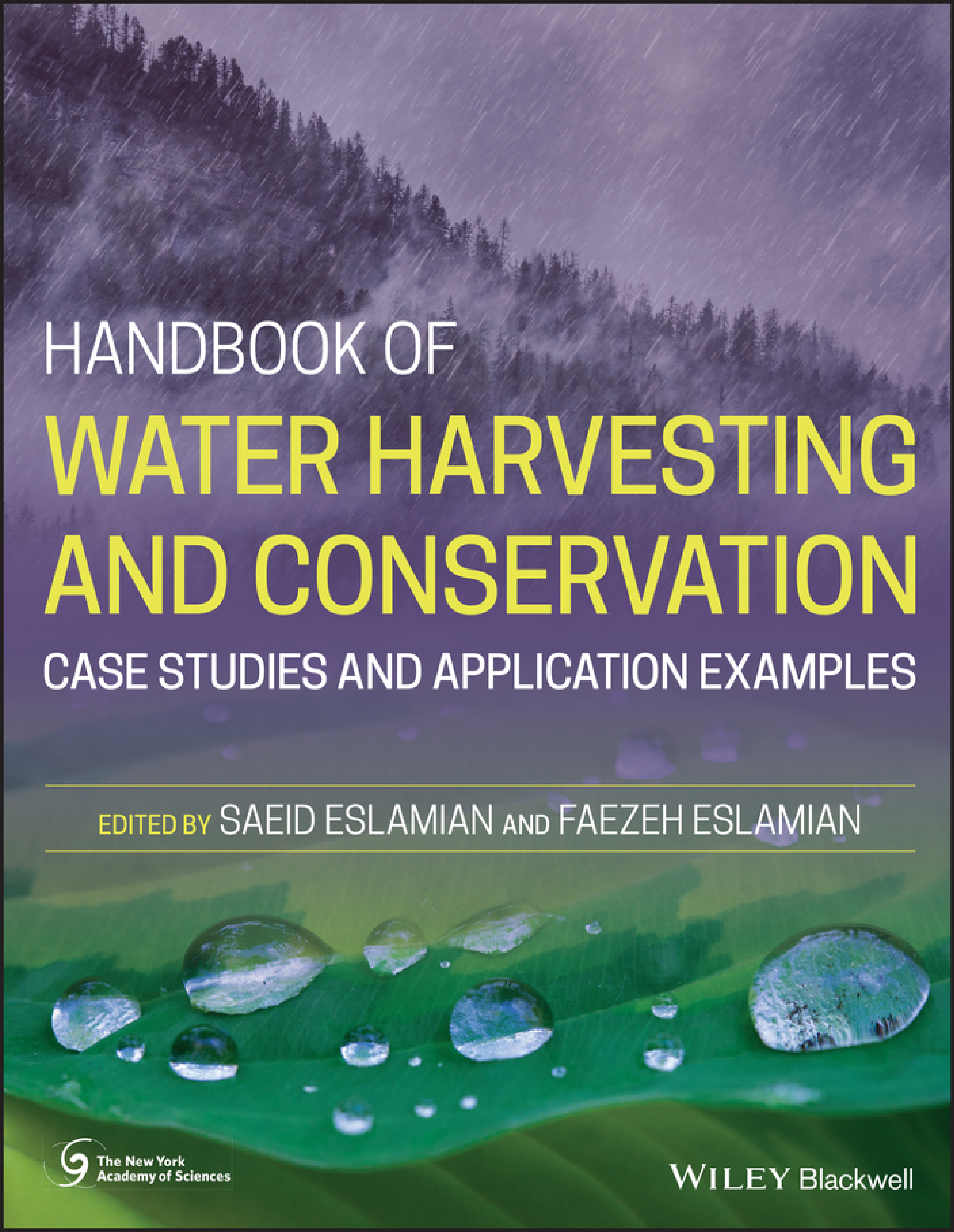

HANDBOOK OF WATER HARVESTING AND CONSERVATION

CASE STUDIES AND APPLICATION EXAMPLES

EDITED BY SAEID ESLAMIAN AND FAEZEH ESLAMIAN

The New York Academy of Sciences

WILEY Blackwell

Handbook of Water Harvesting and Conservation

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Case Studies and Application Examples

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Preface

Water harvesting methods were a vital part of the water supply system of many ancient settlements in the drylands of the Mediterranean region and Western Asia. Various water harvesting techniques evolved during the Bronze Age or earlier, and some of these remain in use even today.

This method has proven to be an effective and sustainable solution for overcoming or reducing water shortages all over the world. To apply water harvesting in a sustainable and effective way, it is important to understand exactly where it can be applied to make full use of its potential.

€59 million has been allocated for achieving Sustainable Development Goals (SDGs) for water in Bangladesh, Ethiopia, Indonesia, Nepal, Tanzania, Uganda, and Zambia. Catchment-based approaches based on IWRM (integrated water resource management) will be further developed in the next 10 years; these water harvesting methods are the main ones.

Water harvesting is gaining more and more recognition as a sustainable alternative to other water supply options. It is economically viable, socially compatible, and environmentally friendly.

Due to the water deficit across the globe, water harvesting and water reuse are the only applied approaches for overcoming this problem. I have recently published the *Urban Water Reuse Handbook* and there is now an urgent need for publishing this *Handbook for Water Harvesting and Conservation*. Dam constructions have caused many problems for humans in the recent century. Water harvesting is a sustainable and simple alternative.

The water conservation titles in this book would be limited to the methods associated with water harvesting. The former books were not in a handbook format and have not included all aspects of water harvesting. Many case studies, particularly from developing countries, have been used as examples in the current work. This handbook will certainly be an important tool for education, research, and technical works in the area of water management and would be highly useful for drought coping, flood management, and adaption to climate change.

In general, the *Handbook of Water Harvesting and Conservation: Case Studies and Application Examples* will express the following subjects:

1. Ancient Water Harvesting and Management
2. Assessment of Freshwater Conservation and How to Increase Water Harvesting in Africa
3. Case studies from countries such as Sudan, Nigeria, Tunisia, New Mexico, Canada, Argentina, China, India, Saudi Arabia, Iran, Japan, Germany, and Romania.
4. Combined Agroforestry and Rainwater Harvesting to Reduce Soil Degradation in the Mediterranean Zone
5. Evolution of Small-Scale Rainwater Harvesting in the Hellenic World through the Millennia
6. Feasibility Study of Rainwater Harvesting Systems
7. Sustainable Water Harvesting and Conservation: Multiple-Criteria Analysis
8. Use of Water Harvesting Approach in Urban Areas of Europe

The primary audiences of the book are the students in various levels for teaching and research. It has also a large benefit for academic researchers in universities and research organizations. As secondary audiences, it is also largely useful for farmers, householders, engineering consultants, and decision and policy makers.

The *Handbook of Water Harvesting and Conservation* is suitable for the following courses: Advanced Surface Hydrology, Advanced Hydrology, Arid Zone Hydrology, Engineering Hydrology, Flood Control, Hydrometeorology, Integrated Water Resources Management, Multipurpose Operation of Water Resources, Rainwater Harvesting and Management, Rainwater Harvesting for Irrigation, Range Land Hydrology, River Engineering, Surface Hydrology, Water Resources Engineering, Water Resources Management, and Water Resources Systems.

Many other courses are also available in colleges and universities with different titles that include water management and water harvesting.

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"It is a huge task that you face. The handbook will be a unique resource when it is published"

Colin Thorne[1]

1 *Colin is a fluvial geomorphologist with an educational background in environmental sciences, civil engineering, and physical geography. He has published 9 books and over 120 journal papers and book chapters. During a career spanning four decades, Colin has held academic posts at UEA, Colorado State University, the USDA National Sedimentation Laboratory, USACE Waterways Experiment Station, NOAA Fisheries, and the University of Nottingham. He is also a Concurrent Professor at Nanjing University and an Affiliate Professor at Colorado State University.*

About the Editors

Saeid Eslamian is a full professor of environmental hydrology and water resources engineering in the Department of Water Engineering at Isfahan University of Technology, where he has been since 1995. His research focuses mainly on statistical and environmental hydrology in a changing climate. In recent years, he has worked on modeling natural hazards, including floods, severe storms, wind, drought, pollution, water reuse, sustainable development and resiliency, etc. Formerly, he was a visiting professor at Princeton University, New Jersey, and the University of ETH Zurich, Switzerland. On the research side, he started a research partnership in 2014 with McGill University, Canada. He has contributed to more than 600 publications in journals, books, and technical reports. He is the founder and chief editor of both the *International Journal of Hydrology Science and Technology* (IJHST) and the *Journal of Flood Engineering* (JFE). Eslamian is now associate editor of four important publications: *Journal of Hydrology* (Elsevier), *Eco-Hydrology and Hydrobiology* (Elsevier), *Journal of Water Reuse and Desalination* (IWA), and *Journal of the Saudi Society of Agricultural Sciences* (Elsevier). Professor Eslamian is the author of approximately 35 books and 180 chapter books.

