could only be supported with a reliability of 80%. When the reliability is reduced, then the evaporation loss reduces as the area increases, since the RSS will be empty at times. However, if evaporation is controlled (GH), then 500 m^2 could be supported with 100% reliability, representing twice the current area. It should be noted that this is based on the average results over the years 1983 to 2017, and annual variability over this period means that, in some years, this reliability may be much lower. This, and the uncertainty of future climates, would need to be considered in any long-term planning. Table 6.4 shows the maximum and hypothetical actual crop for both Nakuru and East Poket under greenhouse conditions with reduced evaporation, but no rain falling on the irrigated area. The yield of 7.21 kg/m^2/y represents the maximum yield of 7.3 kg/m^2/y, and the discrepancy is because the data length does not exactly match the cropping year.

Table 6.4 Open 1 ML rainwater storage system (RSS) maximum, actual, and average crop yields for both Nakuru and East Poket

Crop Area	Max. Crop Yield	Hypothetical Actual Crop Yield (Mixed Vegetables) (Total and Per m^2)							
		Nakuru (GH)		East Poket (GH)		Nakuru (GH_Evap)		East Poket (GH_Evap)	
m^2	kg/y	kg	kg/m^2/y	kg/y	kg/m^2/y	kg/y	kg/m^2/y	kg/y	kg/m^2/y
10	73	72	7.21	72	7.21	71	7.07	55	5.54
20	145	144	7.21	144	7.21	141	7.06	109	5.45
40	291	288	7.21	288	7.21	277	6.93	211	5.29
60	436	433	7.21	433	7.21	407	6.78	308	5.14
80	581	577	7.21	577	7.21	531	6.64	399	4.99
100	727	721	7.21	721	7.21	650	6.50	484	4.84
120	872	865	7.21	865	7.21	764	6.36	565	4.71
160	1163	1153	7.21	1153	7.21	968	6.05	712	4.45
200	1454	1442	7.21	1442	7.21	1154	5.77	845	4.23
240	1744	1730	7.21	1730	7.21	1320	5.50	962	4.01
300	2181	2163	7.21	2163	7.21	1545	5.15	1114	3.71
500	3634	3586	7.17	3406	6.81	2097	4.19	1485	2.97
1000	7269	4708	4.71	3453	3.45	2777	2.78	1875	1.87
1500	10,903	4587	3.06	3238	2.16	2981	1.99	1929	1.29
2000	14,537	4397	2.20	2987	1.49	2974	1.49	1822	0.91
4000	29,074	3431	0.86	1949	0.49	2202	0.55	994	0.25
8000	58,149	1361	0.17	274	0.03	564	0.07	13	0.00
10,000	72,686	655	0.07	30	0.00	171	0.02	0	0.00
15,000	109,029	32	0.00	0	0.00	0	0.00	0	0.00
20,000	145,372	0	0.00	0	0.00	0	0.00	0	0.00

The reduction in crop per m^2 (kg/m^2/y) mirrors the reliability result and under GH conditions, with evaporation from the RSS excluded, the crop reduces to 4.71 kg/m^2/y for 1000 m^2. The maximum total crop yield is 4587 kg for the 1500 m^2 area, with the crop yield being reduced to 3.06 kg/m^2. In comparison, for the semi-arid region of East Poket, the maximum yield is only 3453 kg for 1000 m^2 and increasing the area to 1500 m^2 only reduced the overall yield. If the RSS system is not closed and water is allowed to evaporate from the system (GH_Evap), then the system cannot fully support the irrigating requirements in either location. Interestingly, in this scenario, peak yields are 1500 m^2 in both Nakuru and East Poket, but at 2981 and 1929 kg/y, respectively. Although, in Nakuru, for example, for triple the area, from 500 to 1000 m^2, the yield only increased by less than half from 2097 to 2981 kg/y. Under open field conditions (OF), the crop yield does not peak, but continues to increase with area. This is because there is still 34% (Nakuru) or 26% (East Poket) reliability under rain-fed conditions (Figure 6.6), so any extra land will still increase the crop yield. However, in practice, this may not be viable due to the extra labour and costs involved. A system that maintains a higher reliability and value closer to the maximum yield /m^2 may be preferable. In this case, the open reservoir does not appear to be a good option, due to the excessive evaporation. Without the 8 kL daily input from the recycled water, it is unlikely that the current 1 ML reservoir could support the full irrigation needs of anything larger than a very small garden (Table 4). Therefore, closed RSS systems are preferable.

6.4.3.2 RSS 225 System Results

In this section, the results for a closed 225 kL RSS attached to roof sizes up to 2000 m^2 and garden areas up to 20,000 m^2 (2 Ha) are investigated. The larger roof sizes would be representative of schools, community centres, or clusters of houses. Currently, the Miti Ming Village has a total of 2400 m^2 of roof; however, 800 m^2 is connected to an RSS used to supplement the domestic bore water supply. Masonry tanks of this size are currently being constructed in Africa reasonably cost effectively, so such a system may be economically feasible. Figure 6.7 shows the results for both Nakuru and East Poket. The lower rows of the figure focus on smaller areas and roof sizes.