Dr. Eslamian's professional experience includes membership on editorial boards, and he is a reviewer of approximately 100 Web of Science (ISI) journals, including the *ASCE Journal of Hydrologic Engineering*, *ASCE Journal of Water Resources Planning and Management*, *ASCE Journal of Irrigation and Drainage Engineering*, *Advances in Water Resources*, *Groundwater*, *Hydrological Processes*, *Hydrological Sciences Journal*, *Global Planetary Changes*, *Water Resources Management*, *Water Science and Technology*, *Eco-Hydrology*, *Journal of American Water Resources Association*, and *American Water Works Association Journal*. UNESCO has also nominated him for a special issue of the *Eco-Hydrology and Hydrobiology Journal* in 2015.

Professor Eslamian was selected as an outstanding reviewer for the *Journal of Hydrologic Engineering* in 2009 and received the EWRI/ASCE Visiting International Fellowship in Rhode Island (2010). He was also awarded outstanding prizes from the Iranian Hydraulics Association in 2005 and Iranian Petroleum and Oil Industry in 2011. Professor Eslamian has been chosen as a distinguished researcher of Isfahan University of Technology (IUT) and Isfahan Province in 2012 and 2014, respectively. In 2016, he was a candidate for national distinguished researcher in Iran.

He has also been the referee of many international organizations and universities. Some examples include the U.S. Civilian Research and Development Foundation (USCRDF), the Swiss Network for International Studies, the Majesty Research Trust Fund of Sultan Qaboos University of Oman, the Royal Jordanian Geography Center College, and the Research Department of Swinburne University of Technology of Australia. He is also a member of the following associations: American Society of Civil Engineers (ASCE), International Association of Hydrologic Science (IAHS), World Conservation Union (IUCN), GC Network for Drylands Research and Development (NDRD), International Association for Urban Climate (IAUC), International Society for Agricultural Meteorology (ISAM), Association of Water and Environment Modeling (AWEM), International Hydrological Association (STAHS), and UK Drought National Center (UKDNC).

Professor Eslamian finished Hakimsanaei High School in Isfahan in 1979. After the Islamic Revolution, he was admitted to IUT for a BS in water engineering and graduated in 1986. After graduation, he was offered a scholarship for a master's degree program at Tarbiat Modares University, Tehran. He finished his studies in hydrology and water resources engineering in 1989. In 1991, he was awarded a scholarship for a PhD in civil engineering at the University of New South Wales, Australia. His supervisor was Professor David H. Pilgrim, who encouraged him to work on "Regional Flood Frequency Analysis Using a New Region of Influence Approach." He earned a PhD in 1995 and returned to his home country and IUT. In 2001, he was promoted to associate professor and in 2014 to full professor. For the past 24 years, he has been nominated for different positions at IUT, including university president consultant, faculty deputy of education, and head of department. Eslamian is now director for the Center of Excellence in Risk Management and Natural Hazards (RiMaNaH).

Professor Eslamian made three scientific visits to the United States, Switzerland, and Canada in 2006, 2008, and 2015, respectively. In the first, he was offered the position of visiting professor by Princeton University and worked jointly with Professor Eric F. Wood at the School of Engineering and Applied Sciences for one year. The outcome was a contribution in hydrological and agricultural drought interaction knowledge by developing multivariate L-moments between soil moisture and low flows for northeastern US streams.

Recently, Professor Eslamian has published the editorship of nine handbooks published by Taylor & Francis (CRC Press): the three-volume *Handbook of Engineering Hydrology* in 2014, *Urban Water Reuse Handbook* in 2016, *Underground Aqueducts Handbook* (2017), the three-volume *Handbook of Drought and Water Scarcity* (2017), and *Constructed Wetlands: Hydraulic Design* (2020). *An Evaluation of Groundwater Storage Potentials in a Semiarid Climate* by Nova Science Publishers is also his joint book publication in 2019.

Faezeh Eslamian is a PhD Holder of Bioresource Engineering from McGill University, Montreal, Canada. Her research focuses on the development of a novel lime-based product to mitigate phosphorus loss from agricultural fields. Faezeh completed her bachelor and master's degrees in Civil and Environmental Engineering from Isfahan

University of Technology, Iran, where she evaluated natural and low-cost absorbents for the removal of pollutants such as textile dyes and heavy metals. Furthermore, she has conducted research on the worldwide water quality standards and wastewater reuse guidelines. Faezeh is an experienced multidisciplinary researcher with interest in soil and water quality, environmental remediation, water reuse, and drought management.

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Part I

Introduction

1

Feasibility Study of Rainwater Harvesting Systems

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1.1 Introduction to Rainwater Harvesting Systems

Rainwater harvesting (RWH) and utilization systems have been in use since early Roman times, dating back to 2000BCE (GRDC 2002). Archeological evidence in Israel confirms early RWH; ruins of cisterns built to store runoff water from rainwater harvesting from hillsides for agricultural and domestic use are standing there even today. Any rainwater harvesting system requires many components to meet its objective of construction and use. These components are site specific and are governed by the use to which harvested water is to be put. Also, it is governed by the feasibility of technical, economic, environmental, and socio-cultural factors. However, there are five main water harvesting components that are essential to have in a rainwater harvesting system. They are: collection area, conveyance system, flush filter diverter, leaf screen, and water storage tanks. The technology also has a long history in Asia, where rainwater collection practices have been traced back almost 2000 years in Thailand and over 4000 years in India (Jainer 2016). Rainwater harvesting systems are increasingly being used due to increase in population, water scarcity, and groundwater pollution both in developed and developing countries. It is used in rural and urban areas for potable and non-potable water use. It is used in all climatic zones – arid, semiarid, and humid – and used by rich and poor people. Rich people use it to have water security and to minimize the cost of water, energy, and drainage. Poor people go for it because of its cost effectiveness and simple technology.

Farmers use this technology for supplementary irrigation to increase their crop productivity and for their livestock feeding. It is used in schools, hospitals, individual households, and industries to meet their water requirement in a sustainable way, both singly or in combination with other sources. RWH is one of the quickest and easiest ways to reduce water consumption from outside sources and is an easy and efficient way of meeting water requirements. The best thing about harvested rainwater from rooftops is that in most cases, it is free from pollutants as well as salts, minerals, and other natural or man-made contaminants. In the areas where there is excess rainfall, the surplus harvested rainwater can be used to recharge groundwater through artificial recharge techniques, which will result in stabilizing groundwater levels. RWH is an effective and eco-friendly method of reducing water usage in dwellings, which will lead to reduce water bills. RWH systems require comparatively little maintenance, time, and energy to do the cleaning. RWH is a low-cost maintenance system, provides a supply of safe water to homes close by, as well as schools or clinics, encourages increased consumption, reduces time women and children spend collecting water, and will reduce back strain or injuries from carrying heavy water containers. The RWH system is independent and therefore suitable for scattered settlements. In places where groundwater is saline, or ground and surface water are not available, RWH will be the most preferred, cost-effective, and affordable system. Some of the disadvantages of RWH include the fact that rainfall is hard to predict, and sometimes little or no rainfall can limit the adoption of RWH system and make it unsustainable. Depending on the system size and technology level, the initial cost of the system may be high compared to tap water systems. RWH systems can act as a breeding ground for disease vectors if they are not properly maintained.

The feasibility of RWH systems is carried out to determine the viability of using rainwater for drinking, domestic water, water for livestock, water for gardening and irrigation, and a way to replenish groundwater; to meet the increasing water demand; to overcome water shortage from an existing source and stabilize water supply; to conserve and augment the storage of groundwater; a

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potential alternative source to overcome groundwater quality problems such as arsenic, fluoride, and hardness; as a supplementary source to mature crops as well as to increase crop productivity; to overcome extreme conditions of drought, flooding, soil erosion, sea water intrusion, waterlogging etc.; and to minimize the cost of water, energy, and drainage bills.

1.2 Review of Literature on Feasibility of Rainwater Harvesting Systems

The published literature contains hundreds of studies on feasibility of RWH systems. Many of them are site specific and cover limited aspects of feasibility of the RWH system. To give a glimpse of feasibility studies carried out so far, a few studies covering different aspects are presented in this section.

Xiao (2008) argues that RWH systems are financially attractive to Beijing farmers who are mainly using underground water in the rural areas of Beijing for crop production. The present rate of subsidy to RWH systems did not give any extra benefit over that of conventional irrigation, and as such Beijing farmers are not interested in adopting RWH systems. Increasing subsidies and/or using RWH system tanks during the dry season for different purposes such as mushroom growing will make RWH more attractive to Beijing farmers. In assessing the technical feasibility of RWH systems in Chennai, India, KRG Rainwater Foundation (2010) suggests that survey relating to geology and structural control, hydrogeological survey, well inventory, geophysical survey with vertical electrical sounding, sources of water supply, existing surface water bodies, and drainage system should form part of the feasibility study to conduct a water balance analysis and to assess the RWH potential.

Alam et al. (2012) argues that in heavy rainfall areas such as Sylhet city and suburban areas in Bangladesh, the feasibility of RWH system adoption exists in rural communities and thickly populated urban areas using low-cost technology based on quantity of rainfall runoff. According to them, a carefully planned use of rainwater through RWH system in the roof catchments may fulfill the entire annual domestic water demand of a family in the rural areas of Bangladesh. The Food and Agriculture Organization (FAO 2014), based on a feasibility study conducted on rainwater harvesting for agriculture in the Caribbean sub-region, supports RWH technology as a tool to capture and store rainwater runoff for later use, which will significantly reduce risks of losing some or all of the harvest each year owing to soil water scarcity; in addition, an RWH system will reduce flooding and soil erosion during increasingly high rainfall intensities being experienced in the sub-region. The FAO argues that the role of policy and institutional support for RWH as well as studies to determine the environmental, social, and economic benefits of the technology, must form part of the feasibility study.

Ponces (2015) developed a technical evaluation tool complemented by a comparative financial analysis of different alternatives in order to select the most adequate and appropriate investment in RWH. The developed tool was field tested at two shopping centers located in Portugal and Brazil, respectively, for the most viable configuration in each case. The author argues that this tool can be used as a guidance to feasibility study. In assessing the feasibility of RWH system, climate change factors need to be included to arrive at the correct and robust RWH system. In assessing the feasibility of RWH system, Climate tech Wiki organization suggests the following parameters as essential for evaluation: rainfall quantity and rainfall pattern, collection surface area, available storage capacity, daily consumption rate, number of users, cost of RWH system, alternative water sources and water management strategy. They state that provision of storage tank is the costliest element and usually represents about 90% of the total cost.

Joshi et al. (2005), while reviewing 311 case studies on watershed programs in India with rainwater harvesting and rainwater management as important components found that the mean cost benefit ratio of such watershed programs was relatively high at a mean value of 2 with a minimum of 0.8 and a maximum of 7.3.

Ghimire and Johnston (2013), while providing a holistic assessment of environmental and economic viability of domestic and agricultural RWH system at the watershed scale in three watersheds in the southeastern US using life cycle assessment (LCA) and life cycle cost assessment, compared RWH systems to conventional municipal and well water systems and concluded that RWH systems contribute to water resource sustainability by offsetting surface and groundwater consumption and by reducing environmental and human health impact compared to conventional sources. Increased green water use over blue water, reduced energy demand, savings in life cycle energy costs, and decreased global warming potential indicate the potential of RWH as a sustainable water resource management strategy. The authors also state that policies encouraging RWH practices are increasing across the US in Texas, Ohio, Virginia, North Carolina, Illinois, and California and internationally in Australia, Spain, Canada, Bangladesh, India, and Nepal.

Worm and van Huttum (2006) listed a number of factors in addition to cost to be considered in the feasibility study of RWH systems. From the environmental feasibility point of view, the amount and pattern of rainfall in the area, duration of dry periods, and availability of other water sources need to be considered. They recommend that rainfall should be 50 mm per month for at least half a year or 300 mm per year to make RWH environmentally friendly. The technical aspects relate to construction of the RWH system, which is determined by factors such as type of roofing materials, availability of areas for constructing storage tanks, water consumption rate, storage capacity required, availability of surface and groundwater sources, and availability of construction materials with skilled laborers. The social and gender aspects relate to felt need of the community, social cohesion, cost effectiveness and affordability, and community participation. The authors state that all reasonable alternatives should be investigated and using other options in combination with RWH system should be considered.

Nyamieri (2013) in his thesis explores the community perception and adoption of RWH technologies where the implementers claimed to have used a community-based participatory approach. The study indicates that the intervention and approach used affects the community's perception regarding the newly introduced RWH systems. It was not a demand-driven project but a project thrust on them with no involvement of community in the decision-making process. The support and application methodologies used by the project implementing agency created uncertainties from the community members affecting the perception that in turn negatively influenced the adoption process of the project. Though the community members knew the value of adopting RWH systems, factors such as payback period, land ownership and land tenure issues, and the hard labor required to implement the project affected the adoption of this technology. The decision to adopt or to use RWH systems is dependent on the implementation process adopted and the community's perception of it. Therefore, it is critical to better understand their choices in making the decisions to adopt it.

Kariuki (2011) examined the socioeconomic factors influencing adoption of RWH technology. Among the various socioeconomic factors, education was observed to influence adoption of RWH positively. Financial constraint was cited as a major drawback when it comes to constructing tanks for harvesting rainwater. Gendered division of responsibilities in the community emerged as a challenge to adoption of RWH technologies. The study led to the conclusion that group network plays a major role in the adoption of RWH. Gender and age dimensions should be incorporated in strategies for adopting technology, as the study found that women and girls are left with the responsibility of supplying household water for the family without being part of the decision-making with regard to the source to be used for household supplies. He also suggested that institutions be put in place to assist households to access funds for RWH structures and to work with local communities or households to provide guidance to choose the correct size of water storage tanks to enable stored water to last until the dry season.

Amos (2016) reviewed the feasibility of RWH system on a global scale, with particular reference to Australia and Kenya. They reported that many Australian states have policies promoting uptake of RWH systems. Several authors (DTU 1987; Garnet 2003; NIH 1997–1998; Yamamota 2010; UNEP 1997) have quoted the potential of RWH systems to reduce water and food crises in developing countries. Some African governments are offering financial assistance to accelerate implementation of RWH systems. In Kenya, due to high material cost relative to income, many households are not able to afford the full cost of RWH systems. It is suggested that government funds the cost of RWH systems while the individual looks after the operational and maintenance costs. The international 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, and propose sustainable cost recovery instead.

1.3 Feasibility Study of a Project or an Idea

A feasibility study of any project or idea in general is a process during which one tests an idea's viability. Will it work? Although the specific questions one will have to address will vary depending on the nature of the project or idea, there are some common steps that apply to all feasibility studies.

1.3.1 Feasibility Study of Rainwater Harvesting Systems?

A feasibility study of RWH system, as the name implies, is used to determine the viability of an RWH system to ensure that RWH is socially, technically, and legally feasible, as well as economically justifiable. It tells us whether RWH is demand driven or if it is forced on individuals and/or communities by an external agency. A feasibility study may come out with the suggestion that RWH cannot be implemented due to certain constraints such as inadequate resources to implement, higher costs than the present system of water supply, or the fact that community may not gain much by implementing a RWH project, or it may suggest ways and means of implementation and the process to be adopted for sustainability of the implemented system.

A well-designed project feasibility study should look at the historical background at the proposed site, its ability to perform well, its acceptance by the local community, its future demand and affordability of the RWH system, and willingness to participate in project implementation and to operate and maintain the system. Specifically, a feasibility study involves a SWOT (strengths, weaknesses, opportunities, and threats) analysis of implementing a RWH system.

1.3.2 Steps Involved in Carrying out a Feasibility Study

- The first and the foremost initial step is to decide whether one needs a feasibility study of RWH system. In many situations, conducting a preliminary analysis through a pre-feasibility analysis is more than sufficient and tells us whether you need to proceed with a full-blown detailed feasibility study or not. Conducting a feasibility study is a time-consuming and sometimes expensive process. Hence, a careful decision is to be made with regard to conducting a feasibility study of RWH.
- Having decided to go for a feasibility study, the next step is to find out whether there is a demand and felt need for a RWH system? This can be determined by interacting with local people (stakeholders), as well as looking for installed RWH in that location and its present state of functioning, in addition to the present system of water supply functioning with respect to quantity, quality, reliability, and cost for consumers and consumer satisfaction.
- If there is a demand and need for RWH system, then one should carefully identify other possible alternatives to RWH systems and weigh pros and cons of going for a RWH system either singly or in combination with the existing systems.
- During the feasibility study, one needs to look at the challenges one will face in implementing the RWH system with respect to physical feasibility, technical feasibility, socio-ecological and environmental feasibility, and economic and financial feasibility, and the sustainability of the system put in place.
- The best way to get the requisite information is to look at the history of implementing the RWH system in that area, if one exists, and to interview the stakeholders, primarily consumers, and ask them specific questions such as:
  - How much do they like/do not like the present system of water distribution? Would they like to switch over to other systems of water distribution such as RWH systems?
  - How much money do they spend for the present water supply and distribution system and will they be able to pay more or less than the amount spent presently? In other words, what is the affordability of getting domestic water supplies through RWH systems?
  - In what way would they be able to participate in the implementation of RWH system in their locality in terms of supply of cash, labor, material, and management activities?
  - What, according to their perception, will be the major constraints in implementing the RWH system in their locality and what will be their suggestions to overcome them?
  - Should the RWH system should be operated independently or should it be integrated with the existing system of water supply and distribution? What should be the institutional setup to operate, maintain, and manage the system?
  - What are the cultural and ecological factors that will impinge on designing and implementing a RWH system at the local level? Is the requisite material for construction and skilled labor available locally? If not, where will they be obtained and at what cost?
  - What will be the financial cost of the project? Where will the funding for the project will come from? And what will be the contribution from the local community and the government?