As expected, semi-humid Nakuru has a greater reliability than semi-arid East Poket (Figure 6.7, A & B). Figure 6.7 (A & B) shows that for garden areas above 5000 m^2 the reliability dropped below 50% for any roof area at either location. Although a larger roof will still offer a higher reliability, this advantage becomes negligible with the larger garden areas. With the larger roof catchments, gardens of up to 500 m^2 can be supported quite well in Nakuru, for example, 1000 m^2 of roof can still supply 90% of the water requirements. However, in East Poket, the same roof could only support about half the area. Small roof areas, such as those which might be found on an individual house, can only support small garden areas. For example, the 100 m^2 roof (e.g., 20 m by 5 m) green line (Figure 6.7, C & F) can fully support 40 m^2 of garden in Nakuru, and 20–30 m^2 in East Poket.

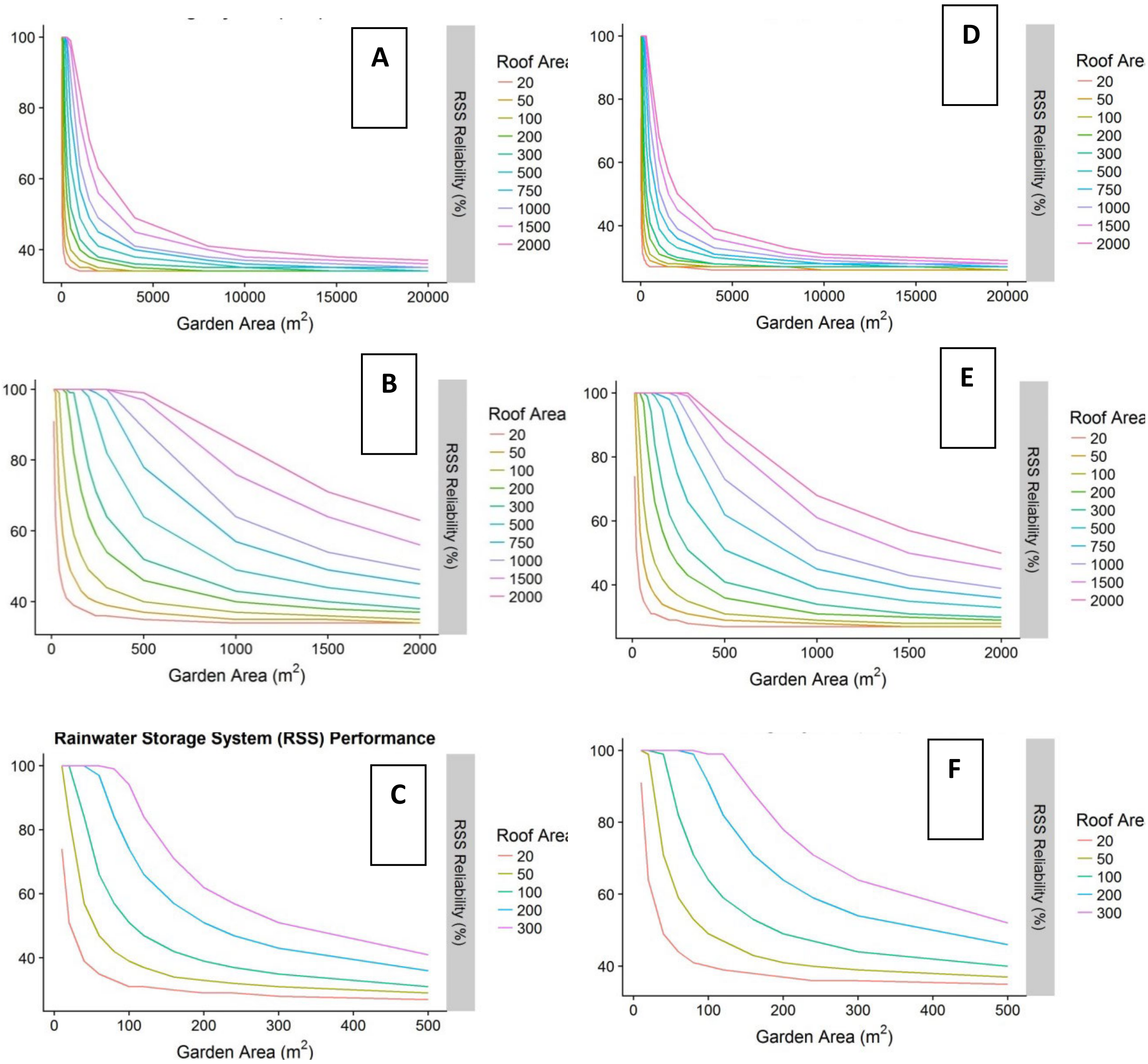

Figure 6.7 RSS reliability for a 225 kL tank, roof areas up to 2000 m², and garden areas up to 2 Ha for Nakuru (A,B,C) and East Poket (D,E,F)

It should be noted, however, that the rain-fed reliability in the semi-arid region is much lower, at 26% compared to 34% (using CHIRPS data), and crop failure is more likely, so the system may still be bringing greater advantages to the semi-arid region. Table 5 shows a comparison of total crop yields for the rain-fed condition (RF) compared to having the closed 225 RRS installed for open field (OF) irrigation The number of people that the system can support with 100 g of vegetables per day (1/4 of the WHO recommendation) is also shown. Roof areas from 500 to 2000 m^2 and garden areas from 40 to 1000 m^2 are considered. For smaller garden areas below 200 m^2, the increase in crop yields is greater in East Poket than in Nakuru, and above 300 m^2, the increase is greater in Nakuru. Presumably, this is because the system is reaching its capacity for the East Poket climate.