Based on the above information, prepare a detailed feasibility report.

1.3.3 Factors to Be Considered in Conducting a Feasibility Study

Water quality of harvested and stored water plays an important role in rooftop water harvesting systems. Special attention needs to be paid if the water is going to be used for drinking. The available literature presents different conclusions on the quality of harvested water from rooftops. While some studies report that rainwater from rooftops generally meets the international guidelines of drinking water (Sazkali et al. 2007), other studies report that chemical and/or microbial contaminants are often present in levels exceeding international guidelines for drinking water (Vasudevan and Pathak 2000). The harvested and stored water may be subjected to waterborne diseases caused by the ingestion of water contaminated by human or animal faces or urine containing pathogenic bacteria or viruses causing cholera, typhoid, bacillary dysentery and other diarrheal diseases and water related diseases transmitted by insect vectors which breed in water causing dengue, filariasis, malaria, and yellow fever (Eisenberg et al. 2001; Vasudevan et al. 2000).

Sustainability of an implemented drinking rainwater harvesting (DRWH) system is an aspect that needs to be considered carefully during the feasibility study. A sustainable DRWH system is one that is implemented after considering not only the physical attributes (rainfall, location, catchment characteristics) and the socioeconomic attributes in its design but also the quality of stored rainwater and the use of alternative water sources that exist in that area. Although DRWH appears to be one of the most promising alternatives for supplying fresh water in the face of increasing water scarcity and escalating demand, it should not be looked upon as the panacea of additional water supply. The sustainability of the DRWH system requires not only close cooperation between the government, the private sector (NGOs and scientists), and the rural households, but also an integrated systems approach where the quantity/quality of the water supplied as well as the associated cost of implementation, operation, and management need to be considered (Kahinda et al. 2005). During the feasibility study, it is essential to check whether there exists a clear policy that will provide a framework which will enable the sustainable use of and upscaling of the DRWH system.

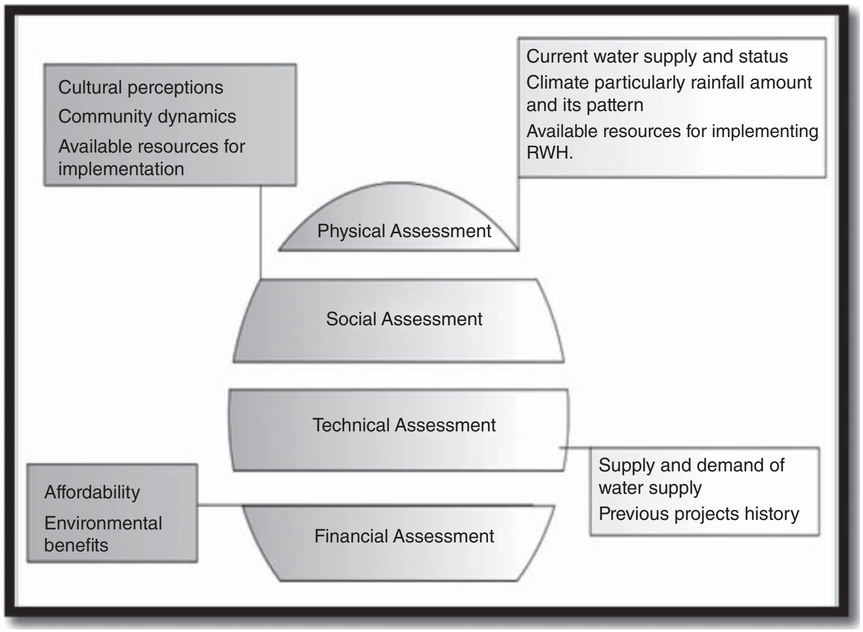
The physical unit of feasibility analysis of RWH is another important factor to be considered while conducting a feasibility study of RWH. The RWH system is adopted at individual household and at community level for both domestic water supply and agricultural water use. Although a feasibility analysis can be carried out either at the household level or at the community level, carrying out feasibility analysis at the watershed level has merit in capturing the holistic impact of the RWH system at the watershed scale, which includes a green infrastructure strategy for climate change adaptation (Ghimire and Johnston 2013). Feasibility analysis at the household level is the simplest of all units of analysis. The complexity of the feasibility analysis increases as one moves from household level to community level and then to watershed level. At the household level, in addition to meeting demand for increasing scarce water supply, affordability and cost saving takes center stage in the feasibility analysis. At the community level, willingness to participate in implementation and sustaining the system implemented need focus during the feasibility study. At the watershed scale, in addition to the above factors, water balance analysis, upstream and downstream impact, including equity aspects, and integrated systems approach of using green and blue water must need focus while assessing the feasibility of RWH system.

The purpose for which harvested and stored rainwater is put to use plays a major role in conducting a feasibility analysis of RWH. The harvested water can be used as potable and non-potable water at the household level, used as a supplementary source to kitchen gardening and small plot rainfed farming, for maintaining lawns, for groundwater recharging, and for diluting underground water from its pollutants. The feasibility analysis to be undertaken needs to focus on the purpose for which the harvested water is to be put into use. For example, if the harvested water is going to be used for drinking, a concentrated effort on the quality of water and how it affects the human health and how it can be prevented need to be looked into during the feasibility study. On the other hand, if the water is used for non-potable use, the quantum of harvested water and not so much the quality of water assumes significance in the feasibility analysis. In the case of agricultural water use, the focus will be on harnessing more rainwater through RWH systems such as farm ponds and checking structures through recharging the aquifer, as well as increasing farm productivity through supplemental irrigation. More emphasis during the feasibility study needs to be put in not only harnessing the rainwater but also in managing that resource in a productive way.

Other factors that need consideration during feasibility studies are: use of RWH system tanks during the dry season for different purposes, such as mushroom growing, to make RWH systems more attractive to farmers; refined methods to assess rainwater available and water harvesting potential; a detailed cost–benefit analysis; and community perception about implementation process adopted in the previously implemented RWH system, as well as various socioeconomic characteristics such as education, gender, family size, income, roofing material, technology access to information, group networking, and sources of income.

1.4 Assessing the Feasibility of Rainwater Harvesting Systems

There are three important questions that should be asked when undertaking any RWH system in a location/region (Jean Charles 2007): Does the community need it? Does the community want it? And can it be done? If yes, at what cost? For a RWH system, these translate into physical, social, technical, and financial assessments. The areas to be addressed when evaluating these feasibilities are the following:



(Source: Jean Charles, 2007)

1.4.1 Physical Assessment

A physical assessment takes inventory of current situation. For example, what sources of water currently exist? What are the potable or non-potable uses? What are their conditions of water distribution with regard to quantity? Are the sources of water located near the community or far away? Are they accessible to the community? What is the quality of water? Is it a reliable source or it is available only in certain seasons or certain times? Answers to these questions will tell us whether or not there is a need for a new or improved water supply. A public water supply, i.e. a well or nearby river, may already be available. The quality and reliability of this water supply and the preference of the people must be taken into account. For the given location, does it rain and how often? Does the amount of rainfall per month or per season warrant the usefulness of a RWH system? The Development Technology Unit (DTU 1987) recommends 50 mm per month for at least half the year for implementing a RWH system. Another source recommends 400 mm yr^{-1} (UNEP 1997). Rainfall data can be obtained from local rain gauge stations. Asking the locals for this information will also give a general idea. An additional observation should be in regard to local building materials. For example, what kinds of surfaces exist for catching rain? It should be noted that some types of materials are not suitable for RWH systems for potable uses.

1.4.2 Social Assessment

Social assessment must begin with a definition of community and the identification of key persons. How many people exist in the community? Who are the real respected leaders of the community? The social assessment goes on to answer the whys of the physical assessment. For example, why is one source of water more preferred than another? Is a water source located in an area by choice or by circumstance? Why does a community not practice RWH? Is there a real felt need for better water provision (UNEP 1997)? A community may have the need for an improved water supply, but there are several reasons the community may not be receptive to the idea of a RWH system. Depending on the kind of system presented, the technology may be above the education level of the community. There may be other priorities for the community depending on the season. RWH may not be considered an immediate need, or there may already be multiple sources of water, each with its own specified purpose. There may be traditional RWH systems already in place and they may not need refinement and/or addition to the existing system. Cultural perceptions and religious views regarding the use of water, as well as traditional preferences for its location, taste, smell, or color, are all important factors to be taken into consideration. “Too often, non-community agencies (government, NGOs, and outside donors) will seek to implement a new technology without taking into account the cultural traditions and social roles of that community" (UNEP 1997). It is those very traditions and social roles that will determine the successful implementation and use of a RWH system.

In many developing countries, women are primarily responsible for water, but decisions to undertake investments, such as installing a RWH system, are typically undertaken by men. Both groups need to be included in any discussions regarding the implementation of a RWH system. Pacey and Cullis (1986) recommended forming community water groups to be responsible for the system. It is important to know the people, to be aware of their concerns, and to encourage their participation in every step of the process. It has been shown that the more a community is involved, the more the potential for a successful project (UNEP 1997).

Other aspects regarding assessment of community dynamics include level of cohesion and communication, community politics and relations with surrounding communities, amount of enthusiasm (often evaluated in terms of willingness to contribute), and assistance from outside groups. These and likely other factors not mentioned here can positively or negatively affect a RWH system. For example, the identification of key persons can extend to outside groups, individuals in surrounding communities, as well as those in regional government agencies or from NGOs who can provide resources or knowledge. Local community leaders must agree on the inclusion of such individuals or groups.

1.4.3 Technical Assessment

The technical assessment seeks to answer the question "Can it be done?" by taking into consideration the resources required for the implementation of the system, by determining expected supply and demand for water based on gathered data, and, where applicable, by taking into consideration previously attempted projects and their reception by the community.

Determining available resources will require taking inventory of local building materials and discussing with those involved which materials are necessary, which can be supplied by the local community, which must be brought from outside, and the transportation options that exist. Available resources must also take into consideration the financial contribution of the community and that from outside sources. Human resources will include skills, training, and management abilities, as well as labor. A plan outlining future maintenance and safety requirements is key from the outset to ensure the sustainability of the system. A site assessment is also important as this determines the location of the water storage catchment or catchments and how the water will be supplied. RWH can be done on a large scale or locally to individual households. This aspect will determine the level of efforts and details to be obtained during the feasibility study.

Potential supply can be estimated based on the size or area of the surface catchments, and the amount of rainfall expected. Expected demand does not dictate how much rain will actually be collected, but it is a useful guide for calculating storage capacity. Demand is estimated based on: the intended uses for the water collected, the number of users, and the expected use of currently existing sources in light of a new water source. Intended uses can range from drinking and cooking to washing, cleaning, or gardening. The number of users as well as consumption patterns will vary depending on age, gender, or season. It may be best to estimate consumption patterns by household, since the women responsible for bringing water to the home generally have a set pattern and a set number of containers for collecting water. Where existing sources are available, or preferred, they may be used until the dry season, when the stored rainwater becomes the main or only source of water. Nevertheless, if the stored rainwater is nearer than a distant source, it may be used more frequently. In short, designing for demand may not be an easy task. It is better to overestimate than to underestimate. Finally, a review of existing projects or previous efforts to implement water supply systems may contribute valuable knowledge and prevent past mistakes from reoccurring. A local community may not always volunteer to give such information. It is critical, in the case of existing projects, to know their owners and any contract or stipulations associated with them. This can prevent making changes in an area where changes are limited, not allowed, or not aligned with the original intentions of the project already there. Some knowledge of regional or country water policies may also be useful.

1.4.4 Financial Assessment

Financial assessment plays an important role in the feasibility analysis. Cost is the major consideration for households and for communities, especially when they need to pay more than what they spend now for the water supply in order to accept or reject implementing the RWH system. Also, when the benefit far exceeds the cost only then there is an interest in accepting the implementation of the RWH system. Although the advantages and benefit that accrue out of using RWH system is known, the affordability for the individual plays a major role in accepting or rejecting the RWH system. Presently, a number of methods are used to estimate the cost and benefit. Some of the important ones are: present net worth, internal rate of return, cost–benefit analysis, and life cycle cost analysis (Gabriela 2017). Many of these analyses take into account only the direct benefits and are not able to quantify the indirect benefits such as impact on climate change due to adoption of RWH systems and energy savings.

1.5 Feasibility Study of Rainwater Harvesting Systems: A Case Study

There are many case studies in the literature. The case study selected is to show the amount of field data that needs to be collected to carry out a detailed feasibility analysis. The case study reported herein describes an observational feasibility assessment of ground-level surface pits in the region of Segou in Mali as a RWH system. The region of Segou falls into the Sudanic climate, with rainfall averaging between 407 and 1930 mm over three years (2004–2007). A large percentage of the population of this region is heavily dependent on agriculture, subsistence farming, animal husbandry, and pastoralism for their livelihood.

In the region of Segou, the river Niger dammed by Markala Bridge Dam is one of the main sources of water used for gardening, for washing clothes, and for harvesting sand and fish. Although Niger water is not fit for drinking, some people still drink that water in the rural area. Apart from the Niger, another source of water is groundwater wells widely used by communities outside the city. Well depth ranges between 2 and more than 6 m below ground level. Most wells are located very near the household with the distance of travel not more than 6–7m.

The dry season spanning March to July makes both surface and ground water sources become dry. During this period, water is carted in from other sources. The real rainy season normally begins in June, peaking in August and September, and is over in early November. Immediately after the rain, natural depressions (pits) and manmade pits become filled with rainwater. The manmade depressions can range from 1 m to 2 km in length and width and be half a meter to three meters deep. These manmade pits grow in number and volume capacity, year after year as men excavate earth each year for the manufacture of bricks and for plastering mud houses. The runoff collected in these pits lasts from one month to five or six months in the larger pits. Although the water is not potable, the supplemental water provided by these pits makes a significant contribution to the local water supply. The stored water alleviates demand on ground water reserves for gardening and other domestic needs; women use this water for vessel cleaning and washing clothes, and thousands of cattle, sheep, and goats often stop to drink at these pits.

Most of the rural population live in thatched roof houses or mud homes in villages of 150–1000 inhabitants, or in towns of up to 8000 inhabitants. Roofing materials in the region of Segou include thatch, mud mixed with manure, millet, and rice husks, or corrugated metal sheets, which are popular in the city. Natural earth is the preferred material for house construction. Land is another source that is widely available. Most of the land is used for growing millet, sorghum, and rice and for grazing livestock. In this region, roof catchment systems appear to have the least potential for RWH due to the predominance of mud roofs and long dry periods of up to eight months. Rainwater harvested from mud roofs is considered dirty and a long dry period suggests the need for a larger roof catchment, which is not available.

One explanation as to why rooftop rain water harvesting has not been widely promoted is to do with it being a "new technology." It is difficult for a community to support a project they do not understand or have not seen before. Moreover, the idea to build a structure that stores water within their house premises seems foreign to them. Although the community could appreciate the value and benefits of rooftop RWH when explained, they are not inclined to support it, because they have not seen any such system working in their area of living.

Storing water in natural pits or man-made ones is very familiar to the people of this region. In most villages, establishment of a water source, either a pit or a well, is the responsibility of men, while bringing water from the source to the household and conserving it is the work of women. Field observation regarding the use of ground-level pits indicates that larger communal surface pit systems show great promise and can be used for the complete range of water needs if well managed. They are the ideal communal surface pit system: socially they are widely accepted; financially, they pay for themselves as the bricks made from the excavated earth are personally used or sold to fellow villagers. Women use the water collected in pits for gardening. Free-ranging animals are able to quench their thirsts. The entire community benefits from the larger communal pit system. The question of whether or not the community wants this kind of RWH system is positively answered because the community automatically takes ownership of these pits in all their life stages. Community is there, technology selection is theirs, risks for social conflicts are minimized, management capacity is built in, labor is willingly provided, financing is minimal, potential for women's involvement is greater, and support from local government and NGOs is forthcoming. Increasing community involvement in such a project is facilitated with this kind of RWH system.

A technical assessment of these pits indicates that smaller pits become dry in a short period of time due to very high temperature of 104 °F. Therefore, there is a proposal to go in for high-capacity (large-volume) pits that can be used for aquaculture to increase the water productivity of stored water. Resources to execute small pits such as picks, shovels, carts, wheelbarrows, drums, and manual labor both by human and animal are available locally. For larger pits, an earth mover is usually preferred. This needs to be rented. The cost of renting cannot be borne by locals because of their economic status. This has to be accommodated in the cost of financing the project and from the community point of view, it is subsidized.