For the 2000 m^2 roof, the increases in crop yield are quite large at both locations, even for the 1000 m^2 (0.1 ha, ¼ acre) garden, increasing from 1854 to 5855 kg and from 1270 to 4483 kg for Nakuru and Poket, respectively. This could supply 160 and 123 adults with ¼ of their daily vegetable requirement, which is enough to supplement a community the size of Miti Mingi Village. Even with a smaller roof area of 500 m^2 and considering the full portion of 400 g, the system could still support 21 or 15 adults, and for the ¼ portion, 84 or 60 adults, respectively. Either way, the system can substantially contribute to household or school nutrition if managed well. This shows that a 225 kL tank can potentially help produce a lot of food in semi-arid regions where there is a roof catchment available to capture the water.

Table 6.5 225 kL RSS crop yields for both Nakuru and East Poket

		Nakuru (RF Reliability of 34%)				East Poket (RF Reliability of 26%)			
Roof Area (m^2)	Garden Area (m^2)	Crop Yield (kg/y)			People Supported with 100 g/day	Crop Yield (kg/y)			People Supported with 100 g/day
		RF	OF	Increase		RF	OF	Increase	
500	40	74	288	214	8	51	288	238	8
1000	40	74	288	214	8	51	288	238	8
1500	40	74	288	214	8	51	288	238	8
2000	40	74	288	214	8	51	288	238	8
500	100	185	721	536	20	127	719	592	20
1000	100	185	721	536	20	127	721	594	20
1500	100	185	721	536	20	127	721	594	20
2000	100	185	721	536	20	127	721	594	20
500	160	297	1149	852	31	203	1078	874	30
1000	160	297	1153	857	32	203	1154	950	32
1500	160	297	1153	857	32	203	1154	950	32
2000	160	297	1153	857	32	203	1154	950	32
500	200	371	1415	1044	39	254	1164	910	32
1000	200	371	1442	1071	39	254	1437	1183	39
1500	200	371	1442	1071	39	254	1442	1188	39
2000	200	371	1442	1071	39	254	1442	1188	39
500	300	556	1707	1150	47	381	1301	920	36
1000	300	556	2156	1599	59	381	1976	1595	54
1500	300	556	2163	1606	59	381	2124	1743	58
2000	300	556	2163	1606	59	381	2155	1774	59
500	500	927	2103	1176	58	635	1559	924	43
1000	500	927	3112	2185	85	635	2429	1794	66
1500	500	927	3496	2569	96	635	2923	2288	80
2000	500	927	3582	2655	98	635	3141	2506	86
500	1000	1854	3051	1196	84	1270	2197	927	60
1000	1000	1854	4202	2348	115	1270	3119	1849	85
1500	1000	1854	5195	3340	142	1270	3920	2650	107
2000	1000	1854	5855	4001	160	1270	4483	3213	123

6.5 Discussion

6.5.1 Lessons learnt from Miti Mingi village

Analysis has confirmed that there is a real potential to increase household agricultural production through rainwater harvesting and the implementation of RSS. The analysis confirms that the AWB's claims that a 225 kL tank can irrigate 1350 m^2 of greenhouse

(Innovations 2019) are quite possible from a water perspective. RSS and HA systems could be used as income or to boost household nutrition, or probably both. Using the larger 1 ML system, the Miti Mingi Village orphanage is already practicing this to some degree and would like to increase their agricultural production. However, there are a number of constraints, including particularly, farm management. Whether for commercial purposes or household nutrition, to be successful, the system will need to part of a larger program, including, among other things, to conduct the following:

- Attain high yields;
- Practice water management;
- Plant the correct crops (for nutrition or sale);
- Practice seed saving;
- Have good pest management–currently an issue;
- Maintain fertilization and soil health; and
- Conduct crop rotation.