Supply and demand of water from such pits needs to be examined. As an example, a pit 100×80 m is to be excavated with a depth of 1.5 m and having a volume of 12 000 m^3 for a local community in Kamian. Water collected in the pit is limited by the dimension of the excavated area and not by expected supply. Water is supplied to the pit from two areas. Area 1 is the pit itself on which rain falls directly and area 2 is the drainage area surrounding the pit. Water supply to the pit can be calculated from the formula: Supply = Rainfall × (1-C) × (area 1 + area 2). The coefficient C is a measure of system efficiency in terms of retaining the captured water. Using this equation and assuming $C = 0.3$ (based on local observation), the drainage area required is determined as 17 625 sq. m. As previously mentioned, land is widely available, even in areas where land is farmed. To calculate the demand, it is important to consider all the watering needs of the community. The women use the pit water for washing pots and clothes as well as for gardening. The men use it for making bricks or preparing plaster for mud houses. It is also used as drinking water for cattle, sheep, and goats. Assuming that the water is carted away for use from this pit, how many people will be accommodated to use the filled Kamian pit for the 8 months (240 days) until the next rainy season is worked out as follows: Assuming that each household with 10 persons uses 12 gal d^{-1}, each household has two cows, four sheep, and four goats (each animal capable of drinking 5 gal a day), and one plot in the community garden requiring 50 gal a day, making 500 bricks per month needing 200 gal per month, the water requirement for just one household for a period of 8 months is 112 m^3 and if the population is 1000 persons (100 households), they need 11 200 m^3 of water, which can be satisfied by the pit constructed.

In addition to the above, the following negative factors in designing ground-level pits must be taken into consideration. Ground pits are open sources of water, capable of receiving contaminated water. As such, locating a pit is an important consideration to minimize entry of polluted water. The management committee needs to oversee the removal of debris and general cleanliness of stored water. Besides, the issue of sanitation, an open water source will attract rodents and insects, especially mosquitos. In some cases, water-loving plants like water hyacinth may emerge in the waterbodies, causing eutrophication. Necessary precaution needs to be taken to overcome these negative effects.

If this ground-level pit is evaluated using five life cycle stages (needs assessment, conceptual design and feasibility, design and action planning, implementation and operation and maintenance) and the five factors of sustainability (socio-cultural aspects, community participation, political cohesion, economic sustainability, and environmental sustainability), rainwater harvesting pits of this type potentially score out 100 when evaluated in the given category (Jean Charles 2007).

1.6 Conclusions

With increasing water scarcity, rapid urbanization, and impact of climate change on water resources, RWH systems are here to stay in all the regions of the world. In implementing the RWH system, one of the first and most important steps is to undertake a feasibility study of the RWH system. The level of feasibility study undertaken depends on a number of factors, mainly the purpose, type, for whom it is undertaken, and the size and cost of implementation. In many situations, a preliminary analysis of RWH system, popularly called a pre-feasibility analysis, is more than sufficient to judge whether to go in for implementation of RWH or not. Since a feasibility study involves a considerable amount of time, money, and field work, careful planning and execution of the feasibility study is important. The diagnostic analysis of why a RWH system needs to be implemented has to be carried out, generally with a SWOT analysis of the RWH system.

The feasibility study starts with preliminary analysis of its need for the case under investigation, what methods are to be used to assess the feasibility of RWH systems, and how to carry out a feasibility study and arrive at the need and usefulness of the RWH system, its merits and demerits, who will implement, operate, maintain, and manage the RWH system and at what cost, with possible funding sources for the RWH system implementation.

A feasibility study leads to positive results where it is implemented in a demand-driven and water-scarce situation. It has been successful where a clear policy is laid down and governmental supports are forthcoming, as in the case of San Mateo County, California, USA. The feasibility study has shown that RWH system implementation has been successful where it is integrated with other water sources and the potential for RWH is estimated on water balance approach at the watershed scale.

The process of RWH implementation, the social cohesion of the group, political group dynamics, social networking, and socio-cultural practices play an important role. Focus must be given to these aspects during the feasibility study to make sure the implementation of RWH is successful and sustainable. A detailed feasibility study comes with a blueprint stating where and why it should be implemented, what are the factors that need to be taken into account for its sustainability, what kind of subsidy needs to be given for a successful RWH system, and what kind of institutional support is needed to operate, maintain, and manage the system.

The feasibility study is carried out using individual assessment of physical, social, technical, and economic, along with historical, data. There are very few studies which integrate all these assessments with climate change impact and look at the feasibility in totality and in a holistic manner. To improve and refine the methodology of feasibility study of RWH, research should focus on integrating all the assessment factors along with refinement in methodological content of economic analysis. A lot of research is needed to arrive at a rational guideline for different regions, for different purposes, and for different levels of socioeconomic consumers and stakeholders.

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2

Sustainable Water Harvesting and Conservation Using Multiple-Criteria Analysis

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2.1 Introduction

The development of water harvesting and conservation systems are critical to human health and ecological sustainability (Rahman et al. 2017). A multiple-criteria analysis (MCA) is proposed to model water harvesting and conservation in developing nations and economies in transitions, as well as in developed nations in the Asia-Pacific region. Water harvesting and conservation projects often occur in low- to moderate-income nations, which may suffer from endemic corruption, environmental degradation, marginalized communities, under-resourced populations, and economic challenges due the large numbers of social, ethical, and environmental issues, as well as pervasive complexity and uncertainty. There are many options for water harvesting and conservation systems. Given the importance and controversy surrounding these projects, it is of value to apply MCA and to study a wide range of multiple criteria decision-making and negotiation strategies for selecting the optimal single water harvesting project (or set of alternatives).

Determining which water harvesting and conservation alternative to pursue, the specific location to select, and the optimal project dimensions requires the involvement of multiple stakeholders, including hydrologists, policy experts, civil engineers, community leaders, environmental leaders, government officials, industry experts, and a wide range of citizen groups and local stakeholders. These parties will have a variety of interests and positions that affect the multiple criteria decision-making process.

Recent attention has focused on the use of MCA methods for water harvesting and conservation decisions. MCA consists of a set of tools to help systematically compare, select, or rank a set of alternatives according to two or more criteria. Like negotiation theory, MCA is also approximately half a century old. The focus of MCA is usually on a single decision-maker who unilaterally chooses between alternatives whose outcomes (which can be either deterministic or uncertain) differ on two or more objectives (also referred to synonymously as "criteria" or "attributes"). Until the 1980s, decision-making methods focused primarily on single objective models (usually considering only profit or cost). However, practical water harvesting and conservation infrastructure decisions are inherently multidimensional, and there are significant gains to be achieved from modeling political, cultural, social, economic, and environmental objectives simultaneously in an inclusive and iterative multiple objective negotiation, planning, and management process.

The remainder of the introduction describes how key multi-criteria concepts of this chapter are organized. In Section 2.2, the phases involved in modeling and analyzing multi-criteria water harvesting and conservation challenges are put forth. These challenges include the following phases:

- problem structuring (establishing context, hierarchical structure of value, selection of indicator variables, and an independence analysis);
- evaluation (the construction of water harvesting and conservation value functions and the identification of water harvesting and conservation rates, the identification of water harvesting and conservation alternatives, and sensitivity analyses)
- recommendation (formulation of water harvesting and conservation recommendations)

A wide number of MCA methods are discussed in the context of water harvesting and conservation projects: Over a dozen MCA methods for water harvesting and conservation are summarized in Section 2.3. This section

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also outlines the distinction between discrete and continuous MCA. The latter involves an infinite number of decision alternatives, as is often referred to in the literature as Multiple Objective Decision Making (MODM). Popular approaches include goal programming, the methods of joint tangency and the method of improving directions. These techniques can be contrasted with discrete MCA commonly referred to as multiple attribute decision-making (MADM) such as the simple additive (weighted sum) method and the analytic hierarchy process (AHP).

Water harvesting practitioners, non-governmental organizations, environmental agencies, and community groups provide feedback about the optimal MCA techniques for the identification, selection, and management of water harvesting and conservation projects (Section 2.3). The discussion (Section 2.4) analyzes the research findings and highlights the specific characteristics of the selected MCA approaches for rainwater harvesting. Section 2.5 discusses the increasing need for water harvesting MCA in the context of global climate change: it is shown that MCA constitutes an ideal set of tools for handling complex water resources bargaining and negotiations and to promote integrated socio-ecological decision-making and resilience.

Section 2.6 concludes that MCA helps water harvesting stakeholders to think about their values, and assists them in quantifying those priorities and applying them to the water harvesting and conservation challenge at hand. It is concluded that MCA approaches represent a *sina qua non* for the effective, systematic, and timely management of water harvesting and conservation projects since they inevitably involve complex tradeoffs and challenging value judgments under uncertainty. Negotiation is particularly relevant in the resolution of water harvesting conflicts, because it is often not possible or desirable for an individual to act unilaterally. It is summarized that multi-criteria bargaining and negotiation processes are important for resolving conflicts related to challenges associated with water harvesting and conservation challenges. In the last half-century, multi-criteria environmental negotiation and bargaining has emerged as a critical topic to promote the sustainability of the biosphere. The need for multi-criteria negotiations often arises in water harvesting and conservation projects when mutually desired resources are insufficient to satisfy all parties or when there is disagreement on priorities.