Other technical issues can also be a problem, for example, in the first year of operation, the 1 ML reservoir leaked because of a poor-quality PVC liner. If pumps are used, pump maintenance is a technical skill that needs to be learnt. Currently, farm management is an issue; if agriculture had been a stronger part of the children’s education, perhaps there would now be some older students who had grown up at the orphanage who could take on a more serious farm management role and help educate the younger children. These skills could be learnt at a young age through school gardens, or involving the children in gardening activities at home, whilst simultaneously improving household nutrition. It is reasonable to think that if children build confidence in growing things, then a higher percentage will go on to successfully produce food, whether as a job or just at home. This would then have a big impact on the country in the long term. This is already being practiced at the orphanage to some degree, but there is room for improvement and there are certain barriers. One major issue is that in education in Kenya, agriculture as a subject is not offered in all secondary schools in Kenya, including those in rural areas where it could be particularly useful. Also, where it is offered, it is not very popular and very few students take is as an examination subject. This is something that should perhaps be reconsidered. In Australia, it is not directly examinable, but in NSW, it can be incorporated and is examinable where it forms part of other subjects, such as Science, and there are plenty of materials available to help with this. For example, the NSW board provides a K-6 teaching agriculture resource (NSW Education Standards: Teaching Agriculture 2019), and large agricultural organisations such as Cotton Australia provide resources that can be used in the Australian Curriculum, such as the “Farm Diaries” produced by the Primary Industries Education Foundation of Australia, which can be incorporated into Design and Technology, Science, Geography, History, and Maths, and addresses sustainability (PIEF 2015). Internationally, FAO produces resources for setting up school gardens, for example, program lessons for “Integrating agriculture and nutrition education for improved young child nutrition” (FAO 2016). The Kenyan government school system may need to change its way of thinking for household agriculture to reach its full potential. Progress in Lesotho, South Africa, the lessons learned, the success of the “Food for Assets” incentive, and the increased interest in including agriculture in education (Billingsley et al. 2013) are also promising for HA implementation in Kenya.

Kenya is a water-scarce country and rainwater harvesting for domestic use and irrigation is being promoted, particularly in arid and semi-arid areas (Oguge and Oremo 2018). Water harvested from roofs is usually of a better quality than that harvested from land surfaces. One major challenge is getting a sufficient roof area, especially in rural areas, where houses are small, or the roofs are made of thatch. Miti Mingi is located within the Nakuru urban area and houses are likely to have bigger and better-quality roof areas for rainwater harvesting compared to East Pokot. In both areas, it is difficult to find households with roof areas exceeding 100 m^2. Therefore, the biggest challenge to exploiting the potential of harvested rainwater for home gardening is the limited roof area. Harvesting runoff from land surfaces and storing it in ponds lined with UV-stabilized waterproof liners would overcome this challenge. However, uncovered ponds lose significant amounts of water from evaporation in drier areas. The water would be suitable for irrigation, but it would have to be purified to make it suitable for domestic use. However, ponds have the added problem of being a mosquito breeding ground, so enclosed tanks could reduce this. Tanks could also be located closer to the house where small-scale gardening takes place, and so encourage use. Shade nets would be more suitable and cheaper for reducing water loss by evaporation and controlling insect pests compared to greenhouses. If greenhouses are used, one can also harvest rainwater from its roof and store it in the pond.

6.5.2 Household agriculture, rainwater storage systems, and the sustainable development goals

The integrated practice of HA and RSS can contribute to many of today's global issues. The sustainable development goals (SDGs) provide a useful framework for demonstrating that contribution. Understanding the underlying nexus that needs to be addressed is important to realizing that potential (Abbott et al. 2017). HA and RSS can contribute to at least eight of the 17 SDGs; on an individual level, particularly Goals 2 to 6, and on a more community and global level, Goals 11, 12, and 15. The fact that it can contribute to food security, improved nutrition, sustainable agricultural, and sustainable water management practices (Goals 2 and 6) needs little explanation. In terms of Goal 3, good health and well-being, many researchers have also reported a variety of other benefits to practicing HA, including reductions in depression, anxiety, and body mass index, and increases in life satisfaction, quality of life, and sense of community, (Genter et al. 2015; Marsh and Spinaze 2016; Soga et al. 2017). It is understood to enhance well-being (Galhena et al. 2013), improve physical and mental health (Milligan et al. 2004), and reduce diabetes by providing a diet less based on often imported and highly processed food. In the republic of Nauru in the Pacific, this is exactly what has happened as populations have shifted towards purchasing cheap imported food and away from producing their own, resulting in high levels of obesity and diabetes (Hamilton et al. 2014). HA in itself also provides a medium for physical activity (Peeters et al. 2014) and is often prescribed for therapeutic and mental health benefits, as well as for its use in the treatment of obesity (Heise et al. 2017). Whilst providing nutrition, it can also help in educating children about nutrition (Christian et al. 2014; Davis et al. 2014), and it is increasingly forming part of the educational curriculum (Keatinge et al. 2012). The estate of New South Wales in Australia, for example, has just this year released a new syllabus for teaching Agriculture at primary school level k-10 (NSW Education Standards: Teaching Agriculture 2019). The Food and Agricultural Organization (FAO) has a number of publications to specifically assist with this; for example, a toolkit for setting up and running a school garden (FAO 2009) and program lessons for “Integrating agriculture and nutrition education for improved young child nutrition”(FAO 2016). In this way, UA is integral to Goal 4, quality education: Ensure inclusive and equitable quality education and promote lifelong learning opportunities for all. For a number of reasons, this addresses Goal 5, gender equality: Achieve gender equality and Empower all women and girls. Firstly, because it is women who predominantly engage in HA and household water management (Hossain and Rahman 2017), they are the primary benefactors. If collecting water from a distant RSS can save time when collecting water, this can produce more time for other things, such as education. If HA produce is also sold, this will also mean that the women are contributing to the household income, while the children start their education at home through their participation.

Sustainable cities and communities, which make cities and human settlements inclusive, safe, resilient and sustainable (Goal 11), can be addressed by a change in lifestyle and healthier living, and HA in the urban environment also means greener cities. Cuba, a world leader in UA (Hamilton et al. 2014), due to trade embargoes, developed a system called organoponics that relies on neither diesel nor chemical fertilizer. The food is grown close to where it is consumed, and organic material is used to fertilize garden beds. The potential reduction in “food miles” and change in consumer consumption patterns addresses Goal 12, responsible consumption and production: Ensure sustainable consumption and production pattern. Finally, it contributes to Goal 15, life on land: Protect, restore and promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification, and halt and reverse land degradation and halt biodiversity loss. HA can increase the biodiversity of plants and insects (Lin et al. 2015). Organisations such as “Garden Organics” in the UK have set up a “heritage seed” library, which encourages individuals to grow forgotten plant varieties in the face of a homogenizing market. For example, in the US, 90% of the 7000 varieties of apples that used to exist have all but disappeared (De Wit 2016). Vegetables cultivated all over the old city in Andernach, Germany, are known to maintain “forgotten varieties” (Eigenbrod and Gruda 2015). Therefore, extensive home gardening can help maintain genetic diversity and the wealth of the world’s collective seed bank, whilst commercial large-scale agriculture tends to focus on a narrow selection of high-yield varieties (Altieri et al. 1987).

While we have only discussed the positives here, there are some negatives and challenges. One particularly malignant issue that warrants serious consideration is the potentially increased risk of malaria due to mosquito breeding grounds associated with urban agriculture (Boelee et al. 2013; Hamilton et al. 2014) and RSS (Jongman and Korsten 2016). This will need to be mitigated by RSS design (Moglia et al. 2016) and open containers are not generally recommended (Helmreich and Horn 2009). Another is diarrhea associated with using wastewater to irrigate and human waste as fertilizer (Hamilton et al. 2014). Jongman and Korsten (2016) investigated water quality in rural villages in South Africa in 80 rainwater tanks and concluded that the use of untreated rainwater in crop irrigation or domestic use poses a potential health risk, especially in areas with a high population of immunocompromised individuals, so they advocate treatment before use. A little consideration will also show that to fully realize the potential, there are a number of barriers. For example, the crop yield is highly variable and dependent not only on resources, but on the gardener’s skill.

6.5.3 International relevance

This study confirms the relevance of RSS use in HA for semi-arid and semi-humid zones. The findings in this study may also be relevant to other climate zones, such as tropical areas that have long dry seasons. For example, Bangladesh has fertile land and a small household garden can produce quality vegetables and fruit. However, during winter months, there is little rain and evapotranspiration exceeds rainfall (Mac Kirby et al. 2014), so the water harvested via RSS in the late monsoon can boost HA during the dry. The arsenic-contaminated groundwater and high-level salinity have affected rural tube-well-based drinking water systems and food chains. The high rainfall suggests that RSS could both supply drinking water to the households and also be used for HA. This can be a game changer at household levels in Bangladesh, increasing nutrition and reducing arsenic intake ingested in food or consumed in drinking water (Amos et al. 2018c). This will contribute to the health and nutrition of children and women and other members of the public in rural areas. It is expected that similar benefits could be realized in many countries internationally.

6.6 Summary and further research

Household gardening using rainwater storage systems (RSS) shows great potential for increasing household nutrition and possibly income. In semi-humid and semi-arid regions, such as Nakuru and East Poket in Kenya, where hunger and malnutrition are frequent, it can have a big impact.

If evaporation were controlled, the current 1 ML RSS at the orphanage that includes 8 kL of recycled water per day, as well as a rainfall input from 1400 mm, could potentially support up to 4000 m^2 with a 72% reliability and yield 19,190 kg of vegetables/fruit per year, which is more than enough to meet the WHO requirement of 400 g/p/day for 100 adults (14,600 kg/year) or the 45 adults and 120 children that the orphanage currently supports. Excess or sections of the garden could be sold for profit and other vegetables and supplies bought to maintain food variety and nutrition. Yields in the greenhouse for the same area were found to be less due to the lack of input from the rain into the soil, at 16,860 kg/year. Greenhouses that are large may not be economically viable and shade cloth may be preferable in the Kenyan environment. However, for specialist or off-season cash crops, a greenhouse may still be viable, and this would require a specific analysis.