2.2 Introduction to MCA for Water Harvesting and Conservation Group Decision and Negotiation Support

MCA provides a structured, integrated, and comprehensive approach for summarizing and integrating varied data types and information sources that are used in water harvesting and conservation negotiations and decision support projects. The MCA approach is especially useful for examining sustainable alternatives in complex water harvesting and conservation management problems because it provides a process for integrating socioeconomic, political-environmental, cultural, and legal dimensions that are not easily included in traditional analysis methods. MCA processes have the following characteristics for assisting in water harvesting and conservation bargaining and decision support: a *transparent decision framework* (decision makers must clearly understand the process and calculation procedures); *problem formulation and value creation* (MCA methods can help decision makers to properly frame a water harvesting and conservation management problem to establish a defensible set of values), and *efficient communication* (judgments, such as attribute weights or subjective probabilities, can be discussed in a structured group setting in order to share insights, resolve conflicts, and encourage participation by all decision makers).

Since MCA is a social and managerial task, one must consider both facts and values. For instance, assessing the benefits and costs of a water harvesting and conservation project on a community and the surrounding environment raises the following questions: Should the project be subsidized by the government? Who will benefit the most from the water harvesting and conservation project? What is the tradeoff between social factors (such as employment for local workers) and environmental factors (e.g. water quality)? Moreover, intangible attributes (i.e. quality of life and environmental quality) are extremely difficult to model. Finally, one must consider the impact of new technologies and the time value of money (including discounting, and intra/intergenerational equity).

Negotiation and bargaining (joint decision-making) over water harvesting and conservation issues involves communication between two or more individuals or groups who are trying to forge an agreement for mutual benefit. However, game theory alone may not be sufficient for a water harvesting and conservation negotiator. Game theorists typically seek equilibrium outcomes that would result from strategic interactions of fully rational players with complete knowledge of the rules of the game. However, in actual negotiation situations, several plausible equilibriums or solutions may exist, with no a priori obvious way to choose among them. Also, one or more of the assumptions of game theory, such as rationality, may be violated. It may also be difficult to assign utility functions for all players, or to anticipate what moves or outcomes are possible. While game theoretic models address these problems by relaxing assumptions of strict strategic sophistication (e.g. fully rational players cognizant of all the rules of the game),

game theory has often failed to provide prescriptive theory and useful advice for water harvesting and conservation negotiators.

MCA provides a rigorous foundation to improve governance, strategy, planning, and management of water harvesting projects by helping decision makers think carefully about their values, quantifying those priorities if possible, and applying them to the group decision or negotiation problem at hand. In this way MCA also assists with understanding data and results, policies, values, and cultural shifts. A variety of procedures and theoretical concepts have been developed to help decision-makers accomplish these goals. In particular, MCA-based processes related to water harvesting and conservation project should have the following characteristics: clarity (the MCA process and calculations should be clear); feedback and user control (MCA methods should allow stakeholders to adjust judgments and to learn how value scaling, weighting, and amalgamation judgments affect decision outcomes); and efficient communication (MCA judgments, such as criteria weights or scaling factors, can be discussed in a structured group setting in order to allow for insights and perspectives to be shared and for differences of opinion to be resolved or clarified).

2.2.1 Discrete MCA for Water Harvesting and Conservation

By definition, a water harvesting and conservation MCA is typically a discrete decision problem which involves a finite number of water harvesting and conservation options. The procedural steps in a discrete multi-criteria analysis for water harvesting and conservation decisions can be arranged into three phases. The first phase involves problem structuring. This involves determining water harvesting and conservation context (i.e. contextualization). A wide number of water harvesting and conservation stakeholders should be consulted to fully articulate the decision context. These include government officials, non-governmental organizations, scientists, and community leaders. The next phase in problem structuring involves creating an organized structure of value. This is often achieved through a network or a hierarchical structure of value. Next, the specific indicators/factors in the decision problem are selected. Finally, an independence analysis is carried out to determine the type of MCA that must be performed.

The second phase in a water harvesting and conservation MCA is evaluation. Here, water harvesting and conservation objectives/criteria and options/alternatives are developed. The next step involves articulating the expected performance of each alternative against the criteria. Here, each alternative is scored to reflect the value associated with the consequences of each alternative. This may entail the construction of an evaluation matrix or formal value functions. In the case of MADM in uncertainty, von-Neumann Morgenstern utility functions also allow for the scoring of water harvesting and conservation indicators across alternatives. Keeney and Raiffa (1976) provided more details about MADM in situations of certainty and uncertainty.

Depending on the MCA technique one may need to determine the criteria scaling factors. Other approaches require assigning weights for each of the criteria to reflect their relative importance to the decision. It is then necessary to combine the weights and scores for each of the alternatives to determine the overall value. After each water harvesting and conservation project receives a preliminary score based on the base model, various sensitivity analyses are performed to determine the impact of small changes in weights and ratings on the overall project rankings. One can then re-examine the results and make further changes in scores or weights. The third and last phase (recommendation phase) involves the formulation of robust water harvesting and conservation recommendations based on the aforementioned modeling and analysis.

2.2.2 Continuous Multi-Objective Analysis for Water Harvesting and Conservation

Decision-making surrounding water harvesting and conservation projects constitutes a “messy” (complex and unstructured) problem with an evolving set of interlocking criteria and constraints; it is difficult to select a water harvesting and conservation project in a manner that provides the optimum on all criteria simultaneously, particularly since water harvesting and conservation projects are comprised of tens of thousands of decision variables. However, multi-criteria analyses and techniques can help to understand the tradeoffs between objectives and to identify alternatives that are dominated by at least one other alternative: mathematically, dominated alternatives are “inefficient” (fall below the efficient frontier). In this manner, a continuous Multi-Objective Decision Making analysis can help to find an efficient (non-dominated) water harvesting and conservation solution. For instance, in Figure 2.1, alternative P is dominated by alternatives Q, R, and W.

2.2.3 Decision Support for Water Harvesting Projects

A number of Decision Support Systems (DSS) have been designed specifically for MCA that have possible applications for water harvesting decision-making, including tools

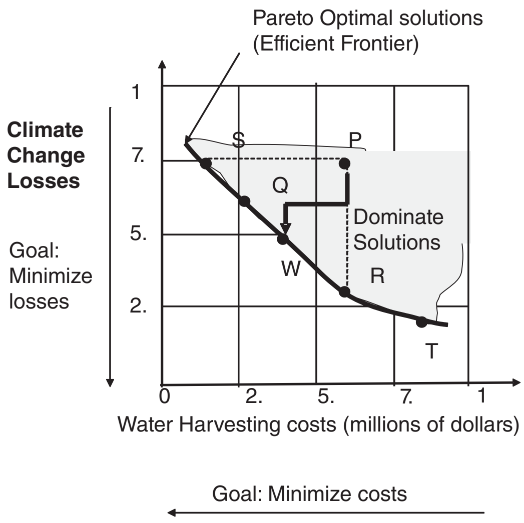


Figure 2.1 MODM and water harvesting decisions.

produced by government agencies and private companies (DNR, Agricultural Research Service, USDA, and Netstorm Pty Ltd 1999), DEFINITE (Janssen et al. 2001), and the Analytic Network Process, ANP (Saaty 1996). The DSS Facilitator (DNR, Agricultural Research Service, USDA, and Netstorm Pty Ltd 1999) was developed jointly by the Queensland Department of Natural Resource and Mines, the Agricultural Research Service of the United States Department of Agriculture, and Netstorm Pty Ltd., Toowong, Brisbane for MCA. This DSS provides a flexible and easy to understand decision framework to manage natural resource problems with multiple criteria, multiple decision makers, and various data sources (Lawrence et al. 2000). Facilitator is written in the Java language and uses algorithms and aggregation which had been developed by the USDA Agricultural Research Service in Tucson, Arizona (Lane et al. 1991; Yakowitz et al. 1992). The weighting algorithm uses the extreme value method and the aggregation is a weighted summation. Definite (Janssen et al. 2001) is a commercial multi-objective decision-support tool that includes the ability to construct hierarchies and to evaluate the options by direct assessment or by pairwise comparison. The MCA module supports a number of aggregation and weighting techniques. Designed to run on the Microsoft Windows operating system, one can carry out both cost–benefit analyses and sensitivity analyses.

2.3 MCA Techniques for Water Harvesting and Conservation Management

There are hundreds of MCA approaches in the literature, including the use of utility functions, which capture a party's willingness to accept risks. Utility theory belongs to the so-called "American School" of MCDM which is characterized by axiomatically defined utility functions and elicitation methods that are consistent with a set of assumptions about the preference structure of the decision makers. This contrasts to the "European School" of MCDM such as PROMETHEE and ELECTRE (which stands for *EL*imination *E*t *C*hoix *T*raduisant la *R*ealité), which employ pairwise comparisons. The latter approach compares two policies at a time and selects one over the other if one alternative is better in most criteria and not unacceptably worse in the remaining criteria. A third group of MCDM valuation approaches, goal programming, measures how close different alternatives come to numerically defined goals. Although it is usually applied to mathematical programming problems, it can also be used to rank discrete alternatives. A fourth group of MCDM methods, regret-based approaches, selects alternatives whose worst performance (across scenarios, relative to other alternatives) is better than the worst performance of other alternatives. Stochastic dominance constitutes a fifth group of MCDM methods. While stochastic dominance may be unable to produce complete alternative rankings it can eliminate infeasible options (those that could never be selected over other options, regardless of the party's risk attitude).

2.3.1 Overview of MCA Approaches for Water Harvesting and Conservation Projects

A number of multi-criteria methods for water harvesting and conservation projects have been applied by the author, as shown in Tables 2.1–2.4. All discrete MCDM tools show in Tables 2.1–2.4 were tested on real-world water harvesting problems that included between 4–60 attributes.

2.3.2 Water Harvesting Stakeholder Recommendations

Based on interviews with a wide range of water harvesting and conservation stakeholders including non-profit water harvesting organizations, engineers, and government agencies, the normalized scores for Deterministic MCA Ranking Methods provided in Tables 2.1 and 2.2 are given in Figure 2.2. Figure 2.3 illustrates the normalized evaluation scores for weight selection methods provided in Table 2.4, whereas Figure 2.4 shows the normalized ratings for uncertainty ranking methods provided in Table 2.5.

2.4 Discussion of Results

Based on the feedback from stakeholders it is shown that that MCA constitutes fundamental and valuable approach to enhance water harvesting and conservation projects: a MCA can address factors ranging from resource acquisition costs and ecological impacts to socioeconomic and political

Table 2.1 Deterministic ranking methods for water harvesting and conservation projects (Part I): holistic assessment, additive linear value function and revision of ranks and ratings (final holistic assessment).

Deterministic ranking method	***n* represents the number of attributes and revised weights are used except where specified.**
Initial holistic assessment	*Alternatives* in a water harvesting and conservation project ranked from most desirable (1) to least desirable (17). The alternatives in the water harvesting and conservation project rated from most desirable (1000) to least desirable (0), using the information provided by stakeholders and experts and facilitators about objectives and criteria. Performed seven times: (i) 36 attributes, (ii) 30 attributes, (iii) 20 attributes, (iv) 14 attributes, (v) 10 attributes, (vi) 8 attributes, (vii) 5 attributes.
Additive linear value functions	$\underset{j}{MAX}\ V(X_j) = \sum_{i=1}^{n} w_i v_i(x_{ij})$ $V(X_j)$ = overall value of water harvesting and conservation project j $v_i(x_{ij})$ = single criterion value function that converts the criterion into a measure of value of worth, $v_i(x_i^{**}) = 1$, $v_i(x_i^{*}) = 0$, with: $v_i(x_{ij}) = \dfrac{(x_{ij} - x_i^{*})}{(x_i^{**} - x_i^{*})}$ Additive value function applied using results of each weighting method.
Revision of ranks and ratings (final holistic assessment)	Participants were given results for all deterministic ranking methods (except fuzzy sets) and asked to provide a final set of ranks and ratings.

challenges. The participants note that water harvesting and conservation challenges are inherently complex, time-bound, and multi-faceted, typically involving many decision makers (with conflicting priorities and dynamic preferences), high decision stakes, limited technical information (both in terms of quality and quantity), and difficult tradeoffs. Accordingly the participants note that MCA and multi-criteria decision support systems (MCDSS) can help to manage this complexity and decision load by combining logistics, security, and technical information in a structured decision framework together with value judgments. It is clear from the results in Section 2.3 that two techniques were viewed as optimal for a wide range of water harvesting and conservation stakeholders: the additive weighted sum method and the AHP.

A simple additive (weighted sum) MCDA (multiple criteria decision analysis) model is often determined to be the most appropriate and tractable; such a model is compensatory: losses on one attribute are compensated by gains on another (e.g. in deciding which repository to select, some environmental quality might be given up for a lower cost). Specifically, letting s_{ij} represent the preference score of option i on attribute j, then the overall score S_i for option i is given by:

$$S_i = \sum_{j=1}^{30} w_j \bullet s_{ij} \tag{2.1}$$

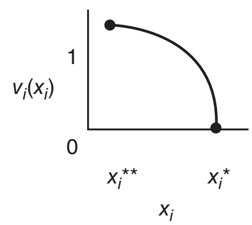
where w_j represents the weight associated with attribute j. The weights are determined based on the decision maker's value for each attribute. Equation (2.1) assumes that there are 30 attributes in total. A normalization process preserves the relative attribute weights and ensures that the final overall result produces scores on a 0–1 scale. This weighted sum (averaging) process is repeated up through the hierarchy until a single overall score was obtained for each water harvesting and conservation project site.

$$WS_i = \frac{\sum_{j=1}^{30} w_j \bullet s_{ij}}{\sum_{i=1}^{13}\sum_{j=1}^{30} w_j \bullet s_{ij}} \tag{2.2}$$

The AHP breaks down the overall rainwater harvesting or conservation objective into a hierarchy of goals, where lower levels become not only more detailed and measurable, but also more conflicting, especially if each criterion represents the interests of a specific group. For example, installing a rainwater harvesting facility may reduce ecological damage, provide an alternative water supply during water restrictions, irrigate agricultural crops, and increase local employment while causing communities to undertake costly regular maintenance costs and high upfront installation expenses (requiring stakeholders to seek loans and undertake challenging financing instruments). Thus, it is rare to find an action that is best according to all criteria, and one must search for a compromise solution (rather than an optimal one) that appropriately reconciles the various criteria. The degree to which the objectives are achieved is measured through a set of performance indicators.

The next step in an AHP case study is to estimate the set of weights using the AHP intensity scale (Table 2.5). Consider the four high-level weights in a hypothetical water harvesting or conservation shown in Tables 2.6–2.8:

Table 2.2 Deterministic ranking methods for water harvesting and conservation projects (Part II): additive non-linear value functions, goal programming, ELECTRE I, fuzzy sets, and revision of ranks and ratings (final holistic assessment).

Deterministic ranking method	***n* constitutes the number of attributes and revised weights used except where specified.**
Additive non-linear value function	Two methods were used to generate $v_i(x_{ij})$, which may be non-linear, for use in additive value function: 1) Mid-value splitting: $x_{i0.5}$ = user-specified value for attribute i that is halfway in desirability between x_i^{**} and x_i^{*}, $v_i(x_{i0.5}) = 0.5$. Linear value function used if appropriate; otherwise, a_i, b_i, and c_i found such that $v_i(x_i) = a_i + b_i \cdot exp(c_i \cdot x_i)$. 2) Users drew a value function representing $v_i(x_i)$, e.g. 
Goal programming	(a) $p = 2$, (b) $p = \infty$. g_i = user-specified maximum acceptable value for attribute i. $\underset{j}{\text{MIN}} \sum_{i=1}^{n} w_i(\text{MAX}\left(0, v_i(g_i) - v_i(x_{ij})\right))^p$ Thus, only undesirable deviations from goals are penalized.
ELECTRE I	Alternative A is superior to B (A "outranks" B) if both of the following conditions are met: 1) Concordance: $C(A,B) > P$ P = specified threshold (0.5 used in this experiment) $C(A, B) = \sum_{i \in N_i} w_i / \sum_{i=1}^{n} w_i$ N_i = set of attributes for which x_{iA} is better than x_{iB}. If there is a tie, then half of the weight is placed in the denominator. 2) Discordance: $D(A,B) \leq qi\ \forall i$ $D_i(A,B) = v_i(x_{iB}) - v_i(x_{iA})$ q_i = user-specified threshold for tolerable dissent for attribute i ELECTRE does not yield a complete ranking of alternatives. The set of alternatives that are not outranked defines a "kernel" of preferred options.
Fuzzy sets	$\underset{j}{\text{MAX}}\ \underset{i}{\text{MIN}}\ v_i(x_{ij})^{w'_i}$ w'_i = weight for attribute i, rescaled so the highest weight for any attribute is 1. $v_i(x_{ij})$ is interpreted as a fuzzy set membership function describing the extent to which j is a "good" solution in terms of attribute i. The above aggregation procedure is one of many possible implementations of fuzzy sets and is often used in electrical engineering applications.
Revision of ranks and ratings (final holistic assessment)	Participants were given results for all deterministic ranking methods (except fuzzy sets) and asked to provide a final set of ranks and ratings.

Cost (C), Labor (L), Supply of Water (S), and Environmental Impact (E). The fundamental input to the AHP is the decision maker's answers to a series of questions of the general form: "How important is criterion A relative to criterion B"? These are termed pairwise comparisons. Questions of this type may be used to establish, within AHP, both weights for criteria and performance scores for options on the different criteria. In order to derive the weights, the decision maker responds to pairwise comparison questions by asking the relative importance of the two. Responses are gathered in verbal or written form based on multiple choice (e.g. "equally important," "moderately important," and so on) and subsequently codified on a nine-point intensity scale, as follows, where 2, 4, 6, and 8 are intermediate values that can be used to represent shades of judgment between the five basic assessments.