Analysis has shown that a closed 225 kL RSS has the potential to considerably increase yields for areas up to at least 1000 m^2 if there is ample roof catchment available in the region of 500 to 2000 m^2. Larger roofs may increase the reliability even more. Yields for 1000 m^2 of land in the semi-arid region of East Pokot could be increased by 1849 kg from 1270 kg to 3119 kg by a 225 kL RSS connected to a roof of 1000 m^2. This could supply 85 people with 25% of the WHO recommended daily fruit/vegetable needs. In the semi-humid region for the same system, yields could be increased by 2348 kg from 1854 kg to 4202 kg and supply 115 people with 25% of the daily vegetable needs.

This analysis has shown that there is water available to increase yields. Future research needs to focus on feasibility. It is expected that realistic solutions will necessarily involve a multidisciplinary approach. To realize the higher crop yields, a community education program will be necessary, and it seems most reasonable that this should begin at the youngest age. Cost is always a hindrance to such projects, so designs appropriate for the countries' circumstances should be investigated in more depth. A trial of 225 kL tanks with roof areas would be a good way forward to assess the underlying issue

Chapter 7

Summary, Conclusion and Recommendations

Chapter 7 Summary, conclusion, recommendations, and further research

7.1 Summary

Household agriculture (HA) or gardening, using rainwater storage systems (RSS) shows great potential for increasing household nutrition and possibly income. In semi-humid and semi-arid regions, such as Nakuru and East Poket in Kenya, where hunger and malnutrition are frequent, it can have a big impact. The literature review identified the following issues:

- RSS and HA are important and emerging practices with significant cultural and economic value.
- RSS and HA will increase food and water security including WASH and address numerous SDGs, especially Goals 2 and 6 (water and food).
- RSS and HA also address two goals which Australia, and many developing countries have not reached: Goal 11 - Cleaner and sustainable cities, and Goal 3 - Health and wellbeing.
- The main obstacles to accomplishing sustainability through RSS and HA are a lack of knowledge, a lack of design methods, a lack of initiatives to implement their use, and in many cases funding.
- There is a lack of tools available to analyse RSS use in HA in any kind of detail and there is a lack of research in this area [this study has sought to address this issue].

- There are difficulties in accommodating various parameters. The form of urban agriculture, the crop varieties grown and the region in which it is practiced are significant influencing factors which have been highlighted in this study. Analysis is necessarily regional, especially if economics are to be taken into consideration.
- The extent of HA that RSS can support is unknown. The economic outcomes and the sustainability of water management technologies used in home gardens have not been researched.
- Developing countries particularly could benefit from implementing or increasing irrigation to urban agriculture and maximising crop production thereby reducing malnutrition and dependence on aid.
- In Australia and other developed nations where there is sufficient food and water supply it can still improve the sustainability of cities and contribute towards a healthier, more satisfying, and sustainable lifestyle.
- Lessons in sustainability can be learned from developing countries, notably Cuba’s forced experience of local production, induced by a lack of access to fuel and fertilizer.
- To achieve this goal a paradigm shift will be needed, from the current practice of designing RWH systems primarily for toilet flushing and in-house washing and cleaning to designing them in conjunction with urban agricultural systems.
- This will require reference to crop selection, crop water requirements, irrigation methods and economic analysis.

These issues led to the formulation of 3 streams of research questions which this study addresses. Firstly, the economic feasibility and social acceptability of RSS. Secondly, RSS use in general domestic water and WASH. Thirdly, RSS use as a water supply for HA. Following is a summary of findings made in this study in response to these research questions.

7.2 Conclusions

Conclusions can be found throughout this study as part of the published journal papers, key conclusions are listed below under each of the three main streams of questions.

7.2.1 Economic feasibility

Two questions were asked in this section, firstly, are RSS economically beneficial from a life cycle cost analysis perspective? And, secondly, are they affordable? These questions are discussed predominantly in chapters 2, 3, & 4, a summary of the findings follows:

Are RSS economically beneficial from a life cycle cost analysis perspective?

If the only benefit of installing an RSS is to offset the cost of mains water supply, then the short answer is "no" - they are not economically beneficial. Research that shows a beneficial life cycle cost analysis and reports any kind of payback period on the basis of mains water savings alone, has almost certainly neglected major costs in their analysis. The most common costs neglected being maintenances and repair costs, and particularly that of the pump. However, there are many other benefits to be considered, and in places where there is no access to clean water, they may be the most cost-effective solution. RSS have been proven to help increase water security, this research shows that it will simply be necessary to find funding to support the implementation of RSS in almost any scenario.

Are RSS affordable?

The answer to the second question will vary according to local circumstances. RSS are easily affordable in developed countries as they are a minor expense in comparison to cost of the whole house. However, in developing countries cost is the main constraint, and especially for the poor who they would benefit the most. In many cases gutters are not installed with a house and so even installing gutters is an extra expense often over and above budget. Innovation can help make RSS affordable in developing countries.

7.2.2 General domestic water and or drinking water supply (WASH)

Two questions were asked in this section, what is the capacity of alternative RSS system configurations? And, is there an optimum design for RSS? These questions are discussed predominantly in chapters 2, 4 and 5; a summary of the findings follows:

What is the capacity of alternative RSS system configurations?

The capacity of alternative RSS system configurations is really a question about the system reliability. Reliability is affected by three main components: storage size, catchment size and demand. The demand also relates to management issues, as careful management and techniques such as timely water restrictions can reduce the demand at times of water shortage and hence increase reliability. Nevertheless without water restrictions and other management techniques it was found for the study area in Bangladesh that rainwater treatment plants that supplies drinking water to clusters of houses of 100 families, (approximately 500 people) at a rate of 5 L/p/d for drinking water can be achieved with a roof or catchment area of 1000 m^2 with a tank or reservoir storage area of 500 kL if evaporation from the storage area can be excluded. Supply for other domestic uses such as cooking, and sanitation can also be achieved at a rate of 50 L/p/d by a reservoir of 5000 kL with a catchment area of 10,000 m^2. To meet the bottom end expectation of an in-house multiple tap connection a 3 m deep RSS 100 m square would be needed to provide both the catchment area of 10,000 m^2 and the storage area of 30,000 kL required to supply 100 L/p/d for 85% of the year. Issues with this scale of system include reducing evaporation, the distribution of water, financing, and management of the treatment plant.

At the individual household scale, a partial year supply of rainwater can be achieved for a relatively small system. AN RSS as small as 1 kL connected to only 20 m^2 of roof could supply water for a family of 5 at 5 L/p/d reliably for nearly 6 months over the wet season and for a month or so after it. Water management strategies such as drinking water when away from home, for example when at school, could increase this reliability considerably during the dry season when it is easier to travel. The advantages of this are lower capital costs due to the smaller tank, and a reliable supply of water at home in the wet season when it is difficult to travel across the wet and muddy tracks. The disadvantage is that it may still be relatively expensive for those whom it could most benefit, namely the poor living at remoter parts of the district.

Is there an optimum design for RSS?

This will depend on the requirements for the system and the location (i.e. the climate). Comparison of results for the individual and village scale agrees that a rough estimate of 1 kL of storage and 4 m^2 of catchment is required to supply 5 L/p/d reliably all year around. Optimum design may also need to consider cost. A full year supply of rainwater can be achieved to over 95% reliability with a larger tank capacity and roof catchment. A 5 kL tank and a roof area of 20 m^2, or a 3 kL tank with a 50 m^2 roof would be sufficient. Monthly results for reliability show that the RSS continues to supply water after the wet season as the tanks are full. This concept could also be applied to extending the growing season for household vegetable production by water being available into November and December when the rains have stopped. Increase in roof area for a standard toilet and laundry only installation in Australia increases both the reliability and BCR while efficiency decreases. For a 3 kL tank only 30% of the available water is used with a small (for Australia) roof area of 100 m^2. This decreases to 10% with the largest roof area (300 m^2) while reliability increases to over 70%. Interestingly it is with smaller tanks that the increased roof area has the biggest effect in increasing the reliability. This implies that if there is a larger catchment available the tank size can be reduced. In summary, optimum design is too specific to requirements and needs to be assessed on a case by case scenario. The main considerations from the user's end will generally be cost and water demand, and for the system reliability, RSS size, catchment size and the local rainfall pattern.

7.2.3 Water supply for household agriculture (HA)

Three questions were asked in this section, what quantity of water is available for irrigation? What quantity of food can be produced with the available water? And, is there an optimum design for a combined RSS and HA system? These questions are discussed predominantly in chapters 2, 4 and 6; a summary of the findings follows:

What quantity of water is available for irrigation?

Analysis has shown that a closed 225 kL RSS has the potential to considerably increase yields for areas up to at least 1000 m^2 if there is ample roof catchment available in the region of 500 to 2000 m^2. Larger roofs may increase the reliability even more. If evaporation were controlled, the current 1 ML RSS at the Miti Mingi orphanage in Kenya, that includes 8 kL of recycled water per day, as well as a rainfall input from 1400 m^2 of roof, could potentially support up to 4000 m^2 with a 72% reliability.

What quantity of food can be produced with the available water?

Yields for 1000 m^2 of land in the semi-arid region of East Pokot could be increased from 1270 kg to 3119 kg, an increase of 1849 kg, by a 225 kL RSS connected to a roof of 1000 m^2. This could supply 85 people with 25% of the WHO recommended daily fruit/vegetable needs. In the semi-humid region for the same system, yields could be increased by 2348 kg from 1854 kg to 4202 kg and supply 115 people with 25% of the daily vegetable needs.

The above mentioned 1 ML RSS and recycled water at the Miti Mingi orphanage in Kenya support 4000 m^2 with a 72% reliability could yield 19,190 kg of vegetables/fruit per year, which is more than enough to meet the WHO requirement of 400 g/p/day for 100 adults (14,600 kg/year) or the 45 adults and 120 children that the orphanage currently supports. Yields in the greenhouse for the same area were found to be less due to the lack of input from the rain into the soil, at 16,860 kg/year. Greenhouses that are large may not be economically viable and shade cloth may be preferable in the Kenyan environment. However, for specialist or off-season cash crops, a greenhouse may still be viable, and this would require a specific analysis. Excess or sections of the garden could be sold for profit and other vegetables and supplies bought to maintain food variety and nutrition.

Is there an optimum design for a combined RSS and HA system?

From an economic perspective and at the household level, an increase in roof area has a greater effect for an installation that includes outdoor usage. The decreased reliability means that there is greater potential for increasing reliability with a larger tank or roof area. This changes the pattern of BCR and NPV in Australian scenarios. Without outdoor use, attached reliability is already high with a small tank, and so a larger tank offers only small increases in reliability. The lower efficiency at larger roof areas compounds the increase in reliability with increasing tank sizes. Without outdoor uses attached, the NPV of a 1.1 kL tank with a roof area of 300 m^2 is more favourable than the 3 kL tank with a roof area of only 100 m^2. When outdoor uses are attached this is no longer the case, and the 3 kL tank becomes more favourable than the 1.1 kL tank.

Including outdoor use considerably reduces the reliability overall while both the efficiency and BCR increase in the Australian scenario. This indicates that it is financially advantageous to use the RWH system for outdoor use where reliability is not a concern, such as when the tank is connected with mains water top-up. Increasing the irrigation use increases the NPVs and BCRs as this increases water use and hence monetary water savings. The highest BCR occurs with a 15 kL tank; while the highest (least negative) NPV occurs with a 10 kL tank. The BCR of smaller tanks do not increase much with larger irrigation areas because the RWH system has already reached its capacity to supply water even with a small area of irrigation. Crop failure due to decreased reliability however will be an issue if the water supply is not supplemented.

7.3 Recommendations

7.3.1 Implementation

A number of recommendations can be drawn from this study that may be of relevance to modellers and researchers, water engineers, environmentalists, town planners, and policy makers concerned with sustainable development, and dealing with integrated water management and the water-energy-food-ecosystem nexus by bringing together knowledge gaps and potential solutions. In terms of RSS systems, the following recommendations can be made:

- It is unlikely that any RSS system will be economically beneficial for an individual household with access to mains town water.
- In developing countries RSS systems will need funding from either NGOs or government initiatives to be effective in reaching the poor who are most in need of WASH initiatives.
- Village scale initiatives should be considered where possible.
- RSS should be integrated with house design at the earliest stage possible.
- Preferably every RSS system should be designed with particular attention being given to water demand, climate, catchment (roof) area, and cost.

In terms of RSS use in HA:

- RSS could be very appropriate at the household scale where there is a large roof area and a small garden area.
- RSS can be used to increase yield and growing seasons in climates that are not suitable for rain fed agriculture alone, or to provide a second growing season in regions with a long dry season.
- Considerable yield increases are possible, but there is a high knowledge base required for success and proper management of crops.
- It can be used as an educational tool, and may be very helpful in regions where agriculture is a major employment.
- It increases water and food security.
- It needs educational and institutional support, and may increase local business and the health of the local community both physical health and social health.

7.3.2 Further research

As anticipated that this study opened up other areas of research in the area of combined RWH and HA systems as this is a growing and important area of research with many factors being brought together with consequences for international food and water security. In general, it is proposed that further research be carried out in conjunction with existing communities and NGOs in developing countries as this will always help to identify real issues that a desk top study alone will struggle to recognise. It is also encouraged that universities take up the role of providing high quality research to developing countries in a bid to help them meet the sustainable development goals, with focus on clean water, sanitation, food and health.

The economics benefits of using RSS in HA should be explored in more detail. Particularly where there is a lack of access to water, introducing RSS to existing HA systems can increase yields, which may have a value greater than the cost of the RSS. This should be investigated further. As it has been identified that economic considerations represent a major hindrance to the uptake of RSS, methods for financing RSS should be investigated. Also, of the upmost importance is minimising costs through effective and simple designs of RSS and their integration into domestic property design. Cost effective manufacturing and distribution of RSS, and also maintenance of systems post installation are also issues that need to be addressed in many regions. Another related issue is that of education, particular areas are in maintenance and construction, and in agricultural production. This could be taught at the school level, for example HA water management for maximum production with limited resources.

A major limitation in this study was access to reliable global data. Now that a method for analysis of RSS in HA has been developed in the ERain model, which also has the capacity to analyse financial data, research should be undertaken in more regions. This would require a large amount of data collection, particularly of financial data which can be difficult in developing countries where on the ground costs can vary considerably. In this case it is proposed that working with NGOs interested in promoting RSS and HA systems may be the best way forward. It is expected that realistic solutions will necessarily involve a multidisciplinary approach. To realize the higher crop yields, a community education program will be necessary, and it seems most reasonable that this should begin at the youngest age. Cost is always a hindrance to such projects, so designs appropriate for the countries' circumstances should be investigated in more depth. At the village scale trial of 225 kL tanks with roof areas would be a good way forward to assess the underlying issues.

Further studies in water treatment schemes in Bangladesh and other regions should focus on the economic and social feasibility, survey and proposed sites. Due consideration should be given to population distribution, flooding and access during cyclones. Ideally a pilot scheme or trial should be monitored. The capacity of household RSS to increase household vegetable production, and hence nutrition, during the dry season should also be investigated.

